DURABILITY, CONSTRUCTION, AND EARLY EVALUATION OF LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC) BRIDGE DECKS

By
James Lafikes
David Darwin
Matthew O'Reilly

A Report on Research Sponsored by

THE ACI FOUNDATION AND
CONSTRUCTION OF LOW-CRACKING HIGH-PERFORMANCE BRIDGE DECKS INCORPORATING NEW TECHNOLOGY
TRANSPORTATION POOLED-FUND PROGRAM
PROJECT NO. TPF-5(336)

Structural Engineering and Engineering Materials
SM Report No. 141
June 2020

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Laboratory evaluations of concrete mixtures based on specifications for low-cracking high-performance concrete (LC-HPC) incorporating internal curing (IC) and supplementary cementitious materials (SCMs) are described. In addition, the development, construction, and evaluation of four IC-LC-HPC bridge decks with IC provided by pre-wetted fine lightweight aggregate (FLWA) in conjunction with a partial replacement of portland cement with slag cement are described along with the evaluation of two Control decks without IC constructed in accordance with standard high-performance concrete (HPC) specifications in Minnesota. Bridge decks containing IC provided by pre-wetted FLWA and SCMs are also evaluated, including two bridge decks in Utah with a partial replacement of portland cement with Class F fly ash and six bridge decks in Indiana, four with IC and a partial replacement of portland cement with silica fume and either slag cement or Class C fly ash constructed in accordance with Indiana HPC specifications (IN-IC-HPC), one with IC and portland cement as the only binder, and one Control without IC.

The laboratory evaluations were performed on three groups of concrete mixtures, one for each for the first three years of IC-LC-HPC bridge deck construction in Minnesota. Variations in IC-LC-HPC mixture proportions include the amount of IC water (contents ranging from 0 to 14.1% by total weight of binder), total absorbed water content (IC water from the FLWA plus water absorbed by the normalweight coarse and fine aggregates ranging from 2.9 to 17.7% by total weight of binder), water-to-cementitious material (*w/cm*) ratios ranging from 0.39 to 0.45, and binder compositions examining the effects of using only portland cement, a 35% Class F fly ash replacement of portland cement, 27 to 30% slag cement replacements of portland cement, and a 2% addition of silica fume of cement for the mixtures containing 27 to 28% slag cement, all by total weight of binder. Tests for scaling resistance, freeze-thaw durability, rapid chloride permeability (RCP), and surface resistivity measurements (SRMs) were completed. The scaling resistance of the IC-LC-HPC mixtures was affected most by the air content, with mixtures having an air content below 7% exhibiting more mass loss than similar mixtures with more than 7% air. Including IC and slag cement did not negatively affect scaling resistance. Freeze-thaw durability was affected most by the total absorbed water content, with increases in absorbed water leading to a decrease in freeze-thaw durability. RCP and SRM results were affected most by the binder composition (specifically, including a partial replacement of portland cement with slag cement).

Experiences and lessons learned during the construction of the first four IC-LC-HPC bridge decks along with the failed placement of one deck indicate that the primary aspects of successfully implementing IC with LC-HPC include determining the moisture content of the FLWA shortly before batching and adjusting mixture proportions to maintain the target quantity of IC water (based on the FLWA absorption). Evaluation of the IC-LC-HPC decks and IN-IC-HPC decks demonstrate that low cracking can be achieved for concrete containing IC and SCMs as long as the paste content (volume of cementitious materials and water) is kept below 26%. An overlay with a paste content of 34.3% on one of the IC-LC-HPC decks exhibited high cracking within the first two years after placement. The two IC decks in Utah and one IC deck in Indiana with paste contents of 28% and 27.6%, respectively, also had high cracking. Durability issues in the form of scaling and aggregate popouts were observed during surveys of the IN-IC-HPC decks; the decks had higher IC water contents than planned (leading to a high total absorbed water content), lower air contents than the IC-LC-HPC decks, and late-season placement dates that provided minimal time for the concrete to dry prior to being exposed to freezing conditions.

Key words: bridge decks, concrete construction, cracking, durability, internal curing, low-cracking high-performance concrete, lightweight aggregate, supplementary cementitious materials

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TABLE OF CONTENTS

TITLE PAGE

ABSTRACT iii

ACKNOWLEDGEMENTS v

TABLE OF CONTENTS vii

LIST OF TABLES xiii

LIST OF FIGURES xv

CHAPTER 1 – INTRODUCTION 1

- 1.1 GENERAL 1
- 1.2 CAUSES OF CRACKING 4
  - 1.2.1 Concrete Shrinkage 4
    - 1.2.1.1 Plastic Shrinkage 5
    - 1.2.1.2 Autogenous Shrinkage 6
    - 1.2.1.3 Drying Shrinkage 8
  - 1.2.2 Thermal Cracking 9
  - 1.2.3 Settlement Cracking 10
  - 1.2.4 External Loading 11
- 1.3 TYPES OF BRIDGE DECK CRACKING 11
- 1.4 FACTORS AFFECTING BRIDGE DECK CRACKING 13
  - 1.4.1 Concrete Material Properties 14
  - 1.4.2 Environmental Conditions and Construction Methods 15
    - 1.4.2.1 Weather and Time of Casting 15
    - 1.4.2.2 Finishing 16
    - 1.4.2.3 Curing 16
  - 1.4.3 Structural Design 17
- 1.5 LIGHTWEIGHT AGGREGATES, INTERNAL CURING, AND SUPPLEMENTARY CEMENTITIOUS MATERIALS 18
  - 1.5.1 Internal Curing with Pre-Wetted Lightweight Aggregate 19
  - 1.5.2 Supplementary Cementitious Materials (SCMs) 22
    - 1.5.2.1 Slag Cement 22
    - 1.5.2.2 Fly Ash 23

1.5.2.3 Silica Fume 24
1.6 FREEZE-THAW DURABILITY OF CONCRETE MATERIALS 24
1.6.1 Cement Paste Freeze-Thaw Damage Mechanism 25
1.6.1.1 Durability Effects of Air Entrainment...26
1.6.1.2 Durability Effects of Water-Cementitious Material Ratio 27
1.6.2 Aggregate Free-Thaw Damage Mechanisms 27
1.6.3 Salt Scaling...29
1.7 PREVIOUS WORK ON APPLICATION OF INTERNAL CURING TO BRIDGE DECKS...31
1.8 OBJECTIVE AND SCOPE 34
1.8.1 Objective #1 – Laboratory Evaluations of Internally Cured Concrete Mixtures for Improved Durability 35
1.8.2 Objective #2 – Construction and Evaluation of Internally Cured Low-Cracking High-Performance Concrete Bridge Decks 36

CHAPTER 2 – LABORATORY TEST PROGRAM FOR INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) MIXTURES 37

2.1 GENERAL...37
2.2 MATERIALS...40
2.2.1 Cement 41
2.2.2 Supplementary Cementitious Materials 42
2.2.3 Coarse Aggregates..44
2.2.4 Fine Aggregates..45
2.2.5 Fine Lightweight Aggregates 46
2.2.6 Chemical Admixtures 48
2.3 TEST PROCEDURES...49
2.3.1 Compressive Strength 49
2.3.2 Scaling Resistance 50
2.3.3 Freeze-Thaw Durability and Fundamental Transverse Frequency.............................50
2.3.4 Rapid Chloride Permeability and Surface Resistivity Measurement 51
2.4 CONCRETE MIXTURES...53
2.4.1 Program 1 (2016 Mixtures)..56
2.4.2 Program 2 (2017 Mixtures)..59
2.4.3 Program 3 (2018 Mixtures) 62

2.4.4 Test Program 66
2.5 SCOPE AND SUMMARY 68

CHAPTER 3 –DURABILITY EVALUATION OF INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) MIXTURES 69

3.1 GENERAL 69
3.1.1 Scaling Resistance 70
3.1.2 Freeze-Thaw Durability 72
3.1.3 Rapid Chloride Permeability and Surface Resistivity 73
3.1.4 Statistical Analysis 74
3.2 DURABILITY TEST RESULTS 75
3.2.1 General 75
3.2.2 Program 1 79
3.2.2.1 Scaling Test Results 81
3.2.2.2 Freeze-Thaw Test Results 85
3.2.3 Program 2 86
3.2.3.1 Scaling Test Results 90
3.2.3.2 Freeze-Thaw Test Results 95
3.2.4 Program 3 100
3.2.4.1 Scaling Test Results 103
3.2.4.2 Freeze-Thaw Test Results 104
3.2.5 Discussion of the Effects of IC Water Content, Binder Composition, and *w/cm* Ratio on IC-LC-HPC Durability 107
3.2.5.1 Factors Affecting Scaling Resistance 108
3.2.5.2 Factors Affecting Freeze-Thaw Durability 110
3.3 RAPID CHLORIDE PERMEABILITY AND SURFACE RESISTIVITY OF IC-LC-HPC. 113
3.3.1 Test Results 113
3.3.2 Discussion and Test Correlation 120
3.4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 124
3.4.1 Summary 124
3.4.2 Conclusions 126
3.4.3 Recommendations 127

CHAPTER 4 - INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE BRIDGE DECK CONSTRUCTION AND CRACK SURVEY RESULTS 128

4.1 GENERAL 128
4.2 MNDOT SPECIFICATIONS FOR IC-LC-HPC 132
  4.2.1 Aggregates 132
  4.2.2 Concrete 135
  4.2.3 Construction 136
4.3 DECK CONSTRUCTION 138
  4.3.1 Aggregates 140
  4.3.2 Concrete Mixture Proportions 142
4.4 BRIDGE DECKS 145
  4.4.1 IC-LC-HPC 1 – St. Paul Pedestrian Bridge (2016) 145
  4.4.2 MN-Control 1 – St. Paul Pedestrian Bridge (2016) 152
  4.4.3 IC-LC-HPC 2 – Cannon Falls (2017) 154
  4.4.4 MN-Control 2 – Cannon Falls (2017) 161
  4.4.5 IC-LC-HPC 3 – Zumbrota (2017) 163
  4.4.6 IC-LC-HPC 4 – Minneapolis (2018) 167
4.5 FAILED IC-LC-HPC BRIDGE DECK PLACEMENT 177
4.6 CRACK SURVEYS AND RESULTS 181
  4.6.1 Cracking During the First Three Years After Placement 181
  4.6.2 Cracking as a Function of Age for IC-LC-HPC and MN-Control Decks 194
4.7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 198
  4.7.1 Summary 198
  4.7.2 Conclusions 200
  4.7.3 Recommendations 200

CHAPTER 5 – OTHER APPRACHES FOR INCLUDING INTERNAL CURING AND SUPPLEMENTARY CEMENTITIOUS MATERIALS IN CONCRETE BRIDGE DECKS 203

5.1 GENERAL 203
5.2 BRIDGES 208
5.3 CONCRETE PROPERTIES AND CONSTRUCTION PROCEDURES 208
5.4 RESULTS 215

5.4.1 IN-IC 216
5.4.2 IN-Control 218
5.4.3 IN-IC-HPC-1 219
5.4.4 IN-IC-HPC-2 223
5.4.5 IN-IC-HPC-3 226
5.4.6 IN-IC-HPC-4 228
5.4.7 UT-IC-1 and UT-IC-2 231
5.5 COMPARING PERFORMANCE 233
5.6 SUMMARY AND CONCLUSIONS 243

CHAPTER 6 - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 246

6.1 SUMMARY 246
6.2 CONCLUSIONS 247
6.2.1 Durability of Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) Mixtures 247
6.2.2 Field Evaluations 248
6.3 RECOMMENDATIONS 250

REFERENCES 252

APPENDIX A: SCALING AND FREEZE-THAW TEST DATA FOR MIXTURES IN CHAPTERS 3 265

APPENDIX B: SURFACE RESISTIVITY MEASRUREMENTS AND RAPID CHLORIDE PERMEABILITY RESULTS FOR MIXTURES IN CHAPTER 3 317

APPENDIX C: MINNESOTA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE 335

APPENDIX D: DETERMINING THE ABSPORPTION, SURFACE MOISTURE, AND TOTAL MISTURE OF FINE LIGHTWEIGHT AGGREGATES USING A CENTRIFUGE 348

APPENDIX E: TRIP TICKETS AND PLASTIC CONCRETE TEST RESULTS FOR MNDOT IC-LC-HPC AND CONTROL DECK PLACEMENTS 350

APPENDIX F: BRIDGE DECK SURVEY SPECIFICATION 355

APPENDIX G: DATA FOR EVALUATION OF BRIDGE DECK CRACKING PERFORMANCE 357

APPENDIX H: KANSAS DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC) – AGGREGATES, CONCRETE, AND CONSTRUCTION 367

APPENDIX I: INDIANA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR INTERNALLY CURED, HIGH PERFORMANCE, STRUCTURAL CONCRETE FOR BRIDGE DECKS..391

LIST OF TABLES

Table 2.1: Cement chemical analysis and physical properties 42
Table 2.2: SCM chemical analysis and physical properties 44
Table 2.3: Physical properties of coarse aggregate..45
Table 2.4: Physical properties of fine aggregate..46
Table 2.5: Physical properties of FLWA..48
Table 2.6: Program 1 mixture proportions 57
Table 2.7: Program 1 mixture properties...58
Table 2.8: Program 2 mixture proportions 61
Table 2.9: Program 2 mixture properties...62
Table 2.10: Program 3 mixture proportions 64
Table 2.11: Program 3 mixture properties...65
Table 2.12a: Tests performed on mixtures in Program 1...66
Table 2.12b: Tests performed on mixtures in Program 2...67
Table 2.12c: Tests performed on mixtures in Program 3 68
Table 3.1: Average durability test results for Program 1 mixtures..81
Table 3.2: Scaling test results for ASTM C672 and BNQ NQ 2621-900 test procedures...........85
Table 3.3: Average durability test results for Program 2 mixtures..91
Table 3.4: Average durability test results for Program 3 mixtures..103
Table 3.5: SRM and RCP and SRM results for mixtures in Program 1...................................116
Table 3.6: SRM and RCP and SRM results for mixtures in Program 2...................................118
Table 3.7: SRM and RCP and SRM results for mixtures in Program 3...................................119
Table 4.1: MnDOT specification requirements for hardened concrete properties 136
Table 4.2: Required curing method based on final bridge deck surface 137
Table 4.3: Minnesota IC-LC-HPC and MN-Control project descriptions 139
Table 4.4: Minnesota IC-LC-HPC and MN-Control project contractors.................................139
Table 4.5: Minnesota IC-LC-HPC and MN-Control deck geometry.......................................140
Table 4.6a: Coarse aggregate properties 141
Table 4.6b: Fine aggregate properties..141
Table 4.6c: FLWA properties 142
Table 4.7: Cementitious material content, water content, *w/cm* ratio, and IC water contents for Minnesota IC-LC-HPC and MN-Control decks 144

Table 4.8: Cementitious material percentages and aggregate proportions (SSD/PSD basis) 144
Table 4.9: Average Minnesota IC-LC-HPC and MN-Control concrete properties 145
Table 4.10: IC-LC-HPC-1 mixture proportions (SSD/PSD Basis)..148
Table 4.11: IC-LC-HPC-1 concrete test results...149
Table 4.12: MN-Control-1 mixture proportions (SSD/PSD Basis) 153
Table 4.13: MN-Control-1 concrete test results 153
Table 4.14: IC-LC-HPC-2 mixture proportions (SSD/PSD Basis)..156
Table 4.15: IC-LC-HPC-2 concrete test results...157
Table 4.16: MN-Control-2 mixture proportions (SSD/PSD Basis) 162
Table 4.17: MN-Control-2 concrete test results 162
Table 4.18: IC-LC-HPC-3 mixture proportions (SSD/PSD Basis)..164
Table 4.19: IC-LC-HPC-3 concrete test results...165
Table 4.20: IC-LC-HPC-4 mixture proportions (SSD/PSD Basis)..171
Table 4.21: IC-LC-HPC-4 trial batch properties for second trial placement 172
Table 4.22: IC-LC-HPC-4 concrete test results...173
Table 4.23: Minnesota IC-LC-HPC and MN-Control crack survey results 182
Table 5.1: Bridge decks..208
Table 5.2: Mixture proportions (SSD/PSD basis)..212
Table 5.3: Average plastic properties and compressive strengths 213
Table 5.4: Summary of IC and total absorbed water contents and bridge deck crack densities 216

LIST OF FIGURES

Figure 1.1: Evaporation rate monograph (ACI Committee 308 1997) 7

Figure 1.2: Major bridge deck crack types as shown on a crack map: transverse, longitudinal, diagonal, and map/random cracking (Darwin et al. 2016, Khajehdehi and Darwin 2018) 12

Figure 3.1: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 1: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratios of 0.42 and 0.39; (c) side-by-side ASTM C672/ BNQ NQ 2621-900 test procedures...84

Figure 3.2: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures in Program 1: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratios of 0.42 and 0.39. All contain slag cement...86

Figure 3.3: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing slag cement: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratio of 0.44; (c) *w/cm* ratio of 0.43; (d) *w/cm* ratio of 0.41 93

Figure 3.4: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing slag cement with a 0.45 *w/cm* ratio and an IC water content of 8.4% 95

Figure 3.5: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing either 100% portland cement or a ternary binder system with a 0.43 *w/cm* ratio or fly ash with a 0.42 *w/cm* ratio..95

Figure 3.6: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles (300 max) for mixtures in Program 2: (a) containing slag cement with a *w/cm* ratio of 0.45 (b) containing slag cement with a *w/cm* ratio of 0.44; (c) containing slag cement with a *w/cm* ratio of 0.43; (d) containing slag cement with a *w/cm* ratio of 0.41; (e) containing either 100% portland cement or a ternary binder system with a *w/cm* ratio of 0.43 or fly ash with a *w/cm* ratio of 0.42......................96

Figure 3.7: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles (2000 max) for mixtures in Program 2: (a) containing slag cement with a *w/cm* ratio of 0.45; (b) containing slag cement with *w/cm* ratios of 0.43 and 0.41; (c) containing either 100% portland cement with a *w/cm* ratio of 0.43 or fly ash with a *w/cm* ratio of 0.42 99

Figure 3.8: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 3: (a) containing slag cement; (b) containing 100% portland cement as binder..........104

Figure 3.9: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures in Program 3: (a) containing slag cement; (b) containing slag cement and 17.6% LWA total aggregate volume; (c) containing 100% portland cement as binder...107

Figure 3.10: Number of freeze-thaw cycles required to drop average E_{Dyn} below 90% of initial value vs. IC water content for mixtures containing slag cement in Programs 2 and 3 112

Figure 3.11: Number of freeze-thaw cycles required to drop average E_{Dyn} below 90% of initial value vs. total absorbed water content for mixtures containing slag cement in Programs 2 and 3 112

Figure 3.12: 28-day RCP vs. 28-day SRM results for mixtures in Programs 1-3 compared with Eqs. (2.4), (3.2a), (3.3a), and (3.4a) 123

Figure 3.13: 56-day RCP vs. 28-day SRM results for mixtures in Programs 1-3 compared with Eqs. (2.4), (3.2b), (3.3b), and (3.4b) 124

Figure 4.1: FLWA Storage for IC-LC-HPC-1 147

Figure 4.2: Finishing the IC-LC-HPC-1 deck surface 151

Figure 4.3: FLWA storage for IC-LC-HPC-2 and IC-LC-HPC-3 155

Figure 4.4: Placement, finishing, and curing setup for IC-LC-HPC-2 158

Figure 4.5: Overlay placement sequence 160

Figure 4.6: IC-LC-HPC-3 deck consolidation and finishing problems 166

Figure 4.7: Placement, finishing, and curing setup for IC-LC-HPC-3 167

Figure 4.8: IC-LC-HPC-4 finishing equipment 175

Figure 4.9: IC-LC-HPC-4 Tining and unfinished sidewalk section 176

Figure 4.10: Finished IC-LC-HPC-4 deck showing spots of uneven curing compound application 176

Figure 4.11: IC-LC-HPC-1 typical crack pattern 183

Figure 4.12: Crack map for IC-LC-HPC-1 (Survey 4) 184

Figure 4.13: Crack map for MN-Control-1 (Survey 4) 185

Figure 4.14: Crack map for IC-LC-HPC-2 (Survey 2) 188

Figure 4.15: Crack map for MN-Control-2 (Survey 2) 189

Figure 4.16: Crack map for IC-LC-HPC-3 (Survey 2) 191

Figure 4.17: Crack map for IC-LC-HPC-4 (Survey 1) 193

Figure 4.18: Poorly tined area on IC-LC-HPC-4 194

Figure 4.19: Crack densities of Minnesota IC-LC-HPC and MN-Control decks vs. deck age ..195

Figure 4.20: Crack densities of Kansas LC-HPC, Minnesota IC-LC-HPC, and Indiana IC-HPC decks vs. deck age 196

Figure 4.21: Crack densities of Kansas Control Decks and MN-Control (HPC) decks vs. deck age 198

Figure 5.1: IN-Control (Survey 2 – 93.0 months) 217

Figure 5.2: IN-Control (Survey 2 – 93.0 months) 219

Figure 5.3: Differential vertical movement of girders in IN-Control 219

Figure 5.4: IN-IC-HPC-1 (Survey 2 – 37.2 months [Placement 1], 34.7 months [Placement 2]) 221

Figure 5.5: Scaling and freeze-thaw damage on IN-IC-HPC-1....222

Figure 5.6: IN-IC-HPC-2 (Survey 2 – 56.8 months) 224

Figure 5.7: Freeze-thaw damage and aggregate pop-out on IN-IC-HPC-2 225

Figure 5.8: IN-IC-HPC-3 (Survey 2 – 43.8 months) 227

Figure 5.9: Freeze-thaw damage and aggregate pop-out on IN-IC-HPC-3 227

Figure 5.10: IN-IC-HPC-4 (Survey 2 – 35.4 months [Placement 1], 32.8 months [Placement 2]) 230

Figure 5.11: Deck surface damage on IN-IC-HPC-4....231

Figure 5.12: UT-IC-1 (Survey by BYU – 24 months, Bitnoff 2014) 233

Figure 5.13: UT-IC-2 (Survey by BYU – 24 months, Bitnoff 2014) 233

Figure 5.14: Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. deck age....235

Figure 5.15: Crack densities of Kansas Control decks and IC decks vs. deck age 236

Figure 5.16: Crack densities of LC-HPC decks and IC decks vs. deck age....237

Figure 5.17: Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. paste content 239

Figure 5.18: Crack density vs. 28-day compressive strength of concrete for Indiana and Utah IC and Indiana Control bridge decks 240

Figure 5.19: Crack density vs. slump for IN-IC-HPC and Utah IC bridge decks....241

Figure 5.20: Crack density vs. actual IC water for Indiana and Utah IC bridge decks 242

CHAPTER 1 – INTRODUCTION

1.1 GENERAL

Cracking in concrete bridge decks presents a wide array of problems for the durability of the transportation infrastructure in the U.S. Cracks provide a direct path for chlorides and moisture to reach steel reinforcement, which can initiate and accelerate corrosion, leading to concrete spalling and significant reductions in service life (Lindquist, Darwin, and Browning 2005, 2006, Darwin et al. 2016). Additionally, cracking increases the potential for freeze-thaw damage in concrete. Bridge deck deterioration due to cracking and corrosion of reinforcement has accelerated within the past 60 years with the increased use of deicing salts (Russell 2004). Although strides have been made over the past decade to address the need for repair and replacement of bridges in the U.S., 8.9% of bridges (more than 54,000) are still classified as structurally deficient (FHWA 2017), with the backlog of repair and rehabilitation costs estimated at $123 billion. Furthermore, the number of bridges that have been in service for more than 50 years is also increasing each year along with the bridges that have been in service beyond the original service life (ASCE 2017). Cracking in concrete bridge decks is a primary factor that leads to a structurally deficient rating.

The principal mechanism of cracking in concrete bridge decks is restrained shrinkage. Shrinkage is caused by volume change within cement paste (volume of cementitious materials and water) due to loss of water. Tensile stresses are induced in the concrete when a high degree of restraint is present, which is the case for bridge decks. As such, many transportation agencies have transitioned towards employing low-shrinkage concrete in new bridge decks. Thermal stresses due to differences in temperature between the concrete, formwork and girders, and ambient air are another major contributor to cracking in concrete bridge decks, particularly at early ages when the concrete is weak (Krauss and Rogalla 1996).

Extensive research on different concrete shrinkage and crack reduction technologies and construction practices has been conducted in a push towards longer service lives for bridge decks. To investigate methods of reducing crack-related problems in bridge decks, a two-phase Pooled-Fund research program at the University of Kansas (KU) entitled *Construction of Crack-Free Bridge Decks* was completed by Darwin et al. (2016). A series of 17 bridge decks (in 22 placements) in Kansas followed specifications by the Kansas Department of Transportation (KDOT) for Low-Cracking High-Performance Concrete (LC-HPC), which focused on minimizing cracking through the control of aggregates, concrete, and construction procedures. The primary characteristics of LC-HPC mixtures include low paste contents (below 25% by volume of concrete) to limit shrinkage, low slump (1½ to 3 in. [40 to 75 mm]) to mitigate settlement cracking, and limitations on compressive strength (3500 to 5500 psi [27.6 to 37.9 MPa]) to allow the concrete to creep more over time and help relieve tensile stresses. Construction procedures were also outlined in the LC-HPC specifications and include concrete temperature control to limit thermal stresses, thorough consolidation, minimal finishing, early application of curing to limit plastic shrinkage cracking, and extended curing to minimize drying shrinkage (Darwin et al. 2016). Decks constructed this study have shown a reduction in cracking compared to a series of 13 control bridge decks constructed using conventional procedures (Yuan et al. 2011, Pendergrass and Darwin 2014, Darwin et al. 2016, and Khajehdehi and Darwin 2018).

The LC-HPC and Control decks in Kansas were constructed using portland cement as the only cementitious material. Over the past decade, crack-reduction technologies have been used by other state Departments of Transportation (DOTs) in an attempt to further minimize cracking. The combination of internal curing (IC) with selected supplementary cementitious materials (SCMs) has been used to reduce bridge deck cracking (Barrett et al. 2012, Bitnoff 2014). Prior to the current study, concrete with IC and SCMs had yet to be applied in conjunction with the LC-HPC approach. Laboratory research and limited field applications have demonstrated that the use of IC provided through pre-wetted fine lightweight aggregate (FLWA) combined with slag cement (with or without small quantities of silica fume) can reduce shrinkage and subsequent cracking more than following the original LC-HPC specifications alone (Pendergrass and Darwin 2014).

Many state DOTs have shifted to specifying high-performance concrete (HPC) in bridge decks as a measure to reduce cracking and mitigate corrosion of reinforcement (Castro et al. 2011). Many HPC mixtures also contain combinations of SCMs. Although HPC mixtures are intended to limit cracking, they are more commonly associated with high compressive strengths. Concrete tends to creep less as the compressive strength increases, which can lead to increased tensile stresses and cracking (Lindquist, Darwin, and Browning 2005, 2006 and Darwin et al. 2016). Additionally, high-strength HPC mixtures are commonly associated with high paste contents and low water-to-cementitious material (*w/cm*) ratios, which can lead to an increased risk of cracking and stricter requirements for early-age curing (Russell 2004, Khayat et al. 2018). Even when low-permeability concretes are used, the concentration of chlorides at the level of steel reinforcement directly under cracks is significantly higher than in un-cracked sections, well above the minimum concentration needed to initiate corrosion (Miller and Darwin 2000, Lindquist et al. 2005, 2006). Durability may also be compromised by an increased potential for freeze-thaw damage due to cracking (Darwin et al. 2016). Durability of concrete bridge decks has become more of an issue as concrete mixtures have evolved to include more SCMs, particularly slag cement at high replacement percentages (Hooton et al. 2010, Hooton and Vassilev 2012, Amini et al. 2019).

This report describes follow-on work to the *Construction of Crack-Free Bridge Decks* project. It describes the laboratory evaluation of concrete mixtures for durability, bridge deck construction, and crack surveys during the first three years of a project to construct bridge decks with low-cracking high-performance concrete incorporating internal curing provided by pre-wetted FLWA (IC-LC-HPC) and a partial replacement of portland cement with slag cement (27 to 30% by total weight of binder). This chapter focuses on the foundations of previous studies of LC-HPC and other internally-cured high-performance concrete (IC-HPC) mixtures as measures to minimize shrinkage and cracking while maintaining overall durability and presents the objective and scope of the study.

1.2 CAUSES OF CRACKING

Cracking in bridge decks occurs when tensile stresses exceed the tensile strength of the concrete. Tensile stresses are induced by a number of causes, but the primary contributors to bridge deck cracking are a combination of volumetric changes of the concrete from shrinkage or temperature changes and restraint from composite action between the deck and girders, reinforcing steel, abutments, etc. Completely unrestrained concrete will not crack while undergoing contractions from decreasing temperatures or shrinkage (Pendergrass and Darwin 2014, Khajehdehi and Darwin. 2018). Flexural stresses do not fall into this category and are considered minimal compared to those induced by volume changes in concrete (Krauss and Rogalla 1996). This section examines the sources of tensile stress and the causes of cracking in concrete bridge decks.

1.2.1 Concrete Shrinkage

Concrete shrinkage is the primary cause of cracking in bridge decks. Shrinkage in concrete encompasses a number of mechanisms that can occur while the concrete is still plastic, within the first few days after hardening, and through long-term drying. The different shrinkage mechanisms can occur individually or simultaneously and can be worsened or mitigated through design, material properties, and construction practices. This section summarizes three types of concrete shrinkage; plastic, autogenous, and drying shrinkage.

1.2.1.1 Plastic Shrinkage

Plastic shrinkage cracking occurs in freshly placed concrete when the rate of surface water evaporation exceeds the rate at which bleed water reaches the surface. When bleed water cannot replace evaporated water on the surface, negative capillary pressures cause the cement paste to shrink, which induces tensile stresses between the surface and underlying concrete volumes (Mindess et al. 2003). Bridge decks have a large surface area to volume ratio, which makes them particularly susceptible to plastic shrinkage cracking (Pendergrass and Darwin 2014). Plastic shrinkage cracks are typically short, randomly oriented, and shallow, tapering down to narrow widths within a few inches of the surface (Krauss and Rogalla 1996). The factors that influence bleeding and plastic shrinkage cracking are well known and can be controlled during construction and shortly after placement.

Concrete with a lower bleeding rate is more susceptible to plastic shrinkage cracking, as less water reaches the surface to replace that lost to evaporation. Finer particle sizes of cement and SCMs can slow the bleeding rate. In particular, bridge deck concrete with silica fume can be particularly prone to plastic shrinkage cracking (Miller and Darwin 2000). Additionally, concrete with lower *w/cm* ratios exhibits lower bleeding rates. Chemical admixtures can also affect the rate that bleed water reaches the surface, including air-entraining admixtures (AEAs) and superplasticizers (Russell 2004).

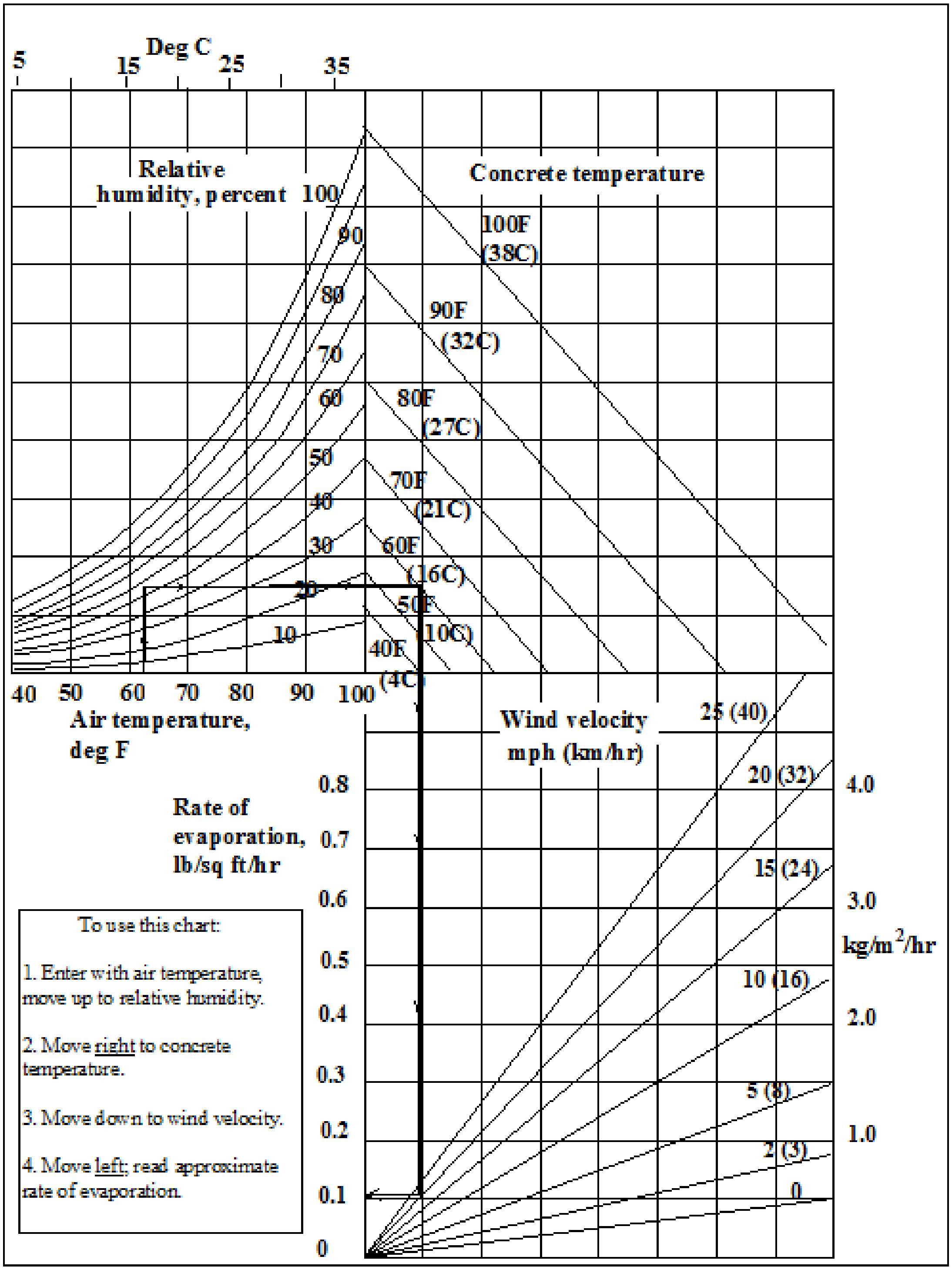
During construction, environmental conditions such as high temperature, high wind speeds, and low humidity present an increased risk of plastic shrinkage cracking. The surface water evaporation rate can be estimated using the monograph in Figure 1.1 and is often included in state

DOT specifications for bridge deck construction. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/m^2/hr), protective measures to reduce the evaporation rate are often required. Mindess et al. (2003) also indicate that concrete with SCMs should be limited to lower evaporation rates (0.1 lb/ft^2/hr [0.5 kg/m^2/hr]) to mitigate plastic shrinkage. Placing warm concrete in cooler air temperatures can particularly aggravate plastic shrinkage as this condition causes the region of air just above the deck surface to have a very low relative humidity (RH) (Krauss and Rogalla 1996, Pendergrass and Darwin 2014).

Regardless of evaporation rate, LC-HPC specifications require the early application of curing as a measure to reduce cracking. Protection from evaporation shortly after placement and finishing is an additional step during construction that helps prevent plastic shrinkage cracking (Miller and Darwin 2000, Darwin et al. 2016). Curing measures can include pre-soaked burlap, curing compounds, fog sprays, and/or plastic sheeting. Pre-wetting formwork and reinforcement shortly before placing fresh concrete helps mitigate water loss from absorption and evaporation (Mindess et al. 2003). In concrete, replacements of mix water with ice can help control the concrete temperature and chemical admixtures that promote the migration of bleed water aid in mitigating plastic shrinkage cracking.

1.2.1.2 Autogenous Shrinkage

Shrinkage that results from the self-desiccation of cement paste in a sealed system (without the loss of water to the environment) is classified as autogenous shrinkage and the reduced volume of hydration products relative to reactants (chemical shrinkage) can lead to early-age cracking (Mindess et al. 2003, Radlińska 2008). With the increasing use of low *w/cm* ratio high-strength HPC mixtures, an elevated risk of early-age cracking due to autogenous shrinkage remains (Radlińska and Weiss 2011).



To use this chart:

1. Enter with air temperature, move up to relative humidity.

2. Move right to concrete temperature.

3. Move down to wind velocity.

4. Move left; read approximate rate of evaporation.

Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

Figure 1.1: Evaporation rate monograph (ACI Committee 308 1997)

The dominant contributor to autogenous shrinkage in concrete is a low *w/cm* ratio. Below a *w/cm* of 0.42, water is consumed from the residual capillary pores, lowering the internal RH and inducing drying shrinkage and self-desiccation within cement paste. This phenomenon can also occur in dense, low-permeability concrete, particularly when silica fume is included, as the low permeability slows the ingress of external curing water (Mindess et al. 2003). Autogenous shrinkage has become a more dominant contributor with increased employment of high-strength HPC mixtures, which usually include large replacements of cement with finer particle SCMs, low *w/cm* ratios, and low permeability. In cases where external curing cannot provide the necessary water to counteract autogenous shrinkage, providing IC water through the use of pre-wetted FLWAs or superabsorbent polymers (SAP) can help maintain the volume of the gel pore space in concrete during hydration and mitigate autogenous shrinkage. In this scenario, the larger FLWA or SAP pores will release water into the surrounding cement paste prior to the loss of any water from the paste matrix (Philleo 1986, Cusson and Hoogeveen 2008, Pendergrass and Darwin 2014).

1.2.1.3 Drying Shrinkage

Shrinkage that occurs in an unsealed system where water is lost to the surrounding environment after the concrete has set is classified as drying shrinkage (Radlińska 2008). Cracking due to drying shrinkage occurs as water is drawn out of cement paste pores and evaporates from exposed surfaces. Drying shrinkage of concrete in the presence of restraint, either internal or external, induces tensile stresses that can cause cracking. Internal restraints can include steel reinforcement as well as the concrete itself when non-uniform drying occurs through the depth of a structural member. In bridge decks, as concrete dries on the surface, a moisture gradient forms through the depth of the slab, producing non-uniform stresses that can cause warping and induce tensile stresses (Khayat et al. 2018). The drying gradient is doubled when stay-in-place formwork is used (Pendergrass and Darwin 2014). External restraints include abutments and girders. Drying shrinkage occurs over a long period of time, although a majority of volume change occurs within the first three months (Pendergrass and Darwin 2014).

Concrete mixture proportions and material properties are principal factors that influence drying shrinkage, with paste content being the most dominant factor (Miller and Darwin 2000, West et al. 2010). Radlińska and Weiss (2011) note that the probability of cracking due to shrinkage depends on the degree of restraint; fully (100%) restrained concrete will begin cracking once the tensile strain do to shrinkage reaches approximately 400 microstrain while concrete with a 60% degree will begin cracking once the tensile strain due to shrinkage reaches approximately 600 microstrain. Concrete porosity also affects the amount of shrinkage. For concrete mixtures with a higher porosity (such as from a higher *w/cm* ratio), more shrinkage will occur as RH levels drop below 95% (Mindess et al. 2003). Concrete with higher *w/cm* ratios tends to exhibit higher drying shrinkage at later ages (Mindess et al. 2003, Cusson and Margeson 2009). Drying shrinkage decreases as the volume and stiffness of the aggregates increases. For concrete with lightweight aggregate (LWA), the lower stiffness of LWA will lead to higher shrinkage than concrete with only normalweight aggregates (Krauss and Rogalla 1996).

1.2.2 Thermal Cracking

Stresses between concrete and restraining elements due to temperature differentials have the potential of inducing a significant amount of cracking in bridge decks at early ages. Krauss and Rogalla (1996) and Lindquist et al. (2005, 2006) identified placements on days with high air temperatures and placing concrete that is warmer than girders, formwork, and reinforcement as primary contributors to thermal cracking. Placing concrete on warm days can lead to high thermal stresses, requiring additional steps to cool the concrete to help mitigate thermal cracking

(*Durability of Concrete Bridge Decks* 1970, Khajehdehi and Darwin 2018). Babaei and Purvis (1996) recommended a maximum temperature differential between the concrete and the girders of 22° F (12° C) “for at least 24 hours after placement” to avoid thermally induced cracks. To control thermal stresses, the concrete temperature for LC-HPC decks was required to be between 55 and 70°F (13 and 21°C). Additional measures in the LC-HPC specifications for temperature control include cooling formwork and reinforcement to below 90°F (32°C) and replacing water with ice or adding liquid nitrogen injection for hot weather placements. Procedures for maintaining concrete temperature limits during cold weather placements include warming the aggregates and providing additional insulation to formwork to maintain temperature during cold weather placements. Additional restrictions to placing LC-HPC in cold weather include a threshold on the low air temperatures and a limit on the difference between concrete and ambient temperature of 25°F (14°C) (Kansas Department of Transportation 2014b). Similar controls for concrete placement in high or low ambient temperatures are also employed by other state DOTs (Russell 2004, Hopper et al. 2015).

1.2.3 Settlement Cracking

Settlement cracking in bridge decks occurs after placement and consolidation of concrete around reinforcing steel, which induces tensile stresses above the bars and may lead to the formation of cracks. Design considerations that affect settlement cracking include reinforcing bar size, where increasing bar sizes and spacing increases settlement cracking, and concrete cover, where increasing depths of concrete above bars decreases settlement cracking (Al-Qassag et al. 2015, Ibrahim et al. 2019). Al-Qassag et al. (2015) showed that the use of fibers and rheology modifying admixtures reduces settlement cracking in a series of concrete mixtures. Further work by Ibrahim et al. (2019) showed the use of shrinkage reduction technologies including IC, SCMs, and a shrinkage reducing admixture (SRA) reduced settlement cracking using similar mixtures and test procedures. Khajehdehi and Darwin (2018) showed that poor consolidation can lead to increased settlement cracking.

1.2.4 External Loading

External loads on bridge decks include self-weight, dead loads from permanent fixtures including medians, barriers, fencing, etc., live loads from traffic or temporary construction, and snow/ice loads, which induce flexural stresses in the deck and supporting girders. Flexural cracking can be most commonly observed in negative moment regions of the bridge deck (over piers of continuous spans or near abutments that provide fixed instead of pinned end conditions). In bridge decks, however, flexural stresses have been shown to be a significantly smaller contributor to cracking than restrained shrinkage or thermal stresses (Krauss and Rogalla 1996). Schmitt and Darwin (1995) and Miller and Darwin (2000) showed that cracks have the propensity of forming in both negative or positive moment regions and are, thus, not dependent on loading conditions. In some selected instances, heavy vehicular loads (fully loaded trucks traveling from nearby mineral mines) can cause cracking an individual traffic lane, as documented by Darwin et al. (2016) and in Chapter 5.

1.3 TYPES OF BRIDGE DECK CRACKING

Most cracks in bridge decks form directly above and parallel to a reinforcing bar significantly increasing the exposure of the steel to the environment and deicing salts, which can initiate corrosion along the full length of the bar. In contrast, cracks perpendicular to a reinforcing bar result in corrosion only at isolated locations. Cracks can be categorized as transverse, longitudinal, diagonal, and pattern/map (*Durability of Concrete Bridge Decks* 1970), as shown in Figure 1.2.

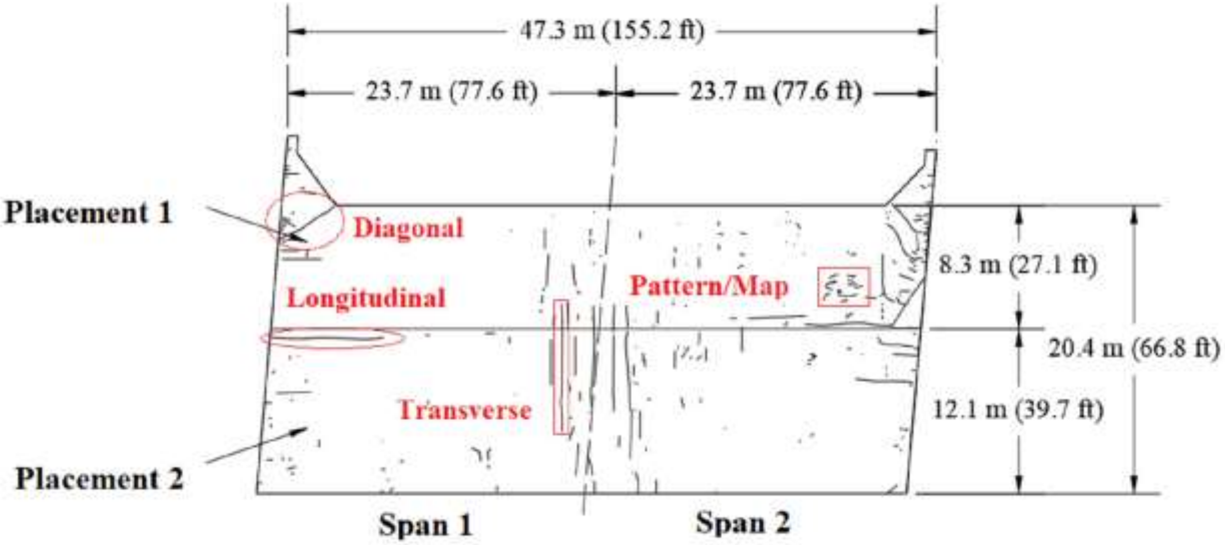


Figure 1.2: Major bridge deck crack types: transverse, longitudinal, diagonal, and pattern/map cracking (Darwin et al. 2016, Khajehdehi and Darwin 2018)

The most common type of cracks observed on bridge decks are transverse, which occur normal to the bridge span/traffic flow. This type of cracking can occur shortly after placing concrete or later in the life of the structure, usually due to restrained volume changes from thermal or shrinkage stresses; these cracks are typically located above and parallel to reinforcing bars. Transverse cracks are often full-depth and are located 3 to 10 ft (1 to 3 m) apart along the length of the bridge (Krauss and Rogalla 1995, *Durability of Concrete Bridge Decks* 1970, Pendergrass and Darwin 2014). Even when using coated reinforcing bars, transverse cracking significantly increases the risk and acceleration of corrosion (O'Reilly et al. 2011).

Longitudinal cracks occur parallel to the bridge spans and traffic flow. This type of cracking can be observed in various types of bridge decks but is more common in solid slab and hollow-core-slab bridges (*Durability of Concrete Bridge Decks* 1970). Longitudinal cracks in bridge decks primarily occur over longitudinal reinforcing bars. Similar to transverse cracking, longitudinal reinforcing bars restrain settlement of surrounding concrete and create a weakened plane over bars that elevates the risk of crack formation (Russell 2004, Pendergrass and Darwin

2014). In continuous span bridges, longitudinal cracks have a higher likelihood of forming over the piers where larger diameter reinforcing bars are used (Russell 2004). Bridge decks with integral abutments restrain the concrete in the transverse direction against volume change and exhibit more longitudinal cracking at the ends (Schmitt and Darwin 1995, Miller and Darwin 2000, Khajehdehi and Darwin 2018). For bridge decks supported by prestressed box girders, differential vertical girder movement has also induced longitudinal cracks that can extend nearly the entire bridge length (Lafikes et al. 2018, Feng and Darwin 2020).

Diagonal cracks typically occur at the abutments or over the piers of skewed bridges, although they may also appear in other locations and types of bridges. It is common to observe diagonal cracks normal to the skew angle of the bridge or pier.

Pattern or map cracks can be found in all types of concrete and bridge decks and are typically shorter and shallower than other types of cracks. Map cracks can develop at any location on the surface of a bridge deck. The most common causes of map cracking include overfinishing the concrete during placement, which raises the paste content near the surface of the deck, and plastic shrinkage due to excessive evaporation from the deck surface caused by late curing application or improper curing conditions. Map cracks commonly occur more on decks with overlays and have the potential of reducing the long-term durability of bridge decks.

1.4 FACTORS AFFECTING BRIDGE DECK CRACKING

The cracking observed on a given concrete bridge deck often cannot often be pinpointed to a single cause. Although restrained volume change from shrinkage and thermal stresses are major contributors to cracking, numerous variables in the design and construction of bridge decks play a role in dictating the severity of cracking. Previous research has identified concrete material properties, construction methods, environmental conditions, and structural design as factors that influence cracking in concrete bridge decks (*Durability of Concrete Bridge Decks* 1970, Schmitt and Darwin 1995, Miller and Darwin, 2000, Lindquist and Darwin 2005, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018). This section analyzes these factors in detail.

1.4.1 Concrete Material Properties

The paste content of the concrete is the most influential characteristic of concrete mixtures that affects bridge deck cracking. The influence of paste content has been evaluated in multiple studies, with a paste content of approximately 27% of the concrete volume being a common threshold for increased cracking (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018). The only exception to this trend can be seen with concrete that includes a shrinkage reducing admixture (SRA), which slightly increases this threshold (Feng and Darwin 2020). Even when using other shrinkage and crack reduction technologies, such as combinations of IC and SCMs, decks with paste contents higher than 27% still tend to exhibit a high degree of cracking than those with lower paste contents (Lafikes et al. 2018, Khajehdehi and Darwin 2018).

In addition to paste content, concrete slump, air content, and compressive strength have been found to affect bridge deck cracking. There have been different conclusions as to the relative significance of these variables. Independent from the increase in creep for concrete with lower compressive strength, a lower early-age compressive strength (including mixtures with SCMs) has tended to result in a reduction in bridge deck cracking (Hopper et al. 2015). The study by Khajehdehi and Darwin (2018) included a regression analysis of concrete properties and construction practices and found that while previous studies identified increases in slump and compressive strength and a decrease in air content as factors that increase cracking, these factors were often tied to high paste contents and construction-related issues and that, by themselves, these variables played significantly less of a role in affecting cracking than paste content.

1.4.2 Environmental Conditions and Construction Methods

Both environmental conditions and construction methods can impact early-age and long-term cracking of bridge decks, even when concrete with desirable material properties and low shrinkage and permeability is used (Krauss and Rogalla 1996, McLeod et al. 2009, Pendergrass and Darwin 2014, Hopper et al. 2015, Khajehdehi and Darwin 2018).

1.4.2.1 Weather and Time of Casting

Environmental conditions play a significant role in bridge deck cracking. Specifically, observations by Schmitt and Darwin (1995) and Miller and Darwin (2000) indicate that increased air temperatures and an increased range in temperature on the day of deck placement lead to increased cracking. Khajehdehi and Darwin (2018) showed that, of the two, the range in air temperature is more influential on cracking than the high temperature on the day of placement. Furthermore, the analyses by Khajehdehi and Darwin (2018) show that decks placed on warmer days exhibited less cracking through 96 months after placement than decks placed on days with lower high temperatures but with a greater temperature range. To minimize cracking due temperature effects, Krauss and Rogalla (1996) suggest placing concrete bridge decks in the early evening or night, which is supported by Khajehdehi and Darwin (2018) who observed lower crack densities in decks finished between midnight and noon compared to those finished in the afternoon or early evening.

1.4.2.2 Finishing

Finishing procedures have the potential to affect cracking. Overfinishing concrete tends to force coarse aggregate to lower depths and increase the relative paste content near the surface, leading to an increase in plastic shrinkage cracking and the potential for durability issues. Similar issues can result with delays in finishing or other conditions that expose unprotected concrete to the environment (Pendergrass and Darwin 2014). The type of finishing equipment may affect how much paste gets concentrated at the surface, with roller screeds having a tendency of overfinishing decks (Lindquist et al. 2005). The use of roller screeds, however, has become more common for bridge deck construction than vibrating screeds (ACI Committee 345 2011). Finishing operations can be affected by the workability of concrete, which can change based on additions of fibers, SCMs, or other technologies (Khajehdehi and Darwin 2018).

1.4.2.3 Curing

As discussed in Section 1.2.1, early application of curing is one of the steps that can be taken to mitigate plastic shrinkage cracking, especially in adverse weather conditions. LC-HPC specifications require curing with pre-soaked burlap applied to the deck surface within 10 minutes of strikeoff, with a second layer applied within 5 minutes of the first (Kansas Department of Transportation 2011). The duration of curing is another important aspect, with KDOT LC-HPC specifications requiring a 14-day curing period and Minnesota Department of Transportation (MnDOT) LC-HPC specifications requiring a minimum 7-day curing period. Lindquist et al. (2008) observed a decrease in drying shrinkage for laboratory specimens containing SCMs when increasing the curing period from 7 to 14 days. Similar observations were made for mixtures containing slag and IC by Reynolds et al. (2009) and fly ash by Yuan et al. (2011).

1.4.3 Structural Design

Previous studies identified structural design aspects of bridges that affect bridge deck cracking, independent of concrete material properties and construction practices. Although Schmitt and Darwin (1995) did not observe a clear relationship between structure type and bridge deck cracking, more recent studies have indicated otherwise. The use of precast stay-in-place concrete deck panels has shown mixed results in terms of cracking behavior. Russell (2004) noted the potential for reflective cracking in concrete toppings over discontinuities in the deck panels. This trend was noted for a series of decks in Utah that used this structure type (Bitnoff 2014). Contrary to those observations, Khajehdehi and Darwin (2018) noted a decrease in cracks for a series of decks supported by deck panels, although this decrease was suspected to be due primarily to the low paste content in the deck toppings.

Girder material and geometry are other factors identified as contributors to bridge deck cracking. Krauss and Rogalla (1996) indicate that support conditions and girder properties play a major role in distributing stresses based on the amount of restraint they provide. Bridge decks supported by steel girders are particularly prone to cracking, especially when shear studs are included to provide composite action and girder spacing is minimized, both of which provide a higher degree of restraint (Krauss and Rogalla 1996, Hopper et al. 2015). A study by Khajehdehi and Darwin (2018) found an increase in cracking for decks supported by steel girders compared to prestressed concrete I-girders for decks with similar concrete mixture proportions, span length, and contractor; however, that same study indicates that construction practices played even more of a role in subsequent cracking than structure type.

Krauss and Rogalla (1996) identified continuous spans, increases in span length, and fixed end conditions as factors that make decks more susceptible to cracking due to increased flexural stresses and negative bending moments. Other studies by Schmitt and Darwin (1996), Miller and Darwin (2000), Lindquist et al. (2005), and Darwin et al. (2016) did not identify these factors as significantly affecting long-term bridge deck cracking. Details such as reinforcing bar size and spacing play a more significant role in bridge deck cracking, where decks with smaller, more closely spaced bars exhibited less cracking (Schmitt and Darwin 2000). Other factors, such as an increase in deck skew, have the potential of increasing cracking due to transverse loading (Pendergrass and Darwin 2014). However, a more significant design component that tends to increase bridge deck cracking is the use of overlays. Increases in cracking in deck overlays compared to monolithic decks with otherwise similar characteristics have been noted for concrete overlay mixtures containing silica fume and conventional (100% portland cement) concrete (Miller and Darwin 2000, Lindquist et al. 2005, Khajehdehi and Darwin 2018).

1.5 LIGHTWEIGHT AGGREGATES, INTERNAL CURING, AND SUPPLEMENTARY CEMENTITIOUS MATERIALS

Although IC and SCMs have recently received attention for use in high-performance, low-shrinkage, and low-cracking concrete, these technologies have been used in the concrete industry for decades. The most common method of providing IC has been through the use of pre-wetted LWAs; however, other means include superabsorbent polymers (SAP), recycled concrete aggregates, and pre-wetted wood fibers (Bentz and Weiss 2011). SCMs have the well-known benefits of, in some cases, reduced costs relative to portland cement and as a use for what would otherwise be a waste by-product. The benefits of using SCMs include lowering CO_2 emissions associated with cement production and consumption (Khajehdehi and Darwin 2018). This section highlights the use of IC via pre-wetted LWAs, as a partial replacement of normalweight aggregate, and slag cement, fly ash, and silica fume, as partial replacements of portland cement in concrete mixtures.

1.5.1 Internal Curing with Pre-Wetted Lightweight Aggregate

Early research on the effects of IC use in concrete was performed by Klieger (1957) who noted that pre-wetted LWA holds water within the pores and releases it in the surrounding cement paste during hydration. More recent studies noticed the benefit of using IC to decrease drying shrinkage (Lindquist et al. 2008, Reynolds et al. 2009) and mitigate autogenous shrinkage (Cusson and Hoogeveen 2008). Modern applications of IC recognize it as a tool that can be used in a multitude of applications during placement through long-term improvements in concrete performance and prevention of cracking (Bentz and Weiss 2011).

Only within the past decade have guidelines been developed for including partial replacements of normalweight fine aggregates with pre-wetted FLWAs to provide IC. FLWA is often characterized by having a high absorption compared to normalweight aggregates, but the absorption can be highly variable and is dependent on the duration and method of pre-wetting (Barrett et al. 2015). For IC to be used to promote cement hydration and mitigate autogenous shrinkage, FLWAs with a fineness modulus less than 3.2 are recommended (Bentz and Weiss 2011). Fine FLWA provides for a better distribution of particles and desorption of the IC water because the maximum distance desorbed water can travel within the surrounding cement paste is approximately 0.12 in (3 mm) within the first day of curing (Henkensiefken et al. 2009, Bentz and Weiss 2011). Current recommendations for IC in mixtures with only portland cement as binder indicate a target quantity of IC water equal to 7% by weight of cement and somewhat higher values when SCMs are used to meet the increased hydration demand and/or mitigate autogenous shrinkage (Bentz and Weiss 2011, ASTM C1761). For instance, a series of internally-cured high-performance concrete (IC-HPC) bridge decks in Indiana constructed between 2012 and 2015 that contain a ternary blend of cementitious materials with pre-wetted FLWA proportioned to provide at least 8% IC water by total weight of binder (Barrett et al. 2012).

Developing mixture proportions and the amount of FLWA based on a target amount of IC water in concrete mixtures is based the FLWA absorption, desorption, and specific gravity values. Desorption is of interest when IC water is used to offset autogenous shrinkage and should be accounted for in cases where IC water is needed during early-age hydration and mitigation of autogenous shrinkage, where the internal RH is still well above 90% in the concrete (Weiss and Montanari 2017, Khayat 2018). During testing of different types of commercially available FLWAs, Castro (2011) and Khayat (2018) found that the desorption values were all near or above 85% at RH levels around 93% and rapidly approached 100% as the RH decreased below 90%. Using these parameters, the design weight of FLWA per yd^3 of concrete can be expressed as

$$M_{FLWA} = \frac{C_f \times IC}{\phi \times \lambda} \tag{1.1}$$

where M_{FLWA} = Amount of oven-dry FLWA (lb/yd^3)
C_f = Amount of cementitious materials (lb/yd^3)
IC = Percentage of internal curing water (7 or 8% by total weight of binder)
ϕ = FLWA absorption (based on pre-wetting method and duration, oven-dry basis)
λ = FLWA desorption at specified RH

Concrete transport properties, defined as the ability of ions and solution to move through a medium, are heavily influenced by the concrete pore structure and are characterized by permeability, diffusion, and absorption properties (Castro et al. 2011). In particular, permeability is often used as an indirect measurement of concrete durability with performance-based testing being included in recent high-strength and IC-HPC specifications (Moradllo et al. 2018). Aside from any reductions in cracking, concrete bridge deck mixtures with IC can be used to improve bridge deck service life through decreased permeability, slowing the rate of chloride ingress. The

IC-HPC bridge decks in Indiana introduced above were cast with mixtures that were intended to slow chloride ingress by using a combination of IC and a ternary binder system, with the goal of delaying the onset of corrosion to 90 years (Barrett et al. 2015). However, as noted in Section 1.1, mitigation of cracking is paramount to mitigate corrosion and the benefits of low-permeability concrete can be negated with the presence of cracks.

Another application for IC in bridge decks is an increase in hydration and earlier development of tensile and compressive strength compared to mixtures without IC (Bentz and Weiss 2011, Castro 2011). To compound the effects of improved durability and decreased permeability, lower *w/cm* ratios can be used with IC and SCMs without an elevated risk of early-age cracking due to autogenous shrinkage (Cusson and Hoogeveen 2008). Although lower *w/cm* ratios are accompanied by higher strength concrete with less creep, these negative effects are offset by a reduction in elastic modulus due to the additions of FLWA (de la Varga et al. 2012).

Regardless of the *w/cm* ratio, binder composition, or exposure condition, IC provides a benefit in fresh and hardened concrete by reducing shrinkage. IC can be used as a measure to prevent plastic shrinkage cracking. In this scenario, internal stresses will draw water from the larger pores of the FLWA before the water in the cement paste capillaries (Barrett et al. 2015). For moderate *w/cm* ratios (0.42 to 0.45), IC water that is not used for cement hydration or mitigation of autogenous shrinkage or plastic shrinkage cracking can be used to decrease drying shrinkage. Similar to the application for preventing plastic shrinkage cracking, water will be drawn from the larger FLWA pores prior to water being drawn from the cement paste, preventing volume change due to changes in cement paste volume (Bentz and Weiss 2011, Castro 2011, Barrett et al. 2012).

1.5.2 Supplementary Cementitious Materials (SCMs)

To slow down the ingress of chlorides and improve concrete durability, the addition of SCMs such as ground granulated blast furnace slag (slag cement), fly ash, and silica fume as partial replacements of portland cement have become common in concrete bridge deck mixtures (Russell 2004). Reduced permeability and ion conductivity have been observed with increasing replacement levels of portland cement with SCMs in studies by Wee et al. (2000), Hooton and Vassilev (2012), O'Reilly et al. (2017a), Moini et al. (2019), and Obla (2019). For these SCMs, however, curing application and duration becomes a significant factor in achieving low-shrinkage, low-permeability concrete.

1.5.2.1 Slag Cement

Slag cement is a by-product from the production of pig iron and is produced when molten slag is rapidly cooled by quenching to form a hydraulically active calcium aluminosilicate glass. Particles are then ground to sizes typically smaller than portland cement. Depending on the slag activity index, slag cements are classified into three grades (80, 100, and 120) with increasing grades typically being associated with finer particle sizes (Mindess et al. 2003).

The benefits of including slag cement in concrete include greater long-term strength gain, decreased permeability due to denser pore structure, and better control of the heat of hydration compared to mixtures with 100% portland cement (Russell 2004). However, mixed results have been noted for bridge decks concrete containing slag cement, particularly with regard to durability. Scaling test results have indicated both notably poor and similar performance to control mixtures containing 100% portland cement (Hooton et al. 2008, Hooton and Vassilev 2012, Taylor and Wang 2014). In these studies, variations in test (or construction) procedures, particularly curing time, have resulted in significantly different results. Work by Amini et al. (2019) examined scaling of concrete mixtures with 0, 20 and 40% replacements of portland cement with slag cement and found similar mass losses between mixtures with 0 and 20% slag cement and slightly higher mass losses for the 40% slag mixtures.

Shrinkage of concrete containing slag cement is largely dependent on the extent of curing. Tazawa et al. (1989) identifies the pore structure of concrete as being closely related to shrinkage; increased curing time results in concrete with slag cement achieving a smaller total pore volume than mixtures with 100% portland cement but with a larger volume of finer pores, resulting in a decrease in shrinkage. For concrete with high volumes of slag cement, water demand, particularly at lower *w/cm* ratios, can lead to autogenous shrinkage and cracking at early ages if adequate curing is not applied (Bentz and Weiss 2011, Shen et al. 2019). In terms of drying shrinkage, Yuan et al. (2011) observed decreased shrinkage in mixtures containing slag cement, while Pendergrass and Darwin (2014) noted reductions in shrinkage when combining slag cement and IC.

1.5.2.2 Fly Ash

Fly ash is a by-product from the burning of coal in power plants. There are two classes of fly ash: C and F. Class C fly ash contains higher levels of calcium oxide from the burning of lignite coals; Class F fly ash has higher levels of silica and is produced from the burning of bituminous and subbituminous coals (Mindess et al. 2003). The benefits of using fly ash include lower costs– approximately half that of portland cement, increased workability due to spherical particle shape, mitigation of the alkali-silica reaction, reduced permeability, and increased resistance to sulfate attack (Mindess et a. 2003, Russell 2004). Concrete with partial replacements of portland cement with fly ash has a higher water requirement for the paste to fully hydrate, and curing time can significantly affect performance (de la Varga et al. 2012). Yuan et al. (2011) noted that concrete mixtures with 40% volume replacements of portland cement with Class F fly ash required at least

28 days of curing to exhibit decreased shrinkage compared to 100% portland cement mixtures. de la Varga et al. (2012) used IC in mixtures with high fly ash contents and noted decreases in autogenous and drying shrinkage along with heat of hydration.

1.5.2.3 Silica Fume

Silica fume consists primarily of silica and is a by-product of the production of silicon metal and ferrosilicon alloys. Its physical characteristics include very small, spherical particles, on the order of 100 times smaller than portland cement (Mindess et al. 2003). Silica fume is often used to increase the strength and reduce the permeability of concrete. Apart from the pozzolanic effects, silica fume also acts as a filler due to its small particle size, filling in voids between larger cement particles and densifying the pore structure, particularly around the interfacial transition zone (ITZ) adjacent to aggregate particles (Mindess et al. 2003). Due to the low permeability of concrete with silica fume, it is often used in bridge deck overlays to slow chloride ion penetration and subsequent initiation of corrosion. The overlays, however, often exhibit a high degree of cracking (Miller and Darwin 2000, Russell 2004). Cracking in silica fume overlays and decks can largely be attributed to the water demand of silica fume, which is greater than that of slag cement and fly ash (Bentz and Weiss 2011), although overlays, in general, tend to crack due to restraint provided by the subdeck. Under ideal curing conditions where the water demand is fully met (particularly when including IC), previous work by Pendergrass and Darwin (2014) and Khajehdehi and Darwin (2018) found that partial replacements of portland cement with both slag cement and silica fume resulted in significant reductions in drying shrinkage.

1.6 FREEZE-THAW DURABILITY OF CONCRETE MATERIALS

If not allowed to dry periodically, concrete subjected to repeated cycles of freezing and thawing in moist conditions will eventually deteriorate if the entire pore system becomes saturated.

The critical degree of saturation is the point at which enough water has been absorbed into the concrete pore system that damage occurs upon freezing (Moradllo et al. 2019). Exposure to deicing chemicals can exacerbate this phenomenon as the chemical solutions increase the degree of saturation of the concrete at the surface (Esmaeeli et al. 2015). This damage can be mitigated if the concrete is allowed to dry. The age of concrete, particularly the time spent curing, also helps mitigate damage, as longer curing times result in an increased degree of hydration, increased compressive strength, and decreased permeability. Concrete placements, however, do not always have the advantage of receiving adequate curing, followed by long drying periods. Early-age damage can occur for concrete placed within a few months of the onset of cold weather, as the concrete is subject to freezing conditions and exposure to deicing chemicals without a chance to fully cure or dry. The effects of freeze-thaw damage are further accelerated by the presence of cracks, which expose more of the concrete to moisture and chlorides. This section highlights freeze-thaw mechanisms in the cement paste and aggregates and describes the phenomenon of salt scaling and examines the effects of concrete physical properties on durability.

1.6.1 Cement Paste Freeze-Thaw Damage Mechanism

Freeze-thaw durability within the cement paste matrix in concrete is directly related to porosity, movement of pore water, and solute concentration within the pore water. In concrete without air entrainment, significant damage can occur within a few freeze-thaw cycles as osmotic pressures create volumetric expansions within the pore structure and cause cracking within the paste. Smaller pores, or more accurately, smaller pore diameters lower the freezing point of water in concrete to below 32° F (0° C). Within concrete and cement paste, water travels towards freezing sites within larger pores, which have a higher freezing temperature than smaller pores (Powers 1975). During this process, dilation occurs and incudes tensile stresses within the capillaries, which can create cracks. As temperature are lowered and maintained for longer durations, more damage will occur.

The two processes that cause freeze-thaw damage within the paste are osmotic pressure and water desorption. In larger pores, water in the pore solution will freeze first, which increases the concentration of the remaining solution near the ice. Osmotic pressure draws water from smaller pores, which have a lower concentration solution, toward the higher concentration solution in larger pores. The resulting osmotic pressure creates tensile stresses in the surrounding paste and can induces cracking. Desorption of water occurs in the smaller pores. Separate from osmosis, the chemical potential of water is greater than that of ice, which creates lower vapor pressures within the pores containing ice and promotes movement towards the freezing sites to maintain equilibrium. This results in shrinkage in unfrozen areas and expansion at freezing sites, which leads to cracking (Powers, 1975, Mindess et al. 2003).

1.6.1.1 Durability Effects of Air Entrainment

The importance of air entrainment in durability has been well-known for decades, where tests for freeze-thaw and scaling have shown that non-air entrained mixtures exhibit significantly more damage in fewer cycles than air-entrained concrete (Klieger and Hanson 1961). Adequate entrained air helps protect against freeze-thaw damage by providing empty spaces for water to travel to and freeze rather than within the pores. Entrained air contents approximately equal to 9% of the mortar fraction or 2 to 8% (depending on the aggregate size and content) of the concrete fraction are optimal to protect against freeze-thaw damage (Mindess et al. 2003). For air entrainment to improve durability, however, an adequate distribution of air bubbles is also critical in ensuring that water within capillary pores can be drawn into a nearby air void. Research indicates that the air void spacing factor, or average distance between air bubbles, should be below

0.008 in. (0.2 mm) to provide adequate protection (Mindess et al. 2003). Compatibility of admixtures can affect the air void system in concrete (Russell 2004). While plastic air contents may indicate adequate durability, interactions between certain combinations of SCMs and chemical admixtures can result in significant decreases in hardened air content and increases in the air void spacing factor, leading to durability failures (Pendergrass and Darwin 2014, 2017). LC-HPC specifications require air contents between 6.5 and 9.5% with no limit on air void spacing specified (Kansas Department of Transportation 2014b).

1.6.1.2 Durability Effects of Water-Cementitious Material Ratio

Apart from an adequate air void system, the *w/cm* ratio is another influential parameter in concrete durability at a given age and curing condition. As the *w/cm* ratio increases, the volume and size of capillary pores increase, as does the air void spacing factor. As a result, permeability increases (Mindess et al. 2003). As the *w/cm* ratio decreases, the opposite occurs, producing a denser pore structure that lowers the amount of absorbed water and slows the ingress of additional water. For this reason, many high-strength HPC mixtures are designed at lower *w/cm* ratios to decrease permeability and improve durability. Specifications for bridge deck concretes often include a maximum *w/cm* ratio to maintain adequate resistance to freeze-thaw damage (Russell 2004). For LC-HPC decks, a maximum *w/cm* ratio of 0.45 is listed in the concrete specifications.

1.6.2 Aggregate Free-Thaw Damage Mechanisms

Even when concrete contains an adequate air void system, dense pore structure, and relatively dry paste matrix, freeze-thaw damage can still occur when aggregate particles become saturated and fail (Powers 1975). Aggregate pores are typically larger than cement paste pores and, thus, have a freezing point at or near 32º F (0º C). Freeze-thaw damage within aggregates occurs due to hydraulic pressures from the formation of ice within aggregate pores. This pressure is relieved when excess water is expelled from the aggregate, but in larger aggregates, the long distance pore water must travel leads to unrelieved hydraulic stress sand fracture of the aggregate. Aggregates with fine pores, high absorption, and high permeability are more susceptible to freeze-thaw damage. In a parallel scenario, the water expelled from the aggregate is forced into the surrounding cement paste, which can cause cracking at the paste-aggregate interface and significantly increase permeability (Mindess et al. 2003).

Freeze-thaw durability of LWAs is of particular concern due to the highly porous structure of the materials. For mixtures with IC, when a greater amount of water is held within the LWA, more water will be forced into the surrounding cement paste upon freezing (Cusson and Margeson 2010, Jones et al. 2014). A study by Klieger and Hanson (1961) serves as major groundwork on the durability of concrete with different types of LWA. One important finding established that concrete with lightweight aggregate can perform much like mixtures containing normalweight aggregates when properly air entrained. For non-air entrained concrete, however, mixtures with LWA exhibits more freeze-thaw damage when the aggregate is pre-wetted prior to batching concrete. In a more recent study, Jones et al. (2014) examined the freeze-thaw durability of concrete mixtures with IC at *w/cm* ratios of 0.42 or 0.45 and only noted failures of mixtures that contained two times or more the amount of IC water needed to mitigate chemical and autogenous shrinkage at lower *w/cm* ratios and concluded that appropriate FLWA and IC contents do not present issues in freeze-thaw durability. In a study by Feng and Darwin (2020), increasing the amount of IC water from 5.3 to 9.7% (by total weight of binder) led to a decrease in the number of freeze-thaw cycles needed to produce damage in test specimens.

1.6.3 Salt Scaling

Concrete with durable aggregates and proper air entrainment can still exhibit surface damage (scaling) when exposed to deicing chemicals (salts) and freeze-thaw cycles. Deicing salts are used in high volumes on bridge decks during winter months to reduce the freezing point of water and provide a safer route for vehicular travel. The vapor pressure of a salt solution is lower than that of pure water, which lowers the evaporation rate and increases the degree of saturation near the surface of the concrete relative to areas not exposed to salt solution. The increased moisture near the surface can promote the formation of ice lenses that can fracture paste and mortar particles. Deicing salts can also create a rapid drop in temperature below the concrete surface when applied, which can cause damage due to a difference in thermal strains as well as encouraging freezing. Furthermore, deicing salts can increase the solute content of the concrete pore solution and increase the freeze-thaw damage from osmotic pressures (Mindess et al. 2003). Scaling damage is progressive and consists of small flakes or chips being removed from the surface, eventually exposing coarse aggregates and causing larger popouts. Scaling resistance can be significantly improved by providing adequate air entrainment, which improves general freeze-thaw resistance and reduces bleeding and thereby strengthens the concrete surface (Valenza and Scherer 2007b).

The “glue spall” mechanism has been proposed as a primary cause of scaling, which is analogous to the phenomena that occurs during epoxy-coated glass production. In concrete, glue spall refers to the contraction of the surface concrete relative to the underlying substrate of concrete due to the presence of a salt solution on the surface. As the salt solution freezes, a brine/ice layer forms on the concrete surface, which undergoes a drop in temperature relative to the underlying concrete, inducing tensile stresses and subsequent cracking on the surface. Scaling will not occur without the presence of a solution on the concrete surface (Valenza and Scherer 2007a). Including SCMs in concrete can affect the scaling performance of concrete depending on the time of curing and replacement level. SCMs that increase bleeding, delay strength evolution of the surface concrete, and reduce the initial bound water demand (such as fly ash and slag cement), tend to worsen scaling damage (Valenza and Scherer 2007b).

Depending on the test procedure (and more specifically, the type of de-icing chemical) used to evaluate scaling resistance, the extent of the reduction in scaling resistance varies depending on the type and replacement level of SCM. In studies by Talbot et al. (1996) and Bouzoubaâ et al. (2008), mixtures containing fly ash exhibited more scaling than control mixtures (those containing only portland cement as binder); scaling also increased as the fly ash content increased. In studies by Bouzoubaâ et al. (2008) and Hooton and Vassilev (2012), concretes with slag cement contents of 20 and 23% (by weight of binder), respectively, exhibited less scaling compared to control mixtures, while concretes with slag contents of 31% and above exhibited increased scaling compared to control mixtures. Pendergrass and Darwin (2014) noted that the addition of silica fume to mixtures containing 30% slag cement (by volume of binder) resulted in increased scaling; scaling also increased as the silica fume content increased from 3 to 6%.

The effect of IC and SCMs on scaling resistance were evaluated in studies by Pendergrass and Darwin (2014) and Feng and Darwin (2020), both of which noted greater scaling in concretes containing both IC and SCMs than control mixtures. Furthermore, concretes containing IC with only portland cement as binder did not exhibit an increase in scaling, and increasing the amount of IC water from 5.3 to 9.7% by weight of binder in concretes containing slag and silica fume did not result in additional damage (Feng and Darwin (2020). Jones et al. (2014) observed that the scaling resistance of concretes containing 20% Class F fly ash (by weight) was not negatively affected by increasing quantities of IC.

Scaling damage is affected by the concentration of salt solution. In a study by Verbeck and Klieger (1956), sodium chloride and calcium chloride concentrations of 2 to 4% were observed to produce the greatest amount of scaling damage. Higher concentrations lead to a reduction in freezing temperature and softened the ice layer in the underlying substrate, reducing stresses and preventing damage (Valenza and Scherer 2007a). Scaling damage can be worsened during construction if the concrete is over finished or over consolidated resulting in higher paste contents and air-void spacing factors near the surface. As with the conventional freeze-thaw mechanism, the best measures to improve scaling resistance in concrete is to provide air entrainment, which helps reduce bleeding in fresh concrete, relieves vapor pressures, and provides freezing sites outside of the cement paste capillaries in hardened concrete. Furthermore, lower *w/cm* ratios help lower permeability and ingress of salt solutions into the concrete (Mindess et al. 2003, Valenza and Scherer 2007a).

1.7 PREVIOUS WORK ON APPLICATION OF INTERNAL CURING TO BRIDGE DECKS

The conclusions reached in the Kansas LC-HPC bridge deck study identified cementitious material and paste content, concrete temperature control, slump, consolidation, finishing, and curing as the major contributors to bridge deck cracking (Darwin et al. 2016). The LC-HPC decks constructed for this study did not use any additional crack reduction technologies and combinations of crack reduction technologies have not yet been evaluated. In a parallel study that included Kansas LC-HPC data, Khajehdehi and Darwin (2018) identified cement paste content and ambient temperature change on the day of placement as the principal contributors to bridge deck cracking, while slump and compressive strength did not significantly affect cracking on their own. In both studies, however, good construction practices were highlighted as significant in minimizing bridge deck cracking. Regardless of the use of low-shrinkage/low-cracking concrete mixtures and technologies, poor construction practices–bridge decks that were not consolidated properly, had workers walk through previously consolidated concrete, were over finished, or had delayed curing–resulted in higher amounts of cracking.

Extensive research on concrete with IC has been conducted for HPC mixtures with low *w/cm* ratios that are subject to self-desiccation and autogenous shrinkage (Castro et al. 2011, Barrett et al. 2012, and Jones et al. 2014). Until recently, however, only limited experimental work has been conducted on IC for concrete with moderate *w/cm* ratios, such as used for bridge decks (including values of 0.43 to 0.45, as used in LC-HPC construction), where autogenous shrinkage is not a concern (Khayat et al. 2018). The use of IC for concrete with *w/cm* ratios above 0.42 has been shown to provide benefits in reducing both drying shrinkage and early-age cracking (Schlitter et al. 2010, Pendergrass and Darwin 2014, and Khajehdehi and Darwin 2018). In addition to evaluating early-age drying shrinkage, Khajehdehi and Darwin (2018) developed procedures for free shrinkage testing to observe swelling effects of IC and SCMs after final set in a series of concrete mixtures and demonstrated that the addition one or both resulted in more swelling than control mixtures (without IC or SCMs). The additional swelling further reduces the total deformation that occurs through the drying period and demonstrates the benefits of IC and SCMs as means to reduce shrinkage.

Although mixtures with IC at moderate *w/cm* ratios have exhibited less early-age drying shrinkage compared to mixtures without IC, there is still some debate on the overall durability performance of concrete with IC. In a study by Schlitter et al. (2010), mortars with IC did not show any significant reduction in freeze-thaw durability compared to control mixtures; however, the amount of IC water relative to the cement content was not more than 5.3% of the total weight of cement, which is lower than the 7% recommended by Bentz and Weiss (2011) and ASTM C1761. Work by Jones et al. (2014) demonstrated that for a series of concrete mixtures with moderate *w/cm* ratios, including twice or more the amount of IC water needed to offset the amount of water lost during early-age hydration of cement led to freeze-thaw damage in significantly fewer cycles than mixtures with only enough IC water to counteract chemical and autogenous shrinkage (and mixtures without IC). While Jones and Weiss (2014) indicate that significantly higher amounts of pre-wetted LWA and IC water can lead to early freeze-thaw damage, they did not discuss the point at which freeze-thaw durability becomes a concern. Moreover, evaluation of the effects that incremental increases of IC water have on the durability of concrete has yet to be completed and no upper limits for IC water have been defined for use in bridge decks.

Castro et al. (2011) showed that IC increased the degree of hydration for a series of concrete mixtures, especially as the *w/cm* decreased. Along with an increased degree of hydration, Castro et al. (2011) also observed that concrete with IC also had a denser pore structure, which in turn improves durability performance. In another study, Khayat et al. (2018) varied the amount of FLWA/IC water in a series of bridge deck and paving mixtures and found that higher amounts resulted in higher surface and bulk resistivity values (measures of ion conductivity within the concrete) compared with control mixtures particularly when specimens received shorter durations of wet curing.

Bridge decks with IC and SCMs have been constructed in a number of states but have shown mixed results to date in terms of cracking in the years after construction. di Bella et al. (2012), Bitnoff (2014), and Barrett et al. (2015a) discussed implementation of IC in a series of bridge decks in Indiana and Utah. For these projects, concrete mixture proportioning and the amount of IC water depended on the handling and storage of the FLWA. For some of the IC decks in Indiana, a higher amount of IC water than originally planned was provided; in some cases, the IC water exceeded design amounts by almost 50%. In a study comparing cracking of these bridge decks between two and seven years after construction, Lafikes et al. (2018) noted higher paste content as the primary factor driving cracking in the first two to three years after construction, regardless of the amount of IC water. Lafikes et al. (2018), however, also noted a potential for increased scaling and freeze-thaw damage in decks with higher amounts of IC water.

1.8 OBJECTIVE AND SCOPE

The purpose of this study is to evaluate concrete mixtures with internal curing (IC) with supplementary cementitious materials (SCMs) in conjunction with low-cracking high-performance concrete (LC-HPC) specifications as an approach to improve bridge deck service life by way of laboratory testing for concrete durability and transport properties and field evaluation of bridge decks. Freeze-thaw tests are performed in accordance with ASTM C666 (Procedure A). Scaling tests are performed in accordance with ASTM C672. As a supplemental indicator for concrete durability, indirect evaluations of transport properties are made based on rapid chloride permeability (RCP), performed in accordance with ASTM C1202, and surface resistivity measurements (SRMs), performed in accordance with AASHTO TP-95 and Kansas Test Method KT-79. Bridge decks containing IC and SCMs are evaluated based on documentation of the construction and crack survey results for 10 bridge decks, plus several control decks. The two objectives of this study are outlined below.

1.8.1 Objective #1 – Laboratory Evaluations of Internally Cured Concrete Mixtures for Improved Durability

The first objective of this study involves the evaluation of concrete mixtures cast in the laboratory using the same materials as three IC-LC-HPC bridge decks placed in Minnesota from 2016 to 2018. Mixtures are evaluated using three programs based on mixtures used for IC-LC-HPC bridge decks; variables include *w/cm* ratio, amount of IC water, and cementitious material/binder composition. A total of 64 concrete mixtures are evaluated, 45 of which have the same slag cement content as the IC-LC-HPC bridge decks. To serve as a comparison to the mixtures containing slag cement and evaluate the effects of including different binder compositions on durability, 10 mixtures include only portland cement, 6 mixtures contain a ternary blend of slag cement, silica fume, and portland cement, and 3 mixtures contain Class F fly ash and portland cement. Mixtures that do not include IC water are included to serve as controls. The IC water contents range from 5.5 to 14.1% for mixtures containing slag cement, 3.8 to 11.8% for mixtures containing only portland cement as the binder, 8.2 to 8.9% for mixtures containing a ternary binder composition, and either 8.9 or 9% for the mixtures containing fly ash.

Freeze-thaw tests are performed on 54 mixtures. Scaling tests are performed on 52 mixtures. Both ASTM C672 and BNQ NQ 2621-900 test are performed on two mixtures to compare results for these two procedures. These tests help quantify the effects of IC on concrete durability and better identify an acceptable range of IC water for future IC-LC-HPC bridge decks. RCP tests are performed at 28 and 56 days after casting for 45 mixtures. SRMs are taken 28 days after casting on all 64 mixtures. Correlation between RCP and SRM is evaluated.

1.8.2 Objective #2 – Construction and Evaluation of Internally Cured Low-Cracking High-Performance Concrete Bridge Decks

The second major objective of this study is to evaluate the effects on cracking of concrete containing IC and SCMs when used in conjunction with high-performance concrete (HPC) specifications. Modifications to the LC-HPC specifications since the completion of the first series of LC-HPC bridge decks placed in Kansas between 2005 and 2011 include the additions of IC and SCMs implemented in four bridge decks placed in Minnesota between 2016 and 2018. Crack surveys up to the first three years after construction (or the latest data available, for decks less than 3 years old) are used as a preliminary estimate for long-term performance. Two decks that were cast following current MnDOT HPC specifications serve as controls. The combination of internal curing and SCMs is also evaluated based on crack surveys for bridge decks in Indiana and Utah, which were not constructed according to LC-HPC specifications. The conclusions based on this objective can aid in the construction of future IC-LC-HPC decks.

CHAPTER 2 – LABORATORY TEST PROGRAM FOR INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) MIXTURES

2.1 GENERAL

Internal curing (IC) in concrete refers to water held within the pores of non-cementitious materials, typically fine lightweight aggregate (FLWA) or absorbent polymers, during mixing that is released into the surrounding cement paste during hydration and drying to decrease shrinkage and improve concrete properties compared to mixtures without IC. Chapter 1 introduced IC, along with the results of previous studies on the effects of IC for high-strength high-performance concrete (HPC) mixtures, which commonly contain partial replacements of portland cement with combinations of supplementary cementitious materials (SCMs) and low water-to-cementitious material (*w/cm*) ratios. Separate from IC and HPC, Chapter 1 discussed the benefits of employing low-cracking high-performance concrete (LC-HPC), which previously did not include the use of IC or SCMs, as an effective measure to reduce long-term cracking in bridge decks. Although the benefits of IC, SCMs, and LC-HPC are well-documented, gaps still remain in the evaluation of the combination of all three approaches for providing durable, low-cracking concrete in bridge decks, especially with full-scale field evaluations. Furthermore, current research on concrete with IC has yet to examine the effects of different amounts of IC water at the moderate *w/cm* ratios (0.43 to 0.45) specified in the LC-HPC specifications. This study aims to bridge these gaps and identify appropriate amounts of IC water for use in future IC-LC-HPC bridge decks by evaluating both laboratory mixtures (Chapters 2 and 3) and bridge decks that contain combinations of IC and SCMs (Chapters 4 and 5).

Performance-based specifications for concrete durability typically include tests for scaling resistance and freeze-thaw durability. Although scaling resistance and freeze-thaw durability are different properties, satisfactory performance in both helps ensure that a concrete mixture is suitable for use in bridge decks. The previous studies on scaling presented in Chapter 1 indicate that high replacements of portland cement with supplementary cementitious materials (SCMs) pose a risk for increased scaling damage (Talbot et al. 2000, Schlorholtz and Hooton 2008, and Amini et al. 2019). Scaling resistance, however, can be highly variable depending on the specimen type, test methods, and exposure conditions. As observed by Bouzoubaâ et al. (2008), scaling specimens tested in accordance with ASTM C672 tended to exhibit more damage than either specimen tested in accordance with Quebec Test BNQ NQ 2621–900 or field placement.

Many performance-based specifications for freeze-thaw durability set limits on the damage that can occur in specimens through 300 freeze-thaw cycles. There are, however, only a limited number of evaluations of the freeze-thaw durability of concrete bridge deck mixtures containing IC and SCMs. One study by Jones et al. (2014) evaluated HPC mixtures with and without IC and only observed freeze-thaw damage in mixtures that contained an “excessive” amount of IC water (more than twice the design IC water content of 7% of the binder weight) in fewer than 300 cycles. Limited evaluation on the effects of incremental increases in the quantity of IC water on freeze-thaw performance has been completed. In a study by Feng and Darwin (2020), increasing amounts of IC water caused freeze-thaw damage in fewer cycles; the tests were conducted in accordance with Kansas Test Method KTMR-22, a modified version of ASTM C666 (Procedure B) that included a longer curing duration and drying period for the test specimens.

Concrete transport properties, defined as the ability of ions and solution to move through a medium, are heavily influenced by the concrete pore structure and are characterized by permeability, diffusion, and absorption properties (Castro et al. 2011). With frequent use of deicing salts on concrete pavements and bridge decks, leading to increased risk of corrosion of reinforcing steel, ensuring that chloride ion permeability is kept under control has emerged as a priority in current IC-HPC specifications (Barrett et al. 2015a, Jenkins 2015). Limiting ion conductivity helps in maintaining durable concrete structures by slowing the corrosion rate of reinforcing. Ion conductivity can be evaluated directly using the rapid chloride permeability (RCP) test or indirectly using bulk electrical conductivity or surface resistivity tests (Moradllo et al. 2018). The RCP test is commonly used by state departments of transportation (DOTs) and other agencies to evaluate ionic conductivity, with results at 56-days typically used to characterize concrete mixtures. Previous work has shown clear reductions in RCP values for concrete mixtures that contain finer particle SCMs that provide a denser pore structure. The age of concrete also plays a significant role, with ion conductivity decreasing as age increases (ASTM C1202, O'Reilly et al. 2017a). In addition to, or as a replacement of RCP in some cases, surface resistivity measurements (SRMs) are becoming more commonly used as an indirect estimation of ion conductivity. Previous studies have evaluated concrete mixtures based on both SRM and RCP test results and found a particularly good correlation between 28-day SRM results and 56-day RCP results (Rupnow and Icenogle 2012, Tanesi and Ardani 2012, Jenkins 2015).

The laboratory testing component of this study examines the effect of IC water on concrete durability and transport properties. Concrete mixtures were evaluated in accordance with the Minnesota Department of Transportation (MnDOT) LC-HPC specifications, which include scaling, freeze-thaw, and RCP tests. Four MnDOT LC-HPC bridges were placed from 2016 to 2018 and contain IC water contents of 6.5 to 8.5% by total binder weight and a partial replacement of portland cement with Grade 100 slag cement (27 to 30% by total binder weight). IC water was provided using pre-wetted FLWA. Mixtures evaluated in this study include IC water contents of 0 to 14.1% and *w/cm* ratios of 0.39 to 0.45. The paste contents of the mixtures ranged from 25.0 to 26.7% by volume, and the binder compositions included only portland cement and portland cement with 35% Class F fly ash or 27 to 30% slag cement replacements and with 27 or 28% slag cement plus 2% silica fume replacements. The study includes three programs, one for each year of this study (2016 to 2018). Program 1 contains 12 mixtures with a 0.45 *w/cm* ratio, including one with only portland cement as binder, seven with 30% slag cement by total weight of binder, and four with 28% slag cement and 2% silica fume. Four of these mixtures have a 0.42 *w/cm* ratio and two have a 0.39 *w/cm* ratio, all with 30% slag cement. Program 2 contains 20 mixtures with slag cement and *w/cm* ratios of 0.41 (five mixtures), 0.43 (six mixtures), 0.44 (two mixtures), or 0.45 (seven mixtures). At a 0.43 *w/cm* ratio, four mixtures contain only portland cement as the binder, and two mixtures contain 28% slag cement and 2% silica fume by total weight of binder. At a 0.42 *w/cm* ratio, three mixtures contain 35% Class F fly ash by weight of binder to evaluate the MnDOT HPC mixture used for the Control deck in 2017. Program 3 evaluates mixtures a range of IC water contents and a *w/cm* ratio of 0.43, including 12 mixtures with a 28% slag cement replacement of portland cement and 5 mixtures with only portland cement as the binder. Each program includes mixtures with proportions matching those used for each MnDOT IC-LC-HPC project. This chapter describes the materials, test procedures, and concrete mixtures in the three Programs. The test results and the evaluation of the durability and ion conductivity of the mixtures are presented in Chapter 3.

2.2 MATERIALS

This section describes the materials used in the IC-LC-HPC mixtures evaluated in the laboratory. Samples 1, 2, and 3 of each material correspond to the materials used in Programs 1, 2, and 3 (2016, 2017, and 2018 bridge decks), respectively. The fine lightweight aggregate FLWA-2 was used in selected mixtures in Program 3, as well as in Program 2; all other materials were used in only a single Program. Individual programs are discussed in Section 2.4.

2.2.1 Cement

Type I/II portland cement was used in all concrete mixtures. With the exception of some of the mixtures in Program 1, the cement used in this study was obtained from the supplier of the IC-LC-HPC projects for that year. For Program 1, the sample of portland cement from the concrete supplier (C1(a)) was only sufficient to cast six batches, as indicated in Section 2.4. Portland cement from a producer in Kansas was used for the other mixtures in Program 1 (C1(b)). The physical properties include specific gravity and Blaine fineness. Chemical analyses were performed by Ash Grove Cement using X-Ray Fluorescence (XRF) elemental analysis. Physical or chemical analyses were not performed on C1(a). Chemical analyses were performed on the remaining portland cement samples. Chemical analysis for C1(b) were obtained from a mill report from the producer. Blaine fineness for C1(b) and C3 were determined in addition to XRF elemental analysis. Physical and chemical properties of the portland cements used in this study are listed in Table 2.1.

Table 2.1: Cement chemical analysis and physical properties

	Percentages by Weight			
	Type I/II Portland Cement			
Sample No.	**C1(a)[†]**	**C1(b)[*]**	**C2**	**C3**
Producer	Lafarge/ Holcim	Ash Grove	Continental Davenport	Lafarge/ Holcim
Specific Gravity	3.15[ǀ]	3.12	3.15	3.11
Blaine Fineness, cm^3/g	--	3986	†	4110
Bogue Analysis				
C_3S	--	63	64	68
C_2S	--	14	7	5
C_3A	--	6	7	7
C_4AF	--	9	9	9
XRF Analysis				
SiO_2	--	20.7	19.4	19.5
Al_2O_3	--	3.97	4.40	4.47
Fe_2O_3	--	3.00	2.97	3.05
CaO	--	64.6	62.5	63.6
MgO	--	1.99	2.55	2.39
SO_3	--	2.97	3.05	3.22
Na_2O	--	0.20	0.08	0.09
K_2O	--	0.52	0.69	0.59
TiO_2	--	†	0.21	0.23
P_2O_5	--		0.22	0.04
Mn_2O_3	--		0.42	0.05
SrO	--		0.04	0.04
CuO	--		0.02	--
ZnO			--	--
LOI		2.29	3.08	2.97
Total		97.9	99.7	100.2

[†] Sample was not tested/data not available
[*] Referenced from mill report
[ǀ] Value provided by producer

2.2.2 Supplementary Cementitious Materials

A majority of the concrete mixtures evaluated in the laboratory test programs in this study contain one or more supplementary cementitious materials (SCM)/mineral admixtures – slag cement, slag cement and silica fume, or Class F fly ash. The producer, specific gravity, and chemical composition of the slag cements and fly ash are listed in Table 2.2. As with the portland cements, a different sample of slag cement was obtained for each program. As with C1(a), physical or chemical analyses were not performed on S1. Program 2 contains several mixtures with a Class F fly ash (FF1). The specific gravity value of 2.87 for the first and second samples of slag cement was provided by the producer. Similarly, a specific gravity of 2.40 was provided for the Class F fly ash sample. The chemical compositions of the second and third samples of slag cement, S2 and S3, and the Class F fly ash sample, FF1, were determined by Ash Grove Cement using XRF; only the third slag cement sample was tested for Blaine fineness. Chemical analysis was not performed on the silica fume used in Programs 1 or 2; the specific gravity of 2.20 was provided by the producers.

It is suspected that the Class F fly ash used in this study was contaminated with metallic particles. As discussed in Chapter 3, the mixtures containing fly ash had higher RCP test results and lower SRM values than the mixtures with only portland cement as binder, contrary to the expected result for mixtures containing fly ash (Russell 2004). After the RCP and SRM tests were complete, to investigate the sample for contaminants, 0.2 lb [0.1 kg] of fly ash was placed in a clear jar that was then filled with water. After agitating the solution, a rare-earth magnet was held to the side of the jar and metallic particles in the solution were observed to move toward it. With the assumption that those metallic particles were also conductive, their presence would help account for an increased amount of charge passed during RCP testing and lower SRM. Although electrical readings were likely affected, no effects from the metallic particles were observed in scaling or freeze-thaw testing.

Table 2.2: SCM chemical analysis and physical properties

	Percentages by Weight			
	Grade 100 Slag Cement			Class F Fly Ash
Sample No.	**S1**[†]	**S2**	**S3**	**FF1**
Producer	Skyway	Skyway	Lafarge Newcem	Coal Creek
Specific Gravity	2.87[ǀ]	2.87[ǀ]	3.11	2.40[ǀ]
Blaine Fineness, cm^3/g	†	†	4710	†
XRF Analysis				
SiO_2	--	37.2	34.5	36.8
Al_2O_3	--	8.27	10.9	18.0
Fe_2O_3	--	0.51	0.67	5.78
CaO	--	38.1	38.7	25.9
MgO	--	11.0	11.0	5.73
SO_3	--	2.78	2.39	1.62
Na_2O	--	0.37	--	1.67
K_2O	--	0.50	0.53	0.37
TiO_2	--	0.39	0.49	1.42
P_2O_5	--	--	0.01	0.88
Mn_2O_3	--	0.69	0.26	0.03
SrO	--	0.05	0.05	0.41
CuO	--	0.12	0.28	--
ZnO	--	0.02	0.07	0.45
LOI	--	0.00[*]	0.00[*]	0.58
Total	--	99.9	99.8	99.7

[†] Sample was not tested
[*] Sample exhibited a positive LOI
[ǀ] Value provided by producer

2.2.3 Coarse Aggregates

Granite was used as the coarse aggregate in Programs 1 and 2; a crushed gravel was used in Program 3. All samples were obtained from the concrete supplier for the IC-LC-HPC deck(s) in that program. The physical properties are listed in Table 2.3 and represent the average of two tests. Tests for absorption and specific gravity were performed in accordance with ASTM C127. Sieve analyses were performed in accordance with ASTM C136. The particle size distribution differed slightly for each sample. The crushed gravel used in Program 3 (CA-3) had a higher absorption (1.4%) than the granite used in Program 1 or 2 (0.4%).

Table 2.3: Physical properties of coarse aggregate

Sample No.	**Coarse Aggregate ID**		
	CA-1 (2016)	**CA-2 (2017)**	**CA-3 (2018)**
Specific Gravity (SSD)	2.71	2.65	2.71
Absorption (%)[‖]	0.4	0.4	1.4
Fineness Modulus	6.58	6.66	6.48
Sieve Size	**Percent Retained on Each Sieve**		
1-1/2-in. (37.5-mm)	0	0	0
1-in. (25.4-mm)	0	0	0
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	36.2	49.3	17.7
3/8-in. (9.5-mm)	26.8	19.8	35.4
No. 4 (4.75-mm)	32.7	28.9	44.1
No. 8 (2.38-mm)	3.1	0.8	2.4
No. 16 (1.18-mm)	0	0	0
No. 30 (0.60-mm)	0	0	0
No. 50 (0.30-mm)	0	0	0
No. 100 (0.15-mm)	0	0	0
No. 200 (0.075-mm)	0	0	0
Pan	1.2	1.2	0.4

[‖] Oven-dry basis

2.2.4 Fine Aggregates

River sand was used as fine aggregate for the mixtures in this study. All samples were obtained from the concrete suppliers for the IC-LC-HPC deck(s) in each program. The physical properties of the fine aggregates are listed in Table 2.4 and represent the average of two tests. Tests for absorption and specific gravity were performed in accordance with ASTM C128. Sieve analyses were performed in accordance with ASTM C136. The sand for Program 3 (FA-3) had a higher absorption (1.2%) than the sand in Programs 1 and 2 (0.5 or 0.8%, respectively).

Table 2.4: Physical properties of fine aggregate

Sample No.	**Fine Aggregate ID**		
	FA-1 (2016)	**FA-2 (2017)**	**FA-3 (2018)**
Specific Gravity (SSD)	2.64	2.61	2.64
Absorption (%)[‖]	0.5	0.8	1.2
Fineness Modulus	2.67	2.67	2.61
Sieve Size	**Percent Retained on Each Sieve**		
1-1/2-in. (37.5-mm)	0	0	0
1-in. (25.4-mm)	0	0	0
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	0	0	0
3/8-in. (9.5-mm)	0	0	0
No. 4 (4.75-mm)	0.2	1.2	0.1
No. 8 (2.38-mm)	8.6	10.1	2.1
No. 16 (1.18-mm)	15.2	14.1	18.8
No. 30 (0.60-mm)	25.2	23.0	32.0
No. 50 (0.30-mm)	36.5	33.9	33.2
No. 100 (0.15-mm)	13.3	15.9	12.5
No. 200 (0.075-mm)	1.0	1.3	1.1
Pan	0	0.5	0.2

[‖] Oven-dry basis

2.2.5 Fine Lightweight Aggregates

The FLWA in this study is an expanded clay. All samples were from the same manufacturer; variations in the manufacturing process, however, resulted in samples with different physical properties. The physical properties are listed in Table 2.5, with the values representing the average of three tests. The FLWA exhibited more variability in both gradation and absorption between samples than the normalweight aggregates. Sieve analyses were performed in accordance with ASTM C136. Tests for absorption and specific gravity were performed in accordance with ASTM C1761 and C128 after the aggregate was placed in a pre-wetted surface dry (PSD) condition. To achieve the PSD state, the aggregate was soaked for 72 hours and allowed to drain for at least 20 minutes. Following the procedure described by Miller et al. (2014), the aggregate was then placed in a centrifuge to remove surface moisture. Use of a centrifuge to place FLWA in a PSD condition has been shown to produce more consistent results than removing surface moisture with paper towels as outlined in ASTM C1761.

The absorption values listed in Table 2.5 were used to proportion the FLWA in mixtures containing IC and were obtained from initial laboratory tests on the FLWA. Absorption values are obtained by oven drying PSD samples for 24 hours, in contrast to the field where absorption is measured by heating PSD samples over a burner for 60 to 90 minutes to remove the absorbed water. The actual amount of IC water in a mixture depends on the FLWA absorption on the day of casting. Due to natural variability in absorption, values determined on the day of casting differed by up to 1.6% from the values listed in Table 2.5, resulting in differences between the design and actual quantities of IC water of up to 0.6% of total binder weight. Variability of FLWA properties was also observed in samples taken from the FLWA stockpiles used for batching the IC-LC-HPC decks as discussed in Chapter 4. For FLWA-2, which was used in Program 2 and for some of the mixtures in Program 3, the average absorption dropped from 24.8% for the Program 2 mixtures to 24.0% when for the Program 3 mixtures.

Table 2.5: Physical properties of FLWA

Sample No.	**FLWA ID**		
	FLWA-1 (2016)	**FLWA-2 (2017)**	**FLWA-3 (2018)**
Specific Gravity (PSD)[*]	1.54	1.67	1.63
Absorption (%)[*‖]	32.8	24.8 (24.0)[a]	28.5
Fineness Modulus	3.93	3.85	3.74
Sieve Size	**Percent Retained on Each Sieve**		
1-1/2-in. (37.5-mm)	0	0	0
1-in. (25.4-mm)	0	0	0
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	0	0	0
3/8-in. (9.5-mm)	0	0	0
No. 4 (4.75-mm)	13.8	14.1	12.0
No. 8 (2.38-mm)	29.4	27.3	27.5
No. 16 (1.18-mm)	25.6	24.6	24.7
No. 30 (0.60-mm)	14.1	15.4	14.9
No. 50 (0.30-mm)	7.5	8.1	8.3
No. 100 (0.15-mm)	3.7	3.9	4.3
No. 200 (0.075-mm)	2.3	2.3	2.8
Pan	3.6	4.2	5.4

[*] Values based on 72-hour soak time in laboratory testing, >72 hour sprinkling time in field

[‖] Oven-dry basis

[a] 24.8% used in Program 2 mixtures; 24.0% used in applicable Program 3 mixtures (See Section 2.4.3)

2.2.6 Chemical Admixtures

The admixtures used by the concrete suppliers in batching IC-LC-HPC bridge decks were used in laboratory testing. BASF admixtures were used in Program 1, GRT admixtures for Program 2, and Sika admixtures for Program 3. Chemical admixtures included a viscosity modifying admixture (VMA), air-entraining admixture (AEA), mid- or high-range water-reducing admixtures (where applicable), and set retarding admixture (where applicable). The VMA was included at a predetermined dosage depending on the program (2 to 5 fl oz per 100 lb of cementitious material (oz/cwt) [1.3 to 3.3 mL/kg]) to aid in pumping the concrete during construction. Water-reducing admixtures, if needed, were used to maintain workability and a similar range of slumps for the mixtures. For laboratory mixtures, the dosage of water-reducing admixture was lower than the dosage used during construction. For Program 2, a set retarder was added in otherwise duplicate mixtures containing IC and slag cement to examine whether its addition had any effects on concrete properties. A set retarder dosage of 3 oz/cwt (2.0 mL/kg) was used for the entirety of one IC-LC-HPC deck and part of a second constructed in 2017. Program 3 mixtures included a constant dose of 1 oz/cwt (0.7 mL/kg) of set retarder to replicate the dosage submitted by the concrete supplier for the IC-LC-HPC project from 2018.

2.3 TEST PROCEDURES

The laboratory testing program for the IC-LC-HPC mixtures involved the tests required by the Minnesota Department of Transportation (MnDOT) specifications for hardened concrete. The program included tests for compressive strength, scaling resistance, freeze-thaw durability, rapid chloride permeability (RCP), and surface resistivity measurement (SRM). The tests were performed in accordance with applicable ASTM procedures (AASHTO/Kansas Test Method for SRM). All test specimens were cured in saturated lime water for the durations outlined in the test procedures. Results are presented in Chapter 3.

2.3.1 Compressive Strength

Compressive strength tests were performed in accordance with ASTM C31 28 days after casting. The MnDOT requirements for IC-LC-HPC include a 28-day compressive strength between 4000 and 5500 psi (27.6 and 37.9 MPa). The compressive strengths listed in this study are the average of three 4 × 8 in. (100 × 205 mm) cylinders.

2.3.2 Scaling Resistance

Tests for scaling resistance followed ASTM C672, with some modifications. Per ASTM C672, evaluation of test specimens was based on visual ratings at each solution change. In addition to the visual ratings, mass losses were recorded at solution changes and at the end of testing. In addition to the standard requirements for solution changes after 5, 10, 15, 20, and 25 freeze-thaw cycles, specimens received an additional solution change at 35 cycles to obtain data between 25 and 50 cycles (end of testing). In Program 1, two mixtures included scaling tests performed in accordance with Quebec test BNQ NQ 2621-900 along with ASTM C672. With the exception of one mixture in Program 2, scaling test specimens were cured for 14 days in saturated lime water. Program 2 included one mixture with three sets of specimens; one set received a 14-day curing period to serve as a control, the second set received a 28-day curing period to examine effects of increased curing, and the third received a 14-day curing period but the underside was tested instead of the top surface. Testing the underside of specimens instead of the top eliminates the contributions to increased scaling due to excessive bleedwater, finishing, or brushing (required by ASTM C672) of the surface. In contrast, the underside of scaling specimens received no finishing and had no bleedwater since bleeding moves water upward. As a result of these differences, lower scaling mass losses were expected on the underside. MnDOT specifies a maximum visual rating of 1, defined as slight scaling (less than a 1/8 in. (3 mm) depth of lost material) with no coarse aggregate visible, after 50 freeze-thaw cycles.

2.3.3 Freeze-Thaw Durability and Fundamental Transverse Frequency

Testing for freeze-thaw durability was performed in accordance with ASTM C666 (Procedure A). The fundamental transverse frequency for the freeze-thaw specimens was measured in accordance with ASTM C215. For freeze-thaw durability, MnDOT specifications require that specimens maintain at least 90% of their initial dynamic modulus of elasticity (E_{Dyn}) through 300 freeze-thaw cycles. The E_{Dyn} is determined for specimens based on measurement of the mass and transverse frequency using Eq. (2.1).

$$E_{Dyn} = C \times M \times n^2 \tag{2.1}$$

where E_{Dyn} = Dynamic modulus of elasticity (Pa)
C = Constant based on specimen shape and Poisson's Ratio (1083.6 m^{-1})
M = Specimen mass (kg)
n = Fundamental transverse frequency (Hz)

Specimens were cured in saturated lime water for 14 days after casting. Mixtures in Program 1 had testing terminated after 300 freeze-thaw cycles. For selected mixtures in Program 2 and all mixtures in Program 3, freeze-thaw testing was continued until specimens dropped below 60% of their initial dynamic modulus of elasticity (E_{Dyn}) or when 2000 freeze-thaw cycles had been completed. Although a number of mixtures were tested well beyond 300 freeze-thaw cycles, mixtures are evaluated based on the Durability Factor (*DF*) defined by Eq. (2.2).

$$DF = \frac{P \times N}{M} \tag{2.2}$$

where DF = Durability Factor
P = Percentage of E_{Dyn} remaining at N cycles
N = Either the number of cycles at which P reached 60% of E_{Dyn} or 300 cycles
M = 300 cycles

2.3.4 Rapid Chloride Permeability and Surface Resistivity Measurement

Rapid Chloride Permeability (RCP) testing was performed 28 and 56 days after casting in accordance with ASTM C1202. The MnDOT specification limits the maximum charge passed to 2500 Coulombs at 28 days and 1500 Coulombs at 56 days. Surface Resistivity Measurement (SRM) data were collected in accordance with AASHTO TP-95 and Kansas Test Method KT-79 28 days after casting using a Wenner probe with 1½-in. (38.1-mm) spacing. In accordance with the test procedure, a correction factor of 1.1 was applied to all SRM values because the specimens were cured in lime-saturated water. The correction factor is part of the test procedure because calcium from the lime increases the electrical conductivity of the specimens, which results in a lower SRM compared to specimens cured in a moist room. SRM testing was completed within 30 minutes of removing specimens from the water, and the specimen surfaces were only dried enough to allow for marker lines to stick. The RCP and SRM results in this study represent the average obtained using three 4 × 8 in. (100 × 205 mm) cylinders.

For mixtures on which both RCP and SRM tests were performed, correlation between the two test methods was investigated to gage the effectiveness of estimating RCP values using SRM values (or vice-versa). The mathematical relationship between SRM and RCP developed by Morris et al. (1996), which assumes that concrete cylinders have a homogeneous semi-infinite geometry (large specimen dimensions and small probe depth relative to probe spacing), is listed in Eq. (2.3).

$$\text{SRM} = 2\pi a\left(\frac{V}{I}\right) \tag{2.3}$$

SRM = Surface resistivity measurement (kΩ-cm)
a = Probe spacing (cm)
V = Voltage (kV)
I = Current (Amps)

Based on the six-hour RCP test duration and a voltage of 60 V used in the RCP test, Jenkins (2015) developed Eq. (2.4), which accounts for specimen geometry and probe spacing. Based on Eq. (2.4), RCP values of 2500 and 1500 Coulombs equate to SRMs of 10.9 and 18.2 kΩ-cm, respectively.

$$\text{RCP} = 2\pi a\left(\frac{K}{SRM}\right) = \frac{27{,}269}{SRM} \tag{2.4}$$

RCP = Charge passed during RCP testing (Coulombs)
a = Probe spacing (cm)
K = Constant (1139.06 kV·s)
SRM = Surface resistivity measurement (kΩ-cm)

2.4 CONCRETE MIXTURES

This section lists the mixture proportions and plastic concrete properties for the IC-LC-HPC mixtures in this study. The IC-LC-HPC mixtures were developed based on findings by Reynolds et al. (2009), Browning et al. (2011), Pendergrass and Darwin (2014), and Khajehdehi and Darwin (2018) who demonstrated that IC and slag cement reduce drying shrinkage, which is a primary concern for concrete bridge decks. The *w/cm* ratios used in the laboratory mixtures of this study ranged from 0.39 to 0.45. The paste content (volume of cementitious materials and water expressed as the percentage of total concrete volume) ranged from 25.0 to 26.7%. Mixtures are identified by binder composition and amount of IC water. Mixture identifications have the form 'A-B-C'. The lead indicator (A) in mixture IDs identifies the binder composition (C for 100% portland cement, S for binary mixtures with slag cement, FA for binary mixtures with Class F fly ash, and T for ternary mixtures with slag cement and silica fume). The second indicator (B) indicates whether a mixture contained IC water (mixtures without FLWA/IC water are identified as a Control). The trailing indicator (C) identifies the amount of IC water, expressed as the percentage of total binder weight-this indicator is omitted for Control mixtures. In Programs 1 and 2, some mixtures with similar binder and IC water contents have an additional indicator in parenthesis to identify duplicate mixture IDs. For example, mixtures S-IC-8.4(1), S-IC-8.4(2), and S-IC-8.4(3) identify three different batches of concrete in Program 2 with the same binder composition (27% slag cement) and IC water content (8.4% by total weight of binder).

To determine the FLWA quantity for concrete mixtures with IC, the FLWA absorption and desorption must be known. As discussed in Chapter 1, IC is commonly used in low *w/cm* mixtures to combat self-desiccation and autogenous shrinkage at early ages. At early ages, the relative humidity of the concrete is high (>90%), and the FLWA desorption (at a 94% RH per ASTM

C1761) must be accounted for to accurately reflect the amount of IC water available during this time. In concrete with *w/cm* ratios above 0.42, however, self-desiccation is minimal (Mindess et al. 2003) and the IC water is assumed to be used to mitigate drying shrinkage at a significantly lower RH (50% or less). In studies by Castro (2011) and Khayat (2018), desorption of various types of FLWA rapidly approached 100% as the relative humidity decreased below 90%. As such, the FLWA desorption was taken to be 100% when the IC-LC-HPC mixture proportions are determined. The quantity of FLWA in each mixture was selected to provide a desired quantity of IC water based on Eq. (1.1), repeated here, which accounts for FLWA absorption (using values listed in Table 2.5) and desorption (taken to be 100%) as a function of the total weight of binder.

$$M_{FLWA} = \frac{C_f \times IC}{\phi \times \lambda} \tag{1.1}$$

where M_{FLWA} = Amount of oven-dry FLWA (lb/yd^3)
C_f = Amount of cementitious materials (lb/yd^3)
IC = Percentage of internal curing water (7 or 8% by total weight of binder)
ϕ = FLWA absorption (based on pre-wetting method and duration, oven-dry basis)
λ = FLWA desorption at specified RH (RH < 90%, λ = 100%)

Coarse aggregates were soaked for a minimum of 24 hours and placed in a saturated surface-dry (SSD) condition in accordance with ASTM C127 for batching concrete. Normalweight fine aggregates were pre-wetted and then tested for free surface moisture in accordance with ASTM C70. FLWA was soaked for 72 hours prior to casting, with free surface moisture determined using a centrifuge as described in Section 2.2.5. The 72-hour soak time was not used for two mixtures in Program 3, which only included a 5-minute soak time to prepare FLWA with lower values of IC water. Adjustments were made to the batch water based on the amount of free surface moisture in the normalweight and lightweight fine aggregate. The FLWA sample used to determine free surface moisture was then tested for absorption, based on a 24-hour oven-dry weight, as described in Section 2.2.5. The actual amount of IC water in mixtures was available only after oven-drying. The quantity of IC is expressed as a percentage of cementitious material (binder) weight. As discussed in Section 2.2.5, individual absorption test results ranged from 1.6% below to 1.4% above the values listed in Table 2.5. In addition to IC water, which refers to water absorbed in the FLWA, absorbed water in normalweight aggregates is also available for internal curing. The sum of internal water absorbed by all aggregates in a mixture is referred to as total absorbed water and is also expressed as a percentage of binder weight. The normalweight aggregates used in Program 3 had a higher absorption than those used in Programs 1 or 2; as a result, Program 3 mixtures with a given IC water content had significantly higher total absorbed water contents than similar mixtures from Programs 1 or 2.

The mixing and casting procedures used for this study are similar to those used by Yuan et al. (2011) and Pendergrass and Darwin (2014). The coarse aggregate and 80% of the mix water were first added to the mixer as the mixer began rotating. For mixtures containing silica fume, the silica fume was then added to the mixer and mixed for 1½ minutes. Cement and SCMs were then added and mixed for an additional 1½ minutes. The fine normalweight aggregate and FLWA were then added, and the concrete was mixed for an additional 2 minutes. 10% of the mix water was added along with the VMA and water reducing admixture (if used) within the next 5 minutes of mixing. After five minutes of mixing, the final 10% of mix water was added along with the AEA. Nearly all mixtures were proportioned using a target air content of 8% to match the target air content of IC-LC-HPC. The exceptions were the mixtures containing fly ash in Program 2 (FA-Control, FA-IC-8.9, and FA-IC-9.0), which were designed for a target air content of 6.5%, the target air content of the concrete in the MnDOT HPC Control deck placed in 2017, as discussed in Chapter 4. After all constituents were added, mixing continued for an additional 5 minutes, followed by a 5-minute resting period, after which the concrete was mixed for 3 minutes prior to testing the concrete properties. Concrete slump (ASTM C143) was measured, along with air content (ASTM C173), temperature (ASTM C1064), and unit weight (ASTM C138). Test specimens were then cast.

2.4.1 Program 1 (2016 Mixtures)

Table 2.6 lists the mixture proportions for Program 1. Materials were obtained from the same sources as used for the 2016 IC-LC-HPC bridge deck. The bridge deck concrete contained 30% slag cement by total weight of binder, a 25.4% paste content, and a 10% replacement of normalweight aggregate with FLWA (FLWA-1) by volume to provide IC water equal to 7% by weight of binder. The *w/cm* ratio was 0.45. Mixtures with IC water contents of 5.5 and 5.6% were batched using the original mixture proportions submitted to MnDOT by the concrete supplier, prior to adjusting the FLWA content to provide an IC water content of 7% by total weight of binder. Additional mixtures were batched with *w/cm* ratios of 0.45, 0.42, and 0.39 and proportioned to include nominal IC water contents of 7 and 9% (actual values, based on FLWA moisture at casting, ranged from 6.6 to 9.4%). Twelve mixtures were cast with a *w/cm* ratio of 0.45; one mixture included only portland cement as a binder with an IC water content of 5.7% (C-IC-5.7), four contained the ternary blend with 28% slag cement and 2% silica fume by total weight of (T-IC-8.2, T-IC-8.3(1), T-IC-8.3(2), and T-IC-8.3(3)), and seven contained 30% slag cement. Four mixtures were cast with a *w/cm* ratio of 0.42 and two with a *w/cm* ratio of 0.39, all with 30% slag cement. The mixtures in Program 1 included 3 oz/cwt (2.0 mL/kg) of a VMA.

Table 2.6: Program 1 mixture proportions

Mixture ID[a]	***w/cm* Ratio**	**Material lb/yd^3 (SSD/PSD)**							**Chemical Admixture[c] (fl oz/cwt)**		
		Cement (Type I/II)	**Gr. 100 Slag Cement**	**Silica Fume**	**Coarse Agg.**	**Fine Agg.**	**FLWA**	**Water**	**VMA**	**WRA**	**AEA**
		C-1	**S-1**	**SF**	**CA-1**	**FA-1**	**FLWA-1**	**W**			
S-IC-5.5(1)[b]	0.45	385	165	-	1757	1035	124	248	3	-	0.49
S-IC-5.5(2)[b]		385	165	-	1760	1041	124	248	3	-	0.52
S-IC-5.6(1)[b]		385	165	-	1760	1041	124	248	3	-	0.62
S-IC-5.6(2)[b]		385	165	-	1760	1041	124	248	3	-	0.49
S-IC-6.6[b]		385	165	-	1648	1130	151	248	3	-	0.77
S-IC-7.3		385	165	-	1740	996	163	248	3	-	0.49
S-IC-9.3		385	165	-	1718	941	210	248	3	-	0.49
C-IC-5.7[b]		557	-	-	1753	1044	126	251	3	-	0.54
T-IC-8.2		385	154	11	1735	979	186	248	3	-	0.49
T-IC-8.3(1)		385	154	11	1735	979	186	248	3	-	0.55
T-IC-8.3(2)		385	154	11	1736	983	181	248	3	-	0.49
T-IC-8.3(3)		385	154	11	1736	983	181	248	3	1.6	0.75
S-IC-7.1	0.42	400	175	-	1747	970	170	241	3	-	0.59
S-IC-7.2		400	175	-	1749	975	166	241	3	-	0.73
S-IC-9.1		400	175	-	1726	919	213	241	3	-	0.85
S-IC-9.4(1)		400	175	-	1724	912	219	241	3	-	0.56
S-IC-7.0	0.39	415	180	-	1766	962	170	233	3	0.7	1.25
S-IC-9.4(2)		415	180	-	1742	903	220	233	3	4	0.88

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)
B: IC=Internally-cured
C: Amount of internal curing water, % binder weight
[b] Cement C1(a) used; otherwise, C1(b) used
[c] Admixture designations (VMA=VMA 358, WRA=MPolyheed1020, AEA=AE-90)
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Values of absorption for FLWA-1 and the concrete properties for the Program 1 mixtures are listed in Table 2.7. As stated in Section 2.2.5, the absorption of a given FLWA tended to vary from test to test. As such, the measured absorption of FLWA-1 at batching ranged from 31.3 to 34.0% compared to the nominal value of 32.8% listed in Table 2.5. In terms of total absorbed water, the water absorbed by the normalweight aggregates provided an additional 1.9 to 2.2% to the IC water in Program 1 mixtures, resulting in a total absorbed water content ranging from 7.7 to 11.5% (a narrower range than Programs 2 or 3). The mixtures in Program 1 included 3 oz/cwt (2.0 mL/kg) of a VMA. Slumps for mixtures with a 0.45 *w/cm* ratio ranged from 1½ to 6½ in. (40 to 165 mm) and air contents ranged from 6 to 10%. Slumps for mixtures with 0.42 and 0.39 *w/cm* ratios ranged from 2 to 3¼ in. (50 to 85 mm), and air contents ranged from 5.5 to 11.25%. The 28-day compressive strengths ranged from 4380 to 6450 psi (30.2 to 44.5 MPa), except for one of the ternary batches (T-IC-8.3(1)), which had a 28-day compressive strength of just 3800 psi (26.2 MPa). It is suspected that additional mixing water was included in T-IC-8.3(1), which led to a relatively high slump of 6½ in. (165 mm) and lower compressive strength.

Table 2.7: Program 1 mixture properties

Mixture ID[a]	**FLWA Absorption (OD basis)**	**Concrete Properties**							
		Total Absorbed Water	***w/cm* Ratio**	**Paste Content**	**Slump**	**Air Content**	**Unit Weight**	**Temperature**	**28-Day Compressive Strength**
	(%)	**(% Binder Weight)**		**(%)**	**(in.)**	**(%)**	**(lb/ft^3)**	**(°F)**	**(psi)**
S-IC-5.5(1)[b]	32.5	7.7	0.45	25.4	2½	6.75	142.9	64	6450
S-IC-5.5(2)[b]	32.4	7.7		25.4	5½	10	137.7	67	4380
S-IC-5.6(1)[b]	32.8	7.8		25.4	3¾	8.75	139.5	64	4480
S-IC-5.6(2)[b]	32.7	7.8		25.4	2¾	8.25	140.6	67	4650
S-IC-6.6[b]	31.3	8.8		25.4	2¾	9.25	139.6	64	5260
S-IC-7.3	32.8	9.5		25.4	1½	6.5	143.6	66	5600
S-IC-9.3	33.0	11.5		25.4	2¾	6	142.4	64	5590
C-IC-5.7[b]	34.0	7.9		25.4	3½	8.25	138.8	68	4580
T-IC-8.2	32.1	10.3		25.5	2	6.5	142.3	64	6320
T-IC-8.3(1)	32.4	10.4		25.5	6½	9.5	136.3	58	3800
T-IC-8.3(2)	34.0	10.4		25.5	1½	6	143.3	64	5150
T-IC-8.3(3)	34.0	10.4		25.5	2	8.75	138.5	66	4750
S-IC-7.1	32.7	9.1	0.42	25.5	2¼	5.5	145.3	63	5850
S-IC-7.2	32.9	9.3		25.5	2	6.5	144.0	63	5510
S-IC-9.1	32.6	11.1		25.5	3	8	140.0	64	5470
S-IC-9.4(1)	32.9	11.4		25.5	2¾	5.5	144.3	68	5730
S-IC-7.0	32.4	9.0	0.39	25.4	3¼	11.25	135.1	60	4560
S-IC-9.4(2)	34.0	11.3		25.4	2¼	8.5	139.8	64	5510

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)

B: IC=Internally-cured

C: Amount of internal curing water, % binder weight

[b] Cement C1(a) used; otherwise, C1(b) used

Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.4.2 Program 2 (2017 Mixtures)

Table 2.8 lists the mixture proportions for Program 2, which correspond to the two IC-LC-HPC and one MnDOT HPC Control deck placed in 2017. The bridge deck concrete contained 27% slag cement by total weight of binder, a 26% paste content, and a 12.8% replacement of normalweight aggregate with FLWA by volume to provide IC water nominally equal 8% by total weight of binder. The *w/cm* ratio was 0.45. Among the laboratory mixtures containing slag cement, seven had a *w/cm* ratio of 0.45, two had a *w/cm* ratio of 0.44, six had a 0.43 *w/cm* ratio, and five had a 0.41 *w/cm* ratio. While the majority of the mixtures had a paste content of 26%, one mixture with a 0.45 *w/cm* ratio (S-IC-9.4), two mixtures with a 0.44 *w/cm* ratio (S-IC-7.2(1) and S-IC-8.3(2)), and two mixtures with a 0.43 *w/cm* ratio (S-IC-8.9(1) and S-IC-9.3, which replicated the average trip ticket proportions for the 2017 IC-LC-HPC decks) had somewhat different paste contents. Variations in the project mixture proportions in laboratory testing included different quantities of IC water to provide 0 and nominally 7 and 9% by total weight of binder (actual values ranged from 6.9 to 9.4%), plus one mixture with a 0.43 *w/cm* ratio and an IC water content of 14.1% (S-IC-14.1) to examine the effects of including significantly more IC water used in the other mixtures. The mixtures in Program 2 contained 2 oz/cwt (1.3 mL/kg) of a VMA, with the exception of one mixture that contained 3 oz/cwt (2.0 mL/kg). Mixtures containing 27% slag cement and a nominal IC water content of 9% by weight of binder with *w/cm* ratios of 0.45, 0.43, and 0.41 (S-IC-8.4(1), S-IC-8.9(1), and S-IC-9.0, respectively) were duplicated, but with the addition of 3 oz/cwt (2.0 mL/kg) of set retarder (S-IC-8.3(1), S-IC-9.3, and S-IC-9.1, respectively), the same dosage used in one IC-LC-HPC deck and part of another placed in 2017, to examine any effects the admixture had on test results.

To examine the effects of different binder compositions on concrete durability, two mixtures with a 0.43 *w/cm* ratio contained a ternary blend with portland cement, 28% slag cement, and 2% silica fume by total weight of binder and four mixtures contained only portland cement as the binder, all had a 26% paste content. Three mixtures with a 0.42 *w/cm* ratio contained 35% Class F fly ash by total weight of binder and a 26.7% paste content. One mixture replicated the MnDOT HPC Control deck mixture proportions, which contained fly ash but no IC water (FA-Control). Two additional mixtures were cast to examine the effects of providing nominally 9% IC water to the MnDOT HPC Control mixture (FA-IC-8.9 and FA-IC-9.0).

Values of absorption for FLWA-2 and the concrete properties for the Program 2 mixtures are listed in Table 2.9. The measured absorption of FLWA-2 at batching ranged from 23.7 to 25.7%, compared to the nominal value of 24.8% listed in Table 2.5. The water absorbed by the normalweight aggregates provided 2.0 to 3.1% by total weight of binder to Program 2 mixtures, resulting in a total absorbed water content ranging from 2.9 to 16.1%. Slumps ranged from 1¼ to 4¾ in. (30 to 120 mm) for mixtures that contained 27% slag cement by total weight of binder. The two ternary mixtures had slumps of 2¾ and 4½ in. (65 and 115 mm). The mixtures with only portland cement as a binder had slumps from 2½ to 4 in. (65 to 100 mm). The mixtures that contained fly ash had the highest slumps in Program 2, 4¾ to 5½ in. (120 to 140 mm). Air contents ranged from 7 to 10% for mixtures with 27% slag cement by total weight of binder. The air content range for the ternary blend mixtures and those containing only portland cement as a binder was slightly narrower, 8 to 9.25%. The mixtures containing 35% Class F fly ash had air contents ranging from 6.75 to 8%. Compressive strengths ranged from 4490 to 6360 psi (31.0 to 43.9 MPa).

Table 2.8: Program 2 mixture proportions

Mixture ID[a]	***w/cm* Ratio**	**Material lb/yd^3 (SSD/PSD)**							**Chemical Admixture**[e] **(fl oz/cwt)**		
		Cement (Type I/II)	**Gr. 100 Slag Cement**	**SCM**	**Coarse Agg.**	**Fine Agg.**	**FLWA**	**Water**	**VMA**	**WRA**	**AEA**
		C-2	**S-2**		**CA-2**	**FA-2**	**FLWA-2**	**W**			
S-Control(1)	0.45	410	154	-	1497	1428	-	254	2	-	0.90
S-IC-6.9		410	154	-	1411	1202	198	254	2	-	0.90
S-IC-8.3(1)[b]		410	154	-	1411	1141	238	254	2	-	0.90
S-IC-8.4(1)		410	154	-	1411	1141	238	254	2	-	0.90
S-IC-8.4(2)		410	154	-	1411	1141	238	254	2	-	0.90
S-IC-8.4(3)		410	154	-	1411	1141	238	254	2	-	0.90
S-IC-9.4		410	160	-	1440	1059	268	257	3	-	0.94
S-IC-7.2(1)	0.44	410	160	-	1427	1181	209	251	3	-	1.05
S-IC-8.3(2)		395	155	-	1407	1206	231	242	3	1.4	1.05
S-Control(2)	0.43	420	159	-	1496	1398	-	249	2	1.2	0.94
S-IC-7.3		420	159	-	1411	1193	204	249	2	1.2	0.94
S-IC-8.9(1)		412	154	-	1420	1175	259	243	2	1.6	0.94
S-IC-8.9(2)		420	159	-	1411	1103	262	249	2	1.2	0.94
S-IC-9.3[b]		412	154	-	1420	1175	259	243	2	0.8	0.94
S-IC-14.1		420	159	-	1641	648	408	249	2	1.2	0.94
T-Control		405	159	12[c]	1598	1330	-	248	2	1.2	0.94
T-IC-8.9		405	159	12[c]	1412	1106	261	248	2	1.4	1.00
C-Control(1)		585	-	-	1597	1329	-	252	2	-	0.92
C-Control(2)		585	-	-	1597	1329	-	252	2	1.17	0.92
C-IC-8.7		585	-	-	1411	1097	265	252	2	1.17	0.92
C-IC-8.8		585	-	-	1411	1097	265	252	2	1.17	0.92
FA-Control	0.42	377	-	203[d]	1731	1234	-	245	2	-	1.17
FA-IC-8.9		377	-	203[d]	1731	821	263	245	2	-	1.17
FA-IC-9.0		377	-	203[d]	1731	821	263	245	2	-	1.17
S-Control(3)	0.41	431	163	-	1544	1383	-	244	2	2.0	1.17
S-IC-7.2(2)		431	163	-	1474	1125	209	244	2	3.3	1.17
S-IC-9.0		431	163	-	1474	1031	269	244	2	2.7	1.17
S-IC-9.1[b]		431	163	-	1474	1031	269	244	2	2.5	1.17
S-IC-9.2		431	163	-	1474	1031	269	244	2	0.8	1.17

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=27% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume, FA=35% fly ash by weight)
B: Control=No LWA/internal curing, IC=Internally-cured
C: Amount of internal curing water (if applicable), % binder weight

[b] Mixtures contains 3 oz/cwt (2 mL/kg) of Polychem RENU set retarder

[c] Silica Fume

[d] Class F Fly Ash

[e] Admixture designations (VMA=Polychem VMA, WRA=KB1200, AEA=Polychem SA)

Note: 1 lb/yd^3 = 0.593 kg/m^{3,} 1 oz/cwt = 0.652 mL/kg

Table 2.9: Program 2 mixture properties

Mixture ID[a]	FLWA Absorption (OD basis)	Concrete Properties							
		Total Absorbed Water	*w/cm* Ratio	Paste Content	Slump	Air	Unit Weight	Temperature	28-Day Compressive Strength
	(%)	(% Binder Weight)		(%)	(in.)	(%)	(lb/ft^3)	(°F)	(psi)
S-Control(1)	-	3.1	0.45	26.0	3½	9.00	139.4	67	4990
S-IC-6.9	24.2	9.6		26.0	3½	8.50	136.7	67	4950
S-IC-8.3(1)	24.5	10.9		26.0	3¼	9.25	134.1	66	5070
S-IC-8.4(1)	24.9	11.0		26.0	3¾	9.00	134.1	68	4490
S-IC-8.4(2)	25.0	11.0		26.0	3½	7.75	137.6	65	5280
S-IC-8.4(3)	25.0	11.0		26.0	3	8.00	134.6	66	5050
S-IC-9.4	24.9	11.8		26.3	4	7.50	133.6	64	4760
S-IC-7.2(1)	24.2	9.8	0.44	26.0	4	10.00	133.2	61	4710
S-IC-8.3(2)	24.7	11.0		25.0	1¼	7.25	139.0	68	6360
S-Control(2)	-	2.9	0.43	26.0	4	9.75	138.3	64	4710
S-IC-7.3	25.1	9.9		26.0	3¾	8.75	135.9	66	4720
S-IC-8.9(1)	24.2	11.6		25.4	3¼	7.75	136.2	70	5290
S-IC-8.9(2)	24.5	11.6		26.0	3¾	8.75	134.5	66	4840
S-IC-9.3	25.5	12.0		25.4	3¾	9.50	134.6	66	4880
S-IC-14.1	25.0	16.1		26.0	3½	8.50	132.2	65	4770
T-Control	-	2.9		26.0	4½	8.50	139.5	61	4960
T-IC-8.9	24.8	11.4		26.0	2¾	9.25	134.5	65	5240
C-Control(1)	-	2.9		26.0	3½	7.75	140.4	65	4850
C-Control(2)	-	2.9		26.0	4	9.25	137.4	68	4510
C-IC-8.7	23.7	11.1		26.0	2½	8.25	135.0	67	5390
C-IC-8.8	24.5	11.3		26.0	3¾	8.00	135.5	63	4830
FA-Control	-	2.9	0.42	26.7	5½	7.25	144.9	64	4600
FA-IC-8.9	24.4	11.2		26.7	4¾	8.00	135.8	67	4600
FA-IC-9.0	24.7	11.3		26.7	5½	6.75	137.0	62	4950
S-Control(3)	-	2.9	0.41	26.0	3¼	8.75	140.4	62	4670
S-IC-7.2(2)	25.6	9.7		26.0	3¼	8.50	138.1	64	4910
S-IC-9.0	24.7	11.3		26.0	3½	9.50	134.0	65	4830
S-IC-9.1	25.0	11.4		26.0	3¾	7.50	136.2	64	4900
S-IC-9.2	25.7	11.6		26.0	2½	7.00	139.5	62	5700

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=27% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume, FA = 35% fly ash by weight)
B: Control=No LWA/internal curing, IC=Internally-cured
C: Amount of internal curing water (if applicable), % binder weight

Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.4.3 Program 3 (2018 Mixtures)

Table 2.10 lists the mixture proportions for Program 3. This program used the same source of materials as used to construct the 2018 IC-LC-HPC bridge deck. The IC-LC-HPC mixture contained 28% slag cement by total weight of binder, a 26% paste content, and a 10.9%

replacement of normalweight aggregate volume with FLWA to provide IC water nominally equal to 8% by total weight of binder. The *w/cm* ratio was 0.43 for the mixtures in Program 3. Variations in mixture proportions in laboratory testing included different quantities of IC water, with values of 0 to 12.1% by total weight of binder and binder compositions of either 28% slag cement or 100% portland cement. The mixtures containing slag cement were designed for nominal IC water contents of 6, 8, 10 and 12% by weight of binder. The actual values ranged from 6.3 to 12.1% (S-IC-6.3 and S-IC-12.1, respectively). The mixtures containing 100% portland cement as the binder were designed for nominal IC water contents of 4, 7, 10 and 12%. The actual values ranged from 3.8 to 11.8% (C-IC-3.8 and C-IC-11.8, respectively). The effect of varying the amount of IC water at a fixed FLWA volume on freeze-thaw durability was evaluated by comparing mixtures containing slag cement and a FLWA content of 17.6% by total aggregate volume, but different absorptions. Mixture S-IC-12.1, which had a FLWA soak time of 72 hours, was used as a control. Mixture S-IC-10.7 used FLWA-2, with a nominal absorption of 24.0. Like Mixture S-IC-12.1, Mixtures S-IC-7.0 and S-IC-7.7 contained FLWA-3, but had just a 5-minute soak time, resulting in reduced IC water contents. Mixtures in Program 3 contained 5 oz/cwt (3.3 mL/kg) of a VMA, except for S-IC-6.6, which contained 5 oz/cwt (3.3 mL/kg) of a water reducing admixture instead. All mixtures in Program 3 included 1 oz/cwt (0.7 mL/kg) of a set retarder.

Table 2.10: Program 3 mixture proportions

Mixture ID[a]	*w/cm* Ratio	Material lb/yd^3 (SSD)						Chemical Admixture[d] (fl oz/cwt)		
		Cement (Type I/II)	Gr. 100 Slag Cement	Coarse Agg.	Fine Agg.	FLWA	Water	VMA	WRA	AEA
		C-3	S-3	CA-3	FA-3		W			
S-Control	0.43	418	164	1778	1204	-	250	5	-	0.67
S-IC-6.3		418	164	1701	1020	160	250	5	-	0.68
S-IC-6.6[b]		418	164	1701	970	201	250	-	5	0.58
S-IC-6.8[b]		418	164	1701	970	201	250	5	-	0.74
S-IC-7.0[c]		418	164	1701	763	299	252	5	-	0.62
S-IC-7.7[c]		418	164	1701	763	299	252	5	-	0.63
S-IC-7.8		418	164	1701	934	213	250	5	-	0.62
S-IC-8.0		418	164	1701	970	201	250	5	-	0.74
S-IC-10.2		418	164	1701	848	266	250	5	-	0.71
S-IC-10.7[b]		418	164	1701	763	325	252	5	-	0.60
S-IC-11.6		418	164	1701	763	319	252	5	-	0.62
S-IC-12.1		418	164	1701	763	319	250	5	-	0.68
C-Control		586	-	1778	1200	-	252	5	-	0.64
C-IC-3.8[b]		586	-	1701	1089	120	252	5	-	0.63
C-IC-7.3[b]		586	-	1701	932	219	252	5	-	0.63
C-IC-9.8[b]		586	-	1701	804	300	252	5	-	0.63
C-IC-11.8[b]		586	-	1701	709	359	252	5	-	0.60

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=28% slag cement by weight, C=100% cement)
B: Control=No LWA/internal curing, IC=Internally-cured
C: Amount of internal curing water (if applicable), % binder weight
[b] FLWA-2 used (lower absorption); FLWA-3 used otherwise
[c] FLWA-3 used, 5-minute soak time
[d] Admixture designations (VMA=Stabilizer 4R, WRA=Viscocrete 1000, AEA=Air 260, Set retarder=SikaTard 440)
Note: 1 lb/yd^3 = 0.593 kg/m^{3,} 1 oz/cwt = 0.652 mL/kg

Values of absorption for the FLWA and the concrete properties for the Program 3 mixtures are listed in Table 2.11. FLWA-3 was used in mixtures S-IC-6.3, S-IC-7.0, S-IC-7.7, S-IC-7.8, S-IC-8.0, S-IC-11.6, S-IC-10.2, and S-IC-12.1. FLWA-2 was used in mixtures S-IC-6.6, S-IC-6.8, S-IC-10.7, and the IC mixtures that contained only portland cement as a binder. The absorption of FLWA-3 measured at batching after a 72-hour pre-wetting ranged from 26.9 to 29.9% compared to the nominal value of 28.5% listed in Table 2.5. For mixtures S-IC-7.0 and S-IC-7.7, FLWA-3 received a 5-minute pre-wetting duration, which resulted in an absorption of 15.8 and 17.7%, respectively. The absorption of FLWA-2 measured at batching ranged from 22.6 to 24.3% compared to the nominal value of 24.0% listed in Table 2.5. The water absorbed by the normalweight aggregates provided 5.4 to 6.7% by total weight of binder to Program 3 mixtures, resulting total absorbed water contents ranging from 6.6 to 17.7%. As noted previously, the absorption of the normalweight aggregates used in Program 3 was greater than those used in Programs 1 and 2; as a result, the S-Control and C-Control mixtures in Program 3 (with no IC water) contained nearly as much total absorbed water as mixtures with IC water contents of 5.5 to 7% in Programs 1 or 2. Slumps for mixtures containing the VMA ranged from 3 to 6 in. (75 to 150 mm). The mixture that contained a water-reducing admixture instead of a VMA had a slump of 10 in. (255 mm). Air contents ranged from 7 to 9.25%. Compressive strengths ranged from 4300 to 5970 psi (29.6 to 41.2 MPa).

Table 2.11: Program 3 mixture properties

Mixture ID[a]	**FLWA Absorption (OD basis)**	**Concrete Properties**							
		Total Absorbed Water	***w/cm* Ratio**	**Paste Content**	**Slump**	**Air**	**Unit Weight**	**Temperature**	**28-Day Compressive Strength**
	(%)	**(% Binder Weight)**		**(%)**	**(in.)**	**(%)**	**(lb/ft^3)**	**(°F)**	**(psi)**
S-Control	-	6.7	0.43	26.0	5¼	8.25	142.3	67	5220
S-IC-6.3	29.6	12.4		26.0	3½	8.50	138.8	71	5100
S-IC-6.6[b]	23.7[b]	12.6		26.0	10	7.00	141.4	72	5930
S-IC-6.8[b]	24.3[b]	12.8		26.0	3½	8.50	140.8	69	5280
S-IC-7.0[c]	15.8[c]	12.6		26.1	6	8.75	134.3	67	4800
S-IC-7.7[c]	17.7[c]	13.3		26.1	3	7.25	138.2	69	5970
S-IC-7.8	27.2	13.7		26.0	4¼	8.25	138.9	70	5960
S-IC-8.0	29.9	14.0		26.0	4½	8.00	134.0	68	4300
S-IC-10.2	28.8	16.0		26.0	4¼	9.25	135.6	69	4920
S-IC-10.7[b]	23.7[b]	16.3		26.1	3½	7.00	138.5	68	5440
S-IC-11.6	26.9	17.2		26.1	2¾	8.00	136.1	70	5680
S-IC-12.1	28.4	17.7		26.0	3¼	8.00	135.6	68	5170
C-Control	-	6.6		26.0	5	8.50	142.1	69	4260
C-IC-3.8[b]	22.6[b]	10.0		26.0	5	8.50	137.6	71	4490
C-IC-7.3[b]	24.1[b]	13.2		26.0	4	8.50	138.5	69	5150
C-IC-9.8[b]	23.6[b]	15.4		26.0	4¾	8.50	135.6	70	4910
C-IC-11.8[b]	23.8[b]	17.2		26.0	3½	8.00	135.1	71	5270

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=28% slag cement by weight, C=100% cement)
B: Control=No LWA/internal curing, IC=internally-cured
C: Amount of internal curing water (if applicable), % binder weight

[b] FLWA-2 used (lower absorption); FLWA-3 used otherwise

[c] FLWA-3 used, 5-minute soak time

Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.4.4 Test Program

Some mixtures in this study were evaluated for scaling resistance, freeze-thaw durability, SRM, and RCP (results are presented in Chapter 3). Tables 2.12a, 2.12b, and 2.12c list the tests performed on the individual mixtures in Programs 1, 2, and 3, respectively.

Table 2.12a: Tests performed on mixtures in Program 1

Mixture ID[a]	***w/cm* Ratio**	**Test**			
		Scaling	**Freeze-Thaw**	**SRM**	**RCP**
S-IC-5.5(1)[b]	0.45	×	×	×	×
S-IC-5.5(2)[b]		×[c]		×	
S-IC-5.6(1)[b]		×	×	×	×
S-IC-5.6(2)[b]		×[c]		×	
S-IC-6.6[b]		×	×	×	×
S-IC-7.3		×	×	×	×
S-IC-9.3		×	×	×	×
C-IC-5.7[b]		×	×	×	×
T-IC-8.2		×	×	×	×
T-IC-8.3(1)		×	×	×	×
T-IC-8.3(2)				×	
T-IC-8.3(3)				×	
S-IC-7.1	0.42	×	×	×	×
S-IC-7.2		×	×	×	×
S-IC-9.1		×	×	×	×
S-IC-9.4(1)		×	×	×	×
S-IC-7.0	0.39	×	×	×	×
S-IC-9.4(2)		×	×	×	×

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)

B: IC=Internally-cured

C: Amount of internal curing water, % binder weight

[b] Cement C1(a) used; otherwise, C1(b) used

[c] Both ASTM C672 and Quebec Test BNQ NQ 2621-900 test procedures used

Table 2.12b: Tests performed on mixtures in Program 2

Mixture ID[a]	*w/cm* Ratio	Test			
		Scaling	Freeze-Thaw	SRM	RCP
S-Control(1)	0.45	×	×	×	×
S-IC-6.9		×	×	×	×
S-IC-8.3(1)		×	×	×	×
S-IC-8.4(1)		×	×	×	×
S-IC-8.4(2)		×		×	
S-IC-8.4(3)				×	
S-IC-9.4		×	×	×	
S-IC-7.2(1)	0.44	×	×	×	
S-IC-8.3(2)		×	×	×	
S-Control(2)	0.43	×	×	×	×
S-IC-7.3		×	×	×	×
S-IC-8.9(1)		×	×	×	×
S-IC-8.9(2)		×	×	×	×
S-IC-9.3		×	×	×	×
S-IC-14.1		×	×	×	×
T-Control		×	×	×	×
T-IC-8.9		×	×	×	×
C-Control(1)		×	×	×	×
C-Control(2)				×	
C-IC-8.7				×	
C-IC-8.8		×	×	×	×
FA-Control	0.42	×	×	×	×
FA-IC-8.9		×	×	×	×
FA-IC-9.0				×	
S-Control(3)	0.41	×	×	×	×
S-IC-7.2(2)		×	×	×	×
S-IC-9.0		×	×	×	×
S-IC-9.1		×	×	×	×
S-IC-9.2				×	

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=27% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume, FA=35% Class F fly ash by weight)
B: Control=No LWA/internal curing, IC=Internally-cured
C: Amount of internal curing water (if applicable), % binder weight

[b] Three sets of scaling test specimens were cast with curing times of 14 or 28 days

Table 2.12c: Tests performed on mixtures in Program 3

Mixture ID[a]	*w/cm* Ratio	Test			
		Scaling	Freeze-Thaw	SRM	RCP
S-Control	0.43	×	×	×	×
S-IC-6.3		×	×	×	×
S-IC-6.6		×	×	×	
S-IC-6.8		×	×	×	×
S-IC-7.0			×	×	
S-IC-7.7			×	×	
S-IC-7.8			×	×	
S-IC-8.0		×	×	×	×
S-IC-10.2		×	×	×	×
S-IC-10.7			×	×	
S-IC-11.6			×	×	
S-IC-12.1		×	×	×	×
C-Control		×	×	×	×
C-IC-3.8		×	×	×	×
C-IC-7.3		×	×	×	×
C-IC-9.8		×	×	×	×
C-IC-11.8		×	×	×	×

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=28% slag cement by weight, C=100% cement)
B: Control=No LWA/internal curing, IC=Internally-cured
C: Amount of internal curing water (if applicable), % binder weight

2.5 SCOPE AND SUMMARY

The experimental work in this study involved laboratory testing of three groups of concrete mixtures with moderate *w/cm* ratios to evaluate the effects of IC water on scaling resistance, freeze-thaw durability, surface resistivity, and rapid chloride permeability. Most mixtures contained materials from the four internally cured low-cracking high-performance concrete (IC-LC-HPC) bridge decks completed in 2016, 2017, and 2018. The individual programs, one based of the materials used in each year, investigated the effects of the quantity of IC water, water-to-cementitious material (*w/cm*) ratio, and binder composition on concrete durability.

CHAPTER 3 –DURABILITY EVALUATION OF INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) MIXTURES

3.1 GENERAL

Laboratory test results for the concrete mixtures described in Chapter 2 are presented in this chapter. The mixtures are divided into three Programs, one for each year of the study (2016 to 2018). The Minnesota Department of Transportation (MnDOT) specifications for low-cracking high-performance concrete (LC-HPC) bridge decks provide a basis for evaluation, which include tests for scaling resistance, freeze-thaw durability, and rapid chloride permeability (RCP). Surface resistivity measurements (SRMs) were taken to compare with the RCP results. Chapter 2 includes a description of the materials, test procedures, concrete mixture proportions and properties, and test matrices for the three programs. Test results are presented in this chapter along with an evaluation of the effects of each of the parameters included in this study. The test results listed in this chapter are the average of three specimens with individual specimen data from scaling and freeze-thaw tests presented in Appendix A and individual specimen data from RCP and SRM tests presented in Appendix B.

The primary focus of this study is to examine the effect of internal curing (IC) water on concrete mixtures, evaluated in accordance with the MnDOT specifications. The objective of the tests is to identify an appropriate amount of IC water and/or fine lightweight aggregate (FLWA) for use in bridge decks. The four MnDOT LC-HPC bridge decks constructed from 2016 to 2018 contain IC water contents provided by pre-wetted FLWA of 6.5 to 8.6% by total weight of cementitious material/binder and a partial replacement of portland cement with Grade 100 slag cement of 27 to 30% by total weight of binder. The mixture proportions for each Program were based on the IC-LC-HPC project(s) constructed during that year and included modifications to mixture proportions to determine their effect on durability. The modifications include IC water contents from 0 to 14.1%, water-to-cementitious material (*w/cm*) ratios ranging from 0.39 to 0.45, paste contents (expressed as the percent volume of water and binder in concrete) ranging from 25.0 to 26.7%, and binder compositions examining the effects of using only portland cement, a 35% Class F fly ash replacement of cement, and a 2% silica fume replacement of cement for the mixtures containing 27 to 28% slag cement by total weight of binder.

3.1.1 Scaling Resistance

As discussed in Section 1.6, the primary concrete properties that affect scaling resistance are the *w/cm* ratio, air content, and air void spacing factor (Hooton and Vassilev 2012). In general, concretes containing increasing quantities of supplementary cementitious materials (SCMs) tend to exhibit more scaling damage than concretes containing portland cement as the only binder (control mixtures) (Tablot et al. 1996, Bouzoubaâ et al. 2008, Hooton and Vassilev 2012). Bouzoubaâ et al. (2008) observed that a control mixture containing portland cement as the only binder exhibited higher scaling mass loss than a mixture containing 23% slag cement (by weight of binder) while a mixture containing 31% slag cement exhibited slightly higher mass loss than the control mixture. In the same study, mixtures containing fly ash exhibited higher mass losses than the control, regardless of replacement percentage. Hooton and Vassilev (2012) observed that control mixtures exhibited similar or higher mass losses than mixtures containing 20% slag cement while mixtures with 35% and 50% slag cement exhibited a higher mass loss than the control mixtures. Hooton and Vassilev (2012) also noted that the increase in mass loss for mixtures with increasing amounts of slag cement was more pronounced in the tests performed in accordance with the Quebec Test BNQ NQ 2621-900 Annex B procedure than those performed in accordance with ASTM C672. The studies by Bouzoubaâ et al. (2008) and Hooton and Vassilev (2012), however, indicate that the ASTM C672 test procedure is overly aggressive, does not correlate well with in-field scaling performance, and the Quebec test is more realistic in evaluating scaling resistance.

An important distinction between the two test methods is the deicing salt used to pond the test specimens: ASTM C672 uses calcium chloride ($CaCl_2$), while BNQ NQ 2621-900 uses sodium chloride (NaCl). For concretes exposed to calcium chloride deicers, the formation of calcium oxychloride ($3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O$) occurs when the calcium hydroxide ($Ca(OH)_2$) produced during the hydration of portland cement reacts with the deicing solution as shown in Eq. (3.1) (Suraneni et al. 2017).

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow 3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O \tag{3.1}$$

Calcium oxychloride forms primarily at cooler temperatures (40 to 50 °F [4 to 10 °C]) and is less stable at higher temperatures. Calcium oxychloride is expansive and causes damage in concrete due to hydraulic stresses in the cement paste (Sutter et al. 2008), likely contributing to the increased damage observed in scaling tests performed in accordance with ASTM C672. In concretes containing slag cement, fly ash, or silica fume, calcium hydroxide is consumed by a reaction with silica in the SCMs, forming additional calcium silicate hydrate (C-S-H) (Mindess et al. 2003). The decrease in available calcium hydroxide in concrete containing SCMs reduces the formation of calcium oxychloride (Sutter et al. 2008) and is a likely reason for the improved relative performance of mixtures containing SCMs when tested in accordance with ASTM C672.

In previous studies that evaluated the effect of IC and SCMs on scaling resistance, Jones et al. (2014) and Feng and Darwin (2020) found no detrimental effect when increasing amounts of IC water were added to concretes containing SCMs. In studies by Pendergrass and Darwin (2014) and Feng and Darwin (2020), the combination of IC and SCMs (slag and silica fume) in concretes led to increased mass loss compared to control mixtures in scaling tests performed in accordance with BNQ NQ 2621-900; including only IC or SCMs resulted in little to no change in scaling performance.

3.1.2 Freeze-Thaw Durability

As discussed in Section 1.6, concrete durability is significantly improved when the air void system provides enough space for freezing water to expand without causing damage; however, a critical saturation point exists for all concretes where the tensile stresses induced upon freezing due to ice formation cause cracking within the cement paste or in and around aggregates. The mixtures evaluated in this study were tested in accordance with ASTM C666 – Procedure A. An important aspect to note in this test procedure is that the concrete is never allowed to dry. By the nature of this test, the concrete pore structure and empty air voids will eventually fill with water and damage the surrounding cement paste upon freezing. Jones et al. (2014) describes this condition as a worst case scenario that is difficult to replicate in field applications. The exposure conditions of ASTM C666 – Procedure A, however, are relevant when concretes with IC are placed in conditions that will subject them to freezing temperatures at early ages. As discussed in Sections 1.7, and 2.1, Jones et al. (2014) noted that mixtures containing “excessive” amounts of IC water (those with more than twice the design IC water content of 7% of the binder weight) exhibited failure (the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn}) in freeze-thaw testing in fewer than 300 cycles. Additionally, Feng and Darwin (2020) noted a decrease in E_{Dyn} in fewer cycles for mixtures containing slag cement and silica fume as the amount of IC water increased, even for a less severe test procedure – Kansas Test Method KTMR-22, a modified version of ASTM C666 – Procedure B that includes freezing in air, a longer curing duration, and a drying period for the test specimens.

Although FLWA is the primary source of IC water in this study, normalweight aggregates also absorb water, and in some cases provide additional water to the cement paste. In this report, "total absorbed water" refers to the water absorbed by all aggregates in a mixture, that is, IC water plus absorbed water in the normalweight aggregates. Both IC and total absorbed water are expressed as a percentage of the total binder weight. As discussed in Chapter 2, Program 1 used normalweight aggregates with lower absorptions (0.4 and 0.5% for coarse and fine aggregate, respectively) than Programs 2 or 3, adding approximately 2.2% water by total weight of binder to the IC-LC-HPC mixtures. Program 2 also used coarse aggregate with a 0.4% absorption, but the fine aggregate absorption was 0.8%, resulting in an additional 2.6% water by total weight of binder to the IC-LC-HPC mixtures. Program 3 used normalweight aggregates with the highest absorptions in this study (1.4 and 1.2% for coarse and fine aggregate, respectively), adding approximately 6.0% water by total weight of binder to the mixtures. One of the main observations noted in this chapter is that the that freeze-thaw durability decreases as the amount of IC water increases, but this trend is better characterized by the total absorbed water.

3.1.3 Rapid Chloride Permeability and Surface Resistivity

As discussed in Chapter 1, the benefits of including SCMs and IC in concrete include achieving improved performance in the Rapid Chloride Permeability (RCP) and Surface Resistivity Measurement (SRM) tests. Wee et al. (2000), Hooton and Vassilev (2012), O'Reilly et al. (2017a), Moini et al. (2019), and Obla (2019) have noted that increasing SCM replacement levels of portland cement results in a reduction in charge passed in RCP testing compared to mixtures containing portland cement as the only binder.

Ionic conductivity (measured by the RCP test) increases and resistivity (bulk and surface) decreases with increasing temperature, degree of saturation, and carbonation (Spragg et al. 2013, Moradllo et al. 2018). The test procedures for RCP and SRM use fully saturated specimens that do not undergo drying prior to testing. Moreover, for the RCP test, specimens are submerged in a pressurized container as part of their preparation, which forces more water into pores than would normally occur in saturated concrete. The air voids in concrete structures, however, are not usually filled with fluid. Thus, basing performance on saturated specimens is questionable and at best conservative in terms of estimating service life (Qiao et al. 2019). Jenkins (2015) observed that SRMs increased as specimens were allowed to dry, even for short periods, increasing the difficulty in obtaining consistent test data.

Previous studies have found a strong correlation between SRM and RCP results over a wide range of *w/cm* ratios and permeability classifications (Rupnow and Icenogle 2011, Jenkins 2015). Although RCP testing is commonly included in performance-based specifications, SRM testing has been increasingly used in addition to and, in some cases, as a replacement for RCP testing. Of the two methods, the RCP test is more labor intensive, time consuming, and expensive to conduct than the SRM test (Jenkins 2015, Moradllo et al. 2018). Furthermore, unless the concrete contains a high SCM content (slag cement, fly ash, or silica fume), electrical resistivity properties are well-established at 28 days, as opposed to RCP results, which are typically measured at 56 days (Rupnow and Icenogle 2011, Jenkins 2015).

3.1.4 Statistical Analysis

Student's t-test was employed to determine whether the differences in performance between test results were statistically significant. Student's t-test is particularly useful for small sample sizes with an unknown population variance, as is the case with the concrete mixtures in the study that include just three specimens per test. The procedure indicates whether the difference in the means of two samples, X_1 and X_2, represents a difference in population means, μ_1 and μ_2, at a specified level of significance, α. For test results in this report, the level of statistical significance α is compared based on the p value, the probability of obtaining a difference in results at least the same or larger than the sample data assuming that there is no difference. The degree of statistical significance between the differences is represented by the level of significance for when the difference does not occur by chance (Devore 2008). In previous studies, *p* values less than 0.02, 0.05, and sometimes even 0.10 indicate that the differences in means are statistically significant and did not occur by chance. Values above 0.20 are universally accepted as indicators that the differences between means are not statistically significant and likely due to chance.

In this study, the differences in results between two mixtures are considered statistically significant if the *p* value is less than 0.05 (5% probability that the differences arose by chance) given the inherent variability of concrete and durability test data. Two-sided tests are used in the data analyses, meaning that it is assumed that there was an equal probability of finding that one mean, μ_1, was either greater or less than the other mean μ_2. Homoscedasticity, or equal variance through the range of results, is also assumed. Scaling test results are evaluated based on the cumulative mass loss at the end of the scaling test (50 cycles for ASTM C672). Freeze-thaw test results are compared for mixtures based on the number of cycles until the average dynamic modulus of elasticity (E_{Dyn}) dropped below 90% of the initial value. RCP test results evaluated based on the amount of charge passed at 56 days while SRMs are evaluated based on the 28-day values. In addition to individual specimen test data, Appendices A and B present the *p*-values determined from Student's t-test comparisons between mixtures.

3.2 DURABILITY TEST RESULTS

3.2.1 General

This section presents the results from scaling and freeze-thaw tests in Programs 1-3. As described in Section 2.4, the concrete mixtures are identified by binder composition and amount of IC water and have the form 'A-B-C' in the tables and figures that follow. The lead indicator (A) in mixture IDs identifies the binder composition (C for 100% portland cement, S for binary mixtures with slag cement, FA for binary mixtures with Class F fly ash, and T for ternary mixtures with slag cement, silica fume, and portland cement). The second indicator (B) identifies whether or not a mixture contained IC (mixtures without FLWA/IC water are identified as a Control). The trailing indicator (C) identifies the amount of IC water, expressed as the percentage of total binder weight (omitted for Control mixtures). For cases in Programs 1 and 2 where duplicate mixture IDs are present, mixtures with similar binder composition and IC water contents have an additional indicator in parenthesis to distinguish between mixtures.

As outlined in Section 2.3.2, scaling tests were performed in accordance with ASTM C672 with an additional solution change at 35 freeze-thaw cycles. At each solution change and at the end of testing, visual ratings based on the amount of scaling damage were assigned and mass loss was determined. For two mixtures in Program 1, two sets of scaling specimens were tested, one in accordance with ASTM C672 and one in accordance with the Quebec Test BNQ NQ 2621-900 Annex B procedures. The MnDOT LC-HPC specifications for scaling resistance list a maximum visual rating of 1 at the end of testing (50 freeze-thaw cycles). The figures that display scaling test results show the average cumulative mass loss as a function of freeze-thaw cycles. The tables that list scaling test results include visual ratings after 20 and 50 cycles along with the average cumulative mass loss after 50 cycles. For mixtures that exhibited minimal scaling damage and were assigned visual ratings of 1 after 50 cycles, a majority of the cumulative mass loss occurred during the first 20 cycles. Similar observations were made for concretes containing slag cement by Talbot et al. (1996), Hooton and Vassilev (2012), and Jones et al. (2014) who noted that a majority of scaling mass loss occurred between 5 and 15 cycles. The visual rating for mixtures in Programs 1 and 2 typically remained the same between 20 and 50 freeze-thaw cycles, although the visual ratings for some mixtures did increase by a rating of 1 during this testing period. The Program 3 mixtures were all within the MnDOT specification limit for scaling visual ratings, with a majority of specimens given a visual rating of 0 through 20 cycles and 1 after 50 cycles.

In this study, including an adequate air content (above 7%) is observed to be the dominant factor for concrete to perform well in scaling tests (visual rating of 0 or 1 per ASTM C672) for the mixtures in Program 1 (all mixtures in Programs 2 and 3 had air contents of at least 7%). Mixtures in Program 2 containing slag cement exhibited a large range of scaling mass loss (0.022 to 0.185 lb/ft^2 [0.11 to 0.90 kg/m^3]) relative to Programs 1 and 3 and included specimens that were assigned visual ratings of 2 or 3. All mixtures in Program 3 exhibited satisfactory scaling results and were assigned a visual rating of 1 after 50 cycles. When the IC water content was approximately 12% or less in mixtures containing either a 28% slag cement replacement for portland cement or portland cement as the only binder, scaling resistance was not negatively affected. In Program 2, one mixture was tested to evaluate the effects of increasing the curing time or using the bottom surface (that received no finishing during casting and was not affected by bleedwater) for testing. Test results for this mixture show that scaling resistance is improved by increasing the curing time or by testing concrete unaffected by bleedwater or finishing.

Using a 27 to 30% slag cement replacement of portland cement had no apparent effect on scaling resistance when compared to mixtures with portland cement as the only binder for any of the Programs. Similarly, compared to mixtures continuing slag cement and portland cement, a 2% addition of silica fume did not negatively affect scaling resistance when adequate entrained air was provided. The mixtures in Program 2 containing fly ash exhibited higher mass losses than mixtures containing slag cement or portland cement as the only binder and were assigned a visual rating of 2 or 3. These mixtures had a *w/cm* ratio of 0.42, an SCM replacement level of 35%, and paste content of 26.7% to replicate the MnDOT Control deck associated with the IC-LC-HPC decks from Program 2. The increased scaling relative to other mixtures in this study is consistent with the observations from the studies discussed above for mixtures containing fly ash (Tablot et al. 1996, Bouzoubaâ et al. 2008).

As outlined in Section 2.3.3, freeze-thaw tests were performed in accordance with ASTM C666 – Procedure A. The MnDOT LC-HPC specifications for freeze-thaw durability require that the E_{Dyn} after 300 freeze-thaw cycles be no lower than 90% of the initial value. Freeze-thaw durability results can be alternatively expressed as a Durability Factor (*DF)*. For specimens that complete 300 cycles of testing, the *DF* represents the ratio of E_{Dyn} after 300 freeze-thaw cycles to the initial E_{Dyn}; for specimens that do not complete 300 cycles, the *DF* is the final percentage of the initial E_{Dyn} value measured before testing was terminated (as specimens dropped below 60% of their initial E_{Dyn}) multiplied by ratio of the number of cycles needed to drop the E_{Dyn} below 60% of its initial value to 300 cycles.

In Program 1, tests were terminated after 300 cycles. For selected mixtures in Program 2 and all mixtures in Program 3, testing continued until the average E_{Dyn} dropped below 60% of the initial value, at which point testing was terminated. If no decrease in the E_{Dyn} was observed through 2000 freeze-thaw cycles, which was the case for three of the Control mixtures in Program 2 (no FLWA/IC water), testing was terminated. The figures that display freeze-thaw test results show the percentage of the initial E_{Dyn} as a function of the number of freeze-thaw cycles. The tables that list the freeze-thaw test results include the *DF* after 300 cycles, and where applicable, the number of freeze-thaw cycles needed for the average E_{Dyn} to drop below 90% of the initial value. Within the parameters evaluated in this study, the *w/cm* ratio had a small but measurable effect for mixtures tested up to 2000 cycles in Program 2. In Program 3, the mixtures containing slag cement withstood slightly fewer freeze-thaw cycles before the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn} than mixtures containing portland cement as the only binder, but the total absorbed water content appears to have been the principal factor affecting the freeze-thaw durability of the IC-LC-HPC mixtures. When mixtures underwent freeze-thaw testing until the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn}, a majority of those containing a total absorbed water content more than 12% exhibited a *DF* below 90; all mixtures with a total absorbed water content of less than 12% were satisfied the MnDOT specifications for freeze-thaw durability.

3.2.2 Program 1

In Program 1, 16 mixtures were tested for scaling resistance and 14 were tested for freeze-thaw durability. Thirteen mixtures contained slag cement with a 30% replacement of portland cement by total weight of binder, while two ternary mixtures contained 28% slag cement and 2% silica fume by total weight of binder. One mixture had 100% portland cement for the binder composition. The IC water content ranged from 5.5 to 9.4% by total weight of binder. The mixtures had *w/cm* ratios of 0.45, 0.42, or 0.39.

The test results for Program 1 are listed in Table 3.1. The scaling test results are more dependent on the air content than the IC or total absorbed water content, binder composition, or *w/cm* ratio. The mixtures with an air content below 7% had the highest mass losses and visual ratings. The two ternary mixtures (slag cement, silica fume, and portland cement) completed testing with visual ratings above the MnDOT specification limit and had relatively high mass losses. As discussed in Section 2.4.1, one of the ternary mixtures (T-IC-8.3(1)) is suspected to have included additional mixing water, which led to a high slump (6½ in. [165 mm]) and low compressive strength (3800 psi [26.2 MPa]). The other ternary mixture (T-IC-8.2) had an air content of 6.5%. Since additional mix water and low air contents are known to negatively affect scaling, the addition of 2% silica fume by total binder weight is not believed to negatively affect the scaling resistance of Program 1 mixtures. The single mixture with portland cement as the only binder (C-IC-5.7, with a *w/cm* ratio of 0.45 and an air content of 8.25%) completed testing with an average mass loss and visual rating that was similar to the mixtures containing slag cement with the same *w/cm* ratio and an air content above 7%. Within the range of parameters examined in Program 1, mixtures with adequate air entrainment (air content above 7%) and similar IC and total absorbed water contents exhibited minimal change in scaling mass loss or visual rating. Only two mixtures with adequate air entrainment had a *w/cm* below 0.45 (two mixtures each for *w/cm* ratios of 0.42 and 0.39); thus, Program 1 provided little information on the effect of *w/cm* ratio on the scaling resistance of IC-LC-HPC mixtures.

The freeze-thaw test specimens in Program 1 were only tested through 300 freeze-thaw cycles. For the parameters investigated in Program 1, based on the results through 300 cycles, no difference in freeze-thaw durability was noted in Program 1 as all mixtures had a *DF* greater than 100. It should be noted that the mixtures in Program 1 contained the lowest total absorbed water content in this study as the normalweight aggregates had the lowest absorptions among the Programs, a variable that was not considered until examining the results of Program 3 mixtures.

Table 3.1: Average durability test results for Program 1 mixtures

Mixture ID[a]	*w/cm* Ratio	Air Content (%)	Total Absorbed Water (% Binder Weight)	Scaling			Freeze-Thaw
				Visual Rating at 20 Cycles	Visual Rating at 50 Cycles	Mass Loss at 50 Cycles[b] (lb/ft^2)	Durability Factor[c]
S-IC-5.5(1)[d]	0.45	6.75	7.7	0	0	0.089	107
S-IC-5.5(2)[d]		10	7.7	0	0	0.029	-
S-IC-5.6(1)[d]		8.75	7.8	0	0	0.035	107
S-IC-5.6(2)[d]		8.25	7.8	0	0	0.041	-
S-IC-6.6[d]		9.25	8.8	0	0	0.014	106
S-IC-7.3		6.5	9.5	1	1	0.179	105
S-IC-9.3		6	11.5	1	2	0.220	107
C-IC-5.7[d]		8.25	7.9	0	0	0.040	105
T-IC-8.2		6.5	10.3	1	2	0.208	105
T-IC-8.3		9.5	10.4	1	2	0.164	107
S-IC-7.1	0.42	5.5	9.1	2	2	0.227	105
S-IC-7.2		6.5	9.3	1	1	0.092	106
S-IC-9.1		8	11.1	1	1	0.096	101
S-IC-9.4(1)		5.5	11.4	2	2	0.237	107
S-IC-7.0	0.39	11.25	9.0	1	1	0.047	105
S-IC-9.4(2)		8.5	11.3	1	1	0.048	104

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)
B: Internally Cured
C: Amount of internal curing water, % binder weight

[b] $1\ \text{lb/ft}^2 = 4.88\ \text{kg/m}^2$

[c] Durability Factor (DF) = (P × N) / 300 cycles, where P is the percentage of the initial dynamic modulus remaining at N cycles. N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller).

[d] Includes cement C1(a)

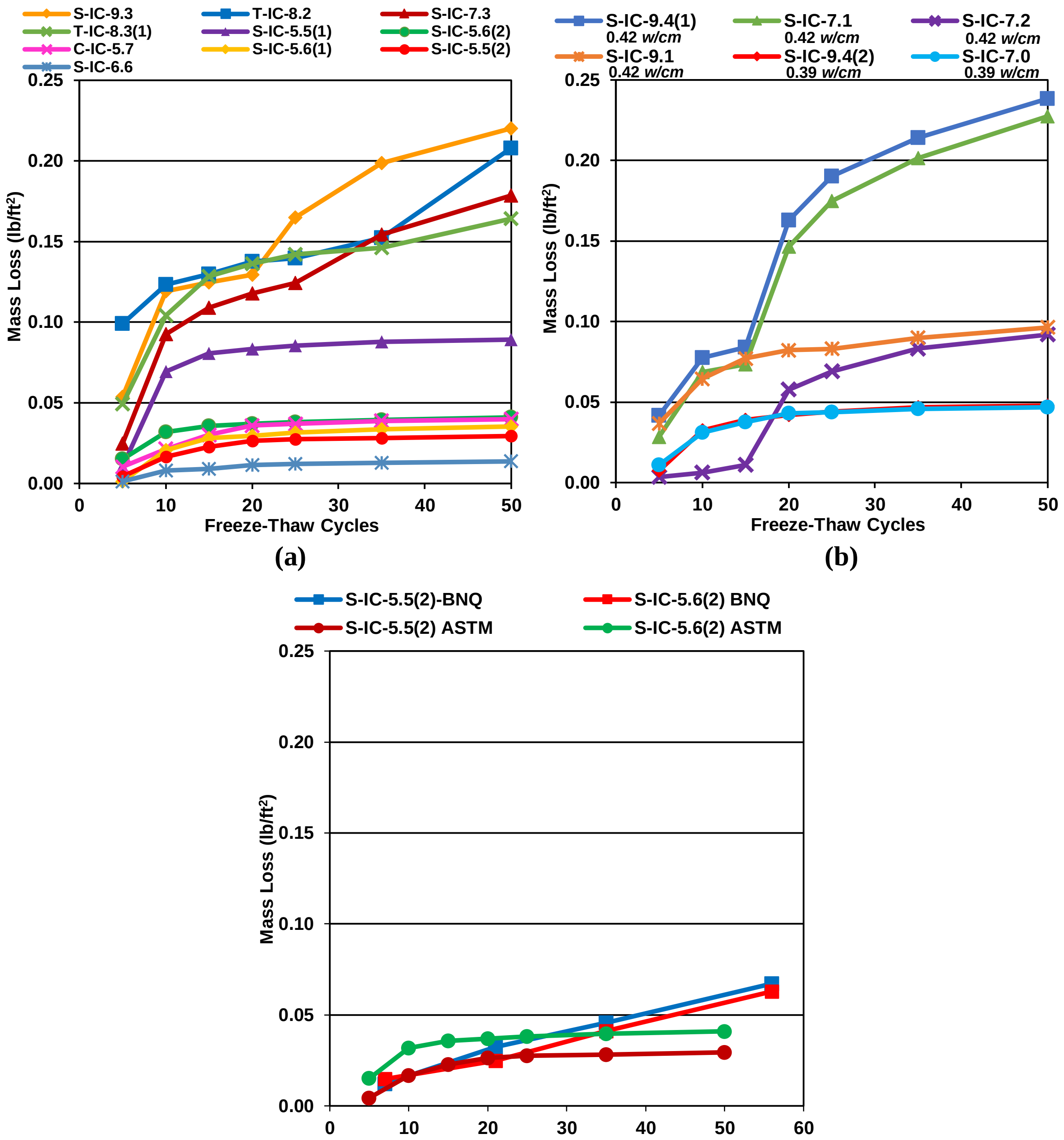
- Test not performed

3.2.2.1 Scaling Test Results

Figure 3.1 compares mass loss due to scaling with the number of freeze-thaw cycles for mixtures in Program 1. For mixtures with a *w/cm* ratio of 0.45 (Figure 3.1a), although the mixtures with an IC water content above 7% exhibited higher mass losses than those with less IC water, the differences in results are believed to be due to the differences in air content. For mixtures containing slag cement, a noticeable increase in mass loss occurred as the air content dropped below 7%. Mixtures with an air content of 8.25% or more exhibited mass losses below 0.05 lb/ft^2 (0.24 kg/m^2), except for ternary mixture T-IC-8.3(1), which had a mass loss of 0.164 lb/ft^2 (0.81 kg/m^2) but is suspected to contain additional mixing water as discussed above. It should be noted that although additional water may have been used in mixture T-IC-8.3(1), the higher air content (9.5%) likely led to a lower cumulative mass loss than mixtures with an air content of 6.5% or less and no additional water, including the other ternary mixture (T-IC-8.2) which had an air content of 6.5% and mass loss of 0.208 lb/ft^2 (1.01 kg/m^2). For mixtures containing 30% slag cement, mass losses at the end of testing ranged from 0.179 lb/ft^2 (0.87 kg/m^2) for S-IC-7.3 (air content of 6.5%) to 0.220 lb/ft^2 (1.07 kg/m^2) for S-IC-9.3 (air content of 6%). The single mixture containing portland cement as the only binder (C-IC-5.7) had an air content of 8.25% and completed testing with an average mass loss of 0.040 lb/ft^2 (0.20 kg/m^2), similar to the mixtures containing cement slag cement and an air content of at least 8.25%. The effect of binder composition on scaling resistance cannot be fully evaluated based on the range of parameters included in Program 1, with only one ternary mixture that contained the correct amount of mixing water and one mixture containing portland cement as the only binder.

Figure 3.1b compares the average cumulative mass loss with the number of freeze-thaw cycles for mixtures with a *w/cm* ratio of 0.42 or 0.39. The effect of air content on scaling is demonstrated with the mixtures containing a 0.42 *w/cm* ratio. The two mixtures with an air content of 5.5% (S-IC-7.1 and S-IC-9.4(1)) exhibit the highest mass loss among mixtures in Program 1 (0.227 and 0.237 lb/ft^2 [1.11 and 1.16 kg/m^2], respectively) and had a visual rating of 2. Batches with similar mixture proportions (S-IC-7.2 and S-IC-9.1) had higher air contents (6.5 and 8%, respectively) and completed testing with mass losses of 0.092 and 0.096 lb/ft^2 (0.45 and 0.47 kg/m^2), respectively, and a visual rating of 1. The two mixtures with a *w/cm* ratio of 0.39 completed testing with mass losses below 0.050 lb/ft^2 (0.24 kg/m^2) and a visual rating of 1. S-IC-7.0 had an air content of 11.25%, which exceeds upper limit for air content in the MnDOT specification.

Figure 3.1c compares the average cumulative mass loss with the number of freeze-thaw cycles for the two mixtures that were tested for scaling resistance in accordance with both ASTM C672 and Quebec Test BNQ NQ 2621-900 Annex B procedures (S-IC-5.5(2) and S-IC-5.6(2), both with a *w/cm* ratio of 0.45. The visual ratings and average cumulative mass loss after 20 and 50 cycles for specimens tested in accordance with ASTM C672 or 21 and 56 cycles for specimens tested in accordance with BNQ NQ 2621-900 are listed in Table 3.2. Although BNQ NQ 2621-900 does not include the assignment of visual ratings to specimens upon solution changes, surface damage was minimal and the specimens were assigned a visual rating of 0 at the end of testing, as were the ASTM C672 specimens. The cumulative mass losses for specimens tested in accordance with ASTM C672 were both below 0.050 lb/ft^2 (0.24 kg/m^2), while mass losses for the BNQ NQ 2621-900 specimens were slightly above 0.060 lb/ft^2 (0.29 kg/m^2); the BNQ NQ 2621-900 test specimens, however, underwent an additional six freeze-thaw cycles. The mass loss trends over time for the ASTM C672 test specimens show that the majority of mass loss occurred within the first 20 freeze-thaw cycles while mass losses for BNQ NQ 2621-900 tended to be more consistent throughout testing. Both mixtures performed well during testing under both test procedures.



(a)

(b)

(c)

Figure 3.1: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 1: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratios of 0.42 and 0.39; (c) side-by-side ASTM C672/ BNQ NQ 2621-900 test procedures

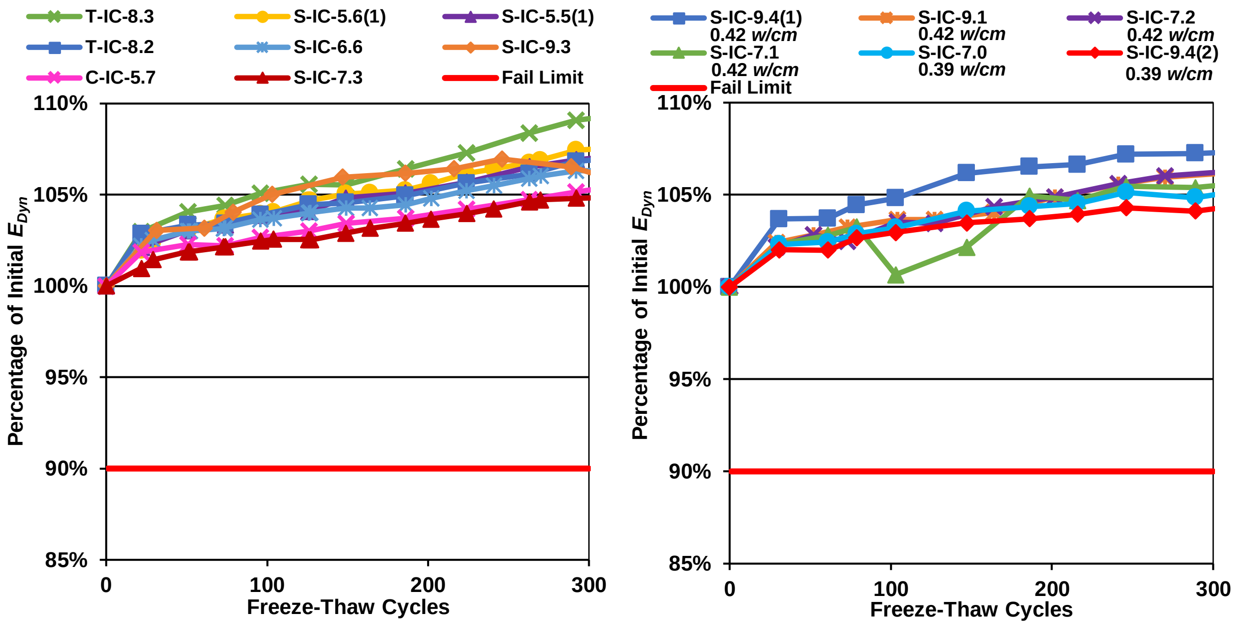
Table 3.2: Scaling test results for ASTM C672 and BNQ NQ 2621-900 test procedures

Mixture ID[a]	**Visual Rating-End of Testing**	**Avg. Mass Loss Midway Through Testing**[b] **(lb/ft^2)**	**Avg. Mass Loss at the End of Testing**[b] **(lb/ft^2)**
ASTM C672[c]			
S-IC-5.5(2)	0	0.026	0.029
S-IC-5.6(2)	0	0.037	0.041
BNQ NQ 2621-900[d]			
S-IC-5.5(2)	0	0.032	0.067
S-IC-5.6(2)	0	0.035	0.063

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)
B: Internally-cured
C: Amount of internal curing water, % binder weight
[b] 1 lb/ft^2 = 4.88 kg/m^2
[c] Midway mass loss taken after 20 cycles, 50 cycles at the end of testing
[d] Midway mass loss taken after 21 cycles, 56 cycles at the end of testing

3.2.2.2 Freeze-Thaw Test Results

In freeze-thaw testing, all specimens from Program 1 mixtures completed 300 cycles exhibiting increases in E_{Dyn} (*DF* above 100), indicating satisfactory freeze-thaw durability. Figure 3.2 compares the average percentage of initial E_{Dyn} with the number of freeze-thaw cycles for mixtures in Program 1. No differences were noted for mixtures as a function of the IC water, which ranged from 5.5 to 9.4%, *w/cm* ratio, or binder composition through 300 cycles. It should be noted that the maximum total absorbed water content in the Program 1 mixtures (11.4%) was relatively low compared to Program 2 (16.1%) and Program 3 (17.7%). For mixtures tested subjected to freeze-thaw cycles until the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn} in Programs 2 and 3, the total absorbed water content is the primary factor affecting freeze-thaw durability for mixtures with values above 12%, leading to damage in fewer than 300 cycles for a majority of mixtures. Student's t-test was not applied for the Program 1 freeze-thaw test results as the mixtures exhibited similar behavior throughout testing.



(a) **(b)**

Figure 3.2: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures in Program 1: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratios of 0.42 and 0.39. All contain slag cement

3.2.3 Program 2

Durability testing in Program 2 involved 24 mixtures evaluated for scaling resistance, all but one of which (S-IC-8.4(2)) was also evaluated for freeze-thaw resistance. Of the 23 mixtures tested for freeze-thaw durability, 13 were evaluated for freeze-thaw durability through 2000 cycles or until the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn}. Key parameters included *w/cm* ratio (0.41 to 0.45), IC water content (0 to 9% by weight of binder), and binder composition. Mixtures with 27% slag cement by total weight of binder (used for IC-LC-HPC decks in 2017) were evaluated with an IC water content of 7% at *w/cm* ratios of 0.41, 0.43, and 0.45. At a *w/cm* ratio of 0.43, two mixtures contained 27% slag cement and 2% silica fume by total weight of binder with IC water contents of 0 and 8.9% (T-Control and T-IC-8.9) and two mixtures contained portland cement as the only binder with IC water contents of 0 and 8.8% (C-Control(1) and C-IC-8.8). Finally, at a *w/cm* ratio of 0.42, two mixtures contained 35% Class F fly ash by total weight of binder and IC water contents of 0 and 8.9% (FA-Control and FA-IC-8.9).

The test results for Program 2 are listed in Table 3.3. Unlike Program 1, where the only specimens that failed the scaling test had air contents below 7%, some of the Program 2 concrete mixtures with slag cement exceeded the maximum MnDOT visual rating despite having a minimum air content of 7.25%. Greater variability in mass loss between mixtures containing slag cement with similar air (within 1.75%) and IC water (within 1% by weight of binder) contents was observed in Program 2 compared to Program 1. For mixtures with slag cement and *w/cm* ratios of 0.45 and 0.43, with one exception, the addition of IC water led to lower mass losses than obtained for the S-Control(1) and S-Control(2) mixtures, respectively. The exception was mixture S-IC-14.1 (*w/cm* ratio of 0.43), which exhibited a higher mass than all other mixtures with this binder composition. This poor performance may be attributed to the high quantity of IC water in S-IC-14.1 (14.1% by weight of binder), which is 76% higher than the 8% that the IC-LC-HPC bridge decks associated with Program 2 were designed for. Additional mixtures with high IC water contents were not tested to verify this trend. Similar to the observations from Program 1, IC water contents between 6.9 and 9.4% (total absorbed water contents of 9.6 to 11.8%, respectively) did not negatively affect scaling results, and decreasing the *w/cm* ratio from 0.45 to 0.41 did not result in a change in scaling resistance for the Program 2 mixtures. This contrasts to some extent with observations by Hooton and Vassilev (2012) who observed that a reduction in the *w/cm* ratio from 0.42 to 0.38 resulted in improved scaling performance.

Within the range of parameters examined with binder compositions in Program 2, including 2% addition of silica fume in addition to slag cement in ternary mixtures was not observed to have any effect on scaling resistance, while the two mixtures that included portland cement as the only binder exhibited slightly lower mass losses than those containing SCMs; additional mixtures with these binder compositions, however, will be needed to verify these observations. The two mixtures containing 35% Class F fly ash replacement of portland cement exhibited higher mass losses than mixtures containing slag cement or portland cement as the only binder. The mixtures containing fly ash, however, contained a greater SCM replacement level (35% vs. 27 to 29% by total weight of binder), greater paste content (26.7 vs 26%), and a different *w/cm* ratio (0.42) than the other Program 2 mixtures, although the *w/cm* ratio is not considered to have been different enough to play a role.

Among the 24 mixtures tested for scaling resistance, one mixture (S-IC-8.4(2)) contained three sets of scaling test specimens to examine the effects of increasing the period of wet curing from 14 to 28 days and testing the bottom surface of the specimen instead of top. The bottom surface of the specimen is not affected by bleedwater or finishing technique, allowing for a useful comparison. For S-IC-8.4(2), the scaling test results indicate that increasing the curing time leads to a decrease in mass loss, but that the test surface and lack of finishing have a greater impact on scaling; the specimens whose bottom surfaces were used for testing were the only ones in Program 2 that were assigned a visual rating of 0 at the end of testing and exhibited the lowest mass losses among Programs 1-3, including mixtures with portland cement as the only binder.

The effect of set retarder on durability was examined for mixtures containing 27% slag cement and a nominal IC water content of 9% by weight of binder. Mixtures with *w/cm* ratios of 0.45, 0.43, and 0.41 (S-IC-8.4(1), S-IC-8.9(1), and S-IC-9.0, respectively) were duplicated, but with the addition of 3 oz/cwt (2.0 mL/kg) of set retarder (S-IC-8.3(1), S-IC-9.3, and S-IC-9.1, respectively), the same dosage used in one IC-LC-HPC deck and part of another placed in 2017. At a *w/cm* ratio of 0.45, difference in the cumulative mass loss in the scaling tests between mixtures with and without set retarder (0.113 and 0.094 lb/ft^2 [0.55 and 0.46 kg/m^2], respectively) was minimal considering the relatively wide range of mass losses exhibited by mixtures containing slag cement (0.042 to 0.185 lb/ft^2 [0.20 to 0.90 kg/m^2]). At *w/cm* ratios of 0.43 and 0.41, however, the cumulative mass losses for mixtures containing set retarder (S-IC-9.3 and S-IC-9.1, respectively) were among the lowest for mixtures containing slag cement. Although additional mixtures need to be tested to better establish the effect of set retarder on IC-LC-HPC durability, the results from this study indicate that the set retarder does not negatively affect scaling resistance.

In freeze-thaw testing, regardless of binder composition, IC water content, or *w/cm* ratio, all mixtures in Program 2 completed more than 300 freeze-thaw cycles prior to dropping below 90% of their initial value of E_{Dyn} value, satisfying the MnDOT specification requirement for freeze-thaw durability. The only mixture that completed 300 cycles with a *DF* below 100 was S-IC-14.1 (which had a *DF* of 93 and dropped below 90% of its initial E_{Dyn} after 315 cycles) which contained 1.76 times more IC water than the target value of 8% used in the IC-LC-HPC bridge decks corresponding to Program 2. This observation is similar to that made by Jones et al. (2014) who noted that only mixtures with more than twice the design amount of IC water had issues in freeze-thaw durability. For cases where both Control and IC mixtures with the same *w/cm* ratio underwent freeze-thaw cycles until the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn} (or up to 2000 cycles), those containing IC water failed in fewer cycles than their respective Control mixture. The *w/cm* ratio was observed to have an effect on freeze-thaw durability for mixtures containing slag cement; as the *w/cm* ratio increased from 0.41 to 0.43 or 0.45, specimens failed in fewer cycles. No effect of binder composition was observed among mixtures tested until the average value of E_{Dyn} dropped below 60% of the initial value of E_{Dyn} in Program 2, although more mixtures with binder compositions other than 27% slag cement need to be tested to verify this observation. As previously indicated in Section 3.2.2, the observation that total absorbed water content is the primary factor affecting freeze-thaw durability was not made until examining the results from Program 3.

3.2.3.1 Scaling Test Results

Figure 3.3 compares the average cumulative scaling mass loss with the number of freeze-thaw cycles for mixtures containing 27% slag cement. For mixtures with a *w/cm* ratio of 0.45 (Figure 3.3a), S-Control(1) exhibited the greatest mass loss with an average of 0.142 lb/ft^2 (0.69 kg/m^2) at the end of testing along with a visual rating of 2 while S-IC-9.4 completed testing with the lowest mass loss (0.048 lb/ft^2 [0.23 kg/m^2]) and was assigned a visual rating of 1. For mixtures with a *w/cm* ratio of 0.44 (Figure 3.3b), mass losses were 0.051 lb/ft^2 (0.25 kg/m^2) for S-IC-8.3(2) and 0.084 lb/ft^2 (0.41 kg/m^2) for S-IC-7.2(1); both mixtures were assigned a visual rating of 1. For mixtures with a *w/cm* ratio of 0.43 (Figure 3.3c), mass losses ranged from 0.042 to 0.185 lb/ft^2 (0.20 to 0.90 kg/m^2) for S-IC-9.3 (visual rating of 1) and S-IC-14.1 (visual rating of 3), respectively. For mixtures with a 0.41 *w/cm* ratio (Figure 3.3d), mass losses ranged from 0.082 lb/ft^2 (0.40 kg/m^2) to 0.163 lb/ft^2 (0.80 kg/m^2) for S-IC-9.1 (visual rating of 1) and S-IC-7.2(2) (visual rating of 2), respectively.

Table 3.3: Average durability test results for Program 2 mixtures

Mixture ID[a]	*w/cm* Ratio	Air Content (%)	Total Absorbed Water (% Binder Weight)	Scaling			Freeze-Thaw	
				Visual Rating at 20 Cycles	Visual Rating at 50 Cycles	Mass Loss at 50 Cycles[b] (lb/ft^2)	Durability Factor[c]	No. of Cycles to 90% $E_{Dyn.}$
S-Control(1)	0.45	9	3.1	2	2	0.142	104	1569
S-IC-6.9		8.5	9.6	2	2	0.102	103	1034
S-IC-8.3(1)[d]		9.25	10.9	2	2	0.113	102	709
S-IC-8.4		9	11.0	2	2	0.094	102	982
S-IC-8.4(2-14)[e]		7.75	11.0	1	1	0.056	-	
S-IC-8.4(2-28)[e]				1	1	0.037		
S-IC-8.4(2-U)[e]				0	0	0.009		
S-IC-9.4		7.5	11.8	1	1	0.048	108	×
S-IC-7.2(1)	0.44	10	9.8	1	1	0.084	108	×
S-IC-8.3(2)		7.25	11.0	1	1	0.051	107	×
S-Control(2)	0.43	9.75	2.9	2	2	0.141	104	×
S-IC-7.3		8.75	9.9	1	1	0.081	103	1038
S-IC-8.9(1)		7.75	11.6	2	2	0.121	103	956
S-IC-8.9(2)		8.75	11.6	1	1	0.134	101	×
S-IC-9.3[d]		9.5	12.0	1	1	0.042	104	×
S-IC-14.1		8.5	16.1	2	3	0.185	93	315
T-Control		8.5	2.9	1	1	0.071	102	×
T-IC-8.9		9.25	11.4	2	2	0.120	102	×
C-Control(1)		7.75	2.9	1	1	0.041	104	>
C-IC-8.8		8.25	11.3	1	1	0.022	102	1070
FA-Control	0.42	7.25	2.9	2	3	0.158	104	>
FA-IC-8.9		8	11.2	2	2	0.123	104	1615
S-Control(3)	0.41	8.75	2.9	1	1	0.096	103	>
S-IC-7.2(2)		8.5	9.7	2	2	0.163	103	×
S-IC-9.0		9.5	11.3	2	2	0.126	102	×
S-IC-9.1[d]		7.5	11.4	1	1	0.081	103	1275

[a] Mixture IDs labeled as 'A-B-C', where:

A: Binder composition (S=27% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)

B: Control=No LWA/internal curing, IC=Internally cured

C: Amount of internal curing water (if applicable), % binder weight

[b] 1 lb/ft^2 = 4.88 kg/m^2

[c] Durability Factor (DF) = (P × N) / 300 cycles, where P is the percentage of the initial dynamic modulus remaining at N cycles. N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller).

[d] Contains 3 oz/cwt (2 mL/kg) of set retarder

[e] S-IC-8.(2-14) - 14-day cure, (-28) - 28-day cure, (-U) - 14-day cure, underside surface used for testing

- Test not performed

Figure 3.4 compares the average cumulative scaling mass loss with the number of freeze-thaw cycles for the mixtures containing 27% slag cement and an IC water content of 8.4%. To compare variability in scaling test results, mixture S-IC-8.4(1), which had the same mixture proportions as the IC-LC-HPC bridge decks corresponding to Program 2, was re-cast as S-IC-8.4(2) and included two additional sets of specimens to examine the effect of either curing specimens through 28 days after casting instead of 14 days or testing the underside of specimens instead of the top. Regardless of curing time, the specimens whose top surfaces were tested completed 50 cycles with a visual rating of 1. For specimens cured for 14 days after casting, S-IC-8.4(1) exhibited a mass loss of 0.094 lb/ft^2 (0.46 kg/m^2), while S-IC-8.4(2) exhibited 40% less mass loss (0.056 lb/ft^2 [0.27 kg/m^2]), signifying a relatively high degree of variability among results despite having a relatively narrow range of air contents (within 1.25%). The higher air content in S-IC-8.4(1) (9%) compared to S-IC-8.4(2) (7.75%), did not result in improved scaling resistance. The specimens cured for 28 days after casting exhibited a mass loss of 0.037 lb/ft^2 (0.18 kg/m^2), indicating that scaling resistance was improved by providing a longer curing time. The lowest mass loss among any mixture in this study, however, was exhibited by the specimens cured for 14 days that had the unfinished bottom surface tested instead of the top, with a value of 0.009 lb/ft^2 (0.04 kg/m^2). The excellent scaling resistance of the underside of the test specimens demonstrates that for mixtures tested within the parameters of this study, testing a surface unaffected by finishing or bleedwater was more influential on scaling resistance than the binder compositions, *w/cm* ratio, or amount of IC or total absorbed water.

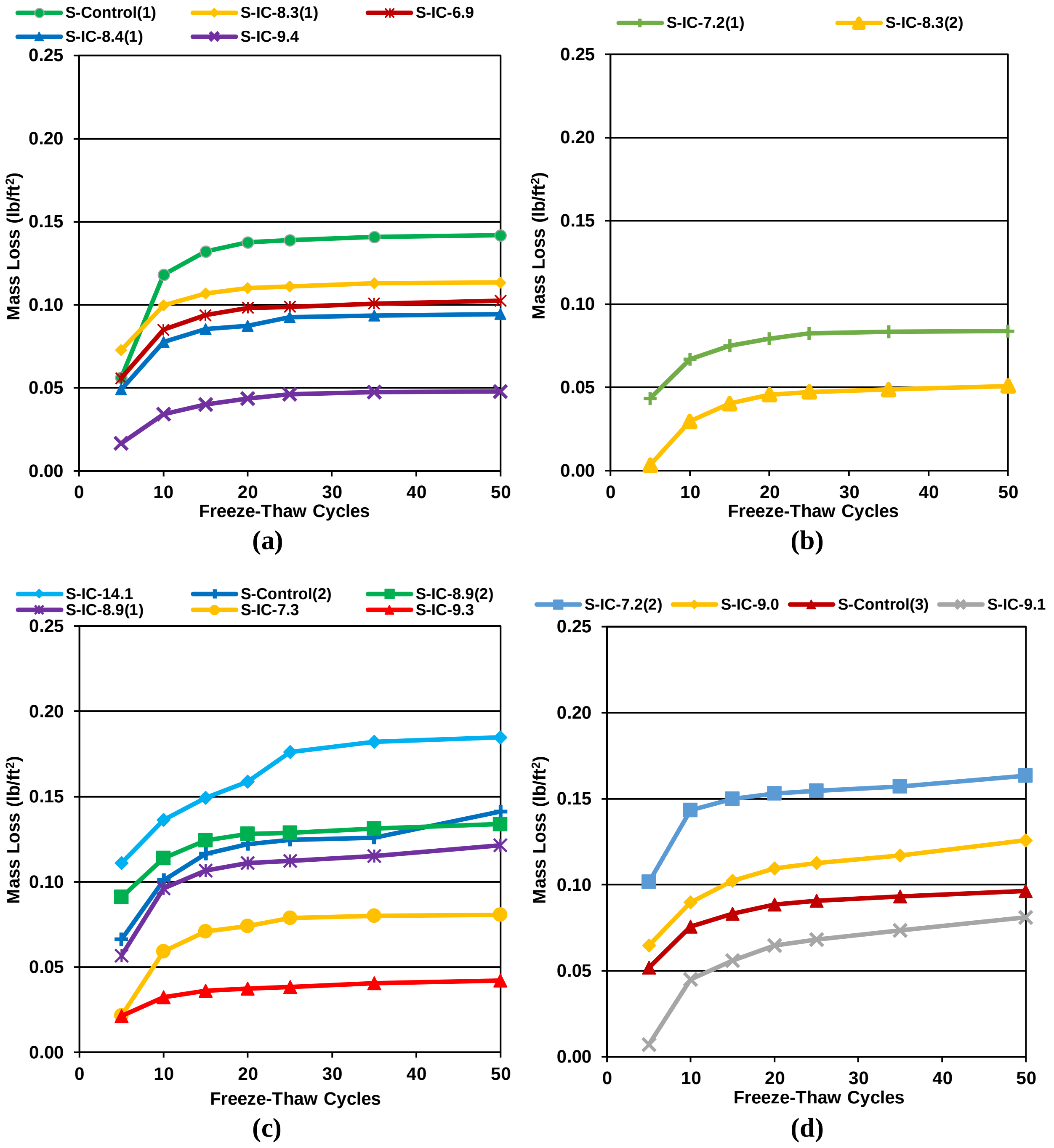


Figure 3.3: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing slag cement: (a) *w/cm* ratio of 0.45; (b) *w/cm* ratio of 0.44; (c) *w/cm* ratio of 0.43; (d) *w/cm* ratio of 0.41

Figure 3.5 compares the average cumulative scaling mass losses with the number of freeze-thaw cycles for the four mixtures with a 0.43 *w/cm* ratio containing either only portland cement or a ternary binder system (27% slag cement and 2% silica fume) and the two mixtures with a *w/cm* ratio of 0.42 containing 35% Class F fly ash. The mixtures with portland cement as the only binder completed testing with mass losses below 0.050 lb/ft^2 (0.24 kg/m^2) and visual ratings of 1. The two ternary mixtures (T-Control and T-IC-8.9) had mass losses of (0.071 and 0.120 lb/ft^2 [0.35 and 0.59 kg/m^2]), higher than the mixtures with portland cement as the only binder, with respective visual ratings of 1 and 2. The increase in mass loss for the internally-cured ternary mixture relative to its control is similar to that observed by Pendergrass and Darwin (2014) and Feng and Darwin (2020), although more mixtures are needed to verify this result. The two mixtures containing Class F fly ash exhibited higher mass losses (0.158 lb/ft^2 [0.77 kg/m^2] for FA-Control and 0.123 lb/ft^2 [0.60 kg/m^2] for FA-IC-8.9) and visual ratings of 3 and 2, respectively. Although concrete mixture proportions differed for the mixtures containing fly ash relative to the other mixtures in Program 2, as discussed above, the increased mass loss observed in the mixtures containing fly ash relative to other binder compositions is consistent with observations by Tablot et al. (1996) and Bouzoubaâ et al. (2008).

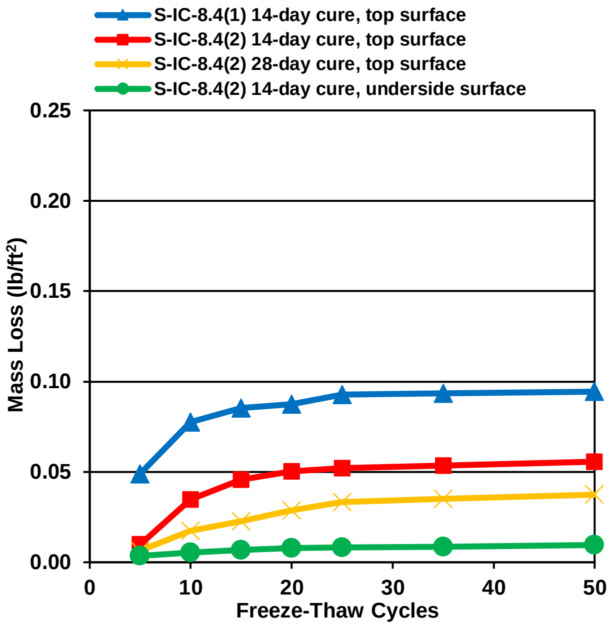


Figure 3.4: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing slag cement with a 0.45 *w/cm* ratio and an IC water content of 8.4%

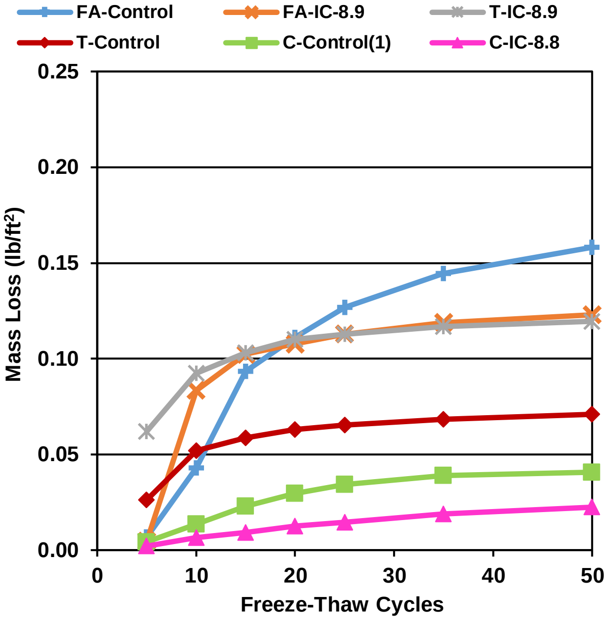
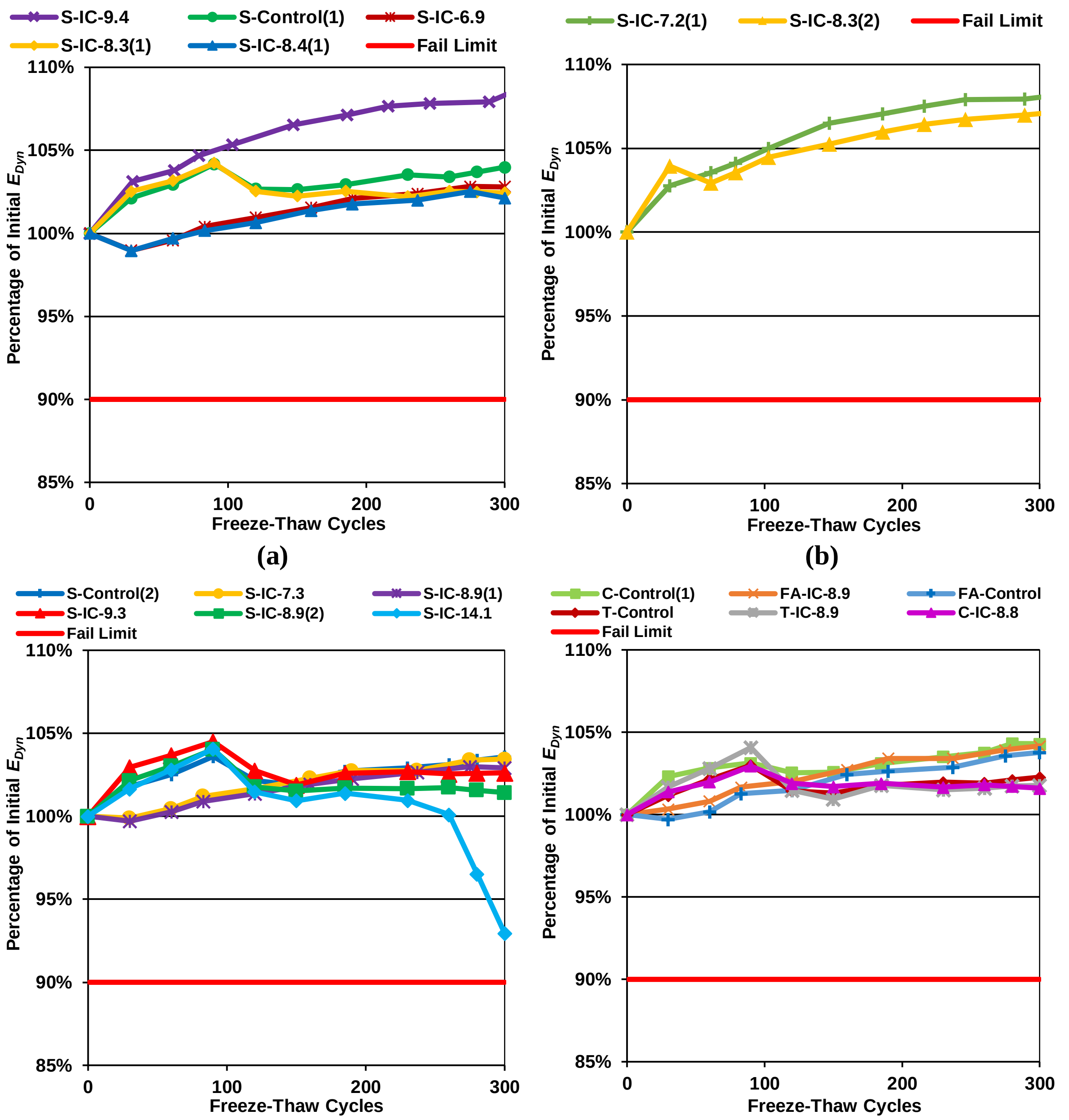


Figure 3.5: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 2 containing either 100% portland cement or a ternary binder system with a 0.43 *w/cm* ratio or fly ash with a 0.42 *w/cm* ratio

3.2.3.2 Freeze-Thaw Test Results

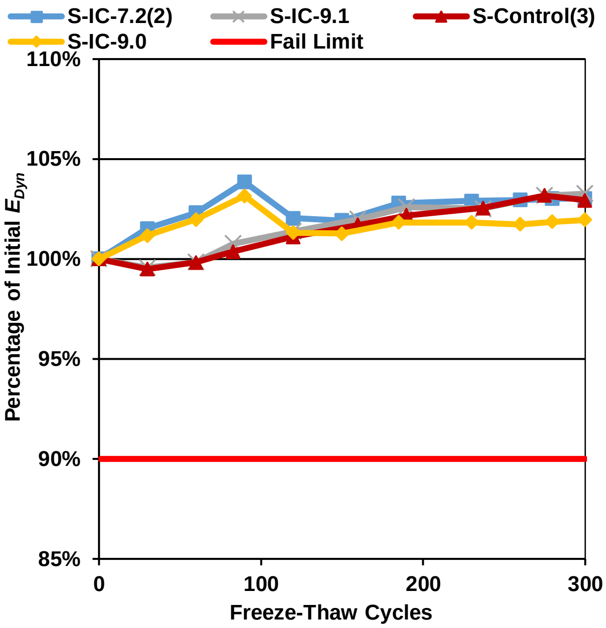
Figure 3.6 shows the freeze-thaw test results in terms of average percentage of initial E_{Dyn} as a function of the number of freeze-thaw cycles (300 max). As previously indicated, only S-IC-14.1 (with a *w/cm* ratio of 0.43 and a *DF* of 93) completed 300 cycles with a *DF* below 100 (as shown in Figure 3.6c). Otherwise, mixtures with an IC water content from 0 to 9.4%, *w/cm* ratio from 0.41 to 0.45, or binder composition other than 27% slag cement exhibited an increase in E_{Dyn} through 300 cycles.



(a) (b)

(c) (d)

Figure 3.6: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles (300 max) for mixtures in Program 2: (a) containing slag cement with a *w/cm* ratio of 0.45 (b) containing slag cement with a *w/cm* ratio of 0.44; (c) containing slag cement with a *w/cm* ratio of 0.43; (d) containing slag cement with a *w/cm* ratio of 0.41; (e) containing either 100% portland cement or a ternary binder system with a *w/cm* ratio of 0.43 or fly ash with a *w/cm* ratio of 0.42

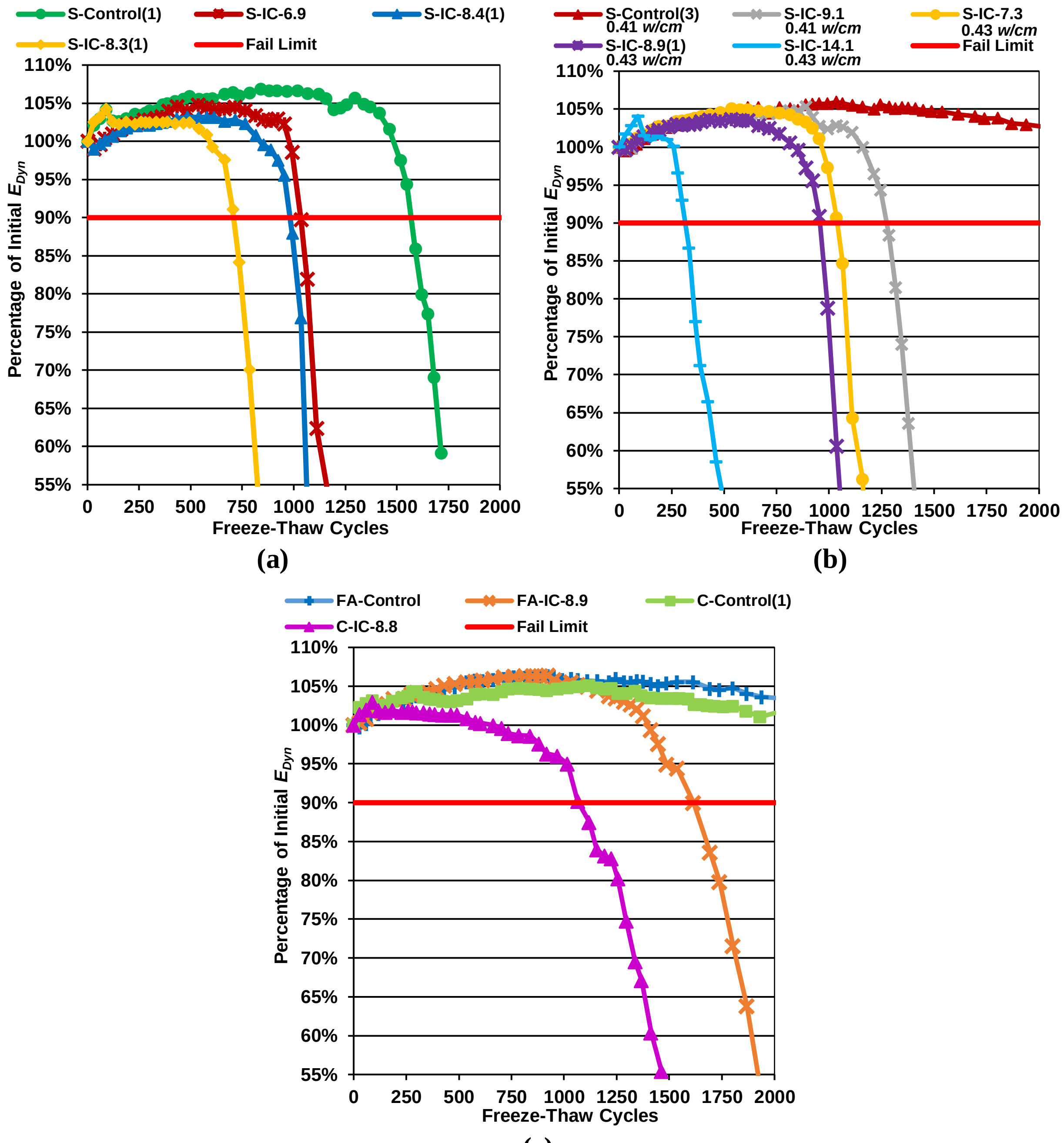


(e)

Figure 3.6 (con't): Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles (300 max) for mixtures in Program 2: (a) containing slag cement with a *w/cm* ratio of 0.45 (b) containing slag cement with a *w/cm* ratio of 0.44; (c) containing slag cement with a *w/cm* ratio of 0.43; (d) containing slag cement with a *w/cm* ratio of 0.41; (e) containing either 100% portland cement or a ternary binder system with a *w/cm* ratio of 0.43 or fly ash with a *w/cm* ratio of 0.42

To observe the effect of IC water or binder composition on the number of freeze-thaw cycles needed for the value of E_{Dyn} to decrease below 60% of its initial value, selected mixtures in Program 2 were subjected to additional cycles. Figure 3.7 shows the freeze-thaw test results in terms of average percentage of initial E_{Dyn} as a function of the number of freeze-thaw cycles (2000 max). For mixtures containing slag cement and a *w/cm* ratio of 0.45 (Figure 3.7a), E_{Dyn} of S-IC-8.3(1) dropped below 90% of its initial value in the fewest number of cycles among mixtures with a *w/cm* ratio of 0.45 (709 cycles). For mixtures containing slag cement and a *w/cm* ratio of 0.43 or 0.41 (Figure 3.7b), E_{Dyn} of S-IC-14.1 dropped below 90% of its initial value in the fewest number of cycles among mixtures in Program 2 (315 cycles) and is the only mixture in Program 2 that indicates potential issues in freeze-thaw durability. For the other mixtures with a *w/cm* ratio of 0.43, E_{Dyn} of S-IC-7.3 and S-IC-8.9(1) dropped below 90% of the initial values after 1038 and 956 cycles, respectively. S-IC-9.1 (*w/cm* ratio of 0.41) required a greater number of cycles (1275) for E_{Dyn} to drop below 90% of its initial value than mixtures with *w/cm* ratios of 0.43 and 0.45 and similar IC contents (6.9 to 8.9%). S-Control(3) (*w/cm* ratio of 0.41) withstood 2000 cycles without exhibiting a drop in E_{Dyn} relative to its initial value, while E_{Dyn} of S-Control(1) (*w/cm* ratio of 0.45) dropped below 90% of its initial value after 1569 cycles. Although mixtures with a *w/cm* ratio of 0.41 exhibited better freeze-thaw durability than mixtures with *w/cm* ratios of 0.43 and 0.45, the amount of IC water had more influence on the freeze-thaw durability than the *w/cm* ratio. The effect of total absorbed water on freeze-thaw durability was not evaluated until the completion of tests of the Program 3 mixtures, although S-IC-14.1 is the only mixture in Program 2 with a total absorbed water content of more than 12%.

The mixtures that were tested beyond 300 freeze-thaw cycles in Program 2 with a binder composition other than 27% slag cement (Figure 3.7c) exhibited similar trends in that mixtures with IC exhibited values of E_{Dyn} below 60% of its initial value in fewer freeze-thaw cycles than the respective Control mixtures. Given the limited number of mixtures that examined the effect of including binder compositions other than 27% slag cement, no other observations can be made based on the parameters of Program 2.



(a)

(b)

(c)

Figure 3.7: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles (2000 max) for mixtures in Program 2: (a) containing slag cement with a *w/cm* ratio of 0.45; (b) containing slag cement with *w/cm* ratios of 0.43 and 0.41; (c) containing either 100% portland cement with a *w/cm* ratio of 0.43 or fly ash with a *w/cm* ratio of 0.42

3.2.4 Program 3

In Program 3, 12 mixtures were tested for scaling resistance and 17 were tested for freeze-thaw durability. The primary difference between the materials used in Program 3 materials and those used in Programs 1 or 2 is the higher absorption of the normalweight aggregates (see Sections 2.2 and 2.4), which introduced additional absorbed water into the concrete mixtures (6% more for the IC-LC-HPC mixture used in bridge deck construction). All mixtures had a *w/cm* ratio of 0.43. The only binder compositions evaluated in Program 3 were 100% portland cement and a 28% slag cement replacement of portland cement. The IC water content ranged from 3.8 to 12.1% by total weight of binder and the total absorbed water content ranged from 6.6 to 17.7%.

The test results for Program 3 are listed in Table 3.4. The scaling losses were similar to those for the mixtures in Program 1 with an air content above 7% (air contents for mixtures in Program 3 ranged from 7 to 9.25%), and lower on average than those Program 2. Mixtures with IC exhibited a visual rating of 0 after 20 cycles, while the two mixtures without IC (S-Control and C-Control) had a visual rating of 1. At the end of testing (50 freeze-thaw cycles), all mixtures had a visual rating of 1, satisfying the MnDOT specification requirements for scaling resistance. Similar to the observations made in Program 2, IC did not have a negative effect on scaling resistance relative to the Control mixtures. Parallel to the effect of IC water content, the total absorbed water content (6.6 to 17.7%) did not affect the scaling mass losses. To better evaluate the scaling resistance of mixtures with a binder composition other than 28% slag cement, more mixtures containing portland cement as the only binder were tested in Program 3 than in Programs 1 or 2. With all mixtures being assigned a visual rating of 1 and exhibiting relatively low mass losses (all below 0.1 lb/ft^2 [0.5 kg/m^2]) at the end of testing, including slag cement caused no reduction in scaling resistance compared to mixtures containing portland cement as the only binder.

Unlike Programs 1 and 2, some mixtures in Program 3 were not able to satisfy the MnDOT specification for minimum *DF* in freeze-thaw testing. All mixtures in Program 3 were tested until the average value of E_{Dyn} dropped below 60% of the initial value. Mixtures containing slag cement and an IC water content of 7.8% or more (S-IC-7.8, S-IC-8.0, S-IC-10.2, S-IC-10.7, S-IC-11.6 and S-IC-12.1) exhibited a *DF* below 90. For mixtures containing portland cement as the only binder, C-IC-11.8, with a *DF* of 87, is the only mixture that did not satisfy the MnDOT specification requirement. The primary reason for the reduced freeze-thaw durability in Program 3 mixtures relative to Programs 1 and 2 is believed to be the increased total absorbed water content. As discussed in Sections 2.4.3 and 3.1.3, the higher-absorption normalweight aggregates used in Program 3 introduced more internal moisture to the concrete than the lower-absorption aggregates used in Programs 1 and 2. As a result of having more internal moisture at a given IC water content and not allowing specimens to dry out prior to the start of freeze-thaw testing, E_{Dyn} dropped below 60% of its initial value in fewer cycles than in Programs 1 or 2. At a given IC/total absorbed water content, mixtures containing 28% slag cement exhibited E_{Dyn} below 60% of the initial value in fewer cycles than those that containing portland cement as the only binder, although the effect of the total absorbed water was more pronounced than the difference in binder composition.

To determine if the drop in E_{Dyn} in fewer freeze-thaw cycles was due to the amount of IC water or the volume of lightweight aggregate, four additional batches were cast with mixture proportions similar to S-IC-12.1, for which E_{Dyn} dropped below 90% of its initial value in just 88 cycles. For these batches, the amount of IC water in the FLWA was adjusted using soaking times of either 5 minutes (for S-IC 7.0 and S-IC-7.7) or 72 hours for (S-IC-10.7, S-IC-11.6, and S-IC-12.1). Although S-IC-7.0 and S-IC-7.7 contained the same volume of FLWA as S-IC-12.1 (17.6%

of the aggregate volume), the highest among Program 3 mixtures, the specimens satisfied the MnDOT specification for freeze-thaw durability, withstanding more than 300 freeze-thaw cycles before dropping below 90% of their initial E_{Dyn}. S-IC-7.0 and 7.7 had total absorbed water contents of 12.6 and 13.3%, respectively. For these mixtures, the value of E_{Dyn} at 300 cycles and number of cycles needed to drop E_{Dyn} below 90% of the initial value are similar to those of specimens with similar total absorbed water contents but a lower volume of FLWA (S-IC-6.3, S-IC-6.6, and S-IC-6.8, with total absorbed water contents of 12.4, 12.6, and 12.8%, respectively). For mixtures with a 72-hour FLWA soaking time (S-IC-10.7, S-IC-11.6, and S-IC-12,1, with total absorbed water contents of 16.3, 17.2, and 17.7%, respectively), specimens exhibited a rapid decrease in E_{Dyn} and were not able to withstand 300 cycles before testing was terminated. The results from these mixtures demonstrate that that freeze-thaw durability is governed by the total absorbed water content in the concrete rather than FLWA volume. Additionally, as will be demonstrated, the results indicate that water absorbed by the FLWA during curing or testing does not likely contribute to issues in freeze-thaw durability.

Table 3.4: Average durability test results for Program 3 mixtures

Mixture ID[a]	*w/cm* Ratio	Air Content (%)	Total Absorbed Water (% Binder Weight)	Scaling			Freeze-Thaw	
				Visual Rating at 20 Cycles	Visual Rating at 50 Cycles	Mass Loss at 50 Cycles[b] (lb/ft^2)	Durability Factor[c]	No. of Cycles to 90% $E_{Dyn.}$
S-Control	0.43	8.25	6.7	1	1	0.047	104	884
S-IC-6.3		8.5	12.4	0	1	0.034	93	316
S-IC-6.6[d]		7	12.6	0	1	0.033	92	315
S-IC-6.8[d]		8.5	12.8	0	1	0.026	101	447
S-IC-7.0		8.75	12.6	-			99	456
S-IC-7.7		7.25	13.3	-			92	321
S-IC-7.8		8.25	13.7	-			69	247
S-IC-8.0		8	14.0	0	1	0.022	54	191
S-IC-10.2		9.25	16.0	0	1	0.025	53	178
S-IC-10.7[d]		7	16.3	-			38	123
S-IC-11.6		8	17.2	-			42	151
S-IC-12.1		8	17.7	0	1	0.040	24	88
C-Control		8.5	6.6	1	1	0.071	101	1193
C-IC-3.8[d]		8.5	10.0	0	1	0.020	95	540
C-IC-7.3[d]		8.5	13.2	0	1	0.022	98	460
C-IC-9.8[d]		8.5	15.4	0	1	0.024	100	451
C-IC-11.8[d]		8	17.2	0	1	0.043	87	279

[a] Mixture IDs labeled as 'A-B-C', where:
A: Binder composition (S=28% slag cement by weight, C=100% cement)
B: Control=No LWA/internal curing, IC=Internally cured
C: Amount of internal curing water (if applicable), % binder weight

[b] 1 lb/ft^2 = 4.88 kg/m^2

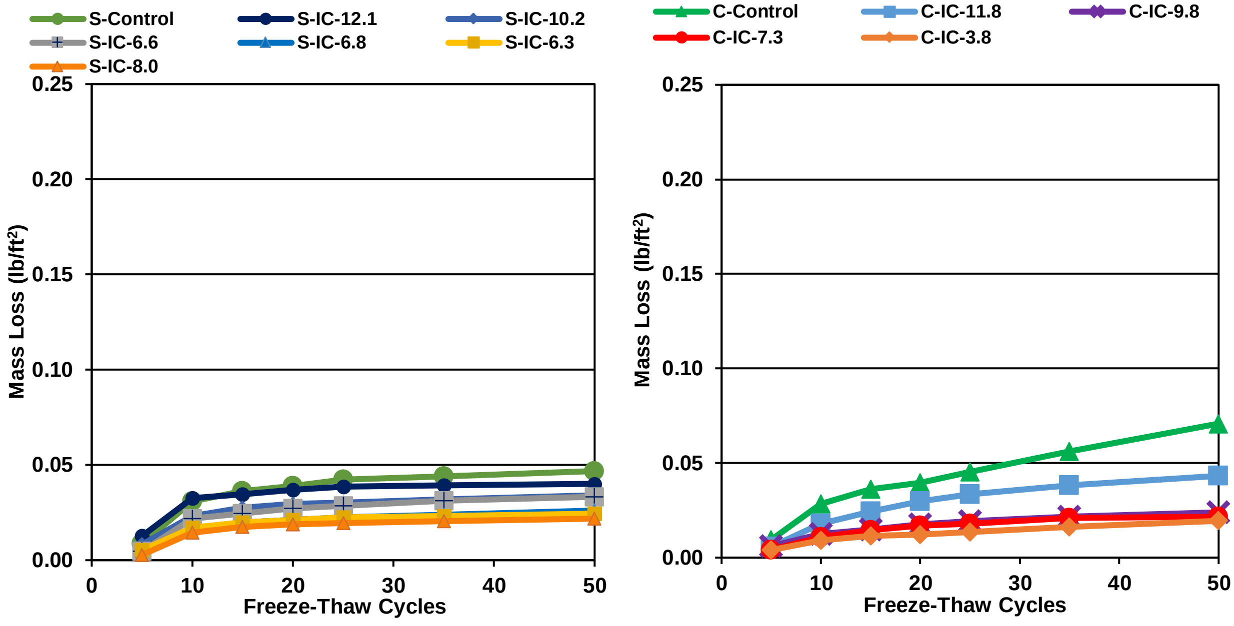
[c] Durability Factor (DF) = (P × N) / 300 cycles, where P is the percentage of the initial dynamic modulus remaining at N cycles. N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller).

[d] FLWA-2 used (lower absorption); FLWA-3 used otherwise

- Test not performed

3.2.4.1 Scaling Test Results

Figure 3.8 compares the average cumulative scaling mass losses with the number of freeze-thaw cycles. All mixtures were assigned a visual rating of 1 after 50 cycles, indicating minimal scaling, and satisfied the MnDOT specification limits. For mixtures containing 28% slag cement (Figure 3.8a), mass losses ranged 0.047 lb/ft^2 (0.23 kg/m^2) with S-Control to 0.022 lb/ft^2 (0.11 kg/m^2) with S-IC-8.0. For mixtures containing portland cement as the only binder (Figure 3.8b), mass losses ranged from 0.071 lb/ft^2 (0.35 kg/m^2) with C-Control to 0.020 lb/ft^2 (0.10 kg/m^2) with C-IC-3.8.



(a) **(b)**

Figure 3.8: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program 3: (a) containing slag cement; (b) containing 100% portland cement as binder

3.2.4.2 Freeze-Thaw Test Results

Figure 3.9 compares the freeze-thaw test results in terms of average percentage of initial E_{Dyn} as a function of the number of freeze-thaw cycles. For mixtures containing slag cement and IC water contents from 0 to 12.1% using FLWA pre-wetted for 72 hours (Figure 3.9a), results indicate that incremental increases in IC water content correspond to progressively more rapid decreases in the value of E_{Dyn}. Most notably, E_{Dyn} for S-IC-12.1 dropped below 90% of its initial value after just 88 cycles, significantly fewer than any other mixture in this study. S-Control dropped below 90% of its initial E_{Dyn} value after 884 cycles, greater than the mixtures containing IC water, but less than some of the Program 2 mixtures with a *w/cm* of 0.43 containing slag cement and IC water on the order of 9% by weight of binder. As discussed previously, the primary difference between the mixtures in Programs 2 and 3 is the total absorbed water content, which may be the prime reason for the difference in number of freeze-thaw cycles needed to produce similar levels of damage. Unlike the Control mixtures in Program 2 (with total absorbed water contents of 2.9 to 3.1%), S-Control in Program 3 contained 6.7% total absorbed water. For an IC water content of 8%, the Program 2 mixtures contained a total absorbed water content of approximately 10.6% compared to 14.0% in Program 3. The only mixtures shown in Figure 3.9a that withstood more than 300 freeze-thaw cycles with a *DF* above 90 contained IC water contents of 6.8% or less and total absorbed water contents of 12.8% or less.

For mixtures containing slag cement and an FLWA content of 17.6% by aggregate volume (Figure 3.9b), the specimens that contained FLWA that was soaked for 72 hours (S-IC-10.7, S-IC-11.6, and S-IC-12.1) exhibited similar degradation in freeze-thaw testing, with E_{Dyn} dropping below 90% of the initial value early during testing (88 to 151 cycles for S-IC-12.1 and S-IC-11.6, respectively). S-IC-10.7 contained FLWA-2, which had an average absorption of 24.0%, while FLWA-3 (included in S-IC-11.6 and S-IC-12.1), had an absorption of 28.5% based on 72 hours of soaking in laboratory testing (as discussed in Section 2.2.5). Although the IC water content in S-IC-10.7 (10.7%) was slightly lower than in S-IC-11.6 or S-IC-12.1, (11.6% and 12.1%, respectively), the range in total absorbed water contents, from 16.3% in S-IC-10.7 to 17.7% in S-IC-12.1, was relatively narrow and all were well above 12.8% (maximum value for mixtures containing slag cement with a 72-hour FLWA soaking time to exhibit a *DF* above 90). For the two mixtures containing FLWA soaked for 5 minutes, S-IC-7.0 and S-IC-7.7, E_{Dyn} dropped below 90% of the initial value in 456 and 321 cycles, respectively. S-IC-7.0 and S-IC-7.7 had total absorbed water contents of 12.6 and 13.3%, respectively, close to the total absorbed water contents of S-IC-6.3, S-IC-6.6, and S-IC-6.8 (12.4, 12.6, and 12.8%, respectively). The *DFs* for mixtures with an IC water content from 6.3 to 7.7% and total absorbed water contents of 12.6 and 13.3% ranged from 92 to 101, satisfying the MnDOT specification limit for freeze-thaw durability. The performance of the mixtures shown in Figures 3.9a and 3.9b demonstrates that the volume of FLWA, by itself, does not affect the ability of concrete to withstand cycles of freezing-thawing.

For mixtures containing portland cement as the only binder with IC water contents of 0 to 11.8% and, when used, FLWA pre-wetted for 72 hours (Figure 3.9c), a trend similar to that of mixtures containing slag cement is observed, with increasing amounts of IC water leading to more rapid decreases in E_{Dyn}. For similar IC and total absorbed water contents (within 1%), however, mixtures with portland cement as the only binder were able to withstand more cycles than mixtures containing slag cement. The total absorbed water content, however, is still more influential than the difference in binder composition as demonstrated by comparing the results for the Program 3 mixtures with the two mixtures in Program 2 with the same binder composition and *w/cm* ratio (0.43). In Program 2, C-IC-8.8 (with a total absorbed water content of 11.3%) withstood 1070 cycles before E_{Dyn} dropped below 90% of its initial value. The only mixture in Program 3 that withstood more cycles than 1070 cycles is C-Control (with a total absorbed water content of 6.6%), for which E_{Dyn} dropped below 90% of its initial value after 1193 cycles. C-Control(1) from Program 2 (with a total absorbed water content of 2.9%) withstood more than 2000 cycles without exhibiting a reduction in E_{Dyn} below 100% of its initial value.

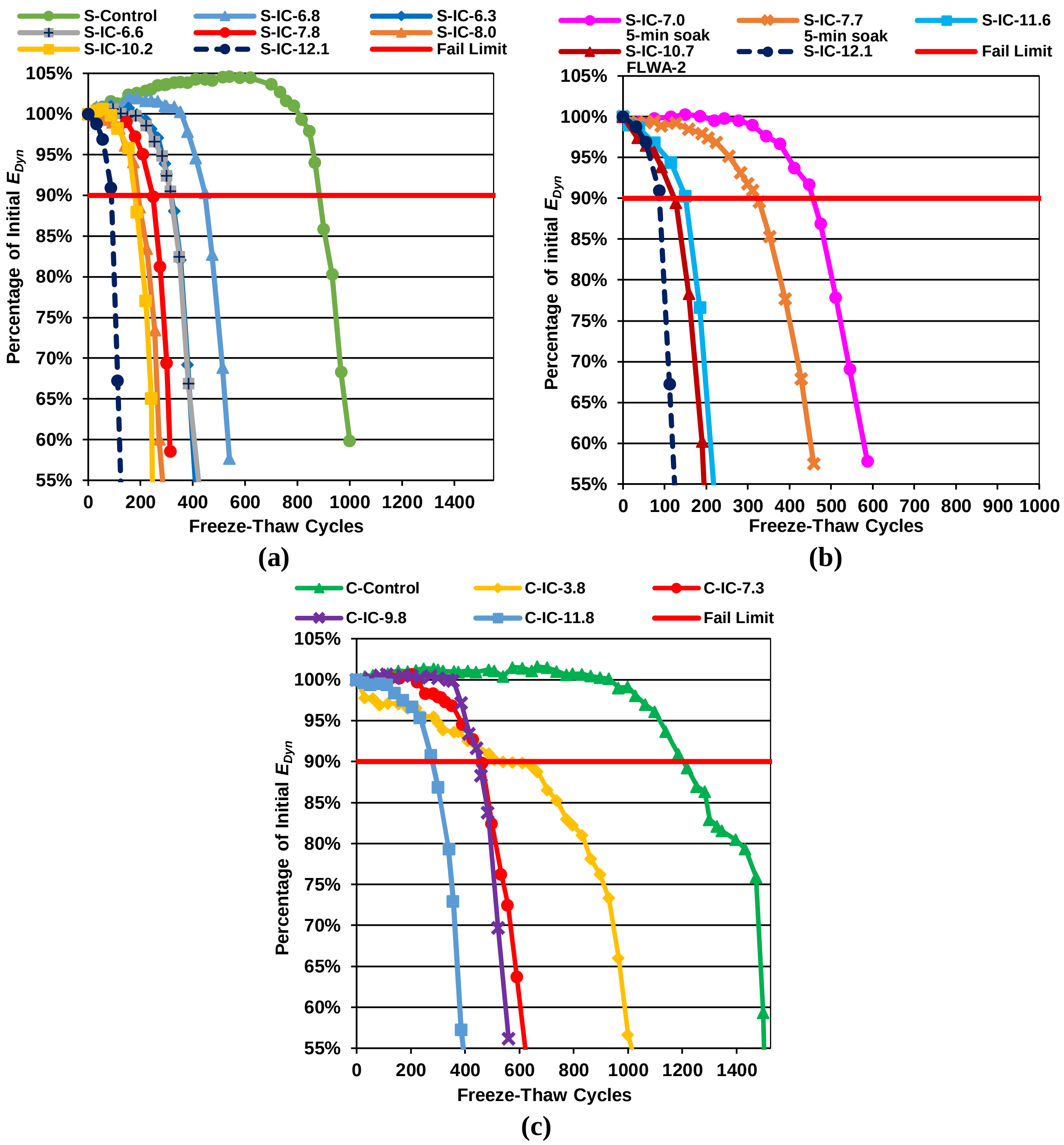


Figure 3.9: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures in Program 3: (a) containing slag cement; (b) containing slag cement and 17.6% LWA total aggregate volume; (c) containing 100% portland cement as binder

3.2.5 Discussion of the Effects of IC Water Content, Binder Composition, and *w/cm* Ratio on IC-LC-HPC Durability

The IC-LC-HPC bridge decks constructed as part of this study include a partial replacement of portland cement with 27 to 30% slag cement and design quantity of IC water equal to 8% (both by weight of binder). As discussed in Chapter 2, mixtures tested in the laboratory were proportioned based on the FLWA absorption to achieve a target IC water content. Over the three Programs, the effect of IC water content (0 to 14.1%) on scaling resistance and freeze-thaw durability was evaluated. In Programs 1 and 2, the effect of using different binder compositions (using only portland cement in three mixtures, a 35% Class F fly ash replacement of cement in two mixtures, and a 2% addition of silica fume of cement for the mixtures containing 27 to 28% slag cement by total weight of binder in a total of four mixtures) was evaluated for a limited number of mixtures. Mixtures with portland cement as the only binder were evaluated more thoroughly in Program 3, with five mixtures. The effect of *w/cm* ratio on durability was examined for values of 0.39 to 0.45. Within the range of the parameters investigated in this study, the IC and total absorbed water contents, partial replacement of portland cement with slag cement, and the *w/cm* ratio did not affect scaling resistance. Scaling resistance was, however, affected by the air content (as demonstrated in Program 1). Providing adequate air entrainment, however, did not protect against relatively high mass losses and visual ratings for some mixtures in Program 2. In evaluating freeze-thaw durability, the primary variable affecting mixtures appears to be the total absorbed water content, which includes IC water from the FLWA along with water absorbed by the normalweight aggregates.

3.2.5.1 Factors Affecting Scaling Resistance

The scaling test results for Program 1 (Section 3.2.2.1) demonstrate that the mixtures with an air content below 7% had higher mass losses than those with higher air contents. This matches the findings of Hooton and Vassilev (2012), who observed that, although providing adequate air entrainment does not prevent scaling in concretes containing slag cement, mixtures with higher air contents exhibit a reduction in scaling mass, and recommended the use of an air content of 8±1%.

Hooton and Vassilev (2012) also recommended extending the curing period from 14 to 28 days for mixtures containing slag cement. Curing duration was only evaluated for one mixture in Program 2, and the results of which agree with their recommendation; the current effort, however, by itself, was not extensive enough to verify the recommendation.

The effect of increasing the IC water content from 5.5 to 9.4% in the mixtures in Program 1 did not produce an increase in mass loss or visual rating in scaling tests. Although the scaling test results for the Program 2 mixtures containing slag cement were highly variable (mass losses ranging from 0.042 to 0.185 lb/ft^2 [0.20 to 0.90 kg/m^2]), using an IC water content up to 9.4% did not negatively affect scaling resistance compared to the Control mixtures (no FLWA/IC water). The range of IC water evaluated in Program 3 (6 to 12% by total weight of binder) did not negatively affect scaling resistance. Likewise, increasing amounts of total absorbed water did not negatively affect scaling resistance, as demonstrated by comparing the results between the mixtures in Programs 1 and 3 that exhibited relatively low mass losses. S-IC-5.5(1) and S-IC-5.5(2) in Program 1 (total absorbed water content 7.7%) and S-IC-12.1 in Program 3 (total absorbed water contents of 17.7%) exhibited mass losses below 0.05 lb/ft^2 (0.24 kg/m^2). It should be noted, however, that unlike the freeze-thaw specimens that remained saturated, the scaling specimens were allowed to dry for 14 days prior to the start of testing, likely mitigating the effects of high absorbed water content (IC and total) at or near the specimen surface.

Based on the binder compositions evaluated in this study, little to no trend is apparent in terms of their effects on the scaling resistance of IC-LC-HPC. The results for the mixtures containing 35% fly ash in Program 2 do indicate that fly ash has a negative effect on scaling resistance, but those mixtures are based on the MnDOT HPC Control deck mixture proportions. A partial replacement of portland cement with 27 to 30% slag cement (with or without a 2% addition of silica fume), however, does not appear to negatively affect scaling resistance when adequate air entrainment is provided. Similarly, no relation between scaling resistance and *w/cm* ratio (0.39 to 0.45) was observed for the mixtures in this study. The caveats to applying the ASTM C672 scaling test results discussed in Section 3.1.1 include the beneficial effect that slag cement has on mitigating calcium oxychloride formation in concrete exposed to calcium chloride along with the test procedure not being as representative of in-field scaling performance as the Quebec test BNQ NQ 2621-900. It would be worthwhile for the trends observed in this study be verified using mixtures tested in accordance with BNQ NQ 2621-900 to verify that slag cement contents up to 30% with a range of IC and total absorbed water contents do not negatively affect IC-LC-HPC scaling resistance.

3.2.5.2 Factors Affecting Freeze-Thaw Durability

The results from Programs 2 and 3 demonstrate that mixtures containing increasing amounts of IC water (starting from zero) exhibit a reduction in E_{Dyn} in progressively fewer freeze-thaw cycles, similar to the observations made by Feng and Darwin (2020). The effect of IC water, however, differs in Programs 2 and 3. Figure 3.10 compares the number of freeze-thaw cycles required for the average value of E_{Dyn} to drop below 90% of the initial value as a function of the amount of IC water (only from the FLWA) for mixtures containing slag cement in Programs 2 and 3 that were tested until the average value of E_{Dyn} decreased below 60% of the initial value. The mixtures in Program 1 were not tested beyond 300 cycles and, thus, cannot be included in this evaluation because none of the specimens exhibited a drop in E_{Dyn}. The results show that although all Program 2 mixtures completed more than 300 cycles before the average E_{Dyn} dropped below 90% of the initial value (even with an IC water content up to 14.1%), increasing IC water contents in Program 3 mixtures led to damage in fewer cycles. Given the large offset of data points between

Programs, this observation suggests that accounting for IC water alone does not adequately characterize the resulting freeze-thaw durability.

Figure 3.11 compares the number of freeze-thaw cycles to drop the average E_{Dyn} value below 90% of the initial value as a function of the total absorbed water from all aggregates. Comparing freeze-thaw durability on the basis of total absorbed water content produces a clearer trend between the mixtures in Programs 2 and 3 than IC water alone. Specifically, accounting for the additional water in the mixtures in Program 3 absorbed by the normalweight aggregates (approximately 4% by weight of binder more than in Program 2) accounts for the difference in the results between the two programs. As the total absorbed water content exceeded 12%, a majority of mixtures containing slag cement were not able to withstand more than 300 freeze-thaw cycles before the E_{Dyn} dropped below 90% of the initial value. As discussed in Section 3.1.2, ASTM C666 – Procedure A exposes concrete to a worst case condition and does not take into account the majority of applications where concretes are allowed to dry before being subjected to freezing conditions. Although the mixtures in this study were never allowed to dry, this condition does simulate the effect of completing placements late in the construction season or during winter months where freezing conditions in the concrete can occur during or soon after the curing period. For IC-LC-HPC mixtures facing this type of construction schedule, particular attention should be paid to limiting the actual IC water content to 7 or 8% by weight of binder, but more importantly, ensuring that the total absorbed water content is kept below 12%.

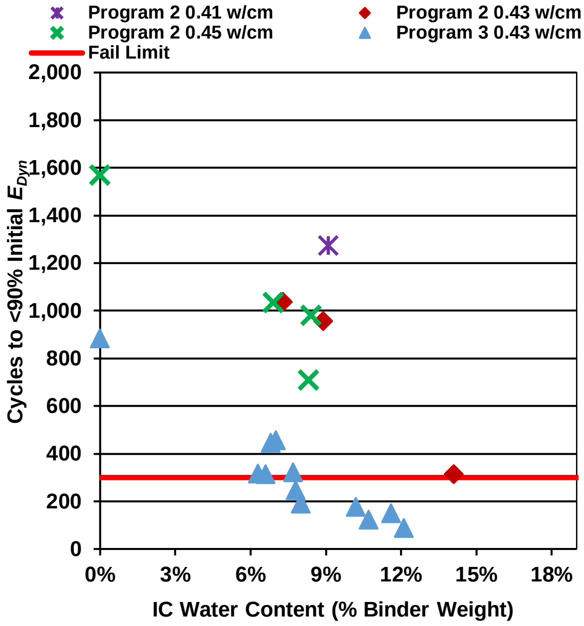


Figure 3.10: Number of freeze-thaw cycles required to drop average E_{Dyn} below 90% of initial value vs. IC water content for mixtures containing slag cement in Programs 2 and 3

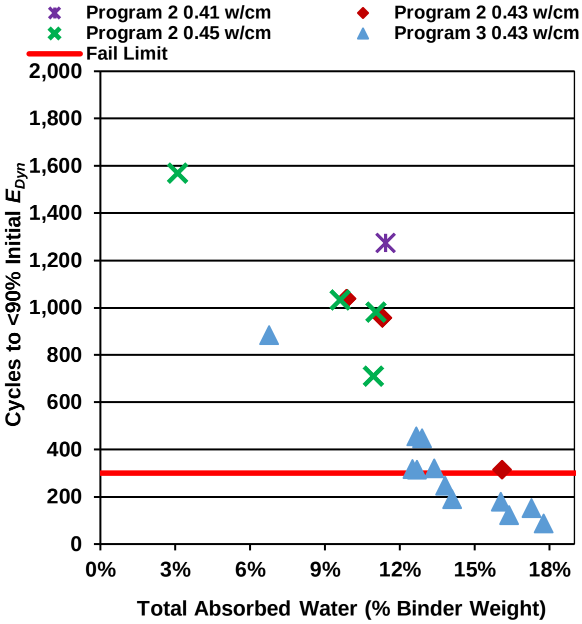


Figure 3.11: Number of freeze-thaw cycles required to drop average E_{Dyn} below 90% of initial value vs. total absorbed water content for mixtures containing slag cement in Programs 2 and 3

In contrast to IC and total absorbed water, the FLWA content does not appear to affect freeze-thaw durability. In reference to the Program 3 mixtures containing an FLWA content of 17.6% (by aggregate volume), the number of cycles needed to produce damage in mixtures containing FLWA with a 5-minute soaking time was similar to or better than in mixtures with similar IC/total absorbed water contents with an FLWA content of 10.9% and a 72-hour soaking time. Although a more extensive evaluation of FLWA volumes and total absorbed water contents was not conducted, the results from the mixtures in Program 3 with the same FLWA volume suggest that the water held within the FLWA voids at casting is more influential on freeze-thaw durability than any additional water absorbed by the FLWA during curing or testing. As discussed in Chapter 4, the MnDOT specifications for IC-LC-HPC mixtures include a maximum FLWA content of 10% of the aggregate volume. Based on the results of this study, it is recommended that this limit be removed, or at least modified, and a limit on total absorbed water content be added.

The evaluation of the effects of binder composition on freeze-thaw durability is limited, but the results from Program 3 suggest that a partial replacement of portland cement with slag cement results in a slight reduction in freeze-thaw durability. The results from Program 2 suggest, as demonstrated in other studies (Jones et al. 2014, Feng and Darwin 2020), that increasing the *w/cm* ratio results in fewer freeze-thaw cycles needed to produce a reduction in E_{Dyn}. The effects of binder composition or *w/cm* ratio, however, are far less pronounced than that of the total absorbed water content. Within the parameters of this study, mixtures containing 27 to 30% slag cement, a *w/cm* ratio of 0.43 to 0.45, and total absorbed water content less than 12% are able to withstand more than 300 freeze-thaw cycles while maintaining in E_{Dyn} equal to at least 90% of its initial value.

3.3 RAPID CHLORIDE PERMEABILITY AND SURFACE RESISTIVITY OF IC-LC-HPC

3.3.1 Test Results

The rapid chloride permeability (RCP) and surface resistivity measurement (SRM) test results for Programs 1, 2, and 3 are presented in Tables 3.5, 3.6, and 3.7, respectively. RCP and SRM tests were performed in accordance with ASTM C1202, and AASHTO TP-95 and Kansas Test Method KT-79, respectively. As explained in Chapter 2, because cylinders cured in lime-saturated water have a lower SRM that those cured in a moist room, laboratory SRM measurements are multiplied by 1.1 in accordance with AASHTO TP-95 and Kansas Test Method KT-79. The corrected values are reported in the tables.

Of the test parameters considered in this study, binder composition had the greatest effect on the RCP and SRM values. The mixtures with portland cement as the only binder exceeded the

MnDOT LC-HPC specification limits for amount of charge passed in RCP testing at 28 and 56 days (2500 and 1500 Coulombs, respectively), regardless of *w/cm* ratio or amount of IC water. In contrast, only one of the 33 mixtures containing slag cement exceeded 2500 Coulombs at 28 days and only four exceeded 1500 Columbus at 56 days. The MnDOT LC-HPC specifications do not have provisions for SRMs. The use of 2% silica fume along with slag cement and portland cement in the ternary mixtures resulted in a further reduction in RCP and an increase in SRM values, except for mixture T-IC-8.3(1) in Program 1, for reasons discussed below. Decreasing the *w/cm* ratio or increasing the amount of IC water also decreased the RCP values, but to a lesser extent than using slag cement or slag cement and silica fume as a partial replacement for cement. SRM values increased slightly when decreasing the *w/cm* ratio but not when increasing the amount of IC water. While SRM values were relatively consistent for measurements taken from a single mixture, small changes in mixture proportions tended to result in large changes in SRM values; the corresponding changes in RCP values were less pronounced. As a result, Student's t-test returned *p*-values below 0.05 for the majority of comparisons using SRM values, as shown in Appendix B, which limits the extent of conclusions than can be made on the effect of *w/cm* ratio or amount of IC water on SRMs.

The results for Program 1 are listed in Table 3.5. In general, mixtures with a partial replacement of portland cement with slag cement exhibited RCP results within the MnDOT specification limit at both 28 and 56 days. In addition to the mixture with portland cement as the only binder (C-IC-5.7), T-IC-8.3(1) exceeded the maximum MnDOT specification limit for RCP at 28 and 56 days; both mixtures had a *w/cm* of 0.45. As discussed in Sections 2.4.1 and 3.2.2, T-IC-8.3(1) is suspected of containing additional mixing water, contributing to the higher RCP and lower SRM results relative to mixtures without silica fume. The three "re-casts" of T-IC-8.3(1)

(T-IC-8.2, T-IC-8.3(2), and T-IC-8.3(3)) had the same mixture proportions but likely contained the intended amount of mixing water and exhibited RCP and SRM results in line with expected values. T-IC-8.2 exhibited the lowest 56-day RCP and highest 28-day SRM result among the Program 1 mixtures. For mixtures containing 30% slag cement, neither the RCP nor the SRM results were affected by the amount of IC water. In Program 1, decreasing the *w/cm* ratio from 0.45 to 0.39 resulted in only a small but statistically significant decrease in charge passed in the RCP test and a small increase in the surface resistivity. With only six mixtures with a *w/cm* ratio below 0.45, however, more mixtures are needed to verify the effect of *w/cm* ratio on RCP or SRM results.

Table 3.5: SRM and RCP and SRM results for mixtures in Program 1

Mixture ID[a]	*w/cm* Ratio	28-Day SRM[c] (kΩ-cm)	28-Day RCP Result (Coulombs)	56-Day RCP Result (Coulombs)
S-IC-5.5(1)[b]	0.45	23.5	1700	1130
S-IC-5.5(2)[b]		21.0	-	-
S-IC-5.6(1)[b]		23.8	1800	930
S-IC-5.6(2)[b]		18.2	-	-
S-IC-6.6[b]		20.2	1700	1220
S-IC-7.3		19.6	2190	1620
S-IC-9.3		21.0	2010	1360
C-IC-5.7[b]		12.5	3220	2560
T-IC-8.2		32.9	1420	790
T-IC-8.3(1)		21.8	2660	1830
T-IC-8.3(2)		32.1	-	-
T-IC-8.3(3)		35.5	-	-
S-IC-7.1	0.42	27.0	1760	1200
S-IC-7.2		24.8	1830	1410
S-IC-9.1		24.8	1830	1410
S-IC-9.4(1)		25.3	1510	1180
S-IC-7.0	0.39	25.6	1820	1330
S-IC-9.4(2)		34.0	1320	940

[a] Mixture IDs labeled as 'A-B', where:
A: Binder composition (S=30% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)
B: Amount of internal curing water, % binder weight

[b] Cement C1(a) used; otherwise C1(b) used

[c] Includes 1.1 correction factor for specimens cured in lime-saturated water rather than in a moist room

The results for Program 2 are listed in Table 3.6. For the mixtures containing 27% slag cement and IC, the RCP test results satisfy the MnDOT specification limits at both 28 and 56 days. The mixtures containing 35% Class F fly ash (FA-Control and FA-IC-8.9) and with 100% portland cement as binder (C-Control(1) and C-IC-8.8) did not satisfy the MnDOT specification limit for RCP at either 28 and 56 days. The mixtures with Class F fly ash had higher RCP and lower SRM values than the mixtures with portland cement as the only binder, which contradicts the expectation that SCMs lead to a reduction in RCP and increase in SRM test results. As discussed in Section 2.2.2, however, it is suspected that the fly ash sample delivered to the laboratory was contaminated with metallic particles that affected the electrical conductivity and resistivity readings. Thus, the RCP and SRM test data for mixtures containing fly ash in this study may not be representative of the MnDOT HPC Control mixture in Program 2 and should not be considered as generally representative of mixtures containing fly ash. The only mixtures containing slag cement that exceeded the MnDOT specification limits were S-Control(2) and S-Control(3) at 56 days. For the mixtures containing slag cement, decreasing the *w/cm* ratio from 0.45 to 0.41 did not affect the SRM or RCP values. Unlike Program 1, the effect of IC water on RCP results can be observed in Program 2. For mixtures containing 27% slag cement at *w/cm* ratios of 0.45, 0.43 and 0.41, the mixtures containing IC water exhibited a decrease in charge passed at both 28 and 56 days during RCP testing relative to the S-Control mixtures. For the other binder compositions (only portland cement, ternary blend including 27% slag cement and 2% silica fume, and 35% Class F fly ash), the mixtures containing IC water exhibited lower RCP results at 56 days than the respective Control mixture. No clear trends are observed when comparing SRM results for Control mixtures to those from mixtures containing IC.

Table 3.6: SRM and RCP and SRM results for mixtures in Program 2

Mixture ID[a]	*w/cm* Ratio	28-Day SRM[d] (kΩ-cm)	28-Day RCP Result (Coulombs)	56-Day RCP Result (Coulombs)
S-Control	0.45	16.4	1420	1400
S-IC-6.9		16.1	2360	1230
S-IC-8.3(1)		20.7	1840	1030
S-IC-8.4(1)		16.6	1900	1210
S-IC-8.4(2)		16.7	-	-
S-IC-8.4(3)		17.1	-	-
S-IC-9.4		16.5	-	-
S-IC-7.2(1)	0.44	18.2	-	-
S-IC-8.3(2)		24.5	-	-
S-Control	0.43	18.9	1870	1714
S-IC-7.3		23.8	1390	1160
S-IC-8.9(1)		21.0	1420	1130
S-IC-8.9(2)		17.9	1860	1340
S-IC-9.3		19.3	1690	1020
S-IC-14.1		18.5	1890	1150
C-Control(1)		10.7	4520	4130
C-Control(2)		8.7	-	-
C-IC-8.7		9.8	-	-
C-IC-8.8		10.7	4410	3500
T-Control		34.2	1260	950
T-IC-8.9		30.1	1490	830
FA-Control	0.42	7.5	5660	3980
FA-IC-8.9		8.8	5350	3230
FA-IC-9.0		8.9	-	-
S-Control	0.41	20.7	1640	1570
S-IC-7.2(2)		21.8	1470	1110
S-IC-9.0		21.9	1490	1200
S-IC-9.1		22.8	1570	1160
S-IC-9.2		20.6	-	-

[a] Mixture IDs labeled as 'A-B-(C)', where:
A: Binder composition (S=27% slag cement by weight, C=100% cement, T=28% slag cement, 2% silica fume by weight)
B: Control=No LWA/internal curing, IC=Internally cured
C: Amount of internal curing water (if applicable), % binder weight
[b] Silica Fume
[c] Class F Fly Ash
[d] Includes 1.1 correction factor for specimens cured in lime-saturated water rather than in a moist room

The results for Program 3 are listed in Table 3.7. The mixtures containing slag cement satisfy the MnDOT specification limits for the RCP test at both 28 and 56 days with some of the lowest coulomb readings in this study. Conversely, the mixtures containing portland cement as the only binder exceeded the MnDOT specification limits at both ages. The effect of *w/cm* ratio on the SRM and RCP values was not evaluated in Program 3 because all mixtures had a *w/cm* ratio of 0.43. The results for mixtures that underwent both RCP and SRM testing in Program 3 provide a more detailed evaluation of the effects of incremental increases in the amount of IC water than those in Programs 1 and 2. The results in this program show that, for both binder compositions, IC water content has no effect on the 28-day SRM or RCP results. For the mixtures containing slag cement, changing the IC water content had no notable effect on the 56-day RCP results. For the mixtures with portland cement as the only binder, however, an incremental increase in the amount of IC water led to a slight reduction in the 56-day coulomb readings in the RCP test.

Table 3.7: SRM and RCP and SRM results for mixtures in Program 3

Mixture ID[a]	*w/cm* Ratio	28-Day SRM[b] (kΩ-cm)	28-Day RCP Result (Coulombs)	56-Day RCP Result (Coulombs)
S-Control	0.43	20.4	1550	1110
S-IC-6.3		21.3	1490	1010
S-IC-6.6		21.5	-	-
S-IC-6.8		21.5	1790	1090
S-IC-7.0		24.1	-	-
S-IC-7.7		26.2	-	-
S-IC-7.8		21.3	-	-
S-IC-8.0		18.4	1760	1190
S-IC-10.2		19.3	1750	1130
S-IC-10.7		22.3	-	-
S-IC-11.6		27.4	-	-
S-IC-12.1		21.7	1320	970
C-Control		12.0	3440	3100
C-IC-3.8		11.8	3230	2830
C-IC-7.3		13.1	3210	2710
C-IC-9.8		12.0	3580	2620
C-IC-11.8		12.4	3250	2490

[a] Mixture IDs labeled as 'A-B-(C)', where:
A: Binder composition (S=28% slag cement by weight, C=100% cement)
B: Control=No LWA/internal curing, IC=Internally cured
C: Amount of internal curing water (if applicable), % binder weight

[b] Includes 1.1 correction factor for specimens cured in lime-saturated water rather than in a moist room

3.3.2 Discussion and Test Correlation

Although the MnDOT LC-HPC specifications list maximum RCP values to qualify mixtures for use in bridge deck construction, this test is only a measure of ion conductivity and provides at best an indirect estimation of permeability. The specifications do not include the SRM test. Lowering the ionic conductivity or increasing the surface resistivity of concrete should not be associated with any reduction in cracking or be considered as an indicator of long-term durability. In uncracked concrete, low charge passed during RCP testing is an indicator that the ingress of chloride ions to the level of reinforcing steel will be slowed (Barrett et al. 2015a). As discussed in Chapter 1, however, the presence of cracks directly over reinforcing steel diminishes any benefit of delayed corrosion initiation provided by low-permeability concrete. Even in cracked concrete, however, reducing ion conductivity does slow the corrosion rate because the flow of water, oxygen, and hydroxide ions is impeded between anodic and cathodic regions on reinforcing steel (O'Reilly et al. 2011 and Darwin et al. 2011).

As noted in Chapter 2, Eq. (2.4) describes the relationship between SRM and RCP value derived from basic principles for 4 × 8 in. (100 × 205 mm) cylinders (Jenkins 2015). For reference, a SRM of 18.2 kΩ-cm equates to a RCP value of 1500 Coulombs, the upper limit of the MnDOT specifications at 56 days.

$$RCP = 2\pi a\left(\frac{K}{SRM}\right) = \frac{27,269}{SRM} \tag{2.4}$$

where RCP = Charge passed during RCP testing (Coulombs)
a = Probe spacing (cm)
K = Constant (1139.06 kV·s)
SRM = Surface resistivity measurement (kΩ-cm)

Empirical equations developed by Jenkins (2015) by Rupnow and Icenogle (2011) (below), characterize the charge passed in the RCP test as a function of the SRM. Because a majority of concretes in these studies did not contain SCMs, they are less applicable, in general, because concretes containing SCMs (fly ash and silica fume) required a later testing age (beyond 28 days) to achieve a similar correlation between results as those containing portland cement as the only binder. Equation (3.2a) was developed by Rupnow and Icenogle (2011) to characterize same-age test results (14, 28, or 56 days) and has an R^2 value of 0.89, indicating a strong correlation between results. Equation (3.2b), also by Rupnow and Icenogle (2011), characterizes the 56-day RCP result based on the 28-day SRM and has an R^2 value of 0.87.

$$RCP = 29{,}647\left(SRM\right)^{-1.019} \tag{3.2a}$$

$$RCP = 33{,}534\left(SRM\right)^{-1.074} \tag{3.2b}$$

Equation (3.3a) was developed by Jenkins (2015) to characterize same-age test results (14 to 90 days) and has an R^2 value of 0.86. Equation (3.3b), also by Jenkins (2015), characterizes the 56-day RCP result based on the 28-day SRM and has an R^2 value of 0.84. The specimens in the study by Rupnow and Icenogle (2011) were cured in a curing room rather than lime-saturated water.

$$RCP = 31{,}653\left(SRM\right)^{-0.966} \tag{3.3a}$$

$$RCP = 33{,}352\left(SRM\right)^{-1.117} \tag{3.3b}$$

Equation (3.4a) is the empirical equation resulting from the best-fit curve obtained from data in Programs 1-3 characterizing the 28-day RCP as a function of the 28-day SRM values and has an R^2 value of 0.73, indicating weaker correlation than obtained in the previous studies. Equation (3.4b) is the empirical equation resulting from the best-fit curve obtained from the data in Programs 1-3 characterizing the 56-day RCP as a function of the 28-day SRM values and has a R^2 value of 0.74, also indicating a weaker correlation than obtained in the previous studies. The equations from Programs 1-3 do not include the results for mixtures containing fly ash due to the suspected metallic particle contamination as previously discussed. The relative drop in R^2 in the datasets from Programs 1-3 with respect to the previous studies is attributed to the slower hydration rate for mixtures containing slag cement, resulting in a wide range of SRM values at 28 days. Establishing SRM values at an age later than 28 days, when the slag cement has more fully hydrated, may reduce this variability.

$$RCP = 33{,}577\left(SRM\right)^{-0.957} \tag{3.4a}$$

$$RCP = 44{,}755\left(SRM\right)^{-1.164} \tag{3.4b}$$

The results from mixtures in Programs 1 through 3 are compared with the relationship between RCP and SRM values given in Eq. (2.4), along with the equations developed by Rupnow and Icenogle (2011) and Jenkins (2015). Figure 3.12 compares the charge passed in RCP testing as a function of SRM at the same test age. The figure shows that Eqs. (3.2a), (3.3a), and (3.4a) predict higher RCP values than Eq. (2.4), and within the range of SRMs in Programs 1-3 (10.7 to 34.2 kΩ-cm), the 28-day SRM is not a good predictor of the 28-day RCP.

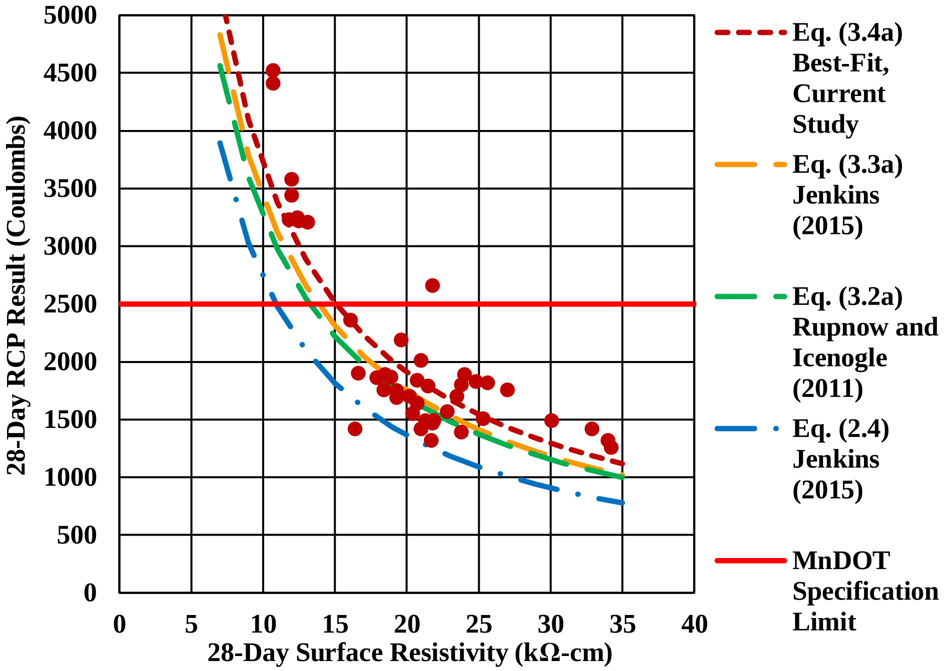


Figure 3.12: 28-day RCP vs. 28-day SRM results for mixtures in Programs 1-3 compared with Eqs. (2.4), (3.2a), (3.3a), and (3.4a)

Figure 3.13 compares the charge passed in the 56-day RCP test as a function of the 28-day SRM. Rupnow and Icenogle (2011) and Jenkins (2015) found that 28-day SRMs relate more closely with 56-day RCP results than with 28-day RCP results. A similar trend can be observed for the results from Programs 1-3. Equations (3.2b), (3.3b), and (3.4b) agree relatively well with Eq. (2.4). Given the relatively wide range of SRM values, particularly among mixtures containing slag cement with SRMs above 16 kΩ-cm, a better understanding of the relationship between RCP and SRM results for LC-HPC mixtures containing SCMs and IC is needed before SRMs are used in place of RCP results to estimate ionic conductivity.

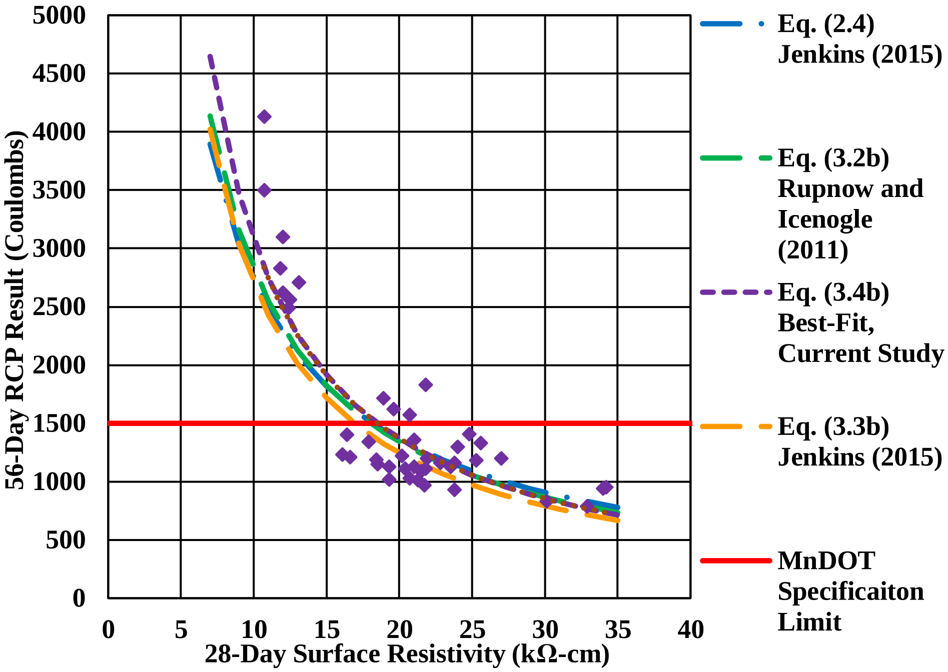


Figure 3.13: 56-day RCP vs. 28-day SRM results for mixtures in Programs 1-3 compared with Eqs. (2.4), (3.2b), (3.3b), and (3.4b)

3.4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

3.4.1 Summary

Results from scaling, freeze-thaw, rapid chloride permeability (RCP), and surface resistivity measurement (SRM) tests for concrete mixtures containing the same materials as those used in the construction of internally-cured low-cracking high-performance concrete (IC-LC-HPC) bridge decks are presented in this chapter. The study is divided into three Programs, one for each of the first three years of IC-LC-HPC bridge deck construction. The test results are compared with the Minnesota Department of Transportation (MnDOT) specification limits for LC-HPC. The IC-LC-HPC mixture proportions include a partial replacement of portland cement with 27 to 30% slag cement by total weight of binder and internal curing (IC) water provided using pre-wetted fine lightweight aggregate (FLWA). Variations in the IC-LC-HPC mixture proportions include the amount of internal curing (IC) water (contents ranging from 0 to 14.1% by total weight of binder), total absorbed water content (IC water from the FLWA plus water absorbed by the normalweight coarse and fine aggregates ranging from 2.9 to 17.7% by total weight of binder), water-to-cementitious material (*w/cm*) ratios ranging from 0.39 to 0.45, and binder compositions examining the effects of using only portland cement, a 35% Class F fly ash replacement of cement, 27 to 30% slag cement replacements of cement, and a 2% addition of silica fume of cement for the mixtures containing 27 to 28% slag cement, all by total weight of binder.

Mixtures in Program 1 exhibited adequate scaling resistance when the air content was above 7%; lower air contents resulted in increased mass losses and visual ratings. Mixtures in Program 2 exhibited more variability in scaling resistance in terms of passing or failing according to MnDOT LC-HPC specifications, but the results were not affected by the amount of IC or total absorbed water, or *w/cm* ratio. Mixtures in Program 3 exhibited adequate scaling resistance; the results were not affected by the IC or total absorbed water content, or the binder composition (28% slag cement or only portland cement).

The mixtures in Programs 1 and 2 exhibited adequate freeze-thaw durability regardless of IC or total absorbed water content, *w/cm* ratio, or binder composition. The mixtures in Program 3, which contained higher total absorbed water contents than those in Programs 1 and 2, exhibited a decrease in freeze-thaw durability. In comparing the results from Programs 2 and 3, the total absorbed water content stands out as more dominant affecting the freeze-thaw durability of IC-LC-HPC than IC water, *w/cm* ratio, or binder composition. A majority of mixtures with a total absorbed water content of more than 12% did not satisfy the MnDOT specification limit for freeze-thaw durability.

The dominant variable affecting the RCP and SRM results in this study is the binder composition, where partial replacements of portland cement with slag cement resulted in the greatest reduction in charge passed in RCP tests and the greatest increase in SRM. Binder composition had a more positive effect on the RCP and SRM test results than reducing the *w/cm* ratio, or including increasing amounts of IC water, all of which resulted in improved RCP and SRM test results. In general, mixtures containing slag cement and IC were satisfied the MnDOT LC-HPC specifications for charge passed in the RCP test. In terms of estimating ion conductivity using SRM values, the 28-day SRMs provided a better correlation with the 56-day RCP results than with the 28-day RCP results.

3.4.2 Conclusions

The following conclusions are based on the results and analyses presented in this chapter:

1. Results from Program 1 mixtures demonstrate that the scaling resistance of concrete with combinations of IC and SCMs is negatively affected when the air content is below 7%. Results from Program 2, however, demonstrate that scaling tests performed in accordance with ASTM C672 that providing an air content of 7% or more, by itself, does not guarantee good scaling performance.
2. Within the range of the parameters of this study, IC and total absorbed water contents, *w/cm* ratio, or partial replacement of portland cement with 27 to 30% slag cement did not affect scaling resistance.
3. The effect of water absorbed by aggregate on the freeze-thaw durability of IC-LC-HPC is better characterized by the total absorbed water content (water absorbed by all aggregates, expressed as a percentage of total binder weight) than by the amount of IC water and is not significantly influenced by the FLWA volume.
4. Including SCMs in the binder composition improves RCP and SRM results more than the presence or the quantity of IC water or *w/cm* ratio, which also improve RCP and

SRM results, within the parameters of this study. The mixtures in this study that contained slag cement and IC exhibited RCP results that generally satisfied the MnDOT specification limits at both 28 and 56 days.

5. The 28-day SRM value provides a better correlation with the 56-day RCP results than with the 28-day RCP results for IC-LC-HPC.

3.4.3 Recommendations

The following recommendations are made based on the results and analyses presented in this chapter:

1. The minimum air content of LC-HPC mixtures should be raised from 6.5% to 7% to promote better scaling resistance.
2. For IC-LC-HPC placements that will be subjected to freezing conditions before being allowed to adequately dry, care should be taken to avoid including an excessive total absorbed water content. Based on the freeze-thaw test results in this study, the total absorbed water content should be limited to 12% by total weight of binder.

CHAPTER 4 - INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE BRIDGE DECK CONSTRUCTION AND CRACK SURVEY RESULTS

Construction and early-age crack evaluations of four bridge decks in Minnesota placed from 2016 to 2018 that incorporate specifications for Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) are documented in this study. Two additional decks that serve as Controls followed specifications for high-performance concrete and were paired with IC-LC-HPC decks are included. Pre-wetted fine lightweight aggregate (FLWA) was used to provide a targeted internal curing water content of 8% by total weight of binder. The IC-LC-HPC mixtures included 27 to 30% slag cement by total binder weight while the Control mixtures included 25 or 35% Class F fly ash by total weight of binder. For one IC-LC-HPC deck, mixture proportions were modified based on a higher measured FLWA absorption than originally used to design the mixture. One IC-LC-HPC placement failed due to errors in FLWA moisture corrections and concrete batching that led to rejections of batches, leaving an inadequate supply of material to complete the deck. Crack surveys were completed for the IC-LC-HPC and Control decks 16 to 36 months after construction. With the exception of one of the IC-LC-HPC decks placed in 2017, which also had an overlay with a high cement paste content and no internal curing that exhibited extensive cracking during the first two years after construction, crack densities at these ages were low compared to most Low-Cracking High-Performance Concrete decks in Kansas and Internally-Cured High-Performance Concrete decks in Indiana. This project serves as a foundation for implementing IC-LC-HPC in upcoming bridge decks in Kansas and Minnesota.

4.1 GENERAL

This chapter describes the construction and crack survey results of four bridge decks placed from 2016 to 2018 in Minnesota that incorporate internal curing (IC) in low-cracking high-performance concrete (LC-HPC), as well as two bridge decks that followed current Minnesota Department of Transportation (MnDOT) specifications for high-performance concrete (HPC) that serve as Controls. Two IC-LC-HPC decks are paired with Control decks that were constructed during the same construction season, have similar geometries, and were placed by the same contractor with concrete from the same supplier. Contract documents include a special provision for including IC concrete for mixture proportioning, required concrete properties, and construction. The specifications developed for IC-LC-HPC projects remained substantially the same throughout the three years. During the period covered by this report, however, changes were made to the specifications based on experience gained from prior projects, including increasing in the maximum slump and removing the upper limit on compressive strength. The implementation of IC-LC-HPC mixture proportioning, batching, and placement is discussed in Lafikes et al. (2019) as well as this chapter. In addition to two IC-LC-HPC decks placed in 2019 (not included in this report), future IC-LC-HPC projects by MnDOT are also planned.

IC water was provided using pre-wetted fine lightweight aggregate (FLWA). The FLWA used on the four bridge decks in this study is an expanded clay, sold as Riverlite fine lightweight aggregate sourced from Erwinville, LA. To effectively implement IC in concrete mixtures, specific procedures were followed for handling and storage of the FLWA at the ready-mix plants to ensure that the stockpiles had a uniform moisture content that was high enough to provide internal curing. Lightweight aggregate has a very high absorption capacity relative to normalweight aggregate, and full saturation of lightweight aggregate is difficult to achieve in field applications. Accordingly, while normalweight coarse and fine aggregates in concrete mixtures are described as being in a saturated surface dry (SSD) condition, FLWA is proportioned based on a pre-wetted surface dry (PSD) condition, since the material is not fully saturated.

Establishing FLWA properties, moisture content (absorption and free surface moisture) and specific gravity in the field are important when implementing IC for concrete mixtures and quantifying results in laboratory testing. For the 2016 IC-LC-HPC projects, mixture proportions were developed solely by the concrete supplier. For the 2017 and 2018 IC-LC-HPC projects, University of Kansas (KU) researchers worked with MnDOT, the concrete suppliers, and the suppliers' testing laboratories to develop mixture proportions. KU researchers traveled to the concrete ready-mix plant prior to placement to provide assistance in establishing aggregate moisture contents and record FLWA material properties for each IC-LC-HPC deck.

IC-LC-HPC mixtures in this study include a partial replacement of portland cement with Grade 100 slag cement ranging from 27 to 30% (actual contents as batched) by weight of cementitious material/binder. The amount of cementitious material in IC-LC-HPC mixtures ranged from 550 to 582 lb/yd^3 (326 to 345 kg/m^3). The as-placed paste contents (volume of cementitious material and water expressed as a percentage of concrete volume) for IC-LC-HPC decks ranged from 25.0 to 25.7%. The concrete mixtures for the IC-LC-HPC bridge decks were proportioned to provide a quantity of IC water equal to 8% by total weight of binder (often expressed as 8 lb per hundred weight or 8 lb/cwt). This report describes the quantity of IC water as a percentage of the total weight of binder rather than in lb or kg per hundred weight. The MN-Control decks mixtures include a partial replacement of portland cement with Class F fly ash. One of the Control decks in this study (MN-Control-2) also included 4 lb/yd^3 (2.4 kg/m^3) of polypropylene-polyethylene macrofibers. The amount of cementitious material in the MN-Control decks ranged from 580 to 595 lb/yd^3 (344 to 353 kg/m^3), with paste contents from 25.1 to 25.8%.

The bridge decks included in this study have different surface finishes, depending on the year of construction. Decks placed in 2016 are on pedestrian bridges and had a broom finish. Decks placed in 2017 had a 7-in. (178-mm) IC-LC-HPC subdeck and a 2-in. (50-mm) low-slump wearing course (overlay) that did not incorporate IC. The bridge deck placed in 2018 was tined during construction, followed by the application of a curing compound prior to application of wet burlap for curing. All decks were cured under wet burlap for a minimum of 7 days after placement.

A second bridge placed in 2016 was originally slated to have an IC-LC-HPC deck. Placement of the IC-LC-HPC on this deck was abandoned during construction when difficulties in pumping could not be resolved and concrete properties were not within MnDOT specifications. After rejecting multiple trucks within the first few hours of construction, the concrete supplier did not have enough FLWA on hand to complete the deck. Problems during construction also included (1) the use of incorrect moisture contents for the FLWA when batching the concrete, (2) using a different size pump in test placements than was used in construction, and thus, not checking the pumpability of the mixture, and (3) not adding the viscosity modifying admixture, as designed, at the time of batching.

Crack surveys for the bridge decks in this study were planned for up to three years after placement. Results from surveys completed in 2018 (one and two years after construction) and presented by Lafikes et al. (2019), showed low crack densities for the decks except for one of the IC-LC-HPC decks placed in 2017 that had an overlay. To date, the two decks cast in 2016 were surveyed four times within three years of placement, the two cast in 2017 were surveyed twice within two years of placement, and the one cast in 2018 was surveyed once at 16 months after placement. Previous surveys on bridge decks in Kansas (Yuan et al. 2011, Pendergrass and Darwin 2014, Darwin et al. 2016, Khajehdehi and Darwin 2018) show that surveys performed at least three years after construction are more indicative of long-term performance than surveys performed at earlier ages. Based on the survey results of the MnDOT IC-LC-HPC and Control decks in the study, the low crack densities of the monolithic IC-LC-HPC and Control decks (2016 and 2018 placements) are positive indicators of long-term performance. The overlays in the 2017 decks had mixed results with one overlay showing a high crack density and the other showing a low crack density within two years after placement. This variation appears to be a result of the season during which the overlays was placed rather than the properties of the concrete in the subdecks.

4.2 MNDOT SPECIFICATIONS FOR IC-LC-HPC

The concrete bridge decks in this study follow MnDOT Specification 2461, "Structural Concrete" and MnDOT Specification 2401, "Concrete Bridge Construction." For the IC-LC-HPC projects, a special provision for Section 2401.2.A, "Concrete," includes modifications in the requirements for materials, mixture proportions, concrete properties, and construction. The MnDOT IC-LC-HPC specifications are shown in Appendix C.

4.2.1 Aggregates

The normalweight coarse and fine aggregates used for all decks satisfied MnDOT bridge construction and material specifications. The special provisions were applied for FLWA in IC-LC-HPC decks. FLWA was required to pass a $^3/_8$-in. (9.5-mm) sieve, and a maximum replacement of 10% of the total aggregate volume was imposed. The latter limit, however, was not followed, with actual replacements ranging from 10.1 to 12.8% to ensure that the target quantity of IC water (8%) was provided. Other provisions for FLWA included requirements for pre-wetting, handling, and stockpiling. For pre-wetting, the MnDOT specifications only noted that the material be pre-wetted to attain an acceptable quantity of absorbed moisture at the time of batching and that absorbed water not be considered as mix water. For handling and stockpiling, the specifications noted that the material should be protected from segregation, contamination, and conditions of non-uniform moisture.

In addition to the MnDOT special provisions, KU researchers provided recommendations for handling and storage of FLWA. These recommendations followed similar procedures that were used for a series of IC bridge decks in Indiana (Barrett et al. 2015a, Lafikes et al. 2018) and were designed to ensure that the aggregate was consistently and uniformly pre-wetted. It was recommended that pre-wetting of FLWA be achieved by sprinkling stockpiles for a minimum of 48 to 72 hours or until no more water is absorbed by the aggregate. If a steady rain of comparable intensity to that provided by the sprinkler system occurs, the sprinkler system may be turned off. To further promote uniform wetting of the FLWA during storage, it was recommended that the piles be turned several times (at least twice a day) during pre-wetting. The absorption of the FLWA needs to be measured several times during pre-wetting to ensure a constant value is reached. If the resulting absorption and amount of FLWA do not provide IC water in the desired range (7 to 9% by total weight of binder for IC-LC-HPC projects), mixture proportions should be adjusted to do so.

For the quantity of FLWA required on the IC-LC-HPC decks, an ordinary lawn sprinkler was sufficient to pre-wet the material. Use of a sprinkler system in lieu of submerging or vacuum-saturating the material was recommended because vacuum saturation forces water into small pores where it may not be readily available for IC and its presence may result in damage to the aggregate when it is subjected to freezing.

Variability of the surface moisture of FLWA within the stockpile can cause problems during batching. To minimize the variability, it was recommended that prior to batching, sprinkling the FLWA stockpiles be stopped 12 to 15 hours prior to batching to allow the surface moisture to drain. It was also recommended that the height of the pile be limited to 5 ft (1.5 m) to allow the majority of the surface moisture to drain during this period and that stockpiles be turned and remixed just prior to loading the material into bins for batching to obtain a homogeneous moisture content. Even when following these procedures, the aggregate at the bottom of the piles can have a substantially higher moisture content than aggregate in the rest of the pile, so it was recommended that the bottom 4 to 6 in. (100 to 150 mm) of aggregate not be used in batching.

Determination of the specific gravity and moisture content of the FLWA is needed for accurate batching of IC concrete. Following procedures in ASTM C1761 or New York State DOT test procedures (NY 703-19E), which involve drying FLWA samples with paper towels to a PSD condition, has been shown to produce highly variable results because the FLWA sample is susceptible to loss of fine particles (smaller than the No. 100 sieve) (Schlitter et al. 2010, Barrett et al. 2015a). This drawback can be overcome by using a centrifuge, which has proven to provide significantly greater precision in obtaining the PSD condition (Miller et al. 2014). For this reason, a centrifuge was used to place the FLWA in a PSD condition and determine the FLWA free-surface moisture on the IC-LC-HPC projects. The procedure and worksheet used for computing FLWA properties using a centrifuge are shown in Appendix D.

For all types of aggregate, the MnDOT IC-LC-HPC specifications also stipulate that the actual gradation of the aggregates used in batching be within a specified percentage of the gradations submitted in the original mixture proportion. Table HPC-6 in Section 2.A.7 in the special provision (as shown in Appendix C) lists the specific limits for the difference in gradations submitted to MnDOT and aggregate samples taken during construction. For the FLWA used in this study, high variability in particle size distribution between samples caused the material to be outside of this range for a majority of tests, which MnDOT allowed.

4.2.2 Concrete

MnDOT specifications require that concrete mixture proportions be submitted to the agency at least 21 calendar days prior to trial placement. Specifications for HPC concrete include a maximum volume of cementitious material and water (paste content) of 27% by volume of concrete. The water to cementitious material ratio (*w/cm*) in the MnDOT specifications was limited to a range of 0.43 to 0.45. For IC-LC-HPC decks placed in 2016 and 2017, the mixtures had a *w/cm* of 0.45, dropping to 0.43 for the IC-LC-HPC deck placed in 2018. The MnDOT specifications required air contents between 6.5 and 9.5% in 2016. For subsequent years, the upper limit on air content was raised to 10%. Slump for 2016 projects was specified to be between 1 and 3½ in. (25 and 90 mm). The upper limit for slump range was increased in the following years to 4 in. (100 mm) in 2017 and 5½ in. (140 mm) in 2018. Ongoing research has found good performance of IC decks in Indiana despite having slumps as high as 5¾ in. (145 mm) (Lafikes et al. 2018), suggesting that slumps above 3½ in. (90 mm) are not detrimental for IC concrete.

Slag cement and silica fume are permitted in IC-LC-HPC mixtures, with upper limits of 28 and 2% by total weight of total cementitious material, respectively. In 2016, the IC-LC-HPC contained 30% slag cement (which was allowed by MnDOT) while in 2017 and 2018, the IC-LC-HPC included 27.3 and 28.2% slag cement, respectively. Silica fume was not used.

The MnDOT specifications for hardened concrete properties are shown in Table 4.1. These include compressive strength, permeability, shrinkage, freeze-thaw, and scaling. The tests are performed in accordance with applicable ASTM procedures. The requirements are discussed in Section 4.3 of this report. The requirements for 28-day compressive strength (ASTM C31) included a range from 4000 to 5500 psi (27.6 to 37.9 MPa). Shrinkage (ASTM C157) was limited to 400 microstrain at 28 days. Rapid chloride permeability (RCP) readings (ASTM C1202) were required to be less than 2500 coulombs at 28 days and 1500 coulombs at 56 days. MnDOT requirements for freeze-thaw testing (ASTM C666 – Procedure A) stated that specimens must maintain at least 90% of their initial dynamic modulus of elasticity through 300 freeze-thaw cycles. The limit for scaling tests included a maximum visual rating of 1 after 50 cycles for specimens tested in accordance with ASTM C672.

Table 4.13: MnDOT specification requirements for hardened concrete properties

HPC Mixtures		
Test	**Requirement**	**Test Method**
Required Strength (Average of 3 cylinders)	4000 psi min. at 28 days, 5500 psi max. at 28 days	ASTM C31
Rapid Chloride Permeability	≤ 2500 coulombs at 28 days (For Preliminary Approval)	ASTM C1202
	≤ 1500 coulombs at 56 days	
Freeze-Thaw Durability	Greater than 90% at 300 cycles	ASTM C666 Procedure A
Shrinkage	No greater than 0.040 percent at 28 days	ASTM C157
Scaling	Visual rating not greater than 1 at 50 cycles	ASTM C672

4.2.3 Construction

For IC-LC-HPC decks, MnDOT specifications require the successful completion of a trial placement of at least two 10 yd^3 (7.6 m^3) loads at least 14 calendar days prior to deck placement. For trial placements, contractors were required to use the same materials, ready-mix plant, mixture proportions, and means of placement that would be used during the actual placement. In particular, the same pump must be used during the trial placement as used for the bridge deck placement to ensure that the concrete can be pumped successfully. Sections of approach slabs, abutments, footings, and other projects in the vicinity of the bridge deck are allowed to be used for the trial placements.

The maximum allowable evaporation rate per MnDOT specifications is 0.2 lb/ft^2/hr (1 kg/m^2/hr). The contractor must provide weather forecast verification prior to bridge deck placement showing that this limit will be maintained and to ensure there would be no rain during construction. The evaporation rate was well within the maximum specified limit for the IC-LC-HPC bridge decks in this study.

The deck type dictated the final finishing and curing regime for IC-LC-HPC projects. Table 4.2 summarizes the types of deck and required curing methods for the projects included in this study. The pedestrian bridges constructed in 2016 had sidewalk finishes, the 2017 projects received a low slump wearing course (overlay), and the 2018 project received a tined texture finish.

Table 4.14: Required curing method based on final bridge deck surface

Bridge Deck Type	Final Bridge Deck Surface	Required Curing Method[‖]
Bridge structural subdeck	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks	Tined Texturing[*]	Conventional wet curing after tined texturing, prior to applying AMS curing compound
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)[*]	Conventional wet curing after applying transverse broom finish, AMS curing Compound after wet cure period

[‖] Apply conventional wet curing to bridge slabs following the finishing machine or air screed.

[*] Prevent marring of broomed finish or tined textured surface by careful placement of wet curing.

Conventional wet curing via pre-wetted burlap was used for the projects in this study. MnDOT specifications require that the burlap be soaked for at least 12 hours prior to application, applied within 20 minutes after final strikeoff of the concrete surface, and be covered with a layer of plastic sheeting to prevent rapid evaporation. Continuous wetting of the burlap for at least seven days after construction is also required. An exception to the 20-minute limit for wet burlap placement was needed for the 2018 IC-LC-HPC deck, which received a tined finish. Here, the specifications permitted a Poly-Alpha-Methylsytrene (AMS) membrane curing compound to be applied within

30 minutes of concrete placement, with wet burlap applied upon the completion of deck placement–up to seven hours after placement.

4.3 DECK CONSTRUCTION

The bridge decks included in this study are summarized in Table 4.3. All decks are supported by prestressed concrete I-girders. The 2016 projects are pedestrian bridges while all others carry vehicular traffic. The decks are either in the Twin Cities area or between Rochester and St. Paul, MN. The failed IC-LC-HPC deck placement was located north of the Twin Cities and will be discussed in Section 4.5. All decks used removable wooden forms. IC-LC-HPC-1, MN-Control-1, and MN-Control-2 were placed in September. The other IC-LC-HPC decks were placed between May and July, which provided a longer time between placement and the deck being exposed to freezing temperatures giving more time for the IC water in the FLWA to evaporate. Overlays on the IC-LC-HPC-2, IC-LC-HPC-3, and MN-Control-2 subdecks were placed over two days, with half of the deck width placed each day.

Table 4.4 lists the concrete suppliers and construction contractors for the decks in this study. All concrete was placed via pump, with two pumps used per deck. Subdecks were placed in a single placement.

Table 4.15: Minnesota IC-LC-HPC and MN-Control project descriptions

Project ID	MnDOT Bridge No.	Location	Structure Type	Deck Finish	Subdeck Placement Date	Overlay Placement Dates[a]
IC-LC-HPC-1	62892	Mackubin St. over I-94; St. Paul, MN	Prestressed I-Girder	Finished Sidewalk	9/22/2016	-
IC-LC-HPC-2	25036	S.B. T.H. 52 near Cannon Falls, MN		Low Slump Wearing Course	7/6/2017	9/7/2017, 9/9/2017
IC-LC-HPC-3	25037	T.H. 58 over T.H. 52; Zumbrota, MN		Low Slump Wearing Course	6/29/2017	7/21/2017, 7/24/2017
IC-LC-HPC-4	9619	38th St. over I-35W, Minneapolis, MN		Tined Texturing	5/15/2018	-
MN-Control-1	62800	Grotto St. over I-94; St. Paul, MN		Finished Sidewalk	9/28/2016	-
MN-Control-2	25032	N.B. T.H. 52 near Cannon Falls, MN		Low Slump Wearing Course	9/15/2017	9/28/2017, 9/30/2017

[a] Overlays were placed over two days, after the subdeck was cured and then shot blasted

Table 4.16: Minnesota IC-LC-HPC and MN-Control project contractors

Project ID	Concrete Supplier	Construction Contractor
IC-LC-HPC-1	Cemstone	Kraemer North America
IC-LC-HPC-2	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.
IC-LC-HPC-3	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.
IC-LC-HPC-4	Aggregate Industries US	Lunda Construction Co.
MN-Control-1	Cemstone	Kraemer North America
MN-Control-2	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.

Table 4.5 summarizes the bridge deck geometry for the projects in this study. None of the decks were skewed. The number of spans ranges from one to four. Bridge deck lengths and widths listed are the outermost dimensions and include barriers and sidewalks (where applicable). Sidewalk concrete, which did not incorporate IC, was placed separately on top of a portion of the deck on IC-LC-HPC-3 and IC-LC-HPC -4 well after deck placement.

Table 4.17: Minnesota IC-LC-HPC and MN-Control deck geometry

Project ID	Skew (deg.)	No. of Spans	Length (ft)	Width (ft)
IC-LC-HPC-1	0	2	182.5	14.3
IC-LC-HPC-2	0	1	153.6	45.3
IC-LC-HPC-3	0	2	215.7	48.9
IC-LC-HPC-4	0	4	213.5	56.0
MN-Control-1	0	2	237.0	14.3
MN-Control-2	0	1	153.6	45.3

Note: 1 ft = 0.305 m

4.3.1 Aggregates

Aggregate properties and gradations submitted to MnDOT for normalweight coarse and fine aggregates used for both IC-LC-HPC and MN-Control decks are listed in Tables 4.6a and 4.6b, respectively. The FLWA properties, including the amount of IC water for IC-LC-HPC decks, are listed in Table 4.6c.

The FLWA in the IC-LC-HPC decks is an expanded clay. All samples were provided by the same manufacturer; however, variations in the manufacturing process produced samples with different physical properties. The absorptions and resulting quantities of IC water listed in Table 4.6c are based on measurements by KU researchers on the day of deck placement after the FLWA had been pre-wetted for at least 72 hours and allowed to drain for 12 to 15 hours. The FLWA samples were obtained in accordance with ASTM D75 after the stockpiles had been turned. The absorption (OD basis) ranged from 23.1 to 30.3%, while the specific gravity (PSD basis) ranged from 1.64 to 1.67. The amount of IC water provided in a concrete mixture is controlled by the quantity of FLWA per cubic yard and amount of water absorbed by the material. Given the variation in FLWA absorption, the subsequent amount of IC water can be significantly higher or lower than the target. This can lead to incorrect amounts of mix water being added or withheld during batching unless free-surface moisture is measured just before batching. Free surface moisture on the FLWA ranged from 5 to 8% just prior to batching. As for gradation, MnDOT observed that even within the same stockpile, particle size varied substantially.

Table 4.18a: Coarse aggregate properties

Bridge Deck Designation	**MnDOT Submitted**		
	IC-LC-HPC-1, MN-Control-1	**IC-LC-HPC-2, -3, MN-Control-2**	**IC-LC-HPC-4**
Specific Gravity (SSD)	2.72	2.65	2.71
Absorption (%)[‖]	0.4	0.3	1.4
Fineness Modulus	6.50	6.50	6.47
Sieve Size	**Percent Retained on Each Sieve**		
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	25	25	22
3/8-in. (9.5-mm)	32	32	30
No. 4 (4.75-mm)	36	36	43
No. 8 (2.38-mm)	7	7	5
No. 16 (1.18-mm)	0	0	0
No. 30 (0.60-mm)	0	0	0
No. 50 (0.30-mm)	0	0	0
No. 100 (0.15-mm)	0	0	0
No. 200 (0.075-mm)	0	0	0
Pan	0	0	0

[‖] Oven-dry basis

Table 4.6b: Fine aggregate properties

Bridge Deck Designation	**MnDOT Submitted**		
	IC-LC-HPC-1, MN-Control-1	**IC-LC-HPC-2, -3, MN-Control-2**	**IC-LC-HPC-4**
Specific Gravity (SSD)	2.65	2.61	2.66
Absorption (%)[‖]	0.5	0.7	0.5
Fineness Modulus	2.69	2.69	2.59
Sieve Size	**Percent Retained on Each Sieve**		
3/8-in. (9.5-mm)	0	0	0
No. 4 (4.75-mm)	0	1	0.1
No. 8 (2.38-mm)	11	12	4.5
No. 16 (1.18-mm)	14	16	15.8
No. 30 (0.60-mm)	25	22	29.2
No. 50 (0.30-mm)	34	33	36.1
No. 100 (0.15-mm)	15	14	13.3
No. 200 (0.075-mm)	0.8	1.3	0.8
Pan	0.2	0.7	0.2

[‖] Oven-dry basis

Table 4.6c: FLWA properties

Bridge Deck Designation		**MnDOT Submitted**			
		IC-LC-HPC-1	**IC-LC-HPC-2**	**IC-LC-HPC-3**	**IC-LC-HPC-4**
Specific Gravity (PSD)		1.68	1.67		1.64
Absorption (%)[‖]	**Design**	25.6[a]	23.5[b]		30.3[c]
	Actual[d]	23.1	24.5	24.9	30.3
Fineness Modulus		4.06	4.06		3.94
LWA Content (% Aggregate Volume)		10.1	12.8		10.9
IC Water Provided[d] **(% of total binder weight)**		6.5	8.5	8.6	7.9
Sieve Size		**Percent Retained on Each Sieve**			
3/8-in. (9.5-mm)		0	0		0
No. 4 (4.75-mm)		10	10		14.5
No. 8 (2.38-mm)		32	32		28.5
No. 16 (1.18-mm)		29	29		25.5
No. 30 (0.60-mm)		15	15		14.5
No. 50 (0.30-mm)		8	8		8
No. 100 (0.15-mm)		3.6	3.6		2.5
No. 200 (0.075-mm)		2	2		2.9
Pan		0.4	0.4		3.6

[a] Based on FLWA producer report

[b] Based on 72-hour soak time in laboratory testing

[c] Based on testing during trial placement one week before deck placement

[d] Values listed are based on measurements on the day of batching IC-LC-HPC bridge decks

[‖] Oven-dry basis

4.3.2 Concrete Mixture Proportions

Total cementitious material and water contents are listed in Table 4.7. While the mixtures were designed to provide an IC water content nominally equal to 8% of the weight of cementitious materials, actual IC water content ranged from 6.5% (for IC-LC-HPC-1) to 8.6% (for IC-LC-HPC-3). Water contents reported as “Actual” are based on the average of values from trip tickets. Data from individual trip tickets are shown in Appendix E.

As shown in Table 4.7, the actual *w/cm* ratios were lower than the design values. This was due to the concrete producers withholding water on a majority of batches, particularly on the MN-Control decks. The design *w/cm* ratio for the MN-Control decks was 0.42, with actual values ranging from 0.371 to 0.395. The design *w/cm* ratios for the IC-LC-HPC decks were either 0.43 or 0.45, with actual *w/cm* ratios ranging from 0.422 to 0.437. The lower water contents also subsequently lowered the paste contents in each of the concrete mixtures. IC-LC-HPC-1 had a design paste content of 25.4% and an actual paste content of 25.0%, the lowest in this study. All other IC-LC-HPC decks had design paste contents of 26%, with actual paste contents as much as 0.8% less. Design paste contents for the MN-Control decks were slightly below 27%, with actual paste contents below 26%. The 2-in. (50-mm) overlays followed mixture proportions defined by MnDOT 3U17A "Low Slump Concrete" and contained only portland cement as a binder (836 lb/yd^3 [496 kg/m^3]), a 0.37 *w/cm* ratio, and a paste content of 34.3%. The overlay concrete on IC-LC-HPC-2, MN-Control-2, and IC-LC-HPC-3 was mixed on-site, and thus, trip tickets were not available. The low paste contents of both the IC-LC-HPC and MN-Control decks are expected to yield good cracking performance; conversely, the lower *w/cm* ratios and significantly higher paste contents used in the overlays tend to result in extensive cracking (Lindquist, Darwin, and Browning 2005, 2006 and Darwin et al. 2016).

Table 4.8 lists the cementitious material percentages and aggregate proportions for the bridge decks in this study. The quantity of FLWA varies as a function of cementitious material content and FLWA absorption.

Table 4.19: Cementitious material content, water content, *w/cm* ratio, and IC water contents for Minnesota IC-LC-HPC and MN-Control decks

Project ID	Cementitious Material Content (lb/yd^3)		Water Content (lb/yd^3)		*w/cm* Ratio		Paste Content (%)		IC Water (% Binder Weight)	
	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]
IC-LC-HPC-1	550	551	248	241	0.451	0.437	25.4	25	8	6.5
IC-LC-HPC-2	564	565	254	245	0.45	0.432	26	25.4	8	8.5
IC-LC-HPC-3	564	568	254	239	0.45	0.422	26	25.2	8	8.6
IC-LC-HPC-4	582	581	250	245	0.43	0.422	26	25.7	8	7.9
MN-Control-1	595	594	250	220	0.421	0.371	26.9	25.1	-	
MN-Control-2	580	582	245	230	0.422	0.395	26.7	25.8	-	
2 in. Overlays[b]	836		312		0.373		34.3		-	

[a] Values listed are based on the average of trip tickets

[b] Overlay construction records do not indicate actual amounts of materials used on the day of placement

Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 4.20: Cementitious material percentages and aggregate proportions (SSD/PSD basis)

Project ID	Cementitious Material Percentages[c]	Coarse Aggregate (lb/yd^3)		Fine Aggregate (lb/yd^3)		FLWA (lb/yd^3)	
		Design	Actual[a]	Design	Actual[a]	Design	Actual[a]
IC-LC-HPC-1	70% C, 30% S	1655	1649	1106	1101	194	190
IC-LC-HPC-2	72% C, 28% S	1411	1415	1141	1143	238	243
IC-LC-HPC-3	72% C, 28% S	1411	1414	1141	1143	238	244
IC-LC-HPC-4	72% C, 28% S	1701	1708	970	973	201	198
Control-1	75%C, 25% F-FA	1719	1719	1318	1318	-	
Control-2	65% C, 35% F-FA	1736	1740	1243	1277	-	
2 in. Overlays[b]	100%C	1411		1373		-	

[a] Values listed are based on the average of trip tickets

[b] Overlay construction records do not indicate actual amounts of materials used on the day of placement

[c] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; F-FA = Class F fly ash

Note: 1 lb/yd^3 = 0.593 kg/m^3

4.4 BRIDGE DECKS

Table 4.9 lists the average slump, concrete temperature, air content, and 28-day compressive strength for the decks in this study. The projects are discussed in greater detail in Sections 4.4.1 through 4.4.6. The average slump for the IC-LC-HPC decks was allowed to increase each year based on the good performance of the IC decks in Indiana (Lafikes et al. 2018), as discussed in Section 4.2.2. The most recent project (IC-LC-HPC-4) had both the greatest average and the greatest range of slumps in the study (see Section 4.4.6). The air contents and *w/cm* ratios of IC-LC-HPC projects were all greater than the concrete used in the Control decks. Concrete temperatures were within 5 °F (3 °C) for the IC-LC-HPC and MN-Control pairs. Although IC-LC-HPC and MN-Control deck pairs did not have the same *w/cm* ratio or binder composition, compressive strengths were within 360 psi (2.5 MPa) for IC-LC-HPC-1 and MN-Control-1 and 580 psi (4.0 MPa) for IC-LC-HPC-2 and MN-Control-2.

Table 4.21: Average Minnesota IC-LC-HPC and MN-Control concrete properties

Project ID	**Slump**	**Temperature**	**Air Content**	**28-Day Compressive Strength**
	(in.)	**(°F)**	**(%)**	**(psi)**
IC-LC-HPC-1	3¼	67	7.5	7090
IC-LC-HPC-2	3½	78	9.1	4560
IC-LC-HPC-3	3½	75	8.3	5140
IC-LC-HPC-4	4¾	64	8.9	5540
MN-Control-1	4	66	6.1	6730
MN-Control-2	3¼	73	6.3	5140

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

4.4.1 IC-LC-HPC 1 – St. Paul Pedestrian Bridge (2016)

The first IC-LC-HPC bridge deck placed in Minnesota was the Mackubin St. pedestrian bridge over I-94 in St. Paul within the MnDOT Metro District. The bridge has two spans with lengths of 92 ft and 90 ft-6 in. (28.0 m and 27.6 m), a 12-ft (3.7-m) wide walkway, and a 1-ft-2 in. (0.4-m) barrier on each side for a total deck width of 14 ft-4 in. (4.4 m). The nominal deck thickness is 7 in. (178 mm). The end spans/approaches for this bridge are cast-in-place T-beams, where the top flanges serve as the deck surface. The T-beams did not incorporate IC-LC-HPC and were placed at a later date.

Kraemer North America was the contractor, and Cemstone was the concrete supplier. Prior to batching, the FLWA used in IC-LC-HPC-1 was stored outdoors at the ready-mix plant. The aggregate was wetted by a lawn sprinkler placed on top of the aggregate pile. The pile was turned one to two times per day with the sprinkler head being moved each time to fully cover the pile in its spray pattern. With the relatively small volume of concrete needed for this bridge (requiring less than 10 tons of FLWA), there were no issues with storage, and the stockpile height remained below the recommended maximum of 5 ft (1.5 m). The sprinkler was turned off on the morning of deck placement, allowing the material to drain approximately 12 hours before batching that evening. The stockpile was remixed before a composite sample was collected for the absorption and free surface moisture tests. Figure 4.1 shows the FLWA stockpile during pre-wetting.

Figure 4.1: FLWA Storage for IC-LC-HPC-1

The mixture proportions for IC-LC-HPC-1 are listed in Table 4.10. The concrete for IC-LC-HPC-1 included a 30% replacement by total weight of binder with Grade 100 slag cement, slightly higher than the 28% upper specification limit. The design *w/cm* ratio was 0.45. During construction, approximately 1 gallon per yd^3 (8 lb/yd^3, 5 kg/m^3) of water was withheld from the concrete batches, which dropped the average *w/cm* ratio to 0.437. Individual *w/cm* ratios on the trip tickets ranged from 0.423 to 0.449. The design and average paste contents were 25.4 and 25.0%, respectively. Based on the trip tickets, individual paste contents ranged from 24.4 to 25.4%. Granite was used as the coarse aggregate and river sand was used as the fine aggregate. The FLWA used for IC-LC-HPC-1 had an absorption of 23.1% (OD basis). The concrete supplier designed the mixture to include FLWA as approximately 10% of the total aggregate volume. The amount of FLWA and mix water were adjusted based on free-surface moisture prior to batching using the value determined by KU researchers (using a centrifuge). Mixture proportions, however, were not adjusted to provide the design quantity of IC water. With a lower than anticipated absorption (23.1% vs. 25.6%) and unchanged mixture proportions, the amount of IC water provided was 6.5% by total weight of binder.

Table 4.22: IC-LC-HPC-1 mixture proportions (SSD/PSD Basis)

Material	**Mixture Proportions (lb/yd^3)**	
	Design	**Actual**
Type I/II Cement	385	387
Gr. 100 Slag Cement	165	164
Water	250	241
Coarse Aggregate	1655	1649
Fine Aggregate	1106	1101
FLWA	194	190
Chemical Admixtures		
BASF	**Type**	**Dosage (oz/cwt)**
MasterAir AE 90	Air Entraining	0.58
VMA 358	Viscosity Modifier	3
MasterPolyheed 1020	Mid-Range Water Reducer	5

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths are listed in Table 4.11. Three tests for slump and air content were performed and were within the MnDOT specification limits for IC-LC-HPC. The slump ranged from 2½ to 3½ in. (65 to 90 mm), with an average of 3¼ in. (85 mm). Three tests for air content ranged from 7.0 to 8.1% with an average of 7.5%. Concrete temperatures ranged from 65 to 68 °F (18.5 to 20 °C), with an average of 67 °F (19.5 °C). One set of three cylinders was tested for compressive strength on IC-LC-HPC-1. Individual strengths ranged from 6990 to 7200 psi (48.2 to 49.6 MPa), with an average of 7090 psi (48.9 MPa), all above the specified limit of 5500 psi (37.9 MPa).

Table 4.23: IC-LC-HPC-1 concrete test results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-1	**in.**	**%**	**°F**	**psi**
Average	3¼	7.5	67	7090
Minimum	2½	7.0	65	6990
Maximum	3½	8.1	68	7200

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Placement began on the evening of September 22, 2016 at 10:30 pm at the north end of the deck and ended shortly before 1:00 am on September 23, 2016 at the south end, with final strikeoff being completed at 1:19 am. The time between placement and strikeoff ranged from 6 to 52 minutes. The time between strikeoff and application of wet curing (wet burlap) ranged from 13 to 77 minutes. The last section of the bridge experienced the longest delay in burlap placement; the concrete in the final truck appeared to be wetter than in previous trucks, and the contractor waited to apply curing in an attempt to avoid marring the finish for this area. During placement, wind speeds at the deck ranged from 4.6 to 8.1 mph (7.4 to 13.0 km/hr). Relative humidity at the deck remained high and ranged between 82 and 86%. Ambient air temperature during construction ranged from 60 to 63 °F (15.5 to 17 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.03 to 0.05 lb/ft^2/hr (0.15 to 0.24 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

The concrete in the first truck had a 6-in. (150-mm) slump at the point of placement, well above the 3½-in. (90-mm) specified limit and was rejected. Both slump and air content were within specification limits in subsequent tests, and the remaining trucks were accepted. Because IC-LC-HPC-1 is a pedestrian walkway, MnDOT specifications required that the deck surface receive a transverse broom finish before applying wet curing. The first accepted load of concrete had a slump of 2½ in. (65 mm), and while it could be pumped, some difficulty in finishing was observed in the first 15 ft (4.3 m) of the deck. The deck was consolidated with a single spud vibrator and finished with a vibrating screed. Within the first 15 ft (4.3 m) of the deck, workers followed the vibrating screed with 2×4 manual screed because of imperfections left in the surface. Trowels were used at the abutments and along the edges, and bullfloats were used elsewhere on the deck. A transverse broom finish was applied as the final finishing operation before placement of the wet burlap. Figures 4.2a and 4.2b show finishing operations on the north end of the deck. Placement proceeded with minimal difficulty. KU personnel were not present during the trial placement, but the mixture was approved by MnDOT. MnDOT personnel indicated that for the trial placement, a smaller pump was initially on site; however, the MnDOT representatives required the concrete supplier to use the same size pump as would be used during deck placement before the trial placement was approved. The issue of using the same size equipment for trial placements as for construction also rose during the failed placement of the second IC-LC-HPC deck slated for 2016, as discussed in Section 4.5.

(a) Surface imperfections at the north end of the deck after first screed pass

(b) Bullfloating the north end of the deck

Figure 4.2: Finishing the IC-LC-HPC-1 deck surface

4.4.2 MN-Control 1 – St. Paul Pedestrian Bridge (2016)

The control deck for IC-LC-HPC-1 is also a pedestrian bridge that spans over I-94 in St. Paul (Bridge No. 62800) and was also placed in September 2016. MN-Control-1 is on Grotto St., approximately 0.5 miles (0.3 km) from IC-LC-HPC-1. The bridge has two spans, each 118 ft-6 in. in length, supported by two prestressed I-girders. The walkway is 12 ft (3.7 m) wide with a 1-ft-2 in. (0.4-m) barrier on each side for a total deck width of 14 ft-4 in. (4.4 m), the same as IC-LC-HPC-1. The nominal deck thickness is also 7 in. (178 mm) and has similar end spans/approaches (cast-in-place T-beams) to IC-LC-HPC-1. As with IC-LC-HPC-1, Kraemer North America and Cemstone served as the contractor and concrete suppler, respectively.

The mixture proportions for MN-Control-1 are listed in Table 4.12. MN-Control-1 had a 25% replacement by total weight of binder with Class F fly ash and a design *w/cm* ratio of 0.42. During construction, approximately 33 lb/yd^3 (20 kg/m^3) of water was withheld throughout concrete batching, dropping the actual *w/cm* ratio to an average of 0.371. Individual *w/cm* ratios from the trip tickets ranged from 0.364 to 0.381. The corresponding design and actual average paste contents were 26.9 and 25.1%, respectively. Based on the trip tickets, individual paste contents ranged from 24.8 to 25.6%. The granite coarse aggregate and river sand used in IC-LC-HPC-1 were the same as used in MN-Control-1.

Table 4.24: MN-Control-1 mixture proportions (SSD/PSD Basis)

Material	**Mixture Proportions (lb/yd^3)**	
	Design	**Actual***
Type I/II Cement	446	445
Class F Fly Ash	149	149
Water	250	220
Coarse Aggregate	1719	1716
Fine Aggregate	1318	1359
Chemical Admixtures		
BASF	**Type**	**Dosage (oz/cwt)**
MasterAir AE 90	Air Entraining	0.43
VMA 358	Viscosity Modifier	3
MasterPolyheed 1020	Mid-Range Water Reducer	1

* Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths, listed in Table 4.13, were within MnDOT HPC specification limits. Three tests for slump were performed, with values of 3¾ or 4 in. (95 or 100 mm). Four tests for air content were performed, with values of 5.6 to 6.8% and an average of 6.1%. Concrete temperatures ranged from 62 to 70 °F (16.5 to 21 °C), with an average of 66 °F (19 °C). One set of three cylinders was tested for compressive strength. Individual cylinders had 28-day compressive strengths that ranged from 6360 to 6820 psi (43.9 to 47.0 MPa), with an average of 6630 psi (45.7 MPa).

Table 4.25: MN-Control-1 concrete test results

Bridge No.	**Slump**	**Air Content**	**Concrete Temperature**	**28-Day Compressive Strength**
MN-Control-1	**(in.)**	**(%)**	**(°F)**	**(psi)**
Average	4	6.1	66	6730
Minimum	3¾	5.6	62	6360
Maximum	4	6.8	70	6820

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

KU researchers were not present for the placement of MN-Control-1. According to the trip tickets, placement began on the evening of September 28, 2016 around 8:50 pm and ended around 11:30 pm.

4.4.3 IC-LC-HPC 2 – Cannon Falls (2017)

The second pair of IC-LC-HPC and MN-Control bridge decks, IC-LC-HPC-2 and MN-Control-2, were placed on bridges carrying southbound and northbound traffic, respectively, over the Little Cannon River on T.H. 52 near Cannon Falls in MnDOT District 6. Both are single span bridges, 153 ft-7 in. (46.8 m) long and 45 ft-4 in. (13.8 m) wide. The driving lanes are 42 ft (12.8 m) wide with an additional 1-ft-8 in. (0.5-m) barrier on each side. The total deck thickness is 9 in. (229 mm), consisting of a 7-in. (178-mm) subdeck and a 2-in. (51-mm) thick overlay that did not incorporate FLWA/IC. The overlays contained only portland cement as a binder and a nominal paste content of 34.3%, as indicated in Table 4.7. The overlays were placed well after construction of the subdecks.

Lunda Construction Co. was the contactor and Ready-Mix Concrete Company, L.L.C. was the concrete supplier for IC-LC-HPC-2 and MN-Control-2. Prior to batching, the FLWA used in IC-LC-HPC-2 was stored outdoors at the ready-mix plant. The FLWA stockpile was pre-wetted using a lawn sprinkler placed on top of concrete blocks used to separate aggregates. The height of the FLWA stockpile was kept under 5 ft (1.5 m). Although the sprinkler did not cover the entire FLWA stockpile, the material was thoroughly mixed one to two times per day and immediately before batching to provide a uniform moisture content. The sprinkler was turned off the evening before deck placement, allowing the material to drain for approximately 14 hours before batching. The FLWA was again mixed immediately before KU researchers collected a composite sample for absorption and free-surface moisture tests. When the material was collected by the loader for placement into aggregate bins, the bottom several inches of the stockpile were left undisturbed based on recommendations by KU researchers. Figure 4.3 shows the FLWA stockpile for both IC-LC-HPC-2 and IC-LC-HPC-3.

Figure 4.3: FLWA storage for IC-LC-HPC-2 and IC-LC-HPC-3

Mixture proportions for IC-LC-HPC-2 are listed in Table 4.14. IC-LC-HPC-2 included a 27.3% replacement by total weight of binder with Grade 100 slag cement. The design *w/cm* ratio was 0.45. During construction, approximately 8 lb/yd^3 (5 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.432. Individual *w/cm* ratios based on the trip tickets ranged from 0.403 to 0.439. The design and actual average paste contents were 26 and 25.4%, respectively. Based on the trip tickets, individual paste contents ranged from 24.6 to 25.7%. Granite was used as the coarse aggregate and river sand was used as the fine aggregate. The mixture proportions included a FLWA content of 12.8% of the total aggregate volume. The FLWA used in IC-LC-HPC-2 had an average absorption of 24.5% (OD basis) on the day of batching, slightly higher than the design absorption of 23.5% (OD basis), which resulted in an IC water content of approximately 8.5% by total weight of binder compared to a design value of 8%.

Table 4.26: IC-LC-HPC-2 mixture proportions (SSD/PSD Basis)

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual*
Type I/II Cement	410	411
Gr. 100 slag cement	154	154
Water	254	245
Coarse Aggregate	1411	1415
Fine Aggregate	1141	1143
FLWA	238	243
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.9
Polychem VMA	Viscosity Modifier	2
KB-1200	Mid-Range Water Reducer	3
Retarder - Polychem Renu	Set Retarder	2

* Actual values based on average of trip tickets

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths, listed in Table 4.15, were within MnDOT specification limits for IC-LC-HPC. Three tests for slump and air content were performed. A slump of 3½ in. (90 mm) was measured in all three tests. Air contents ranged from 9.0 to 9.3% with an average of 9.1%. Concrete temperatures ranged from 76 to 81 °F (24.5 to 27 °C), with an average of 78 °F (25.5 °C). One set of three cylinders was tested for compressive strength. Individual strengths ranged from 4370 to 4670 psi (30.1 to 32.2 MPa), with an average of 4560 psi (31.4 MPa), which was within the specification limits of 4000 to 5500 psi (27.6 to 37.9 MPa).

Table 4.27: IC-LC-HPC-2 concrete test results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-2	**(in.)**	**(%)**	**(°F)**	**(psi)**
Average	3½	9.1	78	4560
Minimum	-	9	76	4370
Maximum	-	9.3	81	4670

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Subdeck placement began about 6:00 am on July 6, 2017 at the south end of the deck and ended shortly before 9:30 am at the north end with final strikeoff completed at 9:46 am. The time between placement and strikeoff ranged from 1 to 3 minutes. The time between strikeoff and application of wet curing (wet burlap) ranged from 4 to 13 minutes. Wind speeds at the deck ranged from 0 to 1.7 mph (0 to 2.7 km/hr). Relative humidity at the deck ranged from 65 to 75%. Ambient air temperature during construction ranged from 74 to 84 °F (23.5 to 29 °C). The environmental conditions resulted in relatively low evaporation rates, ranging from 0.01 to 0.03 lb/ft^2/hr (0.04 to 0.15 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

All test results for slump and air content were within specification limits. No significant delays were experienced during construction. No difficulties in placement or finishing were indicated by MnDOT or construction personnel. A single operator with a spud vibrator followed the path of the pump to consolidate the freshly placed concrete. The vibrator was inserted at regularly spaced intervals. At times, however, the vibrator was rapidly pulled out of the concrete, leaving holes in the plastic concrete, and construction personnel were observed walking through areas that had been recently vibrated, resulting in deconsolidation of the concrete. Both of these actions have been correlated with cracking in Kansas bridge decks, as documented by Khajehdehi and Darwin (2018). The deck was finished using a pair of vibrating screeds placed side by side, each with a carpet drag, as shown in Figure 4.4. The screeds had to be moved laterally to finish the entire width of the deck. Construction personnel followed closely behind the screeds with bullfloats and trowels. A work bridge followed behind finishing operations for application of wet curing. Tight control of the elevation of the concrete was not required because the final grade was adjusted during overlay placement.

Figure 4.4: Placement, finishing, and curing setup for IC-LC-HPC-2

A single trial placement was used for IC-LC-HPC-2 and IC-LC-HPC-3, an abutment for IC-LC-HPC-2, since subdeck placement dates were within one week for these decks. KU personnel were not present during the trial placement. The trial placement concrete pumped easily and was within specification limits for slump and air content.

Overlay construction procedures were similar for the three decks placed in 2017 in this study. Prior to overlay placement, the subdecks surfaces were shot blasted and a mechanical screed was advanced along the length of the deck to verify clearance and grade elevations. The surface of subdeck then received a thin layer of slurry (water and portland cement). A mobile mixer was used to mix the overlay concrete on-site. Buggies deposited the concrete ahead of the finishing equipment. Construction personnel used shovels and an auger attachment in the front of the screed to evenly distribute concrete. A pair of screeds was used to strikeoff the freshly placed concrete at the correct grade. Workers used bullfloats to finish concrete behind the screeds, supplementing with trowels at abutments and edges. A carpet drag followed behind troweling and bullfloating. A work bridge followed behind the carpet drag for a worker to tine the overlay. After tining, the overlay was sprayed with a curing compound. Figures 4.5a and 4.5b show the overlay placement sequence. When the overlay could be walked on (approximately 2 hours after placement), wet burlap followed by plastic sheeting were applied on top of the curing compound to complete construction. For every 30 yd^3 of concrete placed, a single cylinder was made and tested for a 28-day compressive strength.

The overlay for the right lane was placed on July 21, 2017, and the overlay for the left lane was placed on July 24, 2017. KU researchers were present to observe placement on July 24, 2017. The 28-day compressive strength of the single cylinder from the July 21, 2017 placement was 7060 psi (48.7 MPa), while the 28-day compressive strengths of the two cylinders from the July 24, 2017 placement were 7130 and 8450 psi (49.2 and 58.3 MPa), all of which were above the 5600 psi (38.6 MPa) design compressive strength.

(a) Overlay concrete placement

(b) Overlay concrete finishing

Figure 4.5: Overlay placement sequence

4.4.4 MN-Control 2 – Cannon Falls (2017)

The Control deck had the same geometry as IC-LC-HPC-2 and is also on T.H. 52 near Cannon Falls in MnDOT District 6. The subdeck for MN-Control-2 was placed on September 15, 2017. Nominal deck thickness (subdeck and overlay) were the same as IC-LC-HPC-2. Lunda Construction Co. and Ready-Mix Company, L.L.C. also served as the contractor and concrete supplier for this bridge.

Mixture proportions for MN-Control-2 are listed in Table 4.16. MN-Control-2 had a 35% replacement by total weight of binder with Class F fly ash and a design *w/cm* ratio of 0.42. During construction, approximately 19 lb/yd^3 (10 kg/m^3) of water was withheld throughout concrete batching, dropping the average *w/cm* ratio to 0.395. Individual *w/cm* ratios based on the trip tickets ranged from 0.379 to 0.412. The corresponding design and actual average paste contents were 26.7 and 25.8%, respectively. Based on the trip tickets, individual paste contents ranged from 25.3 to 26.3%. The normalweight coarse and fine aggregates used for IC-LC-HPC-2 were used for MN-Control-2. The MN-Control-2 subdeck is the only concrete in this study that contains GRT Advantage macro fibers, dosed at 4 lb/yd^3 (2.4 kg/m^3). The fibers are a polypropylene-polyethylene blend with a length of 1½ in. (38 mm). Fibers were not used in the overlay of MN-Control-2.

The plastic concrete properties and compressive strengths, listed in Table 4.17, were within MnDOT HPC specification limits for Control decks. Three tests for slump and air content were performed. The slump ranged from 3 to 3½ in. (75 to 90 mm), with an average of 3¼ in. (85 mm). Air contents ranged from 5.5 to 7.2% with an average of 6.3%. Concrete temperatures ranged from 72 to 75 °F (22 to 24 °C), with an average of 73 °F (22.5 °C). Two sets of three cylinders were tested for compressive strength with averages of 4950 and 5320 psi (34.1 and 36.7 MPa). Individual strengths ranged from 4520 to 5580 psi (31.2 to 38.4 MPa).

Table 4.28: MN-Control-2 mixture proportions (SSD/PSD Basis)

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual[*]
Type I/II Cement	377	379
Class F Fly Ash	203	203
Water	245	230
Coarse Aggregate	1736	1740
Fine aggregate	1243	1277
Macrofibers[a]	4	4
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.5
KB-1200	Mid-Range Water Reducer	3
Polychem SPC	Superplasticizer	2
Polychem Renu	Set Retarder	3

[*] Actual values based on average of trip tickets
[a] GRT Advantage Macrosynthetic Fibers
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Table 4.29: MN-Control-2 concrete test results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
MN-Control-2	(in.)	(%)	(°F)	(psi)
Average	3¼	6.3	73	5140
Minimum	3	5.5	72	4520
Maximum	3½	7.2	75	5580

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

KU researchers were not present for the subdeck or overlay placements of MN-Control-2. According to the trip tickets, placement began on September 15, 2017 at approximately 11:00 am and ended shortly after 2:00 pm. The overlay was placed following the procedure described in Section 4.4.3. The overlay for the right lane was placed on September 28, 2017, and the overlay for the left lane was placed on September 30, 2017. The 28-day compressive strengths of the two cylinders from the September 28, 2017 placement were 8870 psi (61.2 MPa) and 9480 psi (65.4 MPa) and the 28-day compressive strengths of the two cylinders cast on September 30, 2017 were 7760 and 8650 psi (53.5 and 59.6 MPa).

4.4.5 IC-LC-HPC 3 – Zumbrota (2017)

IC-LC-HPC-3 is a two-lane bridge on T.H. 58 in Zumbrota carrying traffic over T.H. 52, also in MnDOT District 6. Although IC-LC-HPC-3 was placed a week prior to IC-LC-HPC-2, numbering was assigned to keep the IC-LC-HPC and MN-Control pairs sequential. IC-LC-HPC-3 has two spans, each 106 ft (32.3 m) long and 48 ft-11 in. (14.9 m) wide. The bridge includes a 34-ft (10.4-m) wide roadway, barriers on each side (1 ft-8 in. (0.5 m) and 1 ft-3 in. (0.4 m) wide) and a 12-ft (3.7-m) wide sidewalk placed on the deck (which did not incorporate IC) on the north side. Similar to IC-LC-HPC-2, the total deck thickness is 9 in. (229 mm), consisting of a 7-in. (178-mm) IC-LC-HPC subdeck and a 2-in. (51-mm) overlay that did not include IC.

IC-LC-HPC-3 had the same contractor (Lunda Construction Co.) and concrete supplier (Ready-Mix Concrete Company, L.L.C.) as IC-LC-HPC-2 and MN-Control-2. IC-LC-HPC-3 also used the same materials as were used for IC-LC-HPC-2.

Mixture proportions for IC-LC-HPC-3 are listed in Table 4.18. IC-LC-HPC-3 had identical mixture proportions as IC-LC-HPC-2, including a design *w/cm* ratio of 0.45 and 27.3% replacement by total weight of binder with Grade 100 slag cement. During construction, approximately 15 lb/yd^3 (9 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.422. Individual *w/cm* ratios based on the trip tickets ranged from 0.398 to 0.434. The corresponding design and actual average paste contents were 26 and 25.2%, respectively. Based on the trip tickets, individual paste contents ranged from 24.5 to 25.6%. The FLWA in IC-LC-HPC-3 had a slightly higher absorption than the material used for IC-LC-HPC-

2, an average of 24.9% (OD basis) vs. 24.5% for IC-LC-HPC-2. The design absorption was 23.5% (OD basis). The mixture proportions also included a FLWA content of 12.8% of the total aggregate volume. With the slightly higher absorption of the FLWA on-site, the amount of IC water content was approximately 8.6% of the total binder weight.

Table 4.30: IC-LC-HPC-3 mixture proportions (SSD/PSD Basis)

Material	**Mixture Proportions (lb/yd^3)**	
	Design	**Actual[*]**
Type I/II Cement	410	414
Gr. 100 slag cement	154	154
Water	254	239
Coarse Aggregate	1411	1414
Fine Aggregate	1141	1143
FLWA	238	244
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.8-0.9
Polychem VMA	Viscosity Modifier	2
KB-1200	Mid-Range Water Reducer	3
Polychem Renu[a]	Set Retarder	0-3

[a] Set retarder dosage stepped down from 3 to 0 oz/cwt throughout placement

[*] Actual values based on average of trip tickets

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths are listed in Table 4.19. Six tests for slump and air content were performed and the results were within MnDOT specification limits for IC-LC-HPC. Slumps ranged from 2½ to 4 in. (65 to 100 mm), with an average of 3½ in. (90 mm). Air contents ranged from 8 to 9.1% with an average of 8.3%. Concrete temperatures ranged from 73 to 77 °F (23 to 25 °C), with an average of 75 °F (24 °C). Two sets of cylinders were tested for compressive strength with averages of 4420 and 5850 psi (30.5 and 40.3 MPa). Individual strengths ranged from 4160 to 6250 psi (28.7 to 43.1 MPa). One set exceeded the 5500 psi (37.9 MPa) MnDOT specification limit for 28-day compressive strength.

Table 4.31: IC-LC-HPC-3 concrete test results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-3	**(in.)**	**(%)**	**(°F)**	**(psi)**
Average	3½	8.4	75	5140
Minimum	3	7.5	73	4160
Maximum	4	9.1	77	6250

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Placement began at approximately 9:00 am on June 29, 2017 at the north end of the deck with final strikeoff being completed at 12:20 pm at the south end. The time between placement and strikeoff ranged from 3 to 14 minutes. The time between strikeoff and application of wet curing (wet burlap) ranged from 3 to 28 minutes. Wind speeds at the deck ranged from 1 to 5 mph (1.6 to 8 km/hr). Relative humidity at the deck ranged from 59 to 71%. Ambient air temperature during construction ranged from 69 to 79 °F (20.5 to 26 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.03 to 0.06 lb/ft^2/hr (0.15 to 0.29 kg/m^2/hr).

All test results for slump and air content were within specification limits. No significant delays were experienced during construction. No difficulties in placement or finishing were indicated by MnDOT or construction personnel. The placement and finishing operations were similar to IC-LC-HPC-2, including the issues with consolidation observed on IC-LC-HPC-2 (with contractors walking through consolidated concrete (Figure 4.6) and rapid removal of the spud vibrator). Minimal finishing was performed on the north side of the deck where the sidewalk would be placed. The placement, finishing, and application of curing for IC-LC-HPC-3 are shown in Figure 4.7.

(a) Footprints left in the deck

(b) Re-finishing

Figure 4.6: IC-LC-HPC-3 deck consolidation and finishing problems

Figure 4.7: Placement, finishing, and curing setup for IC-LC-HPC-3

KU personnel were not present during the trial or overlay placements. One of the abutments for IC-LC-HPC-2 served as the trial placement for IC-LC-HPC-2 and IC-LC-HPC-3. The overlay was placed following the procedure described in Section 4.4.3. The overlay placement dates were September 7, 2017 and September 9, 2017. The 28-day compressive strengths of the two cylinders from September 7, 2017 placement were 9030 and 9270 psi (62.3 and 63.9 MPa). The 28-day compressive strengths of the three cylinders cast on September 9, 2017 ranged from 8860 psi (61.1 MPa) to 9050 psi (62.4 MPa), with an average of 8970 psi (61.9 MPa).

4.4.6 IC-LC-HPC 4 – Minneapolis (2018)

The fourth and most recently constructed IC-LC-HPC bridge deck in this study is a two-lane bridge carrying traffic on 38th St. over I-35W in Minneapolis in the MnDOT Metro District. The bridge has four spans, with lengths of 27 ft-1 in. (8.3 m), 31 ft-1 in. (9.5 m), and two at 77 ft-8 in. (23.7 m) for a total length of 213 ft-6 in. (65.1 m). The total width of the deck is 56 ft (17.1

m), including a roadway width of 36 ft (11 m) plus sidewalks and barriers totaling 10 ft (3 m) on each side. Sidewalk concrete was placed on the deck at a later date and did not incorporate IC. The deck is 9 in. (229 mm) thick and composed of IC-LC-HPC. The finished IC-LC-HPC deck surface serves as the final driving surface. The deck was tined during construction. In addition, project specifications indicated that a Poly-Alpha-Methylsytrene (AMS) curing compound must be placed on the deck after tining, prior to application of wet curing.

Lunda Construction Co. was the contractor, and Aggregate Industries U.S. served as the concrete supplier. Prior to batching, the FLWA was stored in a garage at the ready-mix plant and pre-wetted using a lawn sprinkler placed on top of the stockpile. The sprinkler was moved periodically to ensure that the aggregate was pre-wetted uniformly. The stockpile was turned one to two times per day. The stockpile had a height over 10 ft (3 m) at its tallest point, which is greater than the recommended 5-ft (1.5-m) limit. The sprinkler was turned off about 14 hours prior to batching the bridge deck concrete, allowing the material to drain. When the material was collected by the loader for placement into the aggregate bins, the bottom several inches of the stockpile were left undisturbed.

KU personnel were not present for the first trial placement, attempted on May 3, 2018. Two batches of concrete could not be pumped. The contractor and pump operator blamed the problem on the slump limitations (1½ to 4 in., [40 to 100 mm]). The problem was, in fact, that incorrect moisture values were used to establish the batch weights. At the ready-mix plant, the total moisture of an aggregate sample is measured, and the free-surface moisture is determined by subtracting the aggregate absorption from the total moisture content. For the first trial placement, tests for the FLWA absorption or specific gravity were not performed at the ready-mix plant; a previously-determined laboratory absorption of 23.6% was used to determine moisture corrections. The total moisture reported during the first trial placements was 36.4%, resulting in a calculated free-surface moisture of 12.8%. When KU personnel were present for the second trial placement, conducted on May 8, 2018, the FLWA absorption was measured on site and was found to be 30.3% (OD basis). Using this value in place of the 23.6% absorption results in a lower free surface moisture for a given total moisture content, and thus less water removed from the mixture. Assuming the absorption measured during the second trial placement was representative of the material used in the first trial placement, about 16 lb/yd^3 (9.5 kg/m^3) of water was incorrectly withheld from the first trial placement. Furthermore, an additional gallon of water per yd^3 (8 lb/yd^3, 5 kg/m^3) was also withheld from the first trial placement batches, resulting in a water content more than 24 lb/yd^3 (14 kg/m^3) less than designed.

The differences between the assumed and actual FLWA material properties caused considerable changes in the water and, subsequently, the paste content between the original and final mixture proportions. The paste content was lowered from 25.5% to around 24% and *w/cm* ratio was lowered from 0.43 to below 0.39 for the first trial placement. For the second trial placement, KU researchers measured a total moisture of 38% for the FLWA. Based on a 30.3% FLWA absorption, the resulting free-surface moisture value was 7.7%. In addition to using correct moisture contents in the FLWA, the two batches of concrete in the second trial placement included a modified paste content and VMA dosage, as discussed below, and were easily pumped.

A key observation from the trial placements is that FLWA properties need to be measured shortly before batching the concrete. Batch weights based on the correct absorption and free-surface moisture are needed to produce the concrete. In addition to using the correct moisture contents, increases were made to the design paste content (25.5% to 26%) and VMA dosage (3 to 5 oz/cwt [2 to 3 mL/kg]) to further aid pumping. The maximum slump allowed on this deck was increased from 4 to 5½ in. (100 to 140 mm). The increase in slump was justified based on experience with IC-HPC decks in Indiana, which included concretes with paste contents similar to those used in the IC-LC-HPC decks and slumps ranging from 4¾ to 5¾ in. (120 to 145 mm), that exhibited minimal cracking up to three years after placement (Lafikes et al. 2016).

The mixture proportions for IC-LC-HPC-4 are listed in Table 4.20. IC-LC-HPC-4 included a 28.2% replacement by total weight of binder with Grade 100 slag cement. Initial mixture proportions were used during the first attempted trial batch. The final mixture proportions were used during the successful trial placement and with deck placement. The mixture proportions, particularly the amount of FLWA, used in the initial trial placement would have provided a higher amount of IC water (9.7% by total weight of binder) than the design value of 8%. Because of the difference, aggregate quantities were adjusted to meet the target IC water content. The design *w/cm* ratio was 0.43 for both initial trials and the final design. During construction, approximately 5 lb/yd^3 (3 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.422. Individual *w/cm* ratios based on the trip tickets ranged from 0.417 to 0.428. The corresponding design and actual average paste contents were 26 and 25.7%, respectively. Based on the trip tickets, individual paste contents ranged from 25.5 to 25.9%. Crushed gravel was used as the coarse aggregate and river sand was used as the fine aggregate. The mixture proportions included a FLWA content of 10.9% of the total aggregate volume. The FLWA used in IC-LC-HPC-4 had an average absorption of 30.3% (OD basis) on the day of batching, the same value measured during the trial placement the previous week. The amount of IC water provided was approximately 7.9% by total weight of binder based on the average amount of FLWA indicated on the trip tickets.

Table 4.32: IC-LC-HPC-4 mixture proportions (SSD/PSD Basis)

Material	Mixture Proportions (lb/yd^3)		
	Initial	Final Design	Actual*
Type I/II Cement	410	418	416
Gr. 100 slag cement	160	164	165
Water	245	250	245
Coarse Aggregate	1731	1701	1708
Fine Aggregate	908	970	973
FLWA	239	201	198

Chemical Admixtures

Sika	Type	Initial Trial Dosage (oz/cwt)	Actual Dosage^a (oz/cwt)
Air-260	Air Entraining	0.21	0.28-0.33
Stabilizer-4R	Viscosity Modifying	3	5
ViscoCrete®-1000	Water Reducing	2.5	1.75-2.75
SikaTard 440	Set Retarding	1	0

[a] Actual values based on average of trip tickets

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Table 4.21 lists the slumps and air contents for the second trial batch (May 8, 2018), which ranged from 3½ to 6 in. (90 to 150 mm) and from 7.2 to 9.6%, respectively, depending on the truck and place of measurement. The first truck was tested immediately after batching and again after being sent out to drive around the ready-mix plant for approximately 15 minutes to simulate the haul time to the bridge deck. MnDOT inspectors required that the concrete be tested after pumping with both horizontal and vertical boom positions to simulate construction conditions. Pumping resulted in a slump loss of approximately 1 in. (25 mm). Air contents were not significantly affected. The first test on the second truck was performed after the simulated 15-minute haul time. In this case, the concrete was sampled from the pump hopper instead of the truck chute and was dropped into a wheelbarrow from a height of about 5 ft (1.5 m). The measured air content from the hopper was 7.2%, between 1.6% and 2.4% lower than the value obtained after pumping. It is likely that the high drop likely resulted in a loss of air, rendering the 7.2% reading invalid. Similar to the first truck, the slump dropped by 1 to 1¼ in. (25 to 30 mm) after pumping.

Table 4.33: IC-LC-HPC-4 trial batch properties for second trial placement

IC-LC-HPC-4 Trial Batch	Concrete Properties	
	Slump (in.)	Air Content (%)
Truck No. 1		
Immediately after batching	5¾	9.2
15 min. haul time	4½	8.2
Vertical Pump Boom	3¼	8.5
Horizontal Pump Boom	3½	8.5
Truck No. 2		
15 min. haul time	6	7.2[a]
Vertical Pump Boom	5	9.6
Horizontal Pump Boom	4¾	8.8

[a] Concrete sample was dropped from 5 ft (1.5 m) height
Note: 1 in. = 25.4 mm

On May 9, 2018, a new shipment of FLWA was delivered to the ready-mix plant to ensure that enough material would be available when the bridge deck concrete was batched. The aggregate properties did not change from the previous shipment of FLWA. Rain in the Minneapolis area caused weather delayed bridge deck placement until the following week on May 15, 2018. The plastic concrete properties and compressive strengths are listed in Table 4.22. A total of 12 tests for slump and air content were performed. Slumps ranged from 3½ to 6 in. (90 to 150 mm), with an average of 4¾ in. (120 mm). Air contents ranged from 7.4 to 11.2%, with an average of 8.9%. During the first two hours of placement, two of the concrete tests exceeded specification limits with a 6 in. (152 mm) slump and air contents of 11.0 and 11.2%. No trucks were rejected, but in subsequent batches the water-reducing admixture was reduced by 0.25 oz/cwt of cementitious material (0.16 mL/kg) and the water content was decreased by 5 lb/yd^3 (3 kg/m^3). Concrete temperatures ranged from 58 to 70 °F (14.5 to 21 °C), with an average of 64 °F (18 °C). Three sets of three cylinders were cast and tested for 28-day compressive strength, with averages of 4780, 5720, and 6130 psi (33.0, 39.4, and 42.3 MPa). Individual strengths ranged from 4570 to 6280 psi (31.5 to 43.3 MPa). One set exceeded the maximum MnDOT specification limit for 28-day compressive strength of 5500 psi (37.9 MPa).

Table 4.34: IC-LC-HPC-4 concrete test results

Bridge No.	**Slump**	**Air Content**	**Temperature**	**28-Day Compressive Strength**
IC-LC-HPC-4	**(in.)**	**(%)**	**(°F)**	**(psi)**
Average	4¾	8.9	64	5540
Minimum	3½	7.4	58	4570
Maximum	6	11.2	70	6280

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Placement began on the evening of May 15, 2018 at 9:50 pm at the east end of the deck and ended at 2:48 am on May 16, 2018 on the west end, with final strikeoff being completed at 3:00 am. The deck had curing compound applied within an hour after tining. Between 4:30 and 6:00 am, wet curing was applied. The subdecks under the sidewalks on each side did not receive any curing compound or finishing – wet burlap was placed on these sections during construction within an hour after being consolidated. The time between placement and bullfloating for the roadway ranged from 17 minutes to 1 hour 10 minutes. The average time between bullfloating and tining ranged from 14 to 32 minutes. The time between bullfloating and curing compound application ranged from 28 to 64 minutes. Wind speeds at the deck during construction were relatively low, with only one of the readings as high as 1 mph (1.6 km/hr). Relative humidity at the deck ranged from 37 to 58%. Ambient air temperature during construction ranged from 52 to 63 °F (11 to 17 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.02 to 0.03 lb/ft^2/hr (0.08 to 0.15 kg/m^2/hr).

Early on during placement, between the first 18 and 30 ft (5.5 and 9.2 m), a wheel on the roller screed broke and needed to be replaced, causing a nearly 50-minute delay. This delay is what accounted for the 70-minute time between placement and bullfloating at this section. No other significant delays were experienced for the remainder of construction, including when pumps were switched midway through placement. No difficulties in placement or finishing occurred. Concrete consolidation was achieved by a single operator with a spud vibrator. Similar to consolidation observed during subdeck placement for IC-LC-HPC-2 and IC-LC-HPC-3, the vibrator was inserted at regularly spaced intervals. At times, however, the vibrator was rapidly pulled out of the concrete, leaving holes in the plastic concrete, and construction personnel were observed walking through areas that had been recently vibrated, resulting in deconsolidation of the concrete.

The concrete was finished with a Bid-Well roller screed. The attachments on the screed included a strikeoff auger, followed by a Rota-Vibe® (a vibrating roller with ridges). It should be noted that the Rota-Vibe® attachment is not permitted during placement of LC-HPC bridges in Kansas. Its intention is to provide a more uniform concrete surface that is easier to finish. Concern with this attachment in Kansas LC-HPC construction is that this piece of equipment forces coarse aggregate below the surface of concrete, leaving a higher paste content at the surface that can subsequently lead to more cracking. Immediately after the Rota-Vibe® attachment, the concrete was finished with a roller screed, followed by metal pan and burlap drags. Figure 4.8 shows these attachments in order from left to right. The finishing equipment advanced in 1-ft (0.3-m) increments along the length of the bridge at a rate of approximately 1 ft (0.3 m) per minute. For most of the bridge deck, the strikeoff auger was usually within 3 ft (0.9 m) of the most recently placed concrete. The sidewalks on either side of the bridge were only consolidated – the Bid-Well equipment was not used to finish these surfaces. The 6-in. (150-mm) sidewalk was placed at a later date. Bullfloats were used on the roadway following the burlap drag. A work bridge was used for workers to tine the deck. The work bridge and tining operation were skewed by approximately 15°

with respect to the width of the deck. Figure 4.9 shows the roadway being tined near the east end. A single layer of curing compound was applied shortly after tining. Although the curing compound appeared to be applied evenly, over time, some bleed water and blotches were observed in different areas on the deck. Figure 4.10 shows the completed deck prior to application of wet burlap.

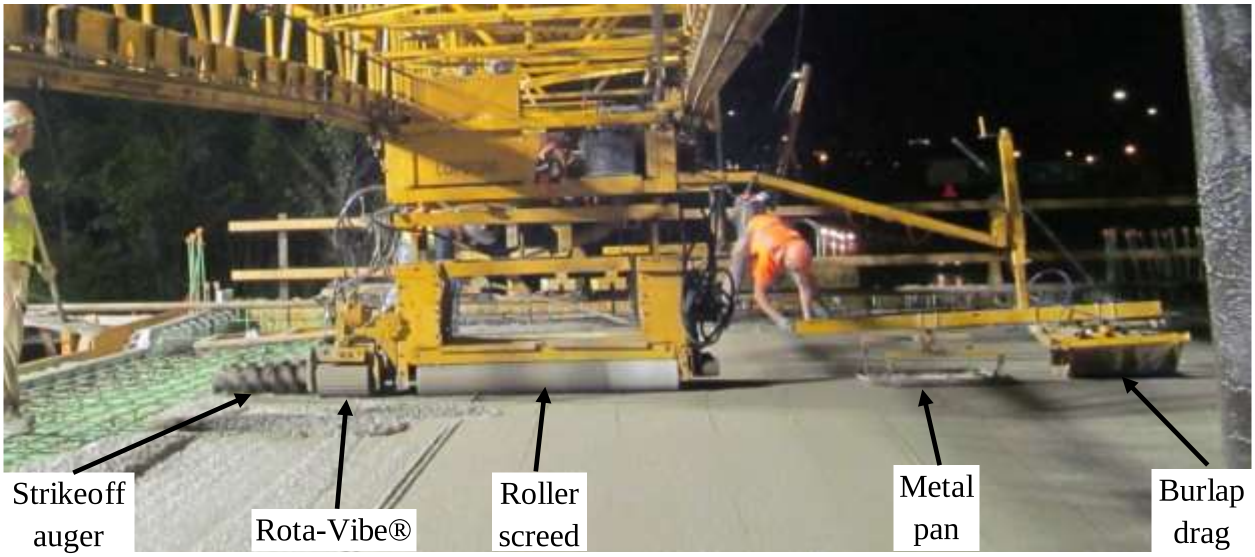


Figure 4.8: IC-LC-HPC-4 finishing equipment

Figure 4.9: IC-LC-HPC-4 Tining and unfinished sidewalk section

Figure 4.10: Finished IC-LC-HPC-4 deck showing spots of uneven curing compound application

4.5 FAILED IC-LC-HPC BRIDGE DECK PLACEMENT

This section describes the failed placement of an IC-LC-HPC bridge deck. This placement was the second of two IC-LC-HPC bridge decks planned for 2016. The bridge is located on southbound I-35 near Hinckley (MnDOT bridge No. 58821) in MnDOT District 1. The lessons learned from this failed placement include the need to measure FLWA properties on the day of batching, using the same equipment to place concrete as used in trial batches, and including all admixtures (particularly VMA) at the time of batching. The need to use the same equipment is not new (Lindquist, Darwin, and Browning 2008, McLeod, Darwin, and Browning 2009).

The placement was attempted on the morning of October 6, 2016. Cemstone was the concrete supplier, and materials and mixture proportions were to be the same as those used to construct IC-LC-HPC-1. KU researchers arrived at the Cemstone ready-mix plant in Rock Creek on the morning of October 5, 2016 to measure FLWA properties. Upon arriving, it was discovered that that the plant was not storing any of the material; the FLWA would be delivered that afternoon. The FLWA was being stored offsite but was still being pre-wetted. The FLWA was delivered to the ready-mix plant around 2:00 pm on October 5th. The quantity of material delivered was about to 10% more than the volume needed to complete the entire bridge deck. When tested, the absorption was found to be 26.0% (OD basis) vs. 25.6% based on results reported by the aggregate producer several months prior. While KU researchers sampled the FLWA, Cemstone employees also took a sample for testing at a Cemstone laboratory in the Twin Cities-area.

The FLWA samples tested on the afternoon of October 5, 2016 (15 hours before deck placement) had a free surface moisture content of 7.5% (corresponding to a total moisture content of 33.5%). The test performed at the Cemstone laboratory yielded a 34% total moisture content; no additional tests for moisture content were performed by Cemstone even though batching was scheduled for the following morning. Although none of the absorbed water in the FLWA was expected to be lost before the next morning, the material would continue draining until batching, resulting in a decreased free-surface moisture. Cemstone loaded FLWA into the aggregate hopper at the ready-mix plant on the afternoon of October 5, 2016, where it would sit for more than 15 hours until batching began.

On the morning of October 6, 2016, KU researchers arrived at the ready-mix plant prior to batching the bridge deck concrete. The free surface moisture of the FLWA in the stockpile, stored and covered outdoors was found to be 4.3%, 4.1% lower than the value Cemstone was using for moisture correction. The material placed in the bin was not available for sampling; as a result, the FLWA used in batching had an unknown moisture content, one likely to be lower than the 34% assumed. The water withheld from batching was based on the difference between 34% and 25.6% (8.4%). Because the actual free-surface moisture was 4.3%, excess water was withheld from the mixture. To prevent this error, IC-LC-HPC batch weights should be based on free surface moisture contents measured within an hour of batching.

The first IC-LC-HPC load was batched at 6:31 am. At this time, bridge approach slabs were still being placed and deck placement could not begin. As a result, the first load was held at the ready-mix plant for nearly 40 minutes before being transported to the construction site, a trip that required approximately 15 minutes. No tests for air content were performed at the ready-mix plant by Cemstone before sending trucks to the bridge. Upon arriving at the construction site around 7:40 am, the first batch of concrete was barely able to be pumped. Acceptance tests for slump and air content were performed at the point of placement (after pumping), although preliminary tests were performed out of the truck (before pumping) as well. The slump was 1¾ in. (45 mm); the contractor (Redstone Construction Co.) urged MnDOT and Cemstone to modify the concrete to provide a higher slump. Cemstone, however, had continued batching at the ready-mix plant after the first truck had left but before it was tested at the construction site. Five IC-LC-HPC loads had been batched by the time of the first test. One gal/yd^3 (8 lb/yd^3, 5 kg/m^3) of water had been withheld from the first five batches. In an attempt to bring the concrete properties within specification limits and improve pumpability, adjustments were made to the concrete after arriving at the bridge, including adding back the trim water initially withheld. VMA had also unintentionally been withheld at the time of batching from the first five trucks. The original IC-LC-HPC mixture proportions included 3 oz/cwt (2 mL/kg) of VMA, which was used for IC-LC-HPC-1. The maximum dosage per the manufacturer's (BASF's) recommendations was 6 oz/cwt (4 mL/kg). After the first truck (which did not contain any VMA) was rejected, VMA was added to the four other trucks at the construction site. The last two trucks to arrive at the job site had the maximum manufacturer's recommended dosage (6 oz/cwt [3.9 mL/kg]) added. The adjustments in mix water and VMA made after the first truck was rejected also did not account for the large amount of elapsed time between batching and testing (approximately 75 minutes). Each truck thereafter was discharged and tested in substantially less time but had pumping issues and air contents below the 6.5% minimum value listed in the MnDOT specifications. Despite these changes, the concrete properties remained out-of-specification, leading to the rejection of all five trucks.

The mixture never achieved a steady flow through the pump. Concrete was also being discharged from the pump 5 ft (1.5 m) above the deck. A portion of the low air content may have been due to a high freefall of the concrete, as most air contents were below 6.5% after pumping. The second truck was rejected after the air content was below 5%. The third truck was rejected when the slump (4¼ in. (110 mm)) exceeded the maximum slump limit of 3½ in. (90 mm) and was not tested for air content. The fourth truck had a 4½ in. (115 mm) slump and a 5% air content and was also rejected. For the fifth and final truck, the slump and air content prior to pumping was 3¼ in. (85 mm) and 9.5%, respectively. After pumping, however, the air content dropped below 5% and the truck was rejected.

While some of these issues could have been rectified in subsequent batches, Cemstone personnel indicated the deck placement could not be completed with IC-LC-HPC concrete due to lack of sufficient FLWA at the ready-mix plant. Placement of IC-LC-HPC concrete was abandoned after the contractor obtained approval from MnDOT to switch to the standard MnDOT HPC bridge deck mixture proportions.

It was later learned from the MnDOT inspector on-site that the trial placement was performed with a smaller pump than the one on site for deck placement. The smaller pump used during the trial placement would have had less friction and lower head losses and made pumping easier than if a larger pump had been used. As such, it is clear that the same equipment to be used for bridge deck placement should also be used during trial placements. The failed placement of this bridge deck, however, was precipitated by problems in preparation and concrete batching. Due to errors in the moisture correction, the first rejected batch had a paste content well below the design value of 25.4%, resulting is a decrease in slump. The lower paste content and low slump, long delays before placement, and a lack of VMA resulted in the difficulties encountered during pumping and placement. Ultimately, the concrete batched and tested that day differed significantly from the design mixture proportions and the IC-LC-HPC used by the same concrete supplier in St. Paul two weeks prior for IC-LC-HPC-1. Moreover, enforcing the MnDOT specification requirements for a trial placement would have likely identified issues with the concrete at this ready-mix plant well in advance of deck placement. These observations reinforce the need to determine FLWA properties within an hour prior to batching, but also points to a greater need for proper planning and control during ready-mix operations, practices that were followed during placement of the completed IC-LC-HPC decks.

4.6 CRACK SURVEYS AND RESULTS

Crack surveys were performed on the two pedestrian bridges (IC-LC-HPC-1 and MN-Control-1) in June 2017 (approximately 9 months after placement), May 2018 (approximately 19 months after construction), June 2019 (approximately 32 months after construction) and September 2019 (approximately 36 months after construction). Crack surveys on the three bridges placed in 2017 (IC-LC-HPC-2, IC-LC-HPC-3, and MN-Control-2), which have 2 in. (50 mm) overlays, were conducted in May 2018 (7.8 to 10.4 months after placement of the subdecks) and June 2019 (20.6 to 23.2 months after construction). IC-LC-HPC-4 was surveyed in September 2019 (16 months after placement). The crack survey procedure is presented in Appendix F. Crack surveys for bridge decks in this study will be continued for at least three years after placement. The results of crack surveys results are compared with cracking in the LC-HPC and matching Control decks in Kansas constructed from 2005 to 2011 and a series of internally-cured HPC (IC-HPC) decks placed in Indiana between 2013 and 2015. Crack maps from previous surveys are shown in Appendix G.

4.6.1 Cracking During the First Three Years After Placement

Crack densities, expressed in m/m^2, for the bridge decks in this study are listed in Table 4.23. The crack densities for the pedestrian bridges remained relatively constant within the first three years after placement. IC-LC-HPC-1 had crack densities of 0.009 during the first survey and 0.007 m/m^2 for the second through fourth surveys, while MN-Control-1 had crack densities of 0.030 and 0.032, for the first and second survey, respectively, and 0.029 m/m^2 for the third and fourth survey. Neither IC-LC-HPC-3 nor MN-Control-2 exhibited any cracking in the first year after construction. During the second survey, these decks had crack densities of 0.042 and 0.050 m/m^2, respectively. The greatest crack density for both the first and second surveys were observed on IC-LC-HPC-2 with 0.165 m/m^2 (10.1 months after subdeck placement) and 0.396 m/m^2 (22.9 months after subdeck placement), respectively. The crack density for IC-LC-HPC-4 was (0.005 m/m^2) at the time of the first survey, 16 months after placement. An important detail to note for the MN-Control decks in this study is that specifications for high-performance concrete (HPC) were used that differ from those used for the Kansas Control decks. Differences include the use of an SCM (fly ash) and paste contents below 26% for the two MN-Control decks vs. no SCM for and paste contents of up to 29% for the Kansas Control decks. The low paste content is expected to result in significantly lower crack densities than observed in the Control decks in the Kansas LC-HPC study (Darwin et al 2016). Future surveys (three years and more after construction) will provide a better indicator of long-term performance and cracking. Individual crack surveys are discussed below.

Table 4.35: Minnesota IC-LC-HPC and MN-Control crack survey results

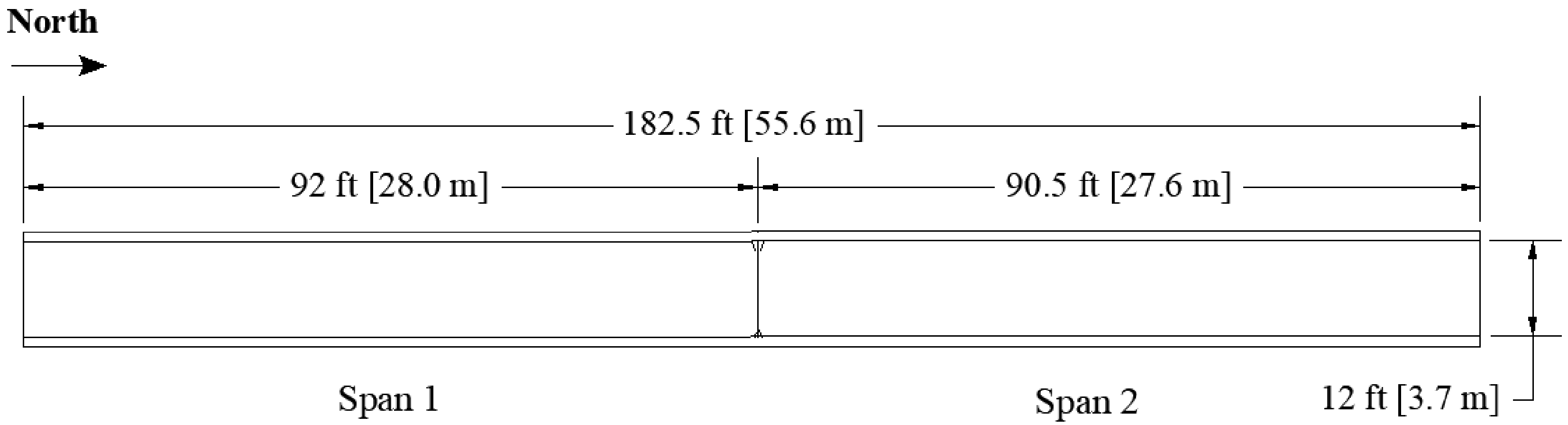
Project ID	**First Year Crack Density (m/m^2)**	**Second Year Crack Density (m/m^2)**	**Third Year Crack Density (m/m^2)**	**Age at Latest Survey (months)**
IC-LC-HPC-1*	0.013	0.007	0.007	35.9
IC-LC-HPC-2	0.165	0.396	-	22.9
IC-LC-HPC-3	0	0.042	-	23.2
IC-LC-HPC-4	0.005	-	-	16.0
Control-1*	0.030	0.032	0.029	35.7
Control-2	0	0.05	-	20.6

* Two third-year surveys completed with the same result

Pedestrian bridges IC-LC-HPC-1 and MN-Control-1 were surveyed during each of the first three years after construction, with the most recent surveys completed on June 3 and September 16, 2019. The September surveys were completed to provide results as close to 36 months after placement as possible and to include three summers of drying. Crack densities and cracking patterns were the same for both 2019 surveys and included a few short (under 2 ft [0.6 m]) cracks on either side of the contraction joint over the over the center pier. Figure 4.11 shows highlighted cracks on one side of the deck at the center pier for IC-LC-HPC-1. The average crack width for both surveys of IC-LC-HPC-1 was 0.003 in. (0.076 mm). Slightly more cracking over the center pier was observed during the 2017 survey than in the 2018 or 2019 surveys, which accounted for the decrease in crack density. The crack map from the latest survey, 35.9 months after construction, is shown in Figure 4.12.

Cracking patterns on MN-Control-1 included multiple cracks on either side of the contraction joint over the center pier along the entire width of the deck. The average crack width for the three surveys was 0.005 in. (0.127 mm). The crack map from the latest survey, 35.7 months after construction, is shown in Figure 4.13.

Figure 4.11: IC-LC-HPC-1 typical crack pattern

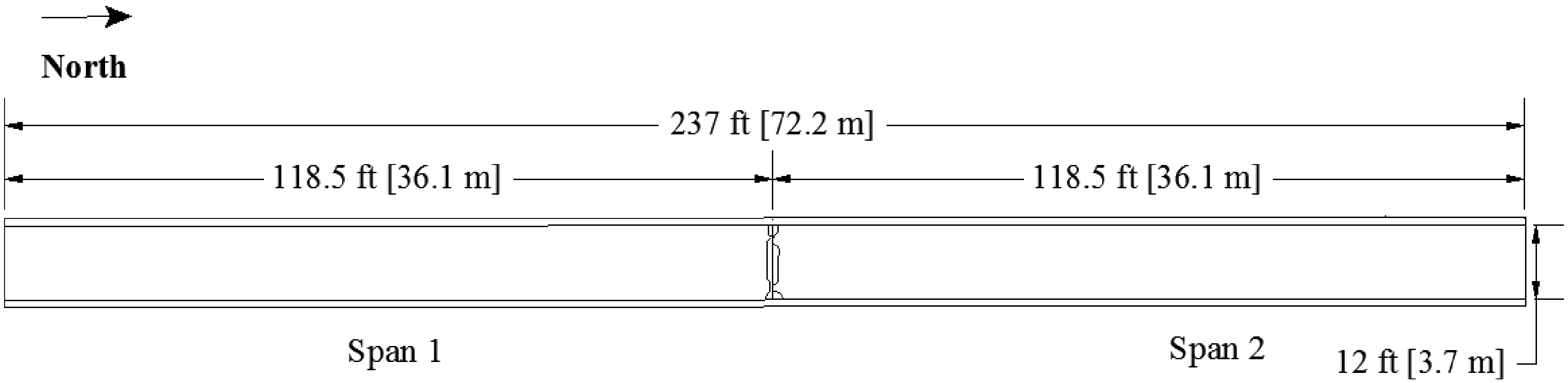


Bridge ID: IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 9/17/2019

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 35.9 months
Crack Density: 0.007 m/m^2
Span 1: 0.007 m/m^2
Span 2: 0.007 m/m^2
Crack Length: 4.9 ft
Span 1: 2.5 ft
Span 2: 2.3 ft

Figure 4.12: Crack map for IC-LC-HPC-1 (Survey 4)



Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 9/17/2019

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
  Span 1: 118.5 ft (36.1 m)
  Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

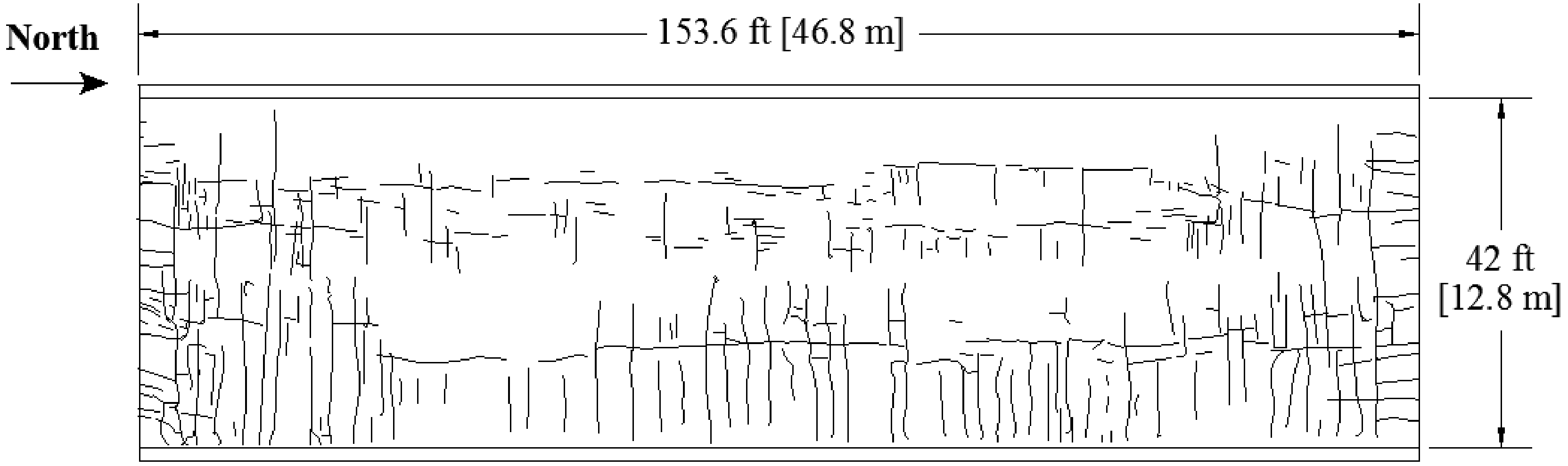
Bridge Age: 35.7 months
Crack Density: 0.029 m/m^2
  Span 1: 0.029 m/m^2
  Span 2: 0.028 m/m^2
Crack Length: 25.1 ft
  Span 1: 12.8 ft
  Span 2: 12.3 ft

Figure 4.13: Crack map for MN-Control-1 (Survey 4)

IC-LC-HPC-2 was surveyed on May 10, 2018, 10.1 months after subdeck placement (9.6 months after overlay placement) and again on June 3, 2019, 22.9 months after subdeck placement (22.4 months after overlay placement). The deck on IC-LC-HPC-2, along with those for MN-Control-2 and IC-LC-HPC-3, has a 2-in. (50-mm) overlay. No cracks observed were observed on the undersides of the three decks.

The crack densities in the overlay on IC-LC-HPC-2 for the first and second survey were 0.165 m/m^2 and 0.396 m/m^2, respectively, the highest to date among projects in this study. The crack map for the second survey is shown in Figure 4.14. During the first survey (Figure G.5), the majority of cracks were within 15 ft (4.6 m) of the abutments. Cracks at the abutments were longitudinal in orientation. The majority of the cracks that were located more than 3 ft (0.9 m) from each end of the deck were transverse and varied in length from less than 1 ft (0.3 m) to more than 20 ft (6.1 m). Crack widths ranged from 0.003 in (0.076 mm) to 0.008 in. (0.203 mm), with an average of 0.004 in. (0.102 mm). During the second survey, both longitudinal and transverse cracks were observed along the entire of the deck. Crack lengths varied from less than 1 ft (0.3 m) to more than 30 ft (9.2 m). Crack widths ranged from 0.003 in (0.076 mm) to 0.010 in. (0.254 mm), with an average of 0.006 in. (0.152 mm). Cracks did not appear to reflect through to the underside of the deck during either survey. It is assumed that with the overlay being placed late in July 2017, cracking due to restrained drying shrinkage of the overlay, made worse by high temperatures, was the primary cause of cracking.

MN-Control-2 was surveyed on May 10, 2018, 7.8 months after subdeck placement (7.3 months after overlay placement) and June 3, 2019, 20.6 months after subdeck placement (20.1 months after overlay placement). No cracks (0 m/m^2 crack density) were observed during the first survey (Figure G.6). The crack density was 0.050 m/m^2 in the second survey. The crack map for the second survey is shown in Figure 4.15. Cracks were located within 15 ft (4.6 m) from each abutment. Cracks at the abutments were longitudinal in orientation. Cracks located more than 3 ft (0.9 m) from each end of the deck were transverse and varied in length from less than 1 ft (0.3 m) to 20.5 ft (6.3 m). Crack widths ranged from 0.003 in (0.076 mm) to 0.007 in. (0.178 mm), with an average of 0.005 in. (0.127 mm). The effect of including fibers in the subdeck concrete cannot be evaluated because of the overlay. Placing the overlay later in the construction season may have helped due to milder environmental conditions. In contrast to the overlay for IC-LC-HPC-2, which was placed in July, the September placement for the MN-Control-2 overlay would have helped mitigate rapid drying shrinkage, worsened by higher summer temperatures for IC-LC-HPC-2.

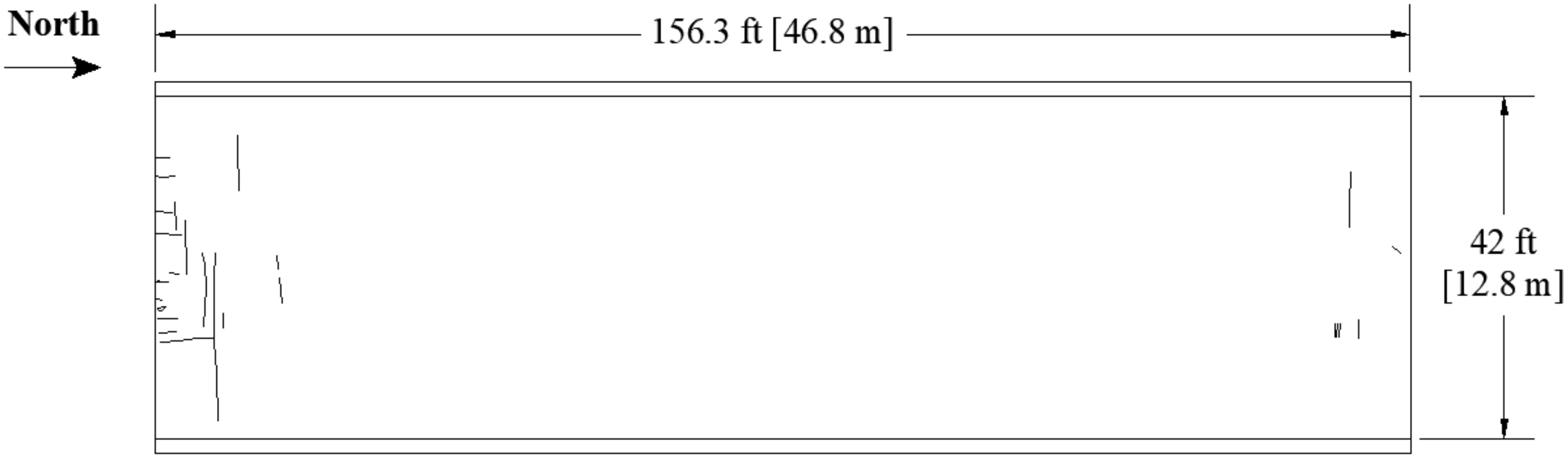


Bridge ID: IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over
Little Cannon River
Construction Date: 7/6/2017
Crack Survey Date: 6/3/2019

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 22.9 months
Crack Density: 0.396 m/m^2
Crack Length: 778.0 ft

Figure 4.14: Crack map for IC-LC-HPC-2 (Survey 2)



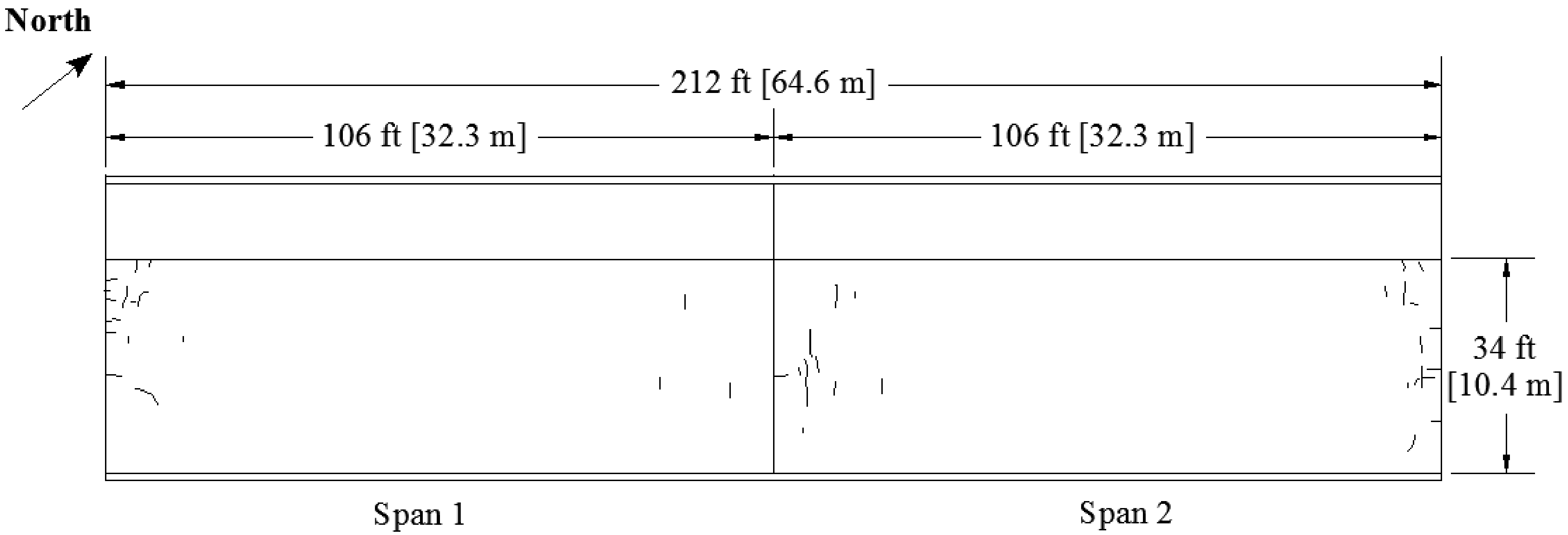
Bridge ID: MN-Control-2
Bridge Number: 25032
Bridge Location: S.B TH 52 over Little Cannon River
Construction Date: 9/15/2017
Crack Survey Date: 6/3/2019

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

Bridge Age: 20.6 months
Crack Density: 0.050 m/m^2
Crack Length: 98.4 ft

Figure 4.15: Crack map for MN-Control-2 (Survey 2)

IC-LC-HPC-3 was surveyed on May 10, 2018, 10.4 months after subdeck placement (8.1 months after overlay placement) and June 3, 2019, 23.2 months after placement (20.9 months after overlay placement. Only the 34-ft (10.4-m) wide roadway was surveyed. The sidewalk on the north side of the deck was placed well after the IC-LC-HPC subdeck and did not incorporate IC. No cracks (0 m/m^2 crack density) were observed during the first survey (Figure G.7). A crack density of 0.042 m/m^2 was found during the second survey. The crack map for the second survey is shown in Figure 4.16. Cracks were located within 15 ft (4.6 m) from each abutment and within 20 ft (6.1 m) on each side of the center pier. Cracks at the abutments were longitudinal in orientation. Cracks located away from the abutments were transverse and varied in length from less than 1 ft (0.3 m) to 6 ft (1.8 m). The majority of cracks had lengths of 3 ft (0.9 m) or less. Crack widths ranged from 0.003 in. (0.076 mm) to 0.006 in. (0.152 mm), with an average of 0.004 in. (0.102 mm). The overlay for this deck was placed in early September, well after the late June placement of the subdeck. Allowing the overlay to cure in cooler ambient temperatures likely reduced the amount of drying shrinkage cracking within the first two years after placement.



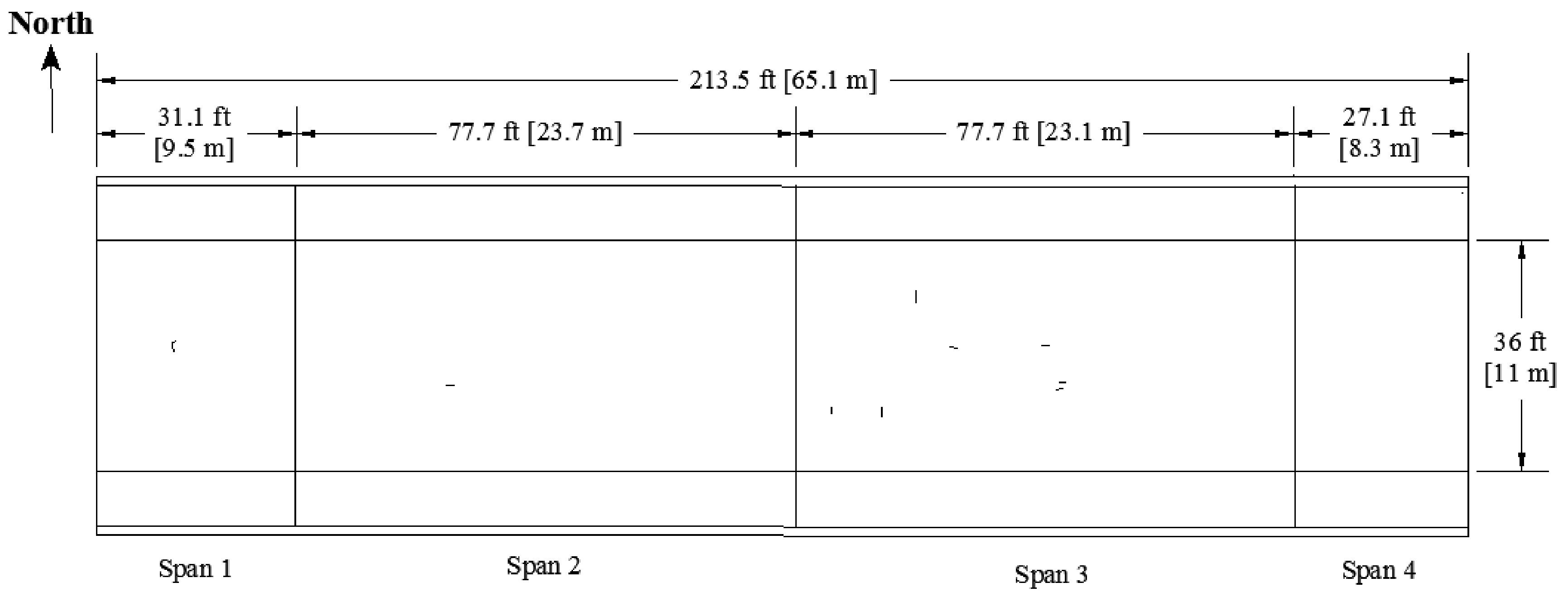
Bridge ID: IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52
Construction Date: 6/29/2017
Crack Survey Date: 6/3/2019

Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)
Skew: 0°
Number of Spans: 2
Span 1: 106 ft (32.3 m)
Span 2: 106 ft (32.3 m)
Number of Placements: 1

Bridge Age: 23.2 months
Crack Density: 0.042 m/m^2
Span 1: 0.033 m/m^2
Span 2: 0.050 m/m^2
Crack Length: 92.0 ft
Span 1: 36.7 ft
Span 2: 55.3 ft

Figure 4.16: Crack map for IC-LC-HPC-3 (Survey 2)

IC-LC-HPC-4 was surveyed on September 17, 2019, 16 months after placement. Only the 36-ft (11-m) wide roadway was surveyed. The sidewalks on the north and south sides of the deck were placed well after the IC-LC-HPC subdeck and did not incorporate IC. A crack density of 0.005 m/m^2 was observed during the survey. The crack map for the survey is shown in Figure 4.17. Only a few short, narrow cracks were observed during the survey with none located at the abutments or over the piers. Cracks were under 2 ft (0.6 m) in length and had widths of 0.003 in. (0.076 mm). Although IC-LC-HPC-4 exhibited limited cracking and no freeze-thaw or scaling damage was noted, tining the deck immediately after finishing appeared to result in inconsistent groove widths and depths throughout the roadway, as shown in Figure 4.18. Lafikes et al. (2018) noted similar tining issues for the IC-HPC decks in Indiana. It is difficult to predict whether poor tining is only aesthetic or if it will result in any detrimental effects on long-term durability or cracking.



Bridge Number: IC-LC-HPC-4
Bridge Number: 9619
Bridge Location: 38th St. over I-35W
Construction Date: 5/16/2018
Crack Survey Date: 9/16/2019

Bridge Length: 213.5 ft (65.1 m)
Bridge Width: 36.0 ft (11.0 m)
Skew: 0°
Number of Spans: 4
  Span 1: 31.1 ft (9.5 m)
  Span 2: 77.7 ft (23.1 m)
  Span 3: 77.7 ft (23.1 m)
  Span 4: 27.1 ft (8.3 m)
Number of Placements: 1

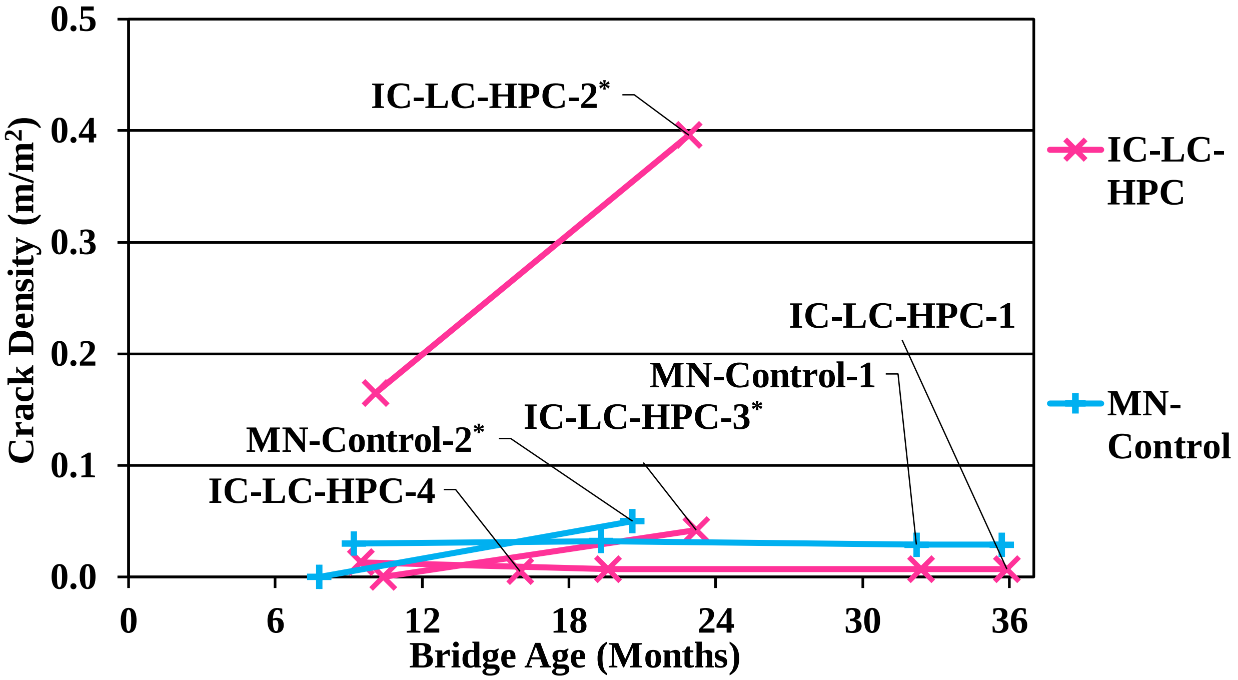
Bridge Age: 16.0 months
Crack Density: 0.005 m/m^2
  Span 1: 0.005 m/m^2
  Span 2: 0.001 m/m^2
  Span 3: 0.009 m/m^2
  Span 4: 0 m/m^2
Crack Length: 11.2 ft
  Span 1: 1.8 ft
  Span 2: 1.2 ft
  Span 3: 8.2 ft
  Span 4: 0 ft

Figure 4.17: Crack map for IC-LC-HPC-4 (Survey 1)

Figure 4.18: Poorly tined area on IC-LC-HPC-4

4.6.2 Cracking as a Function of Age for IC-LC-HPC and MN-Control Decks

Figure 4.19 shows crack densities as a function age for the IC-LC-HPC and MN-Control decks. For the two bridge decks placed in 2016 (IC-LC-HPC-1 and MN-Control-1), crack surveys have shown similar results during the first three years after placement. Of the three decks with overlays placed in 2017, one (IC-LC-HPC-2) has exhibited significant cracking in the two years after placement, whereas the other two (MN-Control-2 and IC-LC-HPC-3) have exhibited low cracking. The single deck placed in 2018 (IC-LC-HPC-4) has exhibited a low crack density to date. It should be noted that all projects in this study should be surveyed through are least three years to obtain an accurate estimate of long-term cracking behavior.



* Deck has non-IC/LC-HPC overlay

Figure 4.19: Crack densities of Minnesota IC-LC-HPC and MN-Control decks vs. deck age

Cracking in the Minnesota IC-LC-HPC decks is compared to cracking in bridge decks from the Kansas LC-HPC study (Darwin et al. 2016) and bridge decks in Indiana (IN) that followed specifications for IC-HPC in Figure 4.20. The Kansas LC-HPC study included a series of bridge decks that followed the Kansas Department of Transportation (KDOT) specifications for low-cracking high-performance concrete bridge decks and were constructed in conjunction with a series of Control decks that followed conventional KDOT bridge deck specifications. Unlike the MnDOT bridges in the current study, the LC-HPC bridge decks in Kansas contained portland cement as the only cementitious material. All decks were surveyed by KU researchers and contain paste contents below 26%. Both the Minnesota and the Indiana decks had IC provided using a pre-wetted FLWA. The Indiana decks contained ternary blends of portland cement, silica fume, and either Class C fly ash or slag cement as binder.

The crack densities for IC-LC-HPC-1, IC-LC-HPC-3, and IC-LC-HPC-4 are among the lowest in these studies. The crack density for IC-LC-HPC-2 was still within the spread of Kansas LC-HPC data within one year after construction but has since surpassed the LC-HPC decks with its second crack survey. Most of the Indiana IC-HPC decks also exhibited significantly lower crack densities than most Kansas LC-HPC decks between three and five years after placement.

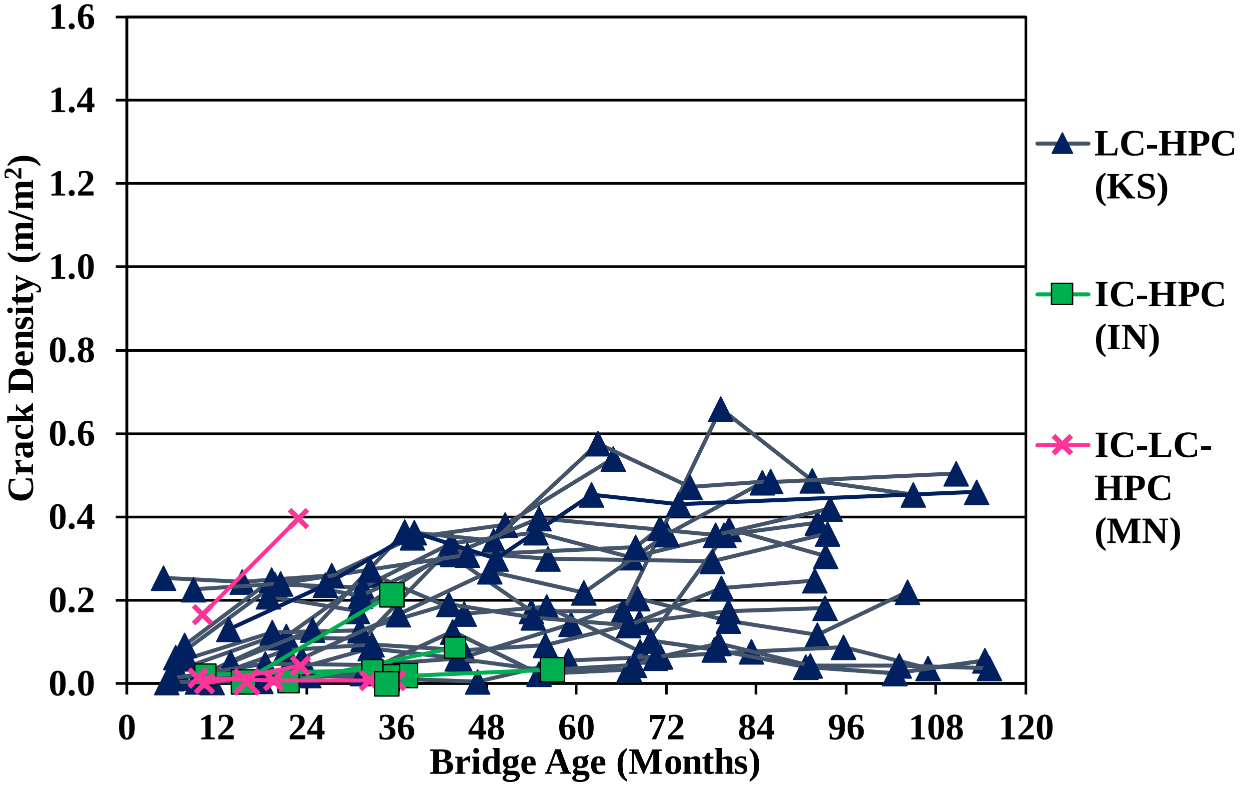


Figure 4.20: Crack densities of Kansas LC-HPC, Minnesota IC-LC-HPC, and Indiana IC-HPC decks vs. deck age

Figure 4.21 shows the crack densities of the Control decks from both the Kansas and Minnesota projects. Compared to the Control (KS) decks, the MN-Control (HPC-Control (MN)) decks are exhibiting significantly less cracking through the first two to three years after construction. The MN-Control and IC-LC-HPC bridge decks contain different mixture proportions, including binder composition and *w/cm* ratio. Most KS-Control decks have a low *w/cm* ratio (0.37) overlay containing silica fume. The paste contents in the MN-Control decks, however, are significantly lower than the majority of Kansas Control decks. The low paste content is the believed to be the primary contributor to the reduction in cracking. As indicated in Section 4.3.2, the Minnesota Control decks have a combination of low paste contents (25.1 to 25.8% by volume) and a partial replacement of cement with Class F fly ash (25 to 35% by weight of binder). The Kansas Control decks have design paste contents ranging from 25.6 to 29% by volume. The Kansas Control decks with design paste contents between 25.6 and 27.1% include only portland cement as the binder, while the other Kansas Control decks have a paste content of 29% and include a 20% replacement of cement with Class F fly ash. As shown in Figure 4.21, these differences result in significantly higher cracking for the Kansas Control decks. As discussed in Chapter 1, Khajehdehi and Darwin (2018) indicate that increased paste content contributes significantly more to bridge deck cracking than increased slump, a trend that is also exhibited when comparing MN-Control and Kansas Control decks. Chapter 1 also includes a description of the study by Ibrahim et al. (2019) where, for slumps from 3 to 8 in. (75 to 205 mm), the use of combinations of IC and SCMs produced a reduction in settlement cracking relative to control mixtures in laboratory test specimens. The KDOT specifications list a maximum slump of 7 in. (180 mm) for the KS-Control decks, although this limit was not strictly enforced. The average slumps of the individual Kansas Control decks ranged from 3¼ to 9¼ in. (85 to 235 mm) (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, and Pendergrass and Darwin 2014). The MnDOT specifications list a slump range of 1 to 4 in. (25 to 100 mm) for the MN-Control decks. As indicated in Section 4.4, the average slumps of the two Minnesota Control decks were 3¼ and 4 in. (85 to 100 mm). Although the difference in slumps between MN-Control and Kansas Control decks is as much as 6 in. (150 mm), it should be noted that all but two of the KS-Control deck placements with an average slump within 1 in. (25 mm) of the MN-Control decks exhibited average crack densities above 0.500 m/m^2 36 months after placement.

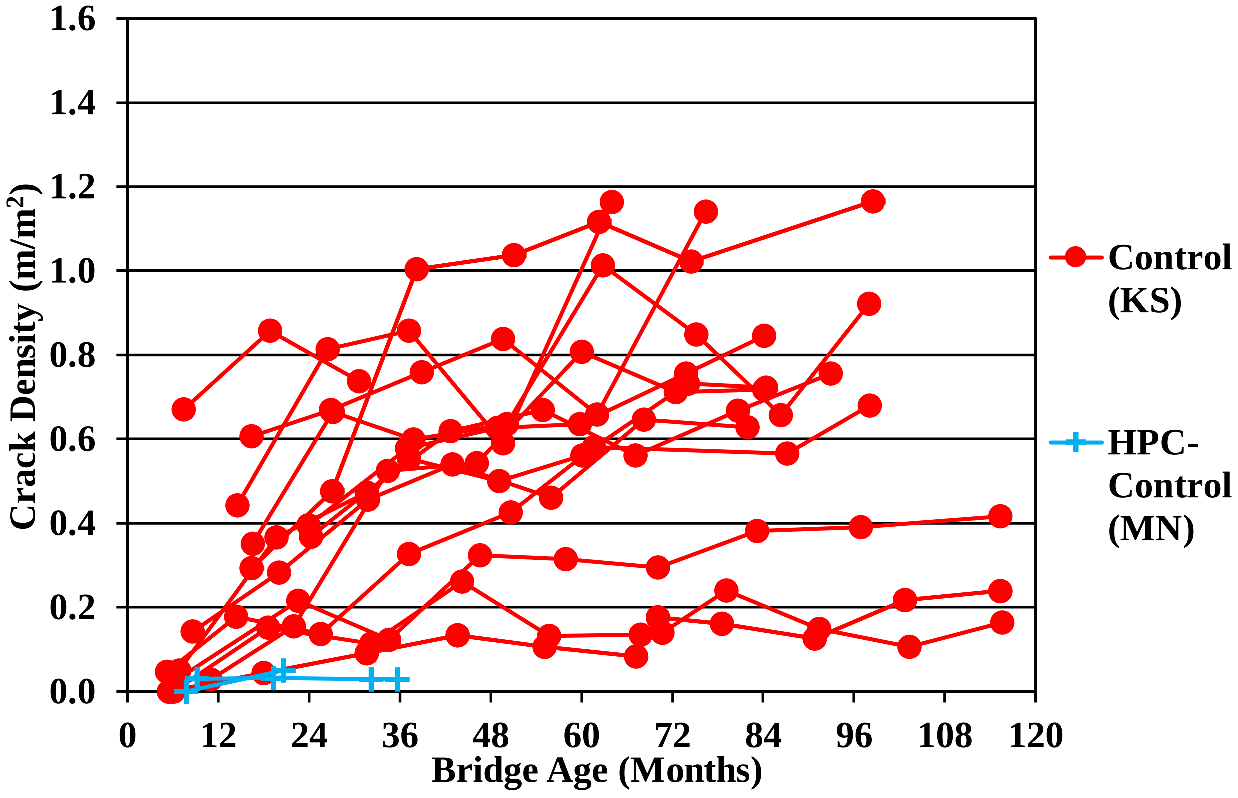


Figure 4.21: Crack densities of Kansas Control Decks and MN-Control (HPC) decks vs. deck age

4.7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.7.1 Summary

The first four bridge decks implementing specifications for Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) were placed in Minnesota during this study. Two Control decks that followed Minnesota specifications for high-performance concrete (HPC) were paired with IC-LC-HPC decks for comparison. IC was provided using pre-wetted fine lightweight aggregate (FLWA), which was proportioned based on its absorption to provide a target quantity of IC water of 8% by total weight of cementitious material. The IC-LC-HPC mixtures contained a 27 to 30% (by weight) replacement of portland cement by slag cement as part of the binder system while the Control mixtures contained a 25 or 35% (by weight) replacement of portland cement by Class F fly ash. University of Kansas (KU) researchers worked with the Minnesota Department of Transportation (MnDOT), the concrete suppliers, and the testing laboratories to develop recommendations for handling, storing, and testing FLWA. For the deck placed in 2018, mixture proportions, namely the quantity of FLWA, needed to be modified after the FLWA delivered to the ready-mix plant had a significantly higher absorption than the FLWA used in the initial design. This study also covered the failed placement of an additional IC-LC-HPC deck in 2016, which had to be abandoned after errors in FLWA moisture corrections and concrete batching led to consecutive rejections of batches when concrete was not within specification limits and the remaining quantity of FLWA was not adequate to complete the deck.

KU researchers observed the construction of the IC-LC-HPC decks. Crack surveys were performed up to three years after construction on the IC-LC-HPC and Control decks. The IC-LC-HPC and Control decks placed in 2016 exhibited low crack densities through the first three years after placement. The two IC-LC-HPC and one Control decks placed in 2017 had 2-in. (50-mm) overlays with high cement paste contents, which tend to result high amounts of cracking. Through two years after placement of the 2017 decks, low crack densities were observed on the overlays that were placed in September; however, the IC-LC-HPC deck with an overlay placed in July exhibited significant cracking within one year of placement that exceeded all Indiana internally-cured high-performance concrete (IC-HPC) and Kansas LC-HPC decks during the second year after placement. The IC-LC-HPC deck placed in 2018 exhibited a low crack density during its first survey, more than one year after placement. With the exception of the 2017 IC-LC-HPC deck and overlay placed in July, the crack densities measured for the IC-LC-HPC decks are, to date, similar to the LC-HPC decks in Kansas and a series of IC-HPC decks in Indiana. Future crack surveys are planned.

4.7.2 Conclusions

The following conclusions can be drawn based on the observations during planning, construction, and early-age crack surveys of the first four IC-LC-HPC decks:

1. The FLWA used throughout this study has shown to be highly variable in its properties (absorption, specific gravity, and gradation).
2. Enforcing specification requirements for trial placements of IC-LC-HPC mixtures is critical in identifying any concrete issues prior to construction. For projects that have concrete placed via pump, the same size pump should be used during trial placements as will be used on the deck.
3. Crack survey results of the monolithic IC-LC-HPC and Control decks included in this study serve as positive indicators for low amounts of long-term cracking.
4. It appears that bridge deck overlays placed later in the construction season exhibit less cracking than those subjected to high temperatures within the first month of curing, but future surveys are needed to establish long-term behavior.

4.7.3 Recommendations

The experience gathered from the construction and evaluation within the first three years after IC-LC-HPC bridge deck placement, along with other studies of IC concrete (Lafikes et al. 2018), provide the basis for the recommendations that follow for future IC-LC-HPC decks. Recommendations 1 through 4 address handling, storage, testing, and proportioning FLWA. Recommendations 5 through 7 address IC-LC-HPC properties.

1. Final IC-LC-HPC mixture proportions should be contingent on test results for FLWA absorption determined on the day of placement and adjusted to provide the correct amount of IC water. Ready-mix suppliers should be authorized to adjust the batch weights of the FLWA and normalweight fine aggregate to maintain the target quantity of IC water.
2. Individual FLWA shipments for use in IC-LC-HPC projects should be delivered to ready-mix plants and tested for specific gravity and absorption prior to finalizing the FLWA content of mixtures. The quantity of material delivered should be enough to complete trial batching and account for the rejection of batches during construction. The same material should be used for both the trial and bridge deck placements.
3. FLWA should be pre-wetted until the material reaches a constant absorption. Pre-wetting should stop 12 to 15 hours prior to batching to allow the material to drain. Additional requirements to turn stockpiles twice per day and again immediately before determining the moisture contents used for batching should be added to the current IC-LC-HPC specifications.
4. Use of a centrifuge to place FLWA in a pre-wetted surface dry (PSD) condition for testing is recommended for IC-LC-HPC projects. The procedure used by KU researchers closely follows one developed by Miller et al. (2014a) and is described in Appendix D.
5. The paste content (volume of cementitious material and water) in IC-LC-HPC mixtures should be limited to 26% of the total concrete volume. Paste content has been shown to be the most important material factor affecting bridge deck cracking and is more critical than slump or compressive strength (Khajehdehi and Darwin 2018). Provided this trend continues to be verified through crack surveys beyond three years after construction, IC-

LC-HPC specifications may include a 5½ in. (140 mm) maximum slump and have the 5500 psi (37.9 MPa) cap on 28-day compressive strength removed.

6. The use of overlays on bridge decks has not been shown to be beneficial in reducing cracking (Miller and Darwin 2000, Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014, Darwin et al. 2016, Khajehdehi and Darwin 2018). Based on crack survey results of the two IC-LC-HPC bridge decks with an overlay in this study, the potential for high amounts of cracking remains despite the use of an IC-LC-HPC subdeck. It is recommended that future IC-LC-HPC decks not have overlays.
7. Khajehdehi and Darwin (2018) identified consolidation and early application of wet curing as variables that should be controlled during construction. For IC-LC-HPC bridge decks, concrete should receive thorough consolidation and be left undisturbed throughout the remainder of construction. Grinding and grooving should replace tining to obtain surface roughness.

CHAPTER 5 – OTHER APPRACHES FOR INCLUDING INTERNAL CURING AND SUPPLEMENTARY CEMENTITIOUS MATERIALS IN CONCRETE BRIDGE DECKS

Shrinkage reduction technologies have been adopted by a number of state departments of transportation to reduce bridge deck cracking. This study focuses on bridge decks in Indiana and Utah that incorporate supplementary cementitious materials (SCMs) in conjunction with pre-wetted fine lightweight aggregate (FLWA) to provide internal curing (IC). The decks incorporated internal curing with various combinations of portland cement, slag cement, Class C and Class F fly ash, and silica fume, in concrete mixtures with water-cementitious material ratios ranging from 0.39 to 0.44. When compared with crack densities in low-cracking high-performance concrete (LC-HPC) and Control bridge decks in Kansas, which contain only portland cement as a binder, concrete mixtures with a paste content (cementitious materials and water) greater than 27% by concrete volume exhibited more cracking, regardless of the use of IC or SCMs. Although IC appears to reduce bridge deck cracking in the first year after placement for the decks with paste contents above 27%, this effect vanishes at later ages. Bridge decks with paste contents below 26% that incorporate IC and SCMs exhibited low cracking through up to five years after construction. The combination of low paste contents, IC, and SCMs is a promising approach for the construction of low-cracking bridge decks; however, durability issues were noted (in the form of aggregate popouts and apparent scaling) on the Indiana decks containing IC and SCMs. These issues are attributed to the combination of excessive amounts of absorbed water held by all of the aggregates, late-season placements, low air contents, and poor finishing and tining procedures.

5.1 GENERAL

Cracking in bridge decks is a serious concern because cracks provide corrosive agents a direct path to reinforcing steel and reduce the freeze-thaw resistance of the concrete. Over the past two decades, the Kansas Department of Transportation (KDOT) has been working with the University of Kansas (KU) to minimize cracking in bridge decks. Through a pooled-fund study supported by KDOT, other state and federal transportation organizations, and concrete material suppliers and organizations, the University of Kansas has developed specifications for Low-Cracking High-Performance Concrete (LC-HPC) bridge decks.

The LC-HPC specifications address cement and water content, plastic concrete properties, construction methods, and curing requirements. The constituent that undergoes shrinkage in concrete is cement paste (cementitious materials plus water in a concrete mixture). As a measure to reduce shrinkage compared to conventional bridge deck concrete, LC-HPC specifications limit paste contents by placing a tight range on water-cement (*w/c*) ratios and limiting cement content to between 500 and 540 lb/yd^3 (296 and 320 kg/m^3). Because of a lack of consensus on the effect of supplementary cementitious materials (SCMs) on drying shrinkage at the time LC-HPC specifications were first written, only portland cement was permitted in LC-HPC decks through 2011. A *w/c* ratio of 0.43 to 0.45 is specified to help limit strength because high strength reduces creep, which can result in increased cracking if drying shrinkage is restrained. Portland cement mixtures that follow LC-HPC specifications for cement content and *w/c* ratio have paste contents ranging from 22.8 to 24.6% of total concrete volume. The 28-day strength of concrete is limited to values between 3500 and 5500 psi (24.1 and 37.9 MPa), and the air content of fresh concrete must be 8.0 ± 1.5% to improve durability and reduce cracking. An optimized aggregate gradation is used in LC-HPC mixtures. This can be achieved with tools such as described by Shilstone (1990) or provided by the KU Mix Method (Lindquist et al. 2008, 2015). These criteria provide concrete with better workability at a lower slump. The LC-HPC specifications for the bridge decks placed from 2005 to 2011 limit slump to values between 1½ and 3 in. (40 and 75 mm) at the point of placement and 3½ in. (90 mm) at the truck because high slump increases settlement cracking above reinforcing bars. To limit thermal and plastic shrinkage cracking, the temperature of fresh concrete must be between 55 and 70 ºF (13 and 21 ºC). The temperature range may be extended to 50 to 75 ºF (10 and 24 ºC) with approval by the Engineer.

To reduce the amount of water lost during construction and to avoid plastic shrinkage cracking, the evaporation rate during bridge deck placement is limited to 0.2 lb/ft^2/hr (1.0 kg/m^2/hr). If the evaporation rate exceeds this limit, special actions, such as cooling the concrete or installing wind breaks, are required. Procedures for ensuring proper consolidation of concrete through the use of vertically mounted internal gang vibrators are also specified. The surface must be finished using a burlap drag, a metal pan, or both, followed by bullfloating (only if needed). Finishing aids, including water, are prohibited. To minimize plastic shrinkage cracking caused by loss of surface water after placement, early initiation of curing is required through the use of a layer of pre-saturated burlap placed on the deck within 10 minutes after final strike-off. A second layer of burlap must be placed within the next 5 minutes. The burlap must be soaked for at least 12 hours prior to placement. The complete LC-HPC specifications are included in Appendix H.

Seventeen bridge decks were constructed in Kansas following the LC-HPC specifications (Kansas Department of Transportation 2011, 2014a, 2014b), with an additional 11 bridge decks constructed following conventional KDOT specifications to provide a basis of comparison. To provide a consistent method to compare bridge decks, a specific crack survey procedure has been developed to minimize variations from year to year (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014). This procedure is presented in Appendix F. Crack surveys were performed annually on both LC-HPC decks and matching control decks for 8 to 10 years after construction beginning with the first LC-HPC deck in 2005. The results of those surveys show that the crack densities of the LC-HPC decks are consistently lower than the control decks (Lindquist et al. 2008, McLeod et al. 2009, Darwin et al. 2010, 2012, 2016, Yuan et al. 2011, Pendergrass and Darwin 2014).

There are other approaches available in addition to LC-HPC to reduce cracking in bridge decks. These include the use of internal curing (IC) through partial replacement of aggregate with pre-wetted fine lightweight aggregate (FLWA). For concrete with water-cementitious material (*w/cm*) ratios below about 0.42, the cement paste can experience self-desiccation during early hydration, resulting in autogenous shrinkage of the concrete. In cases where the concrete is restrained from shrinking, tensile stresses develop and crack the concrete. Proper distribution of IC water has been shown to improve performance of concrete due to the reduction of autogenous shrinkage by providing additional water for hydration throughout the entire cement paste matrix (Bentz and Weiss 2011). IC water is also available to reduce drying shrinkage for concrete made with *w/cm* ratios both above and below 0.42. Applicability of this technology for bridge deck cracking and durability is discussed in this report.

The survey results of four bridges in Indiana constructed with internally cured high-performance concrete (IN-IC-HPC) containing SCMs, either Class C fly ash or slag cement along with silica fume, are the primary focus of this report. The IN-IC-HPC specifications stipulate a slightly higher paste content than Kansas LC-HPC specifications (25 ± 1% of total concrete volume). Additionally, a ternary binder system is also specified with cement replacements of 20-25% of Class F or C Fly Ash or 15-20% of slag cement, along with 3-7% silica fume by weight of cementitious material. The portland cement content for IN-IC-HPC decks is limited to 390 lb/yd^3 (231 kg/m^3). A 6.5% air content and *w/cm* range of 0.36-0.43 is also specified, both lower than Kansas LC-HPC specifications. Limitations to the fine aggregate content and procedures for determining the proportion of FLWA are also included. While the Kansas LC-HPC specifications define a range of concrete compressive strengths, the IN-IC-HPC specifications only list a minimum compressive strength of 5000 psi. The IN-IC-HPC specifications are included in Appendix I. In addition to the IN-IC-HPC decks, two older Indiana decks in this study contain 100% portland cement as binder and include one with internal curing via pre-wetted fine FLWA (IN-IC) and a control deck without internal curing/FLWA (IN-Control). IN-IC and IN-Control were surveyed at 71.6 and 93 months after construction. The only special provisions for the IN-IC specifications include proportioning FLWA into the concrete mixture to provide internal curing. The two older decks had paste contents of 27.6% by volume.

In addition to the six bridges in Indiana, the results of crack surveys conducted by Brigham Young University (BYU) on two internally cured decks in Utah (UT-IC-1 and UT-IC-2) are also included in this chapter for comparison. UT-IC-1 and UT-IC-2 were constructed in spring 2012 and are similar in structure type (including precast panels to support an internally cured deck topping) and mixture proportions. The concrete used in both UT-IC decks incorporated a partial replacement of cement with Class F fly ash and had paste contents of 28% by volume. The age of the Utah bridges was 24 months at the time of most recent surveys; the surveyors followed a procedure similar to that used by KU for visually inspecting bridge decks for cracks.

This study examines the density of cracks in bridge decks in Indiana and Utah that incorporated internal curing with various combinations of portland cement and SCMs, specifically, slag cement, Class C and Class F fly ash, and silica fume, in concrete mixtures with *w/cm* ratios ranging from 0.39 to 0.44. When compared with crack densities in low-cracking high-performance concrete (LC-HPC) and control bridge decks in Kansas, decks cast with concrete mixtures with paste contents higher than 27% exhibited more cracking, regardless of the use of internal curing or SCMs. Bridge decks with paste contents below 26% that incorporate internal curing and SCMs exhibited low cracking through the first three to five years after construction, which serves as a good predictor of long-term performance with good mitigation of cracking (Lafikes et al. 2018).

5.2 BRIDGES

The Indiana bridges are located in two Indiana Department of Transportation (INDOT) districts, Seymour and Vincennes. The four IN-IC-HPC decks are supported by steel girders and have steel stay-in-place forms; the other two (IN-Control and IN-IC) are supported by prestressed box beams. The two Utah IC decks, surveyed by Brigham Young University researchers (included as an additional reference for comparison) consist of toppings supported by precast half-deck concrete panels that are, in turn, supported by precast prestressed concrete girders. Information on the decks is summarized in Table 5.1. In this report, the IC and control decks in Indiana are designated IN-IC and IN-Control, respectively, and the internally cured high-performance concrete decks are designated IN-IC-HPC-1 through IN-IC-HPC-4. The internally cured Utah deck toppings are designated UT-IC-1 and UT-IC-2.

Table 5.1: Bridge decks

Bridge ID	District	Type of Support	Spans	Skew (deg.)	Length (ft)	Width (ft)
IN-IC	Seymour	Prestressed box beams	1	10.6	40.3	29
IN-Control	Seymour	Prestressed box beams	1	0	50	29
IN-IC-HPC-1	Vincennes	Steel beams	3	0	224	34.5
IN-IC-HPC-2	Seymour	Steel beams	1	0	55	43.5
IN-IC-HPC-3	Seymour	Steel beams	4	34.8	256	33
IN-IC-HPC-4	Vincennes	Steel beams	2	6.7	230	43.8
UT-IC-1	-	Deck panels on prestressed girders	1	34	127.5	50.8
UT-IC-2	-	Deck panels on prestressed girders	1	4	119.8	50.8

Note: 1 ft = 0.305 m

5.3 CONCRETE PROPERTIES AND CONSTRUCTION PROCEDURES

Two types of concrete mix designs were used for the internally cured bridge decks in

Indiana–IN-IC and IN-IC-HPC. The IN-IC concrete was intended to demonstrate the advantages of IC over ordinary portland cement concrete mixtures by reducing cracking through eliminating chemical and autogenous shrinkage and reducing drying shrinkage (di Bella et al. 2012) compared to the IN-Control mixture and was not considered to be a high-performance concrete (HPC) mixture. Both decks contain 657 lb/yd^3 (390 kg/m^3) of portland cement, the only binder, and had a *w/c* ratio of 0.39, which resulted in a paste volume of 27.6%, exceeding the paste content range in the Kansas LC-HPC specifications. The only difference between the IN-Control and IN-IC mixture proportions is the IC water in the IN-IC deck was provided through replacement of 24% of total aggregate (by volume) with pre-wetted FLWA that provided 7.2% IC water by weight of cement in the mixture (di Bella et al. 2012). A commercially available expanded shale FLWA with a 24-hour absorption of 10.4% and a PSD specific gravity of 1.56 was used. The mixture proportions conformed to INDOT specifications and determination of FLWA properties followed procedures outlined by the New York State DOT (NYSDOT) for construction of a series of internally cured bridge decks (Streeter et al. 2012). A modified paper towel test method (NY 703-19E Test Method) that includes instructions for determining FLWA properties in the field as well as in the lab was used in lieu of ASTM C128. It should be noted that the paper towel test tends to produce variable results compared to those obtained using a centrifuge, as observed by Miller et al. (2014) for the IN-IC-HPC mixtures.

The second type of internally cured concrete mixture, IN-IC-HPC, was designed to both reduce cracking and reduce the ionic transport properties of concrete (Miller et al. 2015a). A ternary binder system with cement, silica fume (3 to 7% by mass), and slag cement (15 to 20% by mass) or Class C fly ash (20 to 25% by mass) was used to produce a refined pore system and greater calcium hydroxide consumption. Preliminary laboratory testing found that the expanded shale FLWA used for the IN-IC-HPC decks had a 24-hour absorption capacity (based on dry weight) and a PSD specific gravity of approximately 13% and 1.70, respectively; these values were used to develop mixture proportions. Laboratory testing used values based on wetting for 24 hours to ensure that values obtained in the field, where the FLWA was wetted for 72 hours, would easily meet or exceed the initial design. No upper limit on the amount of IC water was designated. Testing on the day of placement found the FLWA had absorptions between 15.8 and 18.5%, but the mixture proportions were not adjusted to account for the higher aggregate absorptions. As a result, the IN-IC-HPC mixtures had between 8.8 and 12% of IC water by weight of binder, greater than the 8% target value. The IN-IC-HPC specifications placed a 25% (±1.0%) limit on the paste content of the mixtures to improve the shrinkage and cracking performance. The actual paste contents of the four IN-IC-HPC decks ranged from 24.6% to 26.0% by volume. As explained by Barrett et al. (2015b), this limitation was applied based on the recommendations by Schmitt and Darwin (1995) as a result of their study of 33 bridge deck placements in Kansas that showed that when the paste volume exceeded 27%, cracking significantly increased. Curing for seven days with wet burlap was used for all Indiana bridges. INDOT removed a requirement for the IN-IC-HPC bridge decks to be sprayed with a commercial sealant. Only wet burlap and plastic sheeting were used to cover the decks after completing the placements.

The mixture proportions used for the bridge decks are shown in Table 5.2. The amount of IC water is reported as a percentage by weight of cementitious material based on the amount of absorbed water in the FLWA. Determination of absorption of lightweight aggregate in the laboratory is typically based on soaking the material for 24 hours before placing it in a pre-wetted surface dry (PSD) condition. For FLWA, absorption tends to increase with longer soak times, so properties are described in terms of the PSD condition rather than the SSD condition since the material is not fully saturated. There are different ways of achieving the PSD condition for FLWA, including following ASTM C128 or ASTM C1761 procedures. However, there have been difficulties in obtaining consistent results for absorption tests as FLWA is more porous and sensitive to wicking out moisture following those test procedures (Miller et al. 2014). As such, for the IN-IC-HPC decks, the FLWA was placed in the PSD condition using a centrifuge following the procedure outlined by Miller et al. (2014), also outlined in Appendix D.

In addition to IC water, the amount of water absorbed by the normalweight aggregates is listed in Table 5.2. As discussed in Chapter 3, increasing the amount of water absorbed by all aggregates (including normalweight aggregates) can have negative effects on the freeze-thaw durability of concrete mixtures, and a maximum amount of absorbed water of 12% by weight of binder (from all aggregates) is recommended. For the Indiana decks, the normalweight aggregate absorptions ranged from 1.1 to 1.9%. This increased the total absorbed water content to 9.7% by weight of cement for the IN-IC deck and to 15.3 to 17.6% by weight of binder for the IN-IC-HPC decks. The absorption of the coarse aggregate used in the internally cured deck toppings in Utah is not available; only a fine aggregate absorption of 1.2% was listed, adding less than 0.1% of absorbed water by weight of binder.

Table 5.2: Mixture proportions (SSD/PSD basis)

Bridge ID	Cementitious Material Content	Water Content	Design IC Water	Actual IC Water	Total Absorbed Water by All Aggregates	*w/cm* Ratio	Paste Content
	(lb/yd^3)	(lb/yd^3)	(% of Binder by Weight)	(% of Binder by Weight)	(% of Binder by Weight)		(% Concrete Volume)
IN-IC	657	256	7	7.2	9.7	0.39	27.6
IN-Control	657	256	-	-	3.5	0.39	27.6
IN-IC-HPC-1[a]	568	228	8	9.1	15.3	0.401	24.6
	567	238	8	8.5	14.7	0.426	25.2
IN-IC-HPC-2	567	237	8	9.2	16.3	0.418	25.3
IN-IC-HPC-3	600	250	8	11.6	17.0	0.417	25.9
IN-IC-HPC-4[a]	582	241	8	12.0	17.6	0.414	25.7
	585	246	8	11.2	16.8	0.42	26.0
UT-IC-1	605	266	7	7.0	7.1[b]	0.44	28.0
UT-IC-2	605	266	7	7.0	7.1[b]	0.44	28.0

[a] The first row is for placement 1 and the second row is for placement 2.

[b] Coarse aggregate absorption not available – only accounts for fine aggregate absorption.

Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 5.2 (con't): Mixture proportions (SSD/PSD basis)

Bridge ID	Date Placed	Cementitious Material Percentages[b]	Coarse Aggregate	Fine Aggregate	FLWA
			(lb/yd^3)	(lb/yd^3)	(lb/yd^3)
IN-IC	9/24/2010	100% C	1764	528	455
IN-Control	9/23/2010	100% C	1764	1224	-
IN-IC-HPC-1[a]	7/19/2013	78% C, 18% S, 4% SF	1805	795	375
	10/18/2013		1800	801	348
IN-IC-HPC-2	10/1/2013	71% C, 25% C-FA, 4% SF	1726	819	334
IN-IC-HPC-3	11/1/2014	72% C, 24% C-FA, 4% SF	1758	644	446
IN-IC-HPC-4[a]	7/14/2015	76% C, 20% S, 4% SF	1763	665	447
	10/3/2015		1768	663	448
UT-IC-1	Spring 2012	79% C, 21% F-FA	1721	706	324
UT-IC-2	Spring 2012	79% C, 21% F-FA	1721	706	324

[a] The first row is for Placement 1 and the second row is for Placement 2.

[b] C=portland cement; S=slag cement; SF=silica fume; C-FA=Class C fly ash; F-FA=Class F fly ash

Note: 1 lb/yd^3 = 0.593 kg/m^3

The plastic concrete properties along with 28-day compressive strengths are listed in Table 5.3. Fresh concrete properties including slump, temperature, and air content are not available for the IN-IC or IN-Control decks, but the 28-day strengths were within the 5500 psi (37.9 MPa) limit for LC-HPC decks. The average slump of the IN-IC-HPC mixtures ranged from 4¾ to 5¾ in. (120 to 160 mm), all above the 3½ in. (90 mm) maximum specified for LC-HPC decks. With the exception of IN-IC-HPC-3, which had an average air content of 7.0%, the average air contents of the other IN-IC-HPC decks were below the minimum 6.5% specified for LC-HPC decks, with values ranging from 5.1 to 6.4%. The average 28-day compressive strengths of the IN-IC-HPC decks were at or above the 5500 psi (37.9 MPa) limit for LC-HPC decks. The average slumps for UT-IC-1 and UT-IC-2 were 3½ in. (90 mm) and 3¼ in. (85 mm), respectively. The average air contents for UT-IC-1 and UT-IC-2 were 6.4% and 6%, respectively. The average 28-day strengths of the concrete for UT-IC-1 and UT-IC-2 were 5710 psi (39.4 MPa) and 5370 psi (37.0 MPa), respectively. The air contents for both decks were below the requirements in the LC-HPC specifications and the strength for UT-IC-1 exceeded the maximum for LC-HPC decks.

Table 5.3: Average plastic properties and compressive strengths

Bridge ID	Slump	Air Content	28-day Strength
	(in.)	(%)	(psi)
IN-IC	-	-	4900
IN-Control	-	-	4380
IN- IC-HPC-1*	4¾	5.1	7680
	5¾	5.5	6640
IN-IC-HPC-2	5	6.4	6720
IN-IC-HPC-3	5½	7	5500
IN-IC-HPC-4*	4¾	6.2	6120[a]
	5¼	5.5	
UT-IC-1	3½	6.4	5710
UT-IC-2	3¼	6	5370

* The first row is for Placement 1 and the second row is for Placement 2

[a] Data on separate placements not available

- Data not available

Note: 1 in. = 25.4 mm; 1 psi = 6.89×10^{-3} MPa

For the IC bridge decks in Indiana, the *w/cm* ratio was permitted to be between 0.36 and 0.43 to achieve high compressive strength and maintain durability, notably lower than the *w/cm* ratios used in the LC-HPC bridge decks in Kansas (0.44 to 0.45). IC water for these bridges was used to eliminate chemical shrinkage, defined as the change in volume due to the chemical reaction between cement and water (Barrett et al. 2015b), and autogenous shrinkage, defined as the change in volume due to self-desiccation, particularly in mixtures with low *w/cm* ratios (di Bella et al. 2012, Barrett et al. 2015b). For mixtures without SCMs, the amount of IC water was specified to be 7% of the cement weight, based on work by Bentz and Weiss (2011), which indicated that chemical and autogenous shrinkage of portland cement can be mitigated by providing 7% internal curing water by weight of cement. For the IN-IC-HPC mixtures, which had a ternary binder system, the amount of IC water was specified to be 8% of the binder weight; the shrinkage and rate of hydration for mixtures containing SCMs requires a higher amount of internal curing water to counteract the effects of chemical and autogenous shrinkage (Bentz and Weiss 2011). As previously discussed, however, the IN-IC-HPC decks had values of IC water from FLWA above 8%, ranging from 8.8 to 12%; including water from normalweight aggregates raised the total absorbed water content to between 15.3 and 17.6% by weight of binder. The four IN-IC-HPC decks had a total of six placements. The placements were 10.5 to 37.2 months old when the first crack surveys were performed and 32.8 to 56.7 months old when the second surveys were performed. All Indiana decks had the concrete placed using pumps, with the exception of IN-IC, where the concrete was placed using buckets. All Indiana decks were tined shortly after concrete placement and before the initiation of curing.

The internally cured deck toppings in Utah were placed on precast half-deck concrete panels supported by five precast prestressed single-span concrete girders. The topping concrete had a *w/cm* of 0.44 and a paste content of 28% by volume. This paste content exceeds the Kansas LC-HPC limits. The deck topping concrete incorporated Class F fly ash (21% by mass) as a partial replacement for portland cement; 16.7% of the total aggregate (by volume) was replaced with pre-wetted FLWA with an absorption capacity of 15% and PSD specific gravity of 1.56 to provide IC water equal to 7% of the weight of binder (Bitnoff 2014). The 24-hour absorption of the pre-wetted FLWA was used to proportion the aggregates. The FLWA stockpile was sprinkled for a minimum of two days prior to mixing. The absorption was measured periodically, and when an absorption of 15% was achieved, the stockpile was drained. Curing compound was sprayed on the deck after finishing, followed by a 14-day period of curing under plastic. The two Utah IC deck toppings were constructed by the same contactor. The deck surfaces were tined shortly after placement.

5.4 RESULTS

The first crack surveys for the Indiana decks were completed in August 2016 and presented by Lafikes et al. (2018) and are shown in Appendix G. At this point in time, the decks had ages between 10.5 and 71.6 months. The second crack surveys for the Indiana decks were completed between June 23 and 25, 2018, when the IN-Control and IN-IC decks were 93 months old. The IN-IC-HPC decks were 32.8 to 56.8 months old. The two-year survey results presented for the Utah decks were completed in 2014 by Brigham Young University researchers (Bitnoff 2014). Crack densities for the Indiana and Utah decks ranged from 0 to 0.784 m/m^2 and are listed in Table 5.4. Based on previous work at KU, surveys are recommended one and three years after placement, with the survey at three years providing a good predictor of long-term performance. The results presented here for the bridge decks in Indiana serve as a good baseline for future surveys and predictors for long-term cracking performance for IC decks.

Table 5.4: Summary of IC and total absorbed water contents and bridge deck crack densities

Bridge ID	FLWA Used	IC Water (% of Binder by Weight)	Total Absorbed Water (% of Binder by Weight)	2016 Survey Age (months)	2016 Crack Density (m/m^2)	2018 Survey Age (months)	2018 Crack Density (m/m^2)
IN-IC	Expanded Shale	7.2	9.7	71.6	0.447	93	0.447
IN-Control	-	-	3.5	71.6	0.507	93	0.67
IN-IC-HPC-1[a]	Expanded Shale	9.1	15.3	34.7	0	-	-
		8.5	14.7	37.2	0.02	-	-
IN-IC-HPC-2	Expanded Shale	9.2	16.3	34.8	0.003	56.8	0.033
IN-IC-HPC-3	Expanded Shale	11.6	17.0	21.6	0.016	43.8	0.086
IN-IC-HPC-4[a]	Expanded Shale	12	17.6	15.6	0.021	35.4	0.214
		11.2	16.8	10.5	0.005	32.8	0.032
UT-IC-1[b]	Expanded Shale	7	7.1[c]	24	0.784	-	-
UT-IC-2[b]	Expanded Shale	7	7.1[c]	24	0.427	-	-

[a] The first row is for Placement 1 and the second row is for Placement 2

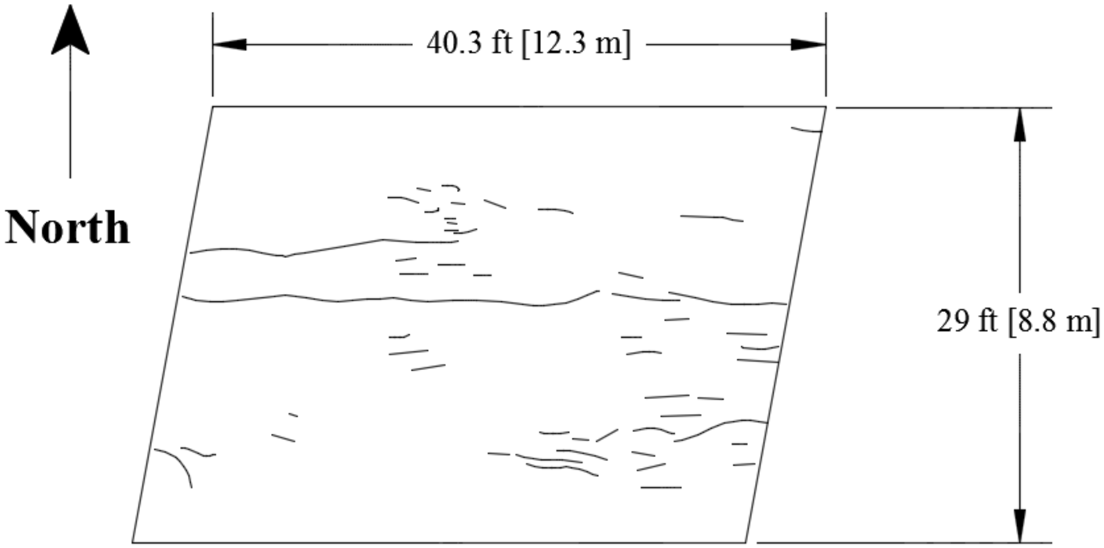
[b] The 24-month UT-IC surveys were completed by BYU researchers in spring 2014

[c] Coarse aggregate absorption not available - only accounts for fine aggregate absorption

5.4.1 IN-IC

IN-IC is a single-span bridge located in the INDOT Seymour district near the city of Bloomington and spans over Stephens Creek on North Gettys Creek Rd. The deck was placed in September 2010 in a single placement. It is supported by prestressed concrete box beams. IN-IC is 29 ft (8.4 m) wide, and the deck varies in depth from 4½ in. (114 mm) at edge gutters to 8 in. (205 mm) at the roadway centerline. A single layer of reinforcing steel was placed at the mid-depth of the deck. The IN-IC bridge spans approximately 40.3 ft (12.3 m). The concrete contained 657 lb/yd^3 (390 kg/m^3) of Type I/II portland cement, compared to a maximum of 540 lb/yd^3 (320 kg/m^3) used for LC-HPC bridge decks. IN-IC contained pre-wetted FLWA for providing IC water. The *w/cm* ratio was 0.39, well below the range of 0.43 to 0.45 used for LC-HPC bridge decks. The paste content was 27.6% by volume, which is higher than the 22.8-24.6% used in LC-HPC bridge decks and the maximum recommended value of 27% based on the work by Schmitt and Darwin (1995, 1999). Without internal curing, these parameters typically lead to concrete with high crack densities. The lightweight aggregate used in this bridge provided an average IC water content of 7.2% by weight of cement. The average 28-day strength of the lab-cured cylinders was 4900 psi (33.8 MPa), which is within the suggested range of 3500-5500 psi (24.1-37.9 MPa) for LC-HPC. The strength, however, is low considering the *w/cm* ratio of 0.39. Fresh concrete properties including slump, temperature, and air content are not available for this deck.

During the 2018 survey at an age of 93 months, IN-IC had a crack density of 0.447 m/m^2, an increase from 0.347 m/m^2 at 71.6-months. Figure 5.1 shows the 93-month crack survey results. The majority of the cracks in this deck are oriented in the longitudinal direction, with the longest cracks appearing at the prestressed box girder boundaries. The average crack width for this bridge was 0.006 in. (0.15 mm). di Bella et al. (2012) conducted crack survey results of IN-IC 12 and 20 months after placement, but no cracks were documented during these surveys. The majority of cracking observed by KU researchers during the 2016 and 2018 surveys (71.6 and 93 months after placement) was likely due to the high cement paste content (greater than 27% of concrete volume).



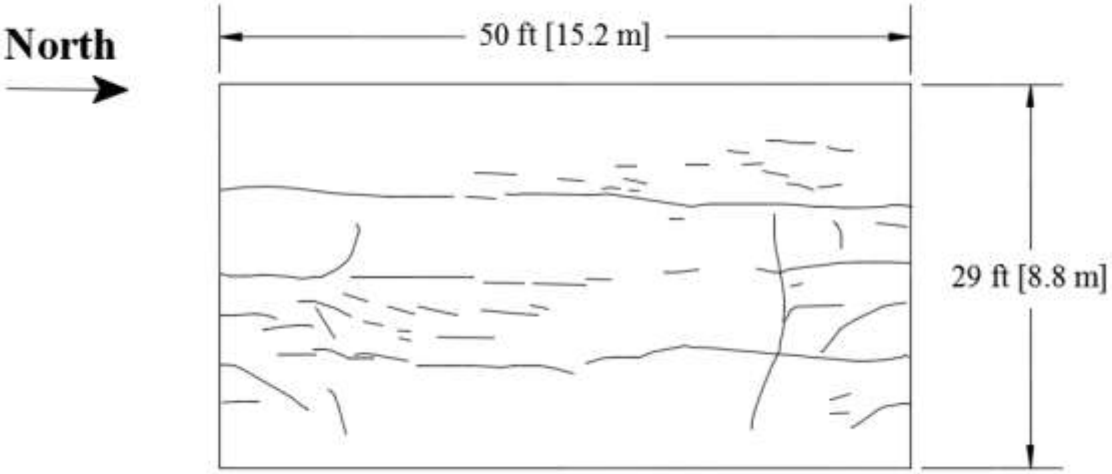
Average crack density = 0.447 m/m^2

Figure 5.1: IN-IC (Survey 2 – 93.0 months)

5.4.2 IN-Control

IN-Control is a single-span bridge, also located on North Mt. Gilead Rd., spanning over Stephens Creek near IN-IC. It serves as the control deck for IN-IC and did not utilize internal curing. Like IN-IC, IN-Control is supported by prestressed concrete box girders. The deck was, like IN-IC, constructed in September 2010 in a single placement. Deck geometry and reinforcement are similar to IN-IC. IN-Control spans approximately 50 ft (15.2 m). This concrete had the same type and quantity of cement and *w/cm* ratio as the concrete used in the IN-IC deck. The average 28-day strength of the cylinders was 4380 psi (30.2 MPa), which is again low considering the low *w/cm* ratio. Fresh concrete properties including slump, temperature, and air content are not available for this deck.

IN-Control was surveyed at an age of 93 months with a resultant crack density of 0.670 m/m^2, an increase from 0.507 m/m^2 at 71.6 months. The results at 93 months are shown in Figure 5.2. Like IN-IC, most of the cracks are oriented in the longitudinal direction, with the longest cracks occurring at or near the prestressed box girder boundaries. There are more transverse cracks in IN-Control than IN-IC. The average crack width in this bridge was 0.010 in. (0.25 mm). In some cases, the box girders experienced differential vertical movement with respect to each other of as much as 3/8 in. (10 mm), as shown in Figure 5.3. This uneven vertical movement of adjacent girders may have contributed to the high number of longitudinal cracks on the deck. Crack surveys at 12 and 20 months after placement conducted by di Bella et al. (2012) noted two longitudinal cracks that were more than half the length of the bridge.



Average crack density = 0.670 m/m^2

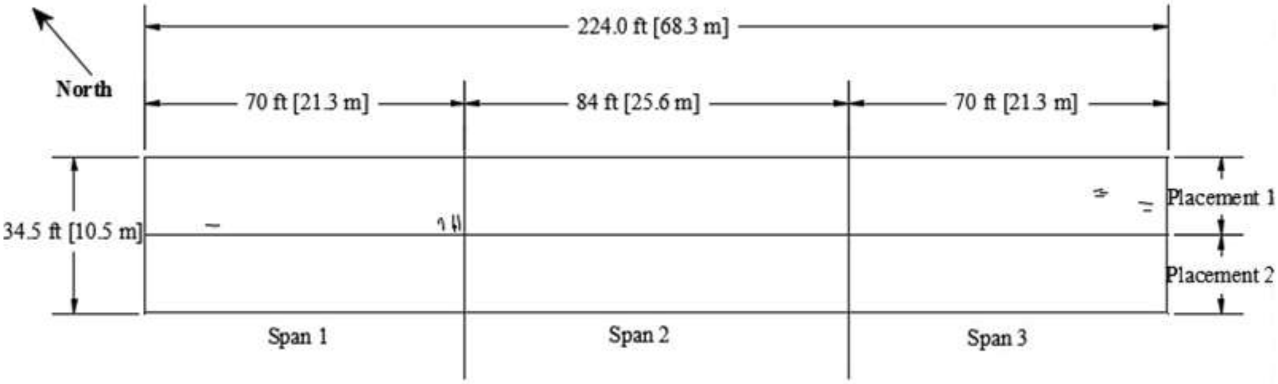
Figure 5.2: IN-Control (Survey 2 – 93.0 months)

Figure 5.3: Differential vertical movement of girders in IN-Control

5.4.3 IN-IC-HPC-1

IN-IC-HPC-1 is located north of West Baden Springs on US 150 crossing the Lost River. It is a three-span bridge with a length and width of 224 ft (68.3 m) and 34.5 ft (10.5 m), respectively. The deck is supported by steel girders and was constructed in two placements, in July and October 2013. The deck has a depth of 8 in. (205 mm), with 2.5 in. (64 mm) top cover over the reinforcing bars. The concrete contained 568 and 567 lb/yd^3 (324 kg/m^3) of cementitious material for Placements 1 and 2, respectively, 18% of which was slag cement and 4% of which was silica fume (by weight). IC was provided by pre-wetted FLWA, accounting for approximately 15% of total aggregate volume. The actual absorption of the FLWA, determined prior to casting, was 18.7% for both placements (versus 14.9% used in design). This resulted in average IC water contents of 9.1 and 8.5% by weight of binder for Placements 1 and 2, respectively. Including the water absorbed by normalweight aggregates resulted in total absorbed water contents of 15.3 and 14.7% by weight of binder for Placements 1 and 2, respectively. Based on batch weights, the *w/cm* ratios for Placements 1 and 2 were 0.401 and 0.426, respectively, which are below the range for LC-HPC decks. The paste contents for Placements 1 and 2 were 24.6 and 25.2% of total volume, respectively. The paste content for Placement 2 was slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slumps as measured at the point of placement for Placements 1 and 2 were 4¾ in. (120 mm) and 5¾ in. (145 mm), respectively, which exceed the maximum slump of 3½ in. (90 mm) specified for LC-HPC decks. The average air contents for Placements 1 and 2 were 5.1 and 5.5%, respectively, which are below the range (8.0 ± 1.5%) in the LC-HPC specifications. The average 28-day strengths for Placements 1 and 2 were 7680 and 6640 psi (53.0 and 45.8 MPa), respectively, which exceed the upper limit for compressive strength under LC-HPC specifications.

The two placements of IN-IC-HPC-1 were surveyed in 2016 at ages of 37 and 35 months and have crack densities of 0.020 and 0 m/m^2, respectively, as shown in Figure 5.4. Both placements had noticeable coarse aggregate pop-outs throughout the deck, more so on Placement 1 than Placement 2. Moderate scaling damage was observed near the north end. Figure 5.5 shows photos of scaling and freeze-thaw damage on IN-IC-HPC-1. Low air contents and high total absorbed water contents are believed to be the main contributors to the scaling and freeze-thaw damage. Placement 1 had a few short longitudinal cracks on an end span, close to the abutment, and a few longer transverse cracks over the pier between the other two spans. The average crack width was 0.006 in. (0.15 mm). Survey could not be completed in 2018 due to weather. During the time of the other 2018 Indiana surveys, the shoulders of IN-IC-HPC-1 were examined by KU researchers, where no cracks were found.



Average crack density = 0.010 m/m^2

Placement 1 crack density = 0.020 m/m^2 Placement 2 crack density = 0 m/m^2

Span 1 crack density = 0.025 m/m^2 Span 2 crack density = 0 m/m^2

Span 3 crack density = 0.011 m/m^2

Figure 5.4: IN-IC-HPC-1 (Survey 2 – 37.2 months [Placement 1], 34.7 months [Placement 2])

(a) Scaling near the north end of IN-IC-HPC-1

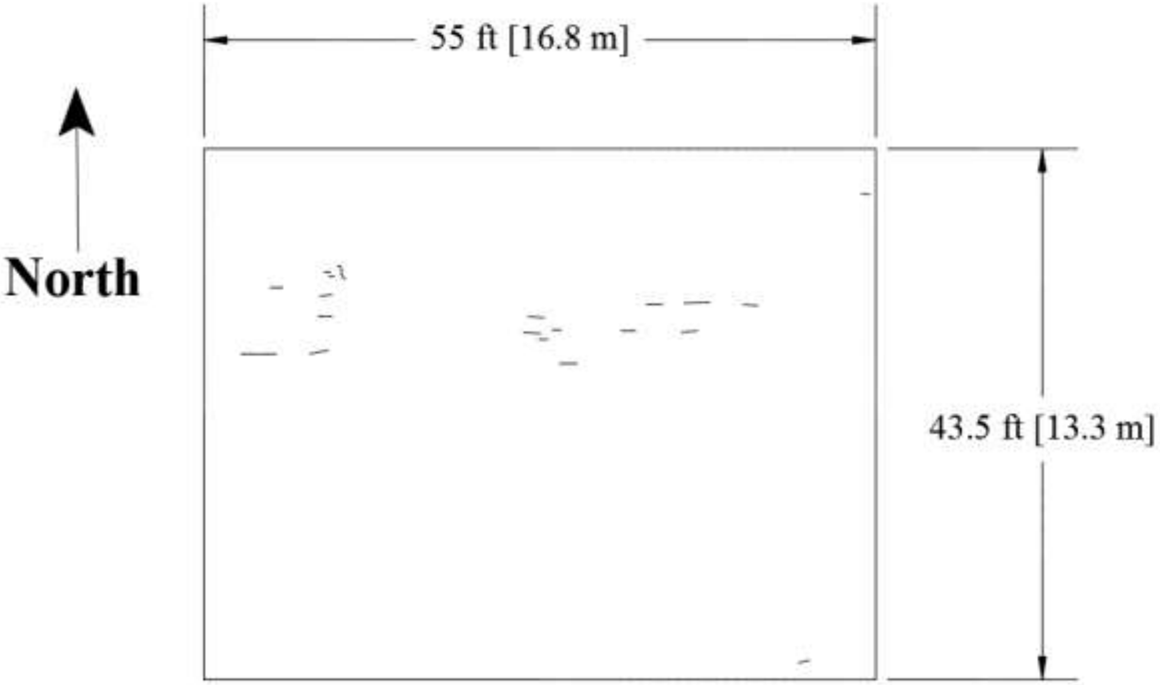
(b) Aggregate popouts (the crack width comparator has a width of approximately 2 in. [50 mm])

Figure 5.5: Scaling and freeze-thaw damage on IN-IC-HPC-1

5.4.4 IN-IC-HPC-2

IN-IC-HPC-2 is located in the town of Austin on US 31 over Hutto Creek. It is a single-span bridge with a length and width of 55 ft (16.8 m) and 43.5 ft (13.3 m), respectively, and is supported by steel girders. The deck was placed in October 2013 and is 8 in. (205 mm) thick. The concrete contained 575 lb/yd^3 (340 kg/m^3) of cementitious material, 25% of which was Class C fly ash and 4% of which was silica fume. IC was provided by pre-wetted FLWA, accounting for 15% of total aggregate volume. The actual absorption of FLWA determined prior to casting for this deck was 20% (versus a design absorption of 13.8%). As with the other IN-IC-HPC decks, mixture proportions were not modified based on actual absorption, resulting in an average IC water content of 9.2% by weight of binder. Including the water absorbed by the normalweight aggregates, the total absorbed water content was 16.3% by weight of binder. The *w/cm* ratio for this deck was 0.418, which is lower than the 0.43-0.45 range used in LC-HPC specifications. The paste content was 25.3%, which is slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slump was 5 in. (125 mm), and the average air content was 6.4%. The average 28-day strength was 6720 psi (46.3 MPa). The concrete slump, air content, and compressive strength were outside of the ranges specified by LC-HPC specifications.

IN-IC-HPC-2 was surveyed in August 2016 and in June 2018 at ages of 35 and 57 months, respectively. The crack density determined during the 2018 survey was 0.033 m/m^2, as shown in Figure 5.6, an increase from the 0.003 m/m^2 crack density found during the 2016 survey. All cracks were less than 2 ft (0.6 m) in length. Crack widths ranged between 0.003 in. (0.08 mm) and 0.006 in. (0.15 mm). Surface defects noted during both 2016 and 2018 surveys include coarse aggregate pop-outs and deterioration on the walls of tined surface grooves, shown in Figure 5.7. These defects may have been caused by a combination of freeze-thaw damage, worsened by a high total absorbed water content and the October placement date (providing minimal time for the concrete to dry out before being exposed to freezing conditions), and poor tining,



Average crack density = 0.033 m/m^2

Figure 5.6: IN-IC-HPC-2 (Survey 2 – 56.8 months)

(a) Freeze-thaw damage

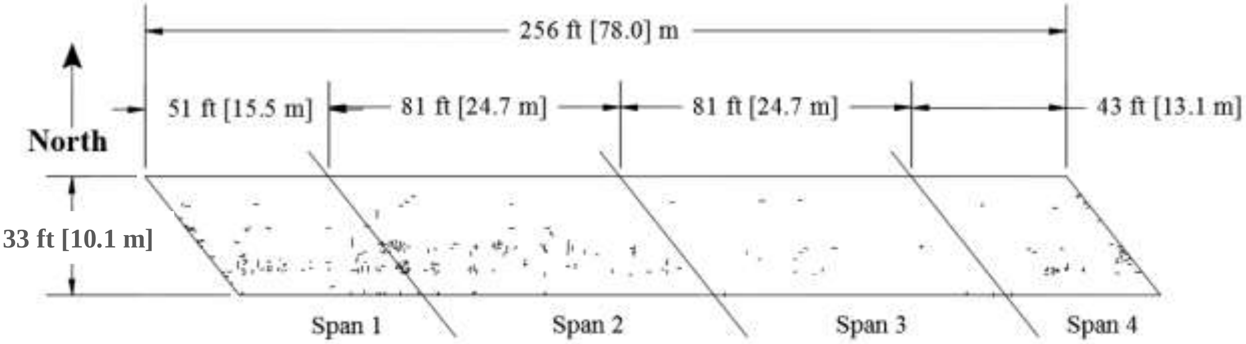
(b) Aggregate pop-out

Figure 5.7: Freeze-thaw damage and aggregate pop-out on IN-IC-HPC-2

5.4.5 IN-IC-HPC-3

IN-IC-HPC-3 is located on SR 46 over interstate highway I-74 in the town of West Harrison. This four-span bridge has a length and width of 256 ft (78 m) and 33 ft (10.1 m), respectively, and is supported by steel girders. The deck was constructed in a single placement in November 2014. The concrete contained 600 lb/yd^3 (355 kg/m^3) of cementitious material, 24% of which was Class C fly ash and 4% of which was silica fume. The pre-wetted FLWA accounted for 21% of the total aggregate volume to provide an IC water content of 11.6% by weight of binder. Including the water absorbed by the normalweight aggregates, the total absorbed water content was 17.0% by weight of binder. The average *w/cm* ratio was 0.417 for this deck, outside the range suggested in the LC-HPC specifications (0.43-0.45). The paste content was 25.9%, which is outside of the range used in LC-HPC decks (22.8-24.6%) but below the upper limit recommended by Schmitt and Darwin (1995, 1999) of 27%. The average slump was 5½ in. (140 mm), and the average air content was 7.0%. The average 28-day strength was 5500 psi (37.9 MPa). Air content and strength met the LC-HPC requirements, but slump was higher than the limit specified within LC-HPC specifications.

IN-IC-HPC-3 was surveyed at 22 and 44 months. As shown in Figure 5.8, the overall crack density in 2018 was found to be 0.086 m/m^2, an increase from the value in 2016 of 0.016 m/m^2. The highest concentration of cracking on this deck was observed on the two west spans, particularly over the pier. The cracks were short and oriented in both the transverse and longitudinal directions. The average crack width was 0.006 in. (0.15 mm) in both surveys. During the 2016 survey, the deck surface did not show any indication of freeze-thaw damage or aggregate pop-outs. Aggregate pop-outs and scaling damage, however, were noted during the 2018 survey. At 7%, the air content was the highest among IN-IC-HPC decks, which likely helped mitigate any durability issues from appearing during the 2016 survey, but the 17% total absorbed water content and November placement date likely contributed to the damage observed during the 2018 survey. Figure 5.9 shows one of the aggregate pop-outs along with worn grooves on the deck.



Average crack density = 0.086 m/m^2

Span 1 crack density = 0.150 m/m^2 Span 2 crack density = 0.115 m/m^2

Span 3 crack density = 0.019 m/m^2 Span 4 crack density = 0.080 m/m^2

Figure 5.8: IN-IC-HPC-3 (Survey 2 – 43.8 months)

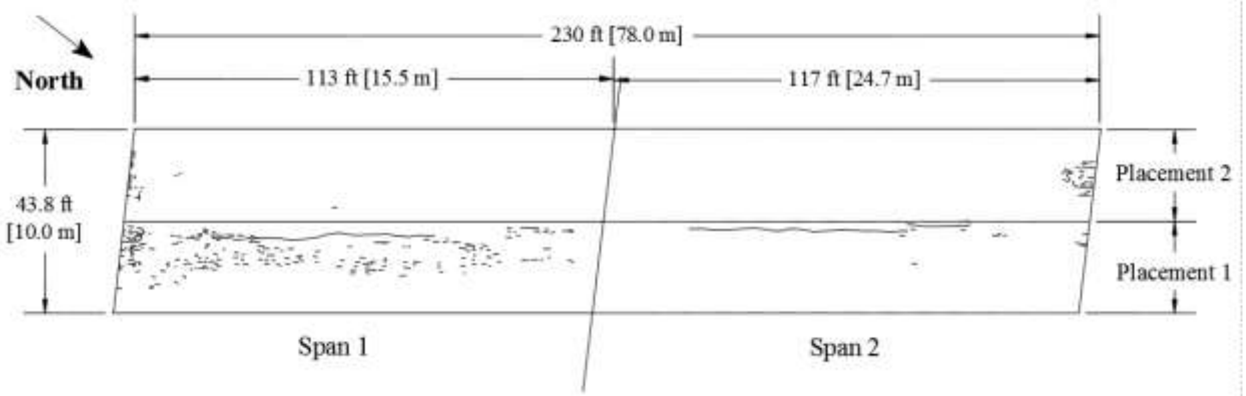
Figure 5.9: Surface damage on IN-IC-HPC-3

5.4.6 IN-IC-HPC-4

IN-IC-HPC-4 is located on SR 61 crossing over I-64. The two-span bridge has a length and width of 230 ft (70.1 m) and 43.8 ft (13.4 m), respectively, and is supported by steel girders. The deck was constructed in two placements, in July and October of 2015. The concrete contained 582 and 585 lb/yd^3 (345 and 347 kg/m^3) of cementitious material for Placements 1 and 2, respectively, 20% of which was slag cement and 4% of which was silica fume (by weight). The pre-wetted FLWA accounted for 21% of the total aggregate by volume. The actual absorptions of the FLWA determined prior to casting were 20.1% and 18.9% for Placements 1 and 2, respectively (versus a design absorption of 13.3%). This resulted in average IC water contents of 12.0 and 11.2% by weight of binder for Placements 1 and 2, respectively. Including the water absorbed by normalweight aggregates resulted in a total absorbed water content of 17.6 and 16.8% by weight of binder for Placements 1 and 2, respectively. The average *w/cm* ratios for Placements 1 and 2 were 0.414 and 0.420, respectively, lower than those used in the LC-HPC decks. The actual paste contents for Placements 1 and 2 were 25.7% and 26%, respectively, slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slumps for Placements 1 and 2 were 4¾ in. (120 mm) and 5¼ in. (130 mm), respectively. The average air content was 6.2% for the first placement and 5.5% for the second placement. Strength data were not provided for separate placements. The average 28-day compressive strength was given as 6120 psi (42.2 MPa). Slump, air content, and strength are outside the ranges given in the LC-HPC specifications.

The two placements of IN-IC-HPC-4 were surveyed in June 2018 at ages of 35 and 33 months, respectively, and have the lowest ages of the Indiana decks included in this study. During the 2016 survey, Placements 1 and 2 had crack densities of 0.021 m/m^2 and 0.005 m/m^2, respectively. Between the 2016 and 2018 surveys, the northbound lane (Placement 1) exhibited an increase in cracking in the form of longitudinal cracks where the driver-side wheels from traffic contact the deck, resulting in an increase in cracking in Placement 1 that was greater than in Placement 2. The crack densities during the 2018 survey for Placements 1 and 2 were 0.214 and 0.032 m/m^2, respectively, as shown in Figure 5.10. Span 1 of Placement 1 and Span 2 of Placement 2 exhibited some plastic shrinkage cracking close to the abutment. In addition to the longitudinal cracking noted above, short longitudinal cracks were also present on both placements, significantly more so on Placement 1. No transverse cracks on IN-IC-HPC-4 were observed, even over the piers. The average crack width was 0.007 in. (0.18 mm) for the bridge. The cracks in Span 1 were wider (average width of 0.008 in. [0.20 mm]) than those in Span 2 (average width of 0.006 in. [0.15 mm]). The longitudinal cracks located in Placement 1 under the driver-side wheel contact path averaged around 0.006 in. (0.15 mm) in width. Some of the shorter longitudinal cracks near the south abutment on Placement 1 had widths up to 0.025 in. (0.64 mm). As shown in Figure 5.11, a photograph taken during the 2016 survey, durability issues were also noted in the form of scaling, freeze-thaw damage, and poor surface finishing (poor tining); more so on Placement 1 than Placement 2. No aggregate pop-outs were observed.

Rather than differences in concrete properties, internal curing water, or construction practices, the longitudinal cracks in the northbound lane (Placement 1) are suspected to be due to excessive loading conditions from coal truck traffic from a mine south of this bridge. A similar observation has been made on one of the Kansas LC-HPC bridge decks, which is located near four major salt mines, where the lane carrying loaded truck traffic exhibited higher cracking than the opposing lane. This characteristic was not considered to be representative of an LC-HPC deck and the cracking in that lane was disregarded in later analyses (Darwin et al. 2016). In addition to the longitudinal cracking noted on the deck, damage in the underlying girders were also noted during a bridge inspection by INDOT that took place between the 2016 and 2018 surveys. As part of an evaluation and subsequent to recommendations by Purdue University researchers to address the damage, some of the lateral cross-braces between the girders were removed as a measure to reduce restraint in the transverse direction, mitigating additional damage to the bridge.



Average crack density = 0.123 m/m^2

Placement 1 crack density = 0.214 m/m^2 Placement 2 crack density = 0.032 m/m^2

Span 1 crack density = 0.174 m/m^2 Span 2 crack density = 0.073 m/m^2

Figure 5.10: IN-IC-HPC-4 (Survey 2 – 35.4 months [Placement 1], 32.8 months [Placement 2])

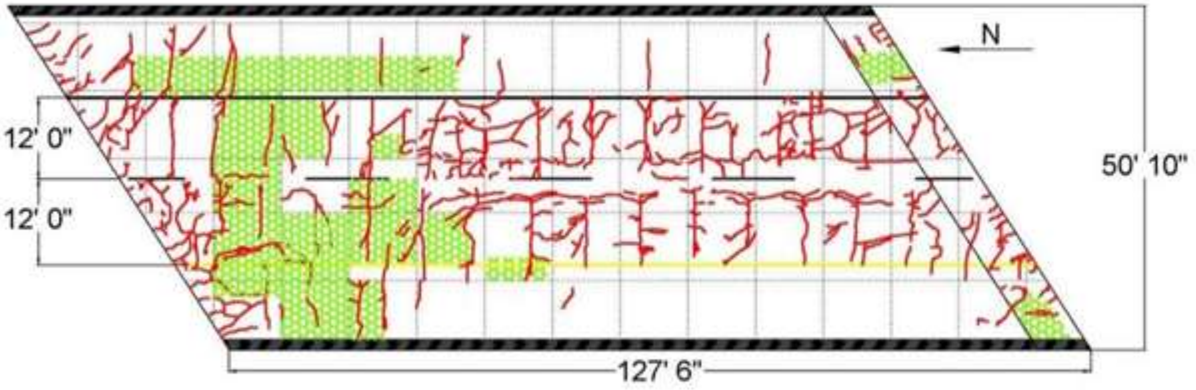
Figure 5.11: Freeze-thaw damage (aggregate popouts) and uneven tining on IN-IC-HPC-4 apparent in 2016

5.4.7 UT-IC-1 and UT-IC-2

UT-IC-1 and 2 are located in the city of West Jordan. UT-IC-1 is on Dannon Way Road, and UT-IC-2 is on 8200 South Road. Both are single span bridges supported by prestressed concrete I-shaped girders and were placed in the spring of 2012. The length and width of UT-IC-1 are 127.5 ft (38.9 m) and 50.8 ft (15.5 m), respectively. The length and width of UT-IC-2 are 119.8 ft (36.5 m) and 50.8 ft (15.5 m), respectively. Precast half-deck concrete panels support the IC deck topping for both bridges and are 8 ft (2.4 m) wide, bearing only at the edges of the girder flanges. The deck topping was specified to have 2½ in. (65 mm) of cover over a single mat of reinforcing bars and varies in thickness from 3½ in. to over 9 in. UT-IC-1 and 2 were paired with control decks which did not contain IC.

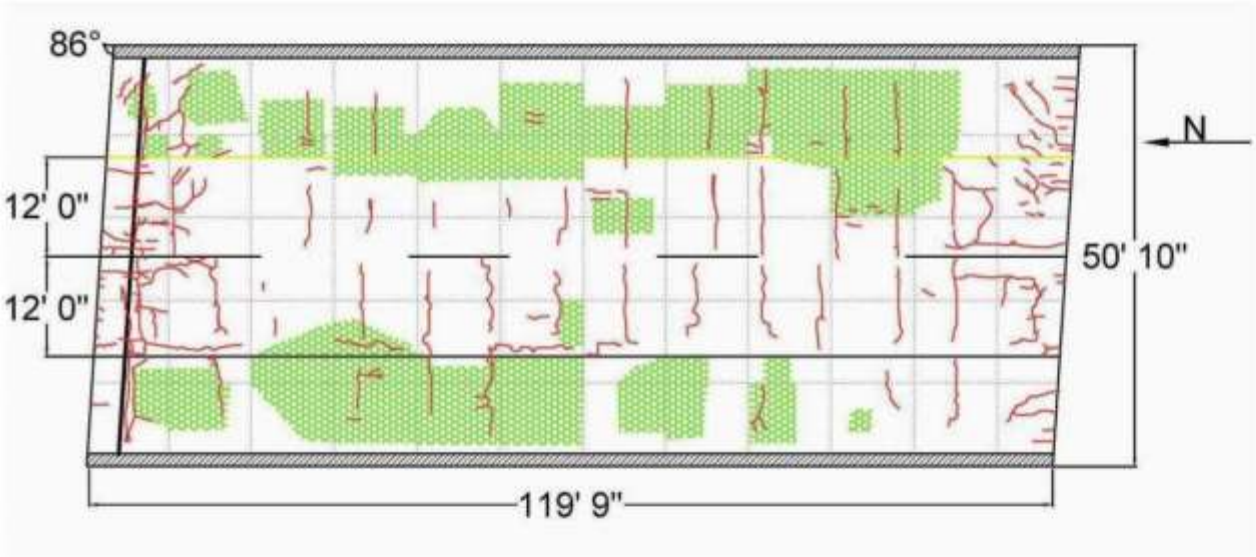
The mixture proportions for the Utah IC and control deck toppings contained 605 lb/yd^3 (347 kg/m^3) of cementitious material, of which 21% (by weight) was Class F fly ash. The *w/cm* ratio was 0.44, which is within the range suggested in LC-HPC specifications. The paste content was 28% of concrete volume, above of the range used in LC-HPC decks (22.8-24.6%) and above the 27% maximum recommended by Schmitt and Darwin (1995, 1999). The UT-IC concrete also contained 16% pre-wetted FLWA of total aggregate volume to provide an IC water content of 7% by weight of binder.

UT-IC-1 and UT-IC-2 were surveyed by a Brigham Young University research team at the ages of 2, 5, 8, 12, and 24 months (Bitnoff 2014). Crack densities through the first 8 months after placement for the UT-IC deck toppings (at or below 0.01 m/m^2) were lower than that of the control decks (0.07 to 0.17 m/m^2). At 12 and 24 months after placement, however, the crack densities of both UT-IC decks increased significantly. Furthermore, UT-IC-1 exhibited more cracking than its control during the 12 and 24-month surveys. While UT-IC-2 exhibited less cracking than its control through 24 months after placement, the increase in crack density from 8 to 12 months was more than tenfold. At 24 months, the crack densities for UT-IC-1 and UT-IC-2 were, respectively, 0.784 and 0.427 m/m^2, as shown in Figures 5.12 and 5.13. In addition to the cracks, the figures also show grid lines spaced at 10 ft (3.05 m). For UT-IC-1, longitudinal, transverse, and map cracks were spread along the driving lanes of the deck with less cracking observed along the shoulders. Short longitudinal cracks formed adjacent to the north abutment across the entire width of the deck. The south abutment displayed a similar cracking pattern but with somewhat fewer cracks than the north abutment. For UT-IC-2, most of the cracks were transverse, with longitudinal cracks adjacent to the abutments. UT-IC-2 had less map cracking than UT-IC-1. The majority of transverse and longitudinal cracks were at the precast half deck panel joints in both decks. The spacing of a majority of transverse cracks away from the abutments were approximately 8 ft (2.4 m), matching the width of the precast half deck panels. The longitudinal cracking that occurred away from the abutments appeared to be at the edges of the precast panels (Bitnoff 2014). For both decks, the crack widths ranged from 0.008 to 0.050 in. (0.20 to 1.27 mm); the majority of cracks had widths between 0.01 and 0.02 in. (0.25 to 0.51 mm).



Average crack density = 0.784 m/m^2

Figure 5.12: UT-IC-1 (Survey by BYU – 24 months, Bitnoff 2014) Note: 1 ft = 0.305 m



Average crack density = 0.427 m/m^2

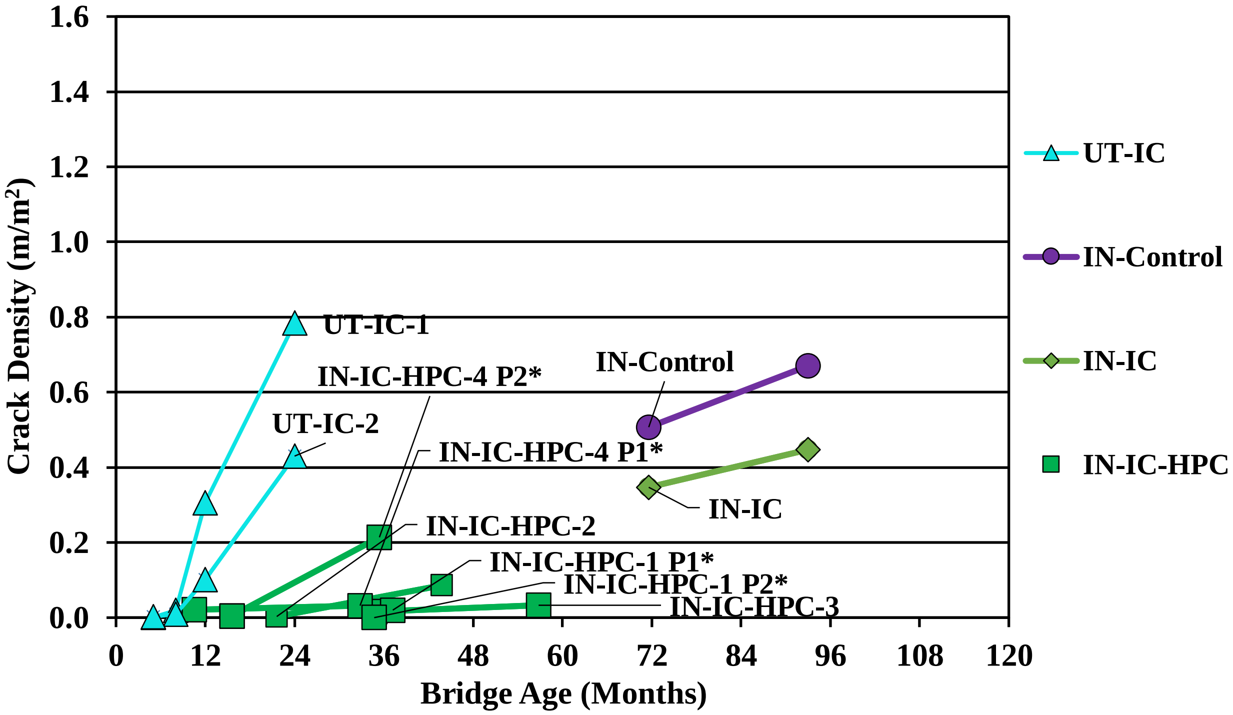
Figure 5.13: UT-IC-2 (Survey by BYU – 24 months, Bitnoff 2014) Note: 1 ft = 0.305 m

5.5 COMPARING PERFORMANCE

To evaluate the effectiveness of IC in reducing cracking in bridge decks, the crack densities of the five Indiana IC bridge decks and two Utah IC deck toppings are compared with Kansas

Control and LC-HPC decks and the control deck in Indiana. Crack densities are plotted for individual placements when more than one placement was used, which is the case for IN-IC-HPC-1 and IN-IC-HPC-4.

Based on previous work examining bridge decks in Kansas, crack surveys are needed through at least three years after construction in order to establish long-term cracking performance. In many cases, surveys conducted prior to three years after construction have not shown future trends for cracking. Based on the results obtained in the 2018 surveys, reasonable estimates of long-term cracking performance can be made for the Indiana decks included in this study. A comparison of crack density in m/m^2 versus time in months for the decks discussed in this chapter is shown in Figure 5.14. The IN-IC-HPC decks have exhibited significantly less cracking than the decks with paste contents above 27% (IN-IC and UT-IC deck toppings). As prior studies have shown, having a low paste content (at or below 26% for IN-IC-HPC decks) is the dominant factor affecting cracking (Darwin et al. 2016, Khajehdehi and Darwin 2018). Previous work has also shown that decks supported by steel girders typically exhibit higher crack densities than those supported by prestressed concrete or box girders due to higher restraint provided by steel girders (Harley et al. 2011, Shrestha et al. 2013, Darwin et al. 2016). The reduction in shrinkage when combining SCMs with IC has been shown previously (de la Varga et al. 2012, Pendergrass and Darwin 2014). Based on the 2018 survey results of IN-IC-HPC decks, all of which were cast with concrete containing a ternary binder, increasing the amount of IC water beyond the design amount (7 or 8% by total weight of binder) does not appear to reduce cracking. On the contrary, increasing amounts of IC water (and total absorbed water) appears to have contributed to freeze-thaw damage on the decks.



*P1 and P2 denotes the first and second placement of the bridge, respectively

Figure 5.14: Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. deck age

Figure 5.15 compares the crack densities of the IC decks in Indiana and IC deck toppings in Utah with the crack densities of the control decks in Kansas (denoted as KS-Control) as a function of age. As shown in the figure, the six IN-IC-HPC placements (IN-IC-HPC-1 through IN-IC-HPC-4) exhibited lower crack densities than the Kansas Control decks at similar ages. The IN-IC deck, which is performing better than the IN-Control deck at the same age, falls within the spread of Kansas Control deck data. The internally cured Utah deck toppings (UT-IC-1 and UT-IC-2), despite their relatively young ages, exhibit the highest cracking density among all IC decks in this study. The crack density of UT-IC-1 was higher at 24 months than all but one of the Kansas Control decks. The crack density for UT-IC-2 was also greater than most Kansas Control decks surveyed at a similar age.

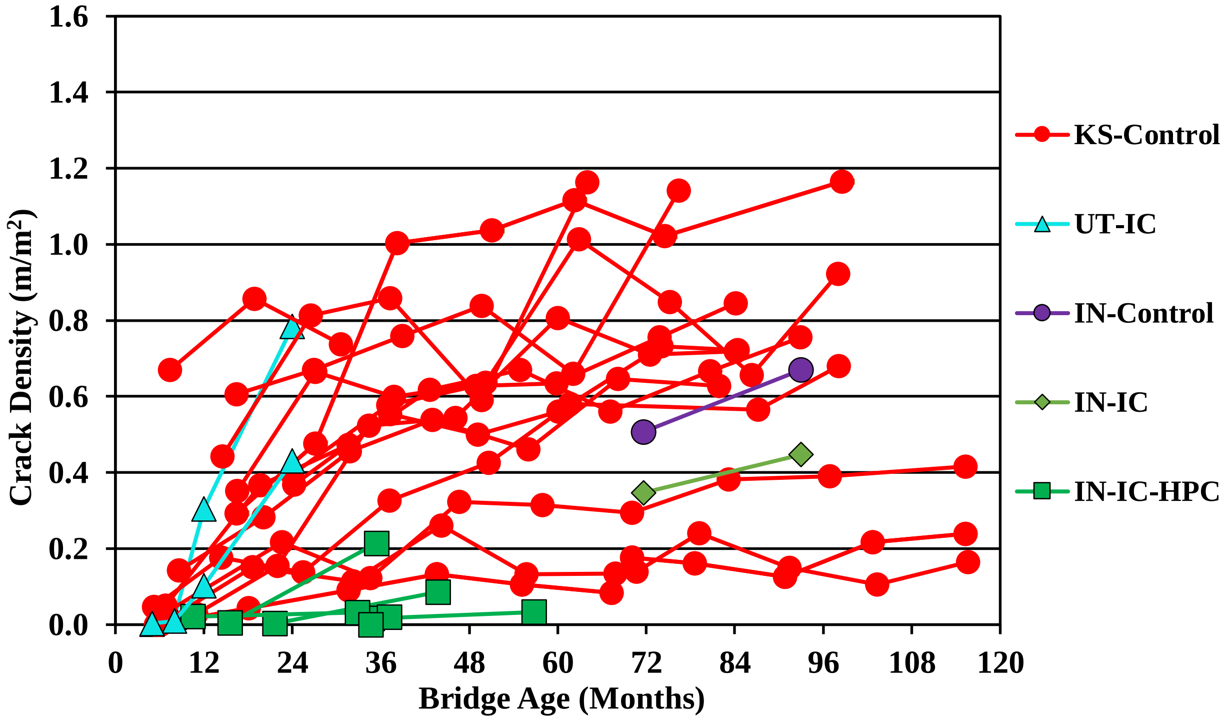


Figure 5.15: Crack densities of Kansas Control decks and IC decks vs. deck age

Figure 5.16 compares the crack densities as a function of age for the IC decks in Indiana and IC deck toppings in Utah with the LC-HPC decks in Kansas. As shown in the figure, the IN-IC-HPC decks had lower crack densities than most of the LC-HPC decks at similar ages. IN-IC and IN-Control exhibited greater crack densities than most LC-HPC decks; at 24 months, the Utah IC deck toppings had higher crack densities than all LC-HPC decks at similar ages. It appears that internal curing and SCMs contributed greatly to reducing the cracking of IN-IC-HPC bridges. IC and SCMs or IC alone, however, provided no advantage for the Utah IC deck toppings (UT-IC-1 and UT-IC-2) or the Indiana IC deck (IN-IC), which had paste contents above 27% by volume and, thus, greater than both the IN-IC-HPC and LC-HPC decks.

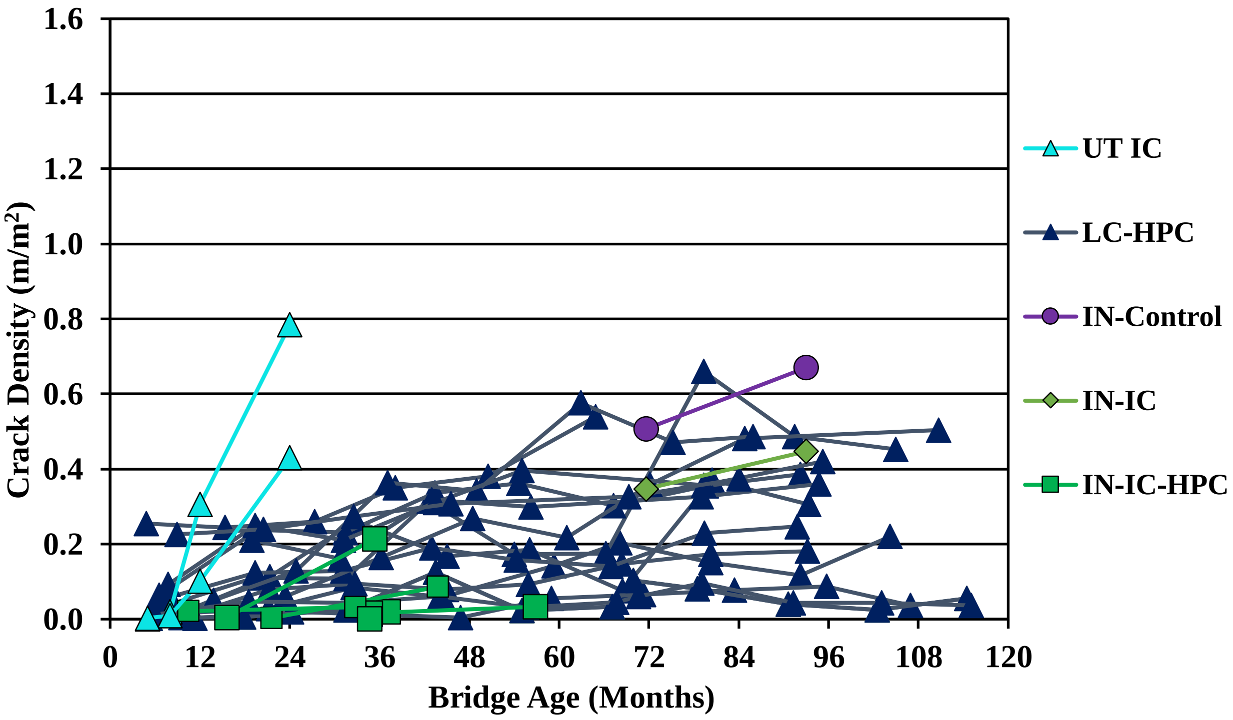


Figure 5.16: Crack densities of LC-HPC decks and IC decks vs. deck age

Figure 5.17 shows the crack densities based on 2018 surveys of the bridge decks in this study as a function of paste content. The aggregates used in these decks is dimensionally stable, regardless of moisture loss. Paste is the constituent of concrete that undergoes shrinkage. Studies conducted at the University of Kansas dating back to over twenty years ago (Schmitt and Darwin 1995; Miller and Darwin 2000; Darwin et al. 2004; Lindquist et al. 2008) and verified by Khajehdehi and Darwin (2018) have shown that increased paste content, independent of other factors, leads to increased cracking in bridge decks. Paste contents less than 27% by volume consistently result in reduced cracking. Figure 5.17 clearly supports this finding. The Utah deck toppings, with paste contents of 28%, and the IN-Control and IN-IC decks, with paste contents of 27.6%, exhibited significantly greater cracking than the IN-IC-HPC decks, with paste contents lower than 26%. Both Utah deck toppings had higher crack densities than all Kansas LC-HPC decks and most of the Kansas Control decks at two years after construction. The IN-Control and

IN-IC decks also had higher crack densities than a majority of Kansas LC-HPC decks, and fell within the spread of Kansas Control decks at similar survey ages. The internally cured Utah deck toppings had the highest cracking densities in spite of having the recommended amount of IC water and being supported by prestressed concrete girders, which are also believed to be more helpful in improving cracking performance of the deck than steel girders (Portland Cement Association 1970). Although the UT-IC deck toppings were the only bridges in this study that included precast half-deck concrete panels, this variable is believed to not significantly affect resultant crack densities. Although the UT-IC deck toppings exhibited significantly less cracking than the matching control decks, the high paste contents are believed to be the primary cause of the high crack densities one and two years after placement. Based on previous studies by KU researchers, a series of bridge decks supported by precast panels have also exhibited cracking at panel joints; however, the crack densities of these decks was not negatively affected compared to those without deck panels for similar concrete mixture proportions with SCMs and paste contents below 26% (Harley et al. 2011, Shrestha et al. 2013, Khajehdehi and Darwin 2018). These findings demonstrate that a high paste volume can significantly increase bridge deck cracking, even when a crack reduction technology or different structure type is used.

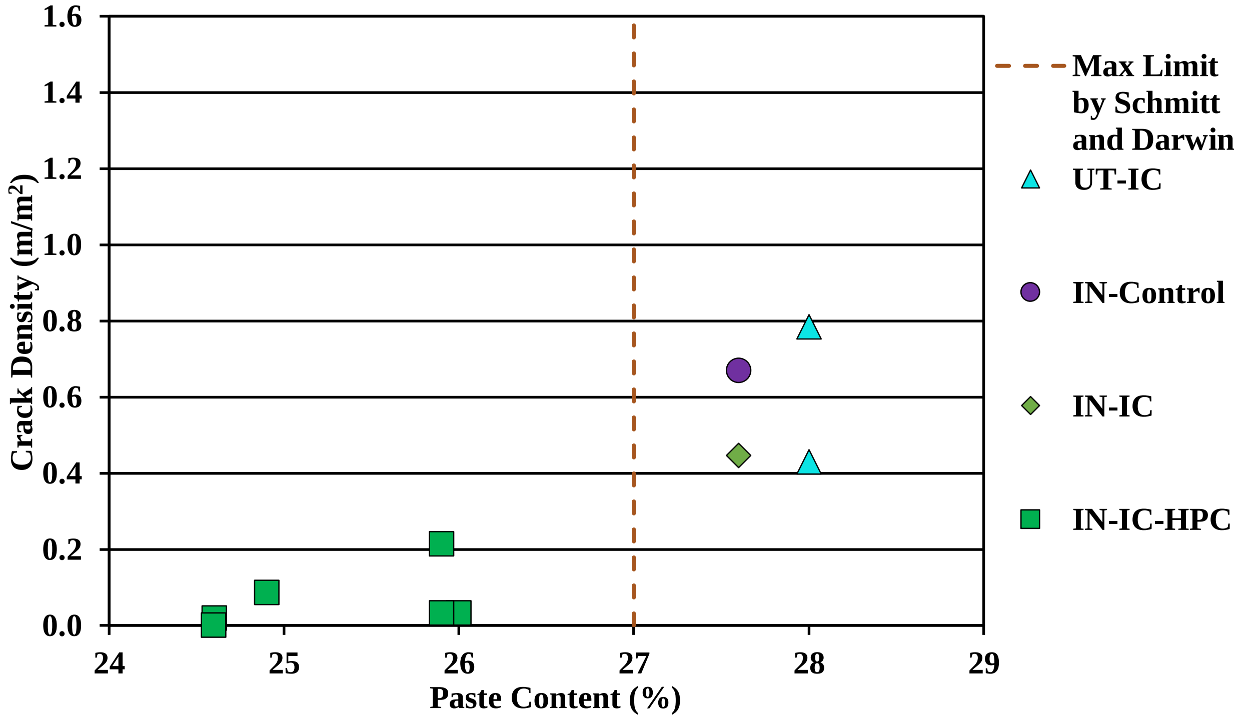


Figure 5.17: Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. paste content

Figure 5.18 shows the crack density based on the 2018 surveys of bridge decks in this study as a function of 28-day compressive strength. Schmitt and Darwin (1995), Miller and Darwin (2008), and Lindquist et al. (2008), in addition to showing the benefits of decreased paste content, also showed the benefits of having decks constructed with lower-strength concrete. As concrete compressive strength increases, creep decreases. Creep reduces stresses caused by restrained shrinkage and, thus, reduces the potential for cracking. As shown in Figure 5.18, the IN-IC and IN-Control decks have 28-day compressive strengths of 4900 and 4380 psi (33.8 and 30.2 MPa), respectively, which are within the recommended range in the LC-HPC specifications, but exhibited crack density values of 0.347 and 0.507 m/m^2, respectively – greater than all of the IN-IC-HPC decks and also greater than most of LC-HPC decks at a similar age. It appears that the higher paste contents of IN-IC, IN-Control, and the UT-IC deck toppings were more influential in increasing cracking than their lower compressive strengths in reducing cracking. Furthermore, the two IN-

IC-HPC decks with the highest compressive strengths (IN-IC-HPC-1 with compressive strengths of 7680 and 6640 psi [53.0 and 45.8 MPa] over two placements and IN-IC-HPC-2 with a compressive strength of 6720 psi [46.3 MPa]) exhibited lower crack densities than almost all LC-HPC decks at similar ages (35 to 57 months). Recent studies have suggested that the use of internal curing and fly ash reduce the modulus of elasticity and increase creep (de la Varga et al. 2012). Menkulasi et al. (2015) showed that IC mixtures exhibit lower shrinkage and higher creep coefficients than mixtures that do not contain any lightweight aggregate.

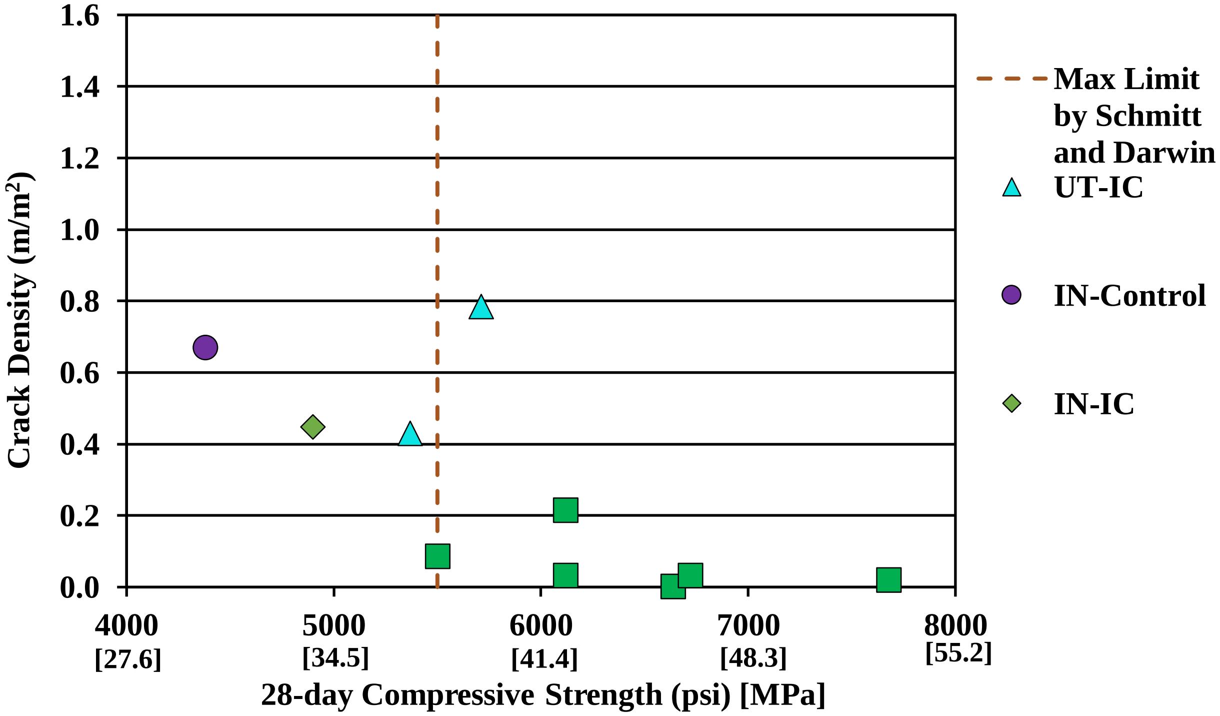


Figure 5.18: Crack density vs. 28-day compressive strength of concrete for Indiana and Utah IC and Indiana control bridge decks

Figure 5.19 compares the 2018 crack densities with slump for the UT-IC and IN-IC-HPC bridge decks. The average slump for these decks ranged from 3¼ in. (85 mm) for UT-IC-2 to 5¾ in. (145 mm) for Placement 2 of IN-IC-HPC-1. The minimum average slump for an IN-IC-HPC deck was 4¾ in. (120 mm), which exceeds the 3½-in. (90-mm) limit in the Kansas LC-HPC specifications. Fresh concrete properties were not available for IN-IC and IN-Control. Although the average slumps for UT-IC deck toppings fell within LC-HPC specifications, the resultant crack densities were higher than all of the IN-IC-HPC decks. Based on work in Kansas that documented cracking of Kansas LC-HPC and Control decks, achieving good consolidation and early application of curing after final strike-off during construction have had more influence on cracking than slump (Darwin et al. 2016, Khajehdehi and Darwin 2018).

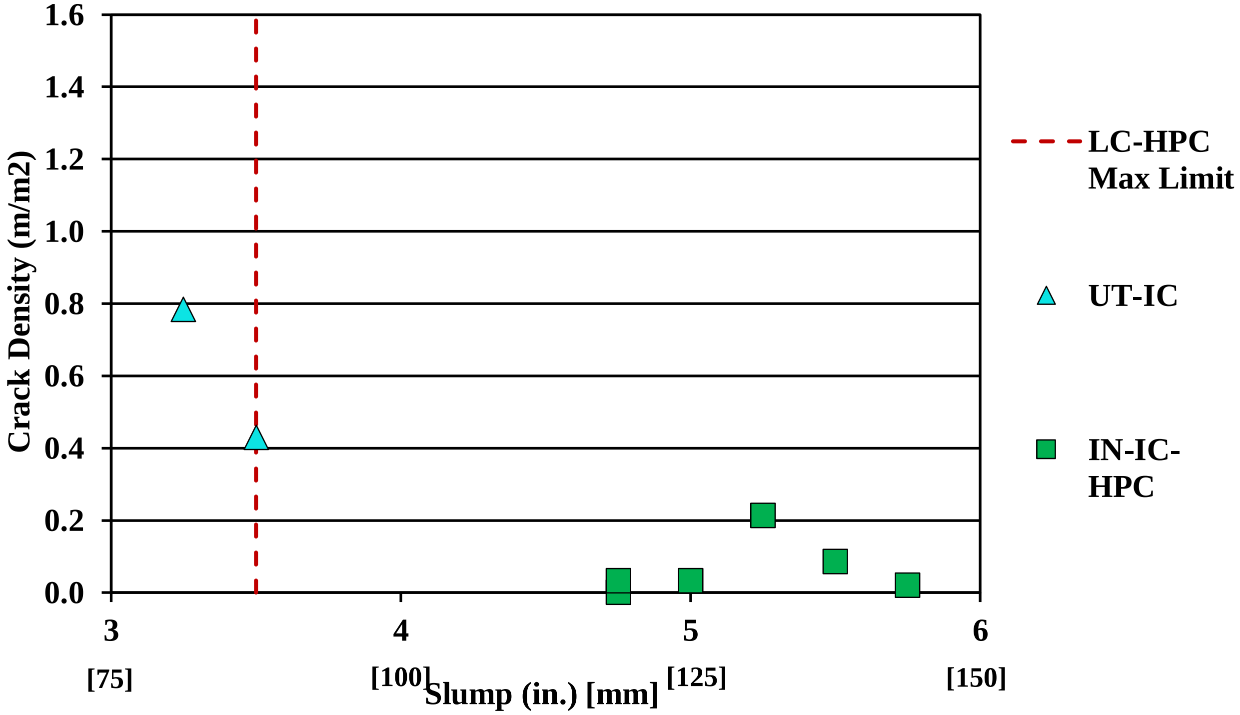


Figure 5.19: Crack density vs. slump for IN-IC-HPC and Utah IC bridge decks

Figure 5.20 compares the crack density for the Utah and Indiana IC bridge decks with the actual amount of IC water. The amount of IC water is also listed in Tables 2 and 4. The results indicate that the IN-IC-HPC decks, which contain more than 8% IC water by weight of binder exhibited lower cracking, although increasing IC water above 8% by weight of binder did not reduce cracking. Pendergrass and Darwin (2014) showed that mixtures containing pre-wetted FLWA, slag cement, and silica fume exhibit a reduction in both early-age (0 to 90 days) and long-term (90 to 360 days) drying shrinkage. They concluded that drying shrinkage was reduced as slag cement was added in conjunction with lightweight aggregate. An additional reduction in shrinkage was observed as silica fume was added in conjunction with the lightweight aggregate and slag cement. A likely explanation for the lower crack densities in the IN-IC-HPC decks is that in addition to including a ternary binder system, the low paste contents (24.6 to 26%) resulted in less shrinkage compared to the other IC decks in this study.

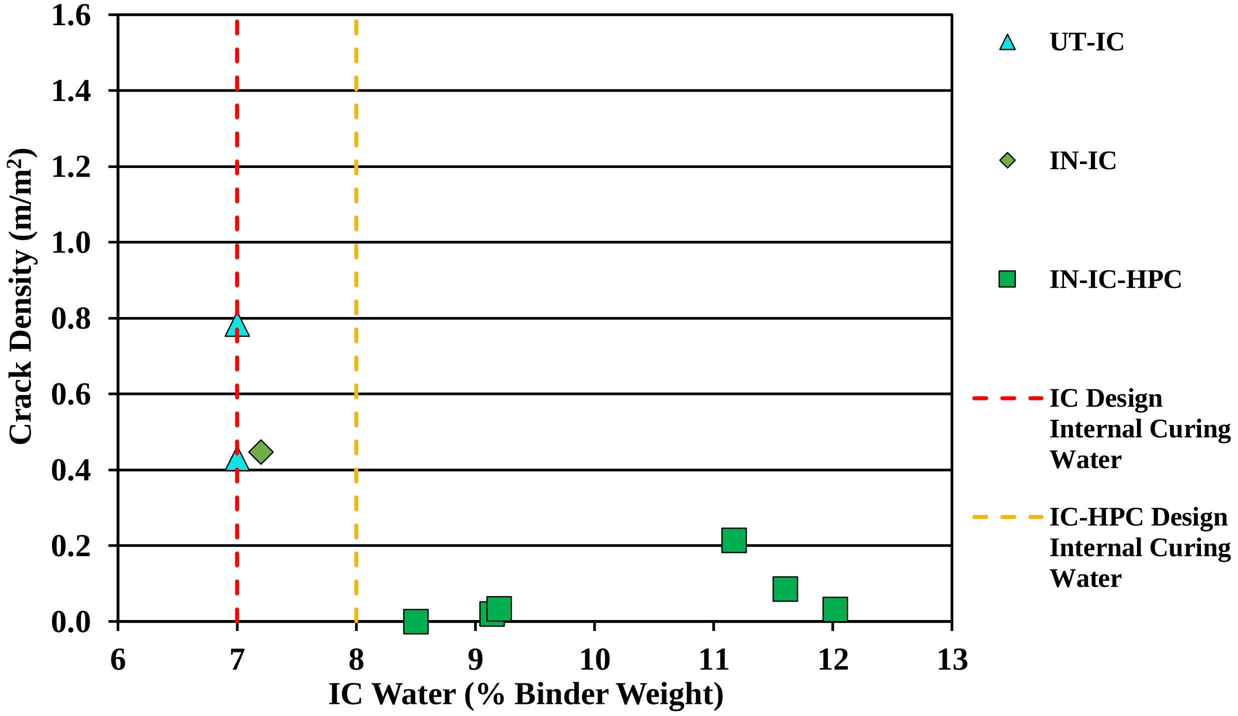


Figure 5.20: Crack density vs. actual IC water for Indiana and Utah IC bridge decks

One area of concern for internally cured concrete is with freeze-thaw durability. For concrete with excess IC water, trapped water can remain in the pores of the FLWA (Jones et al. 2014). Depending on the degree of saturation, on freezing, this water can cause local failures, such as scaling damage and pop-outs, or general freeze-thaw damage (Powers 1975). For concrete placed later in the construction season and prone to freezing prior to the system drying out, excess IC water would tend to compromise durability. The freeze-thaw performance of IC concrete has also been shown to depend on the type and proportions of the FLWA (Jones et al. 2014). In addition to IC water, Chapter 3 identified the total absorbed water content as a primary variable affecting freeze-thaw durability, where concrete mixtures with higher absorption normalweight aggregates (1.2 to 1.4%, similar to those used in the IN-IC-HPC mixtures) and total absorbed water on the order of 12% exhibited failures in freeze-thaw testing in fewer cycles than mixtures with total absorbed water below 12%. For the freeze-thaw damage observed on the IN-IC-HPC decks, it is likely that a reduction in the total absorbed water content from all aggregates would have helped mitigate freeze-thaw damage. Scaling resistance of concrete, including internally cured mixtures, depends heavily on the air content and finishing procedures. Based on results described by Jones et al. (2014) and the results in Chapter 3, scaling resistance does not appear to be negatively affected by providing internal curing to concrete mixtures. Although providing adequate air entrainment cannot prevent concrete from scaling, as noted in Chapter 3, mixtures with an air content of less than 7% exhibit higher scaling mass loss and visual ratings than mixtures with an air content of at least 7%. Except for IN-IC-HPC-3 (which had an average air content of 7.0%), the other IN-IC-HPC decks had average air contents below 7%, which likely contributed to the scaling damage observed in the first three years after construction. For the IN-IC-HPC decks, it is possible that a combination of early curing application, specifying a longer curing time, and grinding and grooving instead of tining the decks to obtain surface roughness would have helped mitigate scaling damage. Providing additional curing time for concrete mixtures with SCMs has also been shown to be beneficial in increasing strength and reducing shrinkage (Tazawa et al. 1989). Ongoing research at KU will examine the effects of varying the amount of IC water on shrinkage and durability.

5.6 SUMMARY AND CONCLUSIONS

To determine the effect of internal curing (IC) water and supplementary cementitious materials (SCMs) on bridge deck cracking, crack surveys were performed on six decks in Indiana; crack surveys by Brigham Young University researchers of two Utah bridges with deck toppings (UT-IC) were also used for comparison. Five of the decks in Indiana had internally cured concrete obtained by replacing a portion of aggregate with pre-wetted fine lightweight aggregate (FLWA). One deck, IN-Control, was constructed with plain concrete (no FLWA) and is used as a control. Four of the decks surveyed in Indiana are supported by steel girders and two are supported by prestressed concrete box beams. The four decks supported by steel girders had a ternary concrete mixture containing SCMs, slag cement or Class C fly ash, with silica fume and IC (IN-IC-HPC). The two decks supported by prestressed box beams contained 100% portland cement mixtures, including IN-Control and one with internally cured concrete (IN-IC). The two internally cured deck toppings in Utah that were surveyed by BYU are both supported by prestressed concrete girders and precast deck panels. The internally cured decks are compared for cracking performance with low-cracking high-performance (LC-HPC) and control bridge decks in Kansas.

Survey results through three to five years have shown low cracking for IN-IC-HPC decks but indicate potential durability issues. Although future surveys at later ages would provide better understanding the long-term performance of bridge decks that utilize IC and/or SCMs, a majority of LC-HPC bridges in Kansas have been shown to follow similar trends at three years and later ages.

The following conclusions can be drawn from the surveys as well as previous studies:

1. The IN-IC-HPC bridge decks are exhibiting less cracking than the IN-IC and IN-Control decks, the UT-IC toppings, and the Kansas LC-HPC and control decks within the first three years after placement.
2. The Kansas LC-HPC decks exhibit less cracking than the IN-IC and IN-Control decks and

the UT-IC deck toppings.

3. Paste content appears to be a dominant factor affecting cracking, with the IN-IC-HPC and LC-HPC decks, with paste contents of 26% or less, performing significantly better than the IC decks with paste contents greater than 27% by volume. Concrete slumps up to 5¾ in. (145 mm) and compressive strengths up to 7680 psi (53.0 MPa) do not appear to have had a negative effect on cracking.
4. Durability issues associated with low air contents and high amounts of IC water have the potential of subjecting the surfaces of bridge decks to scaling and freeze-thaw damage and are likely worsened with increased normalweight aggregate absorption, which raises the amount of total absorbed water. Procedures to control the amount of IC water should be in place during construction to help mitigate this risk.

CHAPTER 6 - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

This study assesses the effectiveness of combining internal curing (IC) and supplementary cementitious materials (SCMs) with specifications for low-cracking high-performance concrete (LC-HPC) based on laboratory evaluation of concrete mixtures designed to reduce cracking while maintaining durability in freezing and thawing environments and the construction and evaluation of LC-HPC bridge decks incorporating IC via a pre-wetted fine lightweight aggregate (FLWA) and SCMs.

The laboratory evaluation includes three groups of concrete mixtures, one for each of the first three years of IC-LC-HPC bridge deck construction in Minnesota. Laboratory tests for scaling resistance, freeze-thaw durability, rapid chloride permeability (RCP) and surface resistivity measurements (SRMs) were performed. A majority of the mixtures contained materials from the four IC-LC-HPC bridge decks in the program, including a binder composition of 27 to 30% slag cement by total weight of binder. Variations in the IC-LC-HPC mixture proportions include the quantity of internal curing (IC) water (contents ranging from 0 to 14.1% by total weight of binder), the total absorbed water content (IC water from the FLWA plus water absorbed by the normalweight coarse and fine aggregates ranging from 2.9 to 17.7% by total weight of binder), water-to-cementitious material (*w/cm*) ratios ranging from 0.39 to 0.45, and binder compositions examining the effects of using only portland cement, a 35% Class F fly ash replacement of cement, 27 to 30% slag cement replacements of portland cement, and a 2% addition of silica fume combined with 27 to 28% slag cement replacement of portland cement, all by total weight of binder.

The second portion of the study includes the construction and evaluation of the first four IC-LC-HPC bridge decks and two Control decks containing Class F fly ash constructed in Minnesota over a three-year span (2016 to 2018). The design and modifications to IC-LC-HPC mixture proportions are described along with proposed revisions to specifications for implementing IC in future projects. The construction of the IC-LC-HPC bridge decks are described along with crack survey results through 16 to 36 months after placement. The effectiveness of including IC or IC and SCMs is examined further based on bridge deck crack surveys completed in Indiana at deck ages of 10 to 93 months. Two decks contain only portland cement as binder (IN-Control and IN-IC), and four decks contain a binder consisting of portland cement with silica fume and either slag cement or Class C fly ash (IN-IC-HPC). Additional crack survey results of two internally-cured deck toppings in Utah are referenced through 24 months after placement. The Utah (UT-IC) deck topping concretes contain a partial replacement of portland cement with Class F fly ash.

6.2 CONCLUSIONS

The following conclusions are based on the results and analyses presented in this report.

6.2.1 Durability of Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) Mixtures

1. Results from Program 1 mixtures demonstrate that the scaling resistance of concrete with combinations of IC and SCMs is negatively affected when the air content is below 7%. Results from Program 2, however, demonstrate that providing an air content of 7% or more, by itself, does not guarantee good scaling performance.

2. Within the range of the parameters of this study, IC and total absorbed water contents, *w/cm* ratio, or partial replacement of portland cement with 27 to 30% slag cement did not affect scaling resistance.
3. The effect of water absorbed by aggregate on the freeze-thaw durability of IC-LC-HPC is better characterized by the total absorbed water content (water absorbed by all aggregates, expressed as a percentage of total binder weight) than by the amount of IC water. For a given absorbed water content, the volume of FLWA does not affect freeze-thaw durability.
4. Within the parameters of this study, using SCMs improves RCP and SRM results more than the presence or the using IC water or decreasing the *w/cm* ratio, which also improve RCP and SRM results. The mixtures in this study that contained slag cement and IC water exhibited RCP results that generally satisfied the Minnesota Department of Transportation specification limits at both 28 and 56 days.
5. The 28-day SRM value provides a better correlation with the 56-day RCP results than with the 28-day RCP results for IC-LC-HPC.

6.2.2 Field Evaluations

1. Enforcing specification requirements for trial placements of IC-LC-HPC mixtures is critical in identifying any concrete issues prior to construction. For projects that have concrete placed via pump, the same size pump should be used during trial placements as will be used on the deck.
2. Crack survey results of the monolithic IC-LC-HPC and Control decks included in this study serve as positive indicators for low amounts of long-term cracking.

3. The bridge deck overlays placed later in the construction season exhibited less cracking than those subjected to high temperatures within the first month of curing, but future surveys are needed to establish long-term behavior.
4. Paste content appears to be a dominant factor affecting cracking. Using IC with or without SCMs in concrete with a paste content above 27% does not prevent cracking in bridge decks. The IN-IC-HPC and LC-HPC decks, with paste contents of 26% by volume or less, perform significantly better than IC decks with paste contents greater than 27%. The Kansas LC-HPC decks (maximum paste content of 24.6%) exhibit less cracking than the IN-IC and IN-Control decks (paste content of 27.6%) and the UT-IC deck toppings (paste content of 28%).
5. Using IC in conjunction with SCMs in concrete with a paste content of 26% or less has the potential to reduce bridge deck cracking relative to concrete with only portland cement as binder. The IN-IC-HPC bridge decks exhibited less cracking than the IN-IC and IN-Control decks, the UT-IC toppings, and the Kansas LC-HPC and control decks within the first three years after placement.
6. Concrete slumps up to 5¾ in. (145 mm) and compressive strengths up to 7680 psi (53.0 MPa) do not appear to have a negative effect on cracking in bridge decks containing IC and SCMs.
7. Low air contents and high total absorbed water contents appear to be associated with bridge decks exhibiting scaling and freeze-thaw damage. The IN-IC-HPC decks exhibited a combination of scaling and freeze-thaw damage, likely due in part to higher IC water contents than designed for. When IC is used, procedures to control the total absorbed water content should be in place to help mitigate this risk.

6.3 RECOMMENDATIONS

1. The minimum air content of LC-HPC mixtures should be raised from 6.5% to 7% to promote better scaling resistance.
2. For IC-LC-HPC placements that will be subjected to freezing conditions before being allowed to adequately dry, care should be taken to avoid including an excessive total absorbed water content. Based on the freeze-thaw test results in this study, the total absorbed water content should be limited to 12% by total weight of binder.
3. Final IC-LC-HPC mixture proportions should be contingent on the FLWA absorption determined on the day of placement and should be adjusted to provide the correct amount of IC water. Ready-mix suppliers should be authorized to adjust the batch weights of the FLWA and normalweight fine aggregate to maintain the target quantity of IC water.
4. Individual FLWA shipments for use in IC-LC-HPC projects should be delivered to ready-mix plants and tested for specific gravity and absorption prior to finalizing the FLWA content of mixtures. The quantity of material delivered should be enough to complete trial batching and account for the rejection of batches during construction. The same material should be used for both trial placements and bridge deck construction.
5. FLWA should be pre-wetted until the material reaches a constant absorption. Pre-wetting should stop 12 to 15 hours prior to batching to allow the material to drain. Additional requirements to turn stockpiles twice per day and again immediately before determining the moisture contents used for batching should be included in IC-LC-HPC specifications.

6. Use of a centrifuge to place FLWA in a pre-wetted surface dry (PSD) condition for testing is recommended for IC-LC-HPC projects. The procedure used by KU researchers closely follows one developed by Miller et al. (2014) and is described in Appendix D.
7. The paste content (volume of cementitious material and water) in IC-LC-HPC mixtures should be limited to 26% of the total concrete volume. Paste content has been shown to be the most important material factor affecting bridge deck cracking and is more critical than slump or compressive strength (Khajehdehi and Darwin 2018). Provided this trend continues to be verified through crack surveys beyond three years after construction, IC-LC-HPC specifications may include a 5½ in. (140 mm) maximum slump and have the 5500 psi (37.9 MPa) cap on 28-day compressive strength removed.
8. The use of overlays on bridge decks has not been shown to be beneficial in reducing cracking (Miller and Darwin 2000, Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014, Darwin et al. 2016, Khajehdehi and Darwin 2018). Based on crack surveys of the two IC-LC-HPC bridge decks with an overlay in this study, the potential for high cracking remains despite the use of an IC-LC-HPC subdeck. It is recommended that future IC-LC-HPC decks not have overlays.
9. Khajehdehi and Darwin (2018) identified thorough consolidation and early application of wet curing as techniques during construction that will aid in minimizing cracking in bridge decks. For IC-LC-HPC bridge decks, concrete should receive thorough consolidation and receive minimal finishing prior to the initiation of curing. Grinding and grooving should replace tining to obtain surface roughness.

REFERENCES

AASHTO TP 95 (2014). Standard Method of Test for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration, American Association of State Highway and Transportation Officials, Washington, DC. 10 pp.

ACI Committee 345. (2011). *Guide for Concrete Highway Bridge Deck Construction*, ACI Committee 345-R11, American Concrete Institute, Farmington Hills, MI. 42 pp.

ACI Committee 309. (2005a). *Report on Behavior of Fresh Concrete During Vibration*, ACI Committee 309, ACI 309.1R-08, American Concrete Institute, Farmington Hills, MI. Aug. 18 pp.

ACI Committee 309. (2005b). *Guide for Consolidation of Concrete*, ACI Committee 309, ACI Committee 309R-05, American Concrete Institute, Farmington Hills, MI. 36 pp.

Al-Qassag, O., Darwin, D., and O'Reilly, M., (2015). "Effect of Synthetic Fibers and a Rheology Modifier on Settlement Cracking of Concrete," *SM Report* No. 116, The University of Kansas Center for Research, Inc., Lawrence, KS, Dec. 130 pp.

Alhmood, A., Darwin, D., and O'Reilly, M. (2015). "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2014-2015," *SL Report* 15-3, The University of Kansas Center for Research, Inc., Lawrence, KS, Sept.,118 pp.

Amini, K., Sadati, S., Ceylan, H., and Taylor P. (2019). "Effects of Mixture Proportioning, Curing, and Finishing on Concrete Surface Hardness," *ACI Materials Journal*, Vol. 116, No. 2, Nov.-Dec., pp. 638-644.

Amini, K., Vosoughi, P., Ceylan, H., and Taylor, P. (2019). "Linking Air-Void System and Mechanical Properties to Salt-Scaling Resistance of Concrete Containing Slag Cement," *Cement and Concrete Composites*, Vol. 104, Nov., 8 pp.

Ardeshirilajimi, A., and Mondal, P. (2019). "Effects of Presoaked Ligthtweight Aggregate Addition on Drying Shrinkage," *Journal of Materials in Civil Engineering*, Vol 31, No. 10, Oct., 10 pp.

ASCE (2017). "2017 Report Card for America's Infrastructure" 2017 American Society of Civil Engineers. <https://www.infrastructurereportcard.org/wp-content/uploads/2017/01/Bridges-Final.pdf> (December 15, 2018).

ASTM C31-19 (2019). "Standard Practice for Making and Curing Concrete Test Specimens in the Field," ASTM International, West Conshohocken, PA, 6 pp.

ASTM C39-18 (2018). "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C70-13 (2013). "Standard Test Method for Surface Moisture of Fine Aggregate," ASTM International, West Conshohocken, PA, 3 pp.

ASTM C127-15 (2015). "Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate," ASTM International, West Conshohocken, PA, 5 pp.

ASTM C128-15 (2015). "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate," ASTM International, West Conshohocken, PA, 6 pp.

ASTM C157-17 (2017). "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C143-15s (2015). "Standard Test Method for Slump of Hydraulic-Cement Concrete," ASTM International, West Conshohocken, PA, 9 pp.

ASTM C173-16 (2016). "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method," ASTM International, West Conshohocken, PA, 9 pp.

ASTM C192-18 (2018). "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C215-14 (2014). "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens," ASTM International, West Conshohocken, PA, 7 pp.

ASTM C490-17 (2017). "Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C666-15 (2015). "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," ASTM International, West Conshohocken, PA, 7 pp.

ASTM C672-12 (2012). "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," ASTM International, West Conshohocken, PA, 3 pp.

ASTM C1202-19 (2017). "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C1761-15 (2015). "Standard Specification for Lightweight Aggregate for Internal Curing of Concrete," ASTM International, West Conshohocken, PA, 8 pp.

ASTM D75-14 (2014). "Stand Practice for Sampling Aggregates," ASTM International, West Conshohocken, PA, 8 pp.

Azad, V., Erbektas, A., Qiao, C., Isgor, B., and Weiss, W. J. (2019). "Relating the Formation Factor and Chloride Binding Parameters to the Apparent Chloride Diffusion Coefficient of Concrete," *Journal of Materials in Civil Engineering*, Vol. 31, No. 2, 10 pp.

Babaei, K., and Purvis, R., (1995). "Prevention of Cracks in Concrete Bridge Decks: Report on Surveys of Existing Bridges," *Report*, PA-FHWA-95-001+89-01, 100 pp.

Babaei, K. and Purvis, R. L. (1996). "Prevention of Cracks in Concrete Bridge Decks Summary Report," *Report* No. 233, Wilbur Smith Associates, Falls Church, VA, 30 pp.

Bharadwaj, K., Glosser, D., Moradllo, M., Isgor, O., and Weiss, J. (2019). "Toward the Prediction of Pore Volumes and Freeze-Thaw Performance of Concrete Using Thermodynamic Modelling," *Cement and Concrete Research*, Vol. 124, Oct., 11 pp.

Barrett, T., Miller, A., and Weiss, J. (2015a). "Documentation of the INDOT Experience and Construction of the Bridge Decks Containing Internal Curing in 2013," *SPR* 3752. Joint Transportation Research Program, Indiana Department of Transportation, and Purdue University, West Lafayette, IN, 108 pp.

Barrett, T., Miller, A., and Weiss, J. (2015b). "Documentation of Bridge Deck Construction Using Industrially Produced Internally Cured, High Performance Concrete," 27th Biennial National Conference of the Concrete Institute of Australia in conjunction with the 69th RILEM Week, Melbourne, Australia, 10 pp.

Battaglia, I., Munoz, J., and Cramer, S. (2010). "Proposed Behavioral Model for Deicer Sclaing Resistance of Slag Cement Concrete," *Journal of Materials in Civil Engineering*, Vol 22, No. 4, Aug., pp. 361-368.

Beushausen, H., and Bester, N. (2016). "The Influence of Curing on Restrained Shrinkage Cracking of Bonded Concrete Overlays," *Cement and Concrete Research*, Vol. 87, Sept., pp. 87-96.

Bentz, D., and Weiss, J. (2011). *Internal Curing: A 2010 State-of-the-Art Review*, US Department of Commerce, National Institute of Standards and Technology, 94 pp.

Bitnoff, A. (2014). "Internal Curing of Concrete Bridge Decks in Utah: Two-Year Update for Mountain View Corridor Project," M.S. Thesis, Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT, 138 pp.

Bouzoubaâ, N., Bilodeau, A., Fournier, B., Hooton, R. D., Gagné, R., and Jolin, M. (2008). "Deicing Salt Scaling Resistance of Concrete Incorporating Supplementary Cementing Materials: Laboratory and Field Test Data," *Canadian Journal of Civil Engineering*, Vol. 35, No. 11, Nov. pp. 1261-1275.

Browning, J., Darwin, D., Reynolds, D., and Pendergrass, B. (2011). "Lightweight Aggregate as Internal Curing Agent to Limit Concrete Shrinkage," *ACI Materials Journal*, Vol. 108, No. 6, Mar.-Apr., pp. 119-126.

Castro, J. (2011). Moisture transport in cement based materials: Application to transport tests and internal curing (Doctoral dissertation). West Lafayette, IN: Purdue University. Retrieved from http://docs.lib.purdue.edu/dissertations/

Castro, J., Bentz, D., and Weiss, J. (2011). "Effect of sample conditioning on the water absorption of concrete." *Cement and Concrete Composites* Vol. 33, No. 8, pp.805-813.

Castro, J., de la Varga, I., and Weiss, J. (2012). “Using Isothermal Calorimetry to Assess the Water Absorbed by Fine LWA during Mixing,” *Journal of Materials in Civil Engineering*, Vol 24, No. 8, Aug., pp. 996-1005.

Castro, J., Lura, P., Rajabipour, F., Henkensiefken, R., and Weiss, J. (2010). “Internal Curing: Discussion of the Role of Pore Solution on Relative Humidity Measurements and Desorption of Lightweight Aggregate (LWA),” *Advances in the Material Science of Concrete*, SP 270—8, American Concrete Institute, Farmington Hills, MI, pp. 89-100.

Castro, J., Spragg, R., and Weiss, J. (2011). “Internal Curing for W/C Systems Between 0.30 and 0.45: Impact on Water Absorption and Electrical Conductivity,” *Journal of Civil Engineering Materials*. Vol. 24, No. 2, Feb., pp 223-231.

Cusson, D., and Hoogeveen, T. (2008). “Internal Curing of High-Performance Concrete with Pre-Soaked Fine Lightweight Aggregate for Prevention of Autogenous Shrinkage Cracking,” *Cement and Concrete Research*, Vol. 38, No. 6, pp. 757-765.

Cusson, D., and Margeson, J. (2010). “Development of Low-Shrinkage High-Performance Concrete with Improved Durability,” National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada. 10 pp.

Darwin, D., Browning, J., and Lindquist, W. (2004). “Control of Cracking in Bridge Decks: Observations from the Field,” *Cement, Concrete, and Aggregates*, Vol. 26, No. 2, Dec., pp. 148-154.

Darwin, D., Browning, J., Lindquist, W., McLeod, H., Yuan, J., Toledo, M., and Reynolds, D. (2010). “Low-Cracking, High-Performance Concrete Bridge Decks—Case Studies Over First 6 Years,” *Transportation Research Record*: Journal of the Transportation Research Board, No. 2202, Dec. pp. 61-69.

Darwin, D., Browning, J., McLeod, H. A. K., Lindquist, W., and Yuan, J. (2012). “Implementing Lessons Learned From Twenty Years of Bridge-Deck Crack Surveys,” *Andy Scanlon Symposium on Serviceability and Safety of Concrete Structures: From Research to Practice*, SP-284, American Concrete Institute, Farmington Hills, MI. 18 pp.

Darwin, D., Browning, J., O’Reilly, M., Locke, C.E., and Virmani, Y.P. (2011). “Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Components,” Publication No. FHWA-HRT-11-060, Federal High Administration, *SM Report* No. 101, University of Kansas Center for Research, Lawrence, KS, Nov., 255 pp.

Darwin, D., Khajehdehi, R., Alhmood, A., Feng, M., Lafikes, J., Ibrahim, E., and O’Reilly. M. (2016). “Construction of Crack-Free Bridge Decks: Final Report,” *SM Report* No. 121, University of Kansas Center for Research, Lawrence, KS, Dec., 160 pp.

de la Varga, I., Castro, J., Bentz, D, and Weiss, J. (2012). “Application of Internal Curing for Mixtures Containing High Volumes of Fly Ash,” *Journal of Cement & Concrete Composites*, Vol. 34, No. 9, Oct., pp. 1001-1008.

Deshpande, S., Darwin, D., and Browning, J. (2007). “Evaluating Free Shrinkage of Concrete for Control of Cracking in Bridge Decks,” *SM Report* No. 89, University of Kansas Center for Research, Lawrence, KS, Jan., 290 pp.

Devore, J. (2008). *Probability and Statistics for Engineering and the Sciences* 7th Edition. Belmont, CA, Thomson Brooks/Cole.

Di Bella, C., Schlitter, J., Carboneau, N., and Weiss, J. (2012). “Documenting the Construction of a Plain Concrete Bridge Deck and an Internally Cured Bridge Deck,” Indiana LTAP Center, TR-1-2012.

Durability of Concrete Bridge Decks – A Cooperative Study, Final Report. (1970). The state highway departments of California, Illinois, Kansas, Michigan, Minnesota, Missouri, New Jersey, Ohio, Texas, and Virginia; Bureau of Public Roads; and Portland Cement Association, 35 pp.

Esmaeeli, H., Farnam, Y., Zavattieri, P., Bentz, D. P, and Weiss, W. J., (2017). “Numerical Simulation of the Freeze-Thaw Behavior of Mortar Containing Deicing Salt Solution,” *Materials and Structures*, Vol. 50, No. 1, 20 pp.

Esmaeeli, H., Zavattieri, P., Olek, J., and Weiss, W. J., (2017). *Numerical Simulation of the Freeze-Thaw Behavior of Mortar Containing Deicing Salt Solution*, ProQuest Dissertations and Theses, 133 pp.

Feng, M., and Darwin, D. (2020). “Implementation of Crack-Reducing Technologies for Concrete in Bridge Decks: Synthetic Fibers, Internal Curing, and Shrinkage-Reducing Admixtures,” *SM Report* No. 136, University of Kansas Center for Research, Lawrence, KS, Jan., 242 pp.

Ghourchian, S., Wyrzykowski, M., Plamondon, M., and Lura, P. (2019). “On the Mechanism of Plastic Shrinkage Cracking in Fresh Cementitious Materials,” *Cement and Concrete Research*, Vol. 115, Jan., pp. 251-263.

Gross, J., King, D., Harrington, D., Ceylan, H., Chen, Y., Kim, S., Taylor P., and Kaya, O. (2017). “Concrete Overlay Performance on Iowa’s Roadways,” Iowa Highway Research Board, Ames, IA, IHRB Project TR-698, July, 149 pp.

Harley, A., Darwin, D., and Browning, J. (2011). “Use of Innovative Concrete Mixes for Improved Constructability and Sustainability of Bridge Decks 2010-2011,” *SL Report* 11-5, The University of Kansas Center for Research, Inc., Lawrence, KS, Dec., 82 pp.

Henkensiefken, R., Briatka, P., Bentz, D., Nantung, T., and Weiss, W. J. (2010).” Plastic Shrinkage Cracking in Internally Cured Mixtures,” *Concrete International*, Vol. 32, Issue. 2, pp. 49-54.

Henkensiefken, R., Bentz, D., Nantung, T., and Weiss, W. J. (2009). “Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions,” *Cement and Concrete Composites*, Vol. 31, No. 7, pp. 427-437.

Henkensiefken, R., Castro J., Bentz D., Nantung, T., and Weiss W. J. (2009). “Water Absorption in Internally Cured Mortar Made with Water-Filled Lightweight Aggregate,” *Cement and Concrete Research*, Vol. 29, No. 10, Oct., pp. 883-892.

Hooton R.D., and Vassilev, D. (2012). “Concrete Overlay Performance on Iowa’s Roadways,” No. InTrans Project 10-374, Iowa State University Institute for Transportation, July, 58 pp.

Hopper, T., Manafpour, A., Radlińska, A., Warn, G., Rajabipour, F., Morian, D., and Jahangirnejad, S. (2015). “Bridge Deck Cracking: Effects on In-Service Performance, Prevention, and Remediation,” Report No. FHWA-PA-2015-006-120103., Pennsylvania Department of Transportation, Harrisburg, PA, 244 pp.

Ibrahim, E., Darwin, D., and O’Reilly, M. (2019). “Effect of Crack-Reducing Technologies and Supplementary Cementitious Materials on Settlement Cracking of Plastic Concrete and Durability Performance of Hardened Concrete,” *SM Report* No. 134, University of Kansas Center for Research, Lawrence, KS, Sept., 268 pp.

Jana, D., Erlin, B., and Pistilli, M. (2005). “A Closer Look at Entrained Air in Concrete,” *Concrete International*, Vol. 27, No. 7, June, pp. 31-34.

Jenkins, A. (2015). “Surface Resistivity as an Alternative for Rapid Chloride Permeability Test of Hardened Concrete,” No. FHWA-KS-14-15, Kansas Department of Transportation. Bureau of Materials and Research, Topeka, KS, Mar. 39 pp.

Jones, W., House, M., and Weiss, W. J. (2014). “Internal Curing of High-Performance Concrete Using Lightweight Aggregates and other Techniques,” *Technical Report* No. CDOT-2014-3, Colorado Department of Transportation Applied Research and Innovation Branch, Feb. 129 pp.

Kansas Department of Transportation (2014a). “Low-Cracking High-Performance Concrete - Aggregates,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2014b). “Low-Cracking High-Performance Concrete,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2011). “Low-Cracking High-Performance Concrete - Construction,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2017). “Structural Concrete,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2015a). “Low-Cracking High-Performance Concrete - Aggregates,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2015b). “General Low-Cracking High-Performance Concrete – Concrete,” *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2015c). "Structural Low-Cracking High-Performance Concrete," *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Kansas Department of Transportation (2015d). "Low-Cracking High-Performance Concrete - Construction," *Standard Specifications for State Road and Bridge Construction*, Topeka, KS.

Khajehdehi, R., and Darwin, D. (2018). "Controlling Cracks in Bridge Decks," *SM Report* No. 129, University of Kansas Center for Research, Lawrence, KS, Dec., 236 pp.

Khajehdehi, R., Feng, M., Darwin, D., Lafikes, J., Ibrahim, E., and O'Reilly, M. (2018). "Combined Effects of Internal Curing, SCMs, and Expansive Additives on Concrete Shrinkage," *Advances in Civil Engineering Materials*, Vol. 7, Issue 4, Sept. pp. 644-659.

Khanzadeh, M.; Qiao, C.; Keys, M.; Hall, H.; Ley, T.; Reese, S.; and Weiss, W. J., (2019). "Quantifying Fluid Absorption in Air-Entrained Concrete using Neutron Radiography," *ACI Materials Journal*, Vol. 116, No. 6, Nov., pp. 1-10.

Khayat, K., Meng, W., Valipour, M., and Hopkins, M. (2018). *Use of Lightweight Sand for Internal Curing to Improve Performance of Concrete Infrastructure* (No. cmr 18-005). Missouri Department of Transportation Construction and Materials Division. Jefferson City, MO, Mar., 82 pp.

Klieger, P. (1957). "Early High Strength Concrete for Prestressing". *World Conference on Prestressed Concrete Proceedings*, San Francisco CA, pp. A5-1-A5-14.

Klieger, P., and Hanson, J. (1961). "Freezing and Thawing Tests of Lightweight Aggregate Concrete," *ACI Journal Proceedings*, Vol. 57, No. 1, Jan., pp 779-796.

Krauss, P.D., and Rogalla, E.A. (1996). "Transverse Cracking in Newly Constructed Bridge Decks," *National Cooperative Highway Research Program Report* 380, Transportation Research Board, Washington, D.C., 126 pp.

KT-79 Kansas Test Method. (2015). "Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration," Kansas Department of Transportation construction manual, part V. Topeka, KS, Kansas Department of Transportation. 4 pp.

Lafikes, J., Khajehdehi, R., Feng, M., O'Reilly, M., and Darwin, D. (2018). "Internal Curing and Supplementary Cementitious Materials in Bridge Decks," *SL Report* 18-2, University of Kansas Center for Research, Lawrence, KS, Apr., 67 pp.

Lafikes, J., Darwin, D., O'Reilly, M., Feng, M., Bahadori, A., and Khajehdehi, R. (2018). "Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology," *SM Report* No. 132, University of Kansas Center for Research, Lawrence, KS, June, 98 pp.

Lindquist, W., Darwin D., and Browning J. (2005). "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Lawrence, KS, Feb., 482 pp.

Lindquist, W. D., Darwin, D., Browning, J., and Miller, G. G. (2006) "Effect of Cracking on Chloride Content in Concrete Bridge Decks," *ACI Materials Journal*, Vol. 103, No. 6, Nov.-Dec. pp. 467-473.

Lindquist, W., Darwin D., and Browning J. (2008). "Development of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production," *SM Report* No. 92, University of Kansas Center for Research, Lawrence, KS, Nov., 540 pp.

Lucero, C., Bentz, D., Hussey, D., Jacobson, D., and Weiss, W. J., (2015). "Using Neutron Radiography to Quantify Water Transport and the Degree of Saturation in Entrained Air Cement Based Mortar," *Physics Procedia*, Vol. 69, pp. 542-550.

Mayercsik, N., Vandamme, M., and Kurtis, K. (2016). "Assessing the Efficiency of Entrained Air Voids for Freeze-Thaw Durability through Modeling," *Cement and Concrete Research*, Vol. 88, Issue 2, Oct., pp. 43-59.

McLeod, H. A. K., Darwin, D., and Browning, J. (2009). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Construction Methods, Specifications, and Resistance to Chloride Ion Penetration," *SM Report* No. 94, University of Kansas Center for Research, Lawrence, KS, Sept., 815 pp.

Menkulasi, F., Nelson, D., Roberts Wollmann, C. and Cousin, T. (2015). "Reducing Deck Cracking in Composite Bridges by Controlling Long Term Properties," *Sustainable Performance of Concrete Bridges and Elements Subjected to Aggressive Environments: Monitoring, Evaluation and Rehabilitation at ACI Fall Convention*, ACI SP-304, American Concrete Institute, Farmington Hills, MI, pp. 21-40.

Miller, A., Albert, E., Spragg, R., Antico, F. C., Ashraf, W., Barrett, T., Behnood, A., Bu, Y., Chiu, Y., Desta, B., Farnam, Y., Jeong, H., Jone, W., Lucero, C., Luo, D., Nickel, C., Panchmatia, P., Pin, K., Qiang, S., Qiao, C., Shagerdi, H., Tokpatayeva, R., Villani, C., Wiese, A., Woodard, S., and Weiss, W. J. (2014). "Determining the Moisture Content of Pre-Wetted Lightweight Aggregate: Assessing the Variability of the Paper Towel and Centrifuge Methods," *4th International Conference on the Durability of Concrete Structures*, Purdue University, West Lafayette, IN, 5 pp.

Miller, A., Barrett, T, Zander, A., and Weiss, W. J. (2014). "Using a centrifuge to determine moisture properties of lightweight fine aggregate for use in internal curing". *Advances in Civil Engineering Materials*, Vol. 3, No. 1, Feb., ASTM International, West Conshocken, PA, pp. 142-157.

Miller, G., and Darwin, D. (2000). "Performance and Constructability of Silica Fume Bridge Deck Overlays," *SM Report* No. 57, The University of Kansas Center for Research, Lawrence, KS, Jan., 444 pp.

Mindess, S., Young, F., and Darwin, D. (2003). *Concrete*, second edition, Prentice Hall., Englewood Cliffs, NJ, 644 pp.

Moini, M., Sobolev, K., Flores-Vivian, I., Muzenski, S., Pham, L. T., Cramer, S., and Beyene, M. (2019). "Durability of Concrete Mixtures Containing Supplementary Cementitious Materials in Rapid Chloride Permeability Test," *ACI Materials Journal*, Vol. 116, No. 5, Sept., pp. 67-76.

Montanari, L., Amirkhanian, A., Suraneni, P., and Weiss, W. J. (2018). "Design Methodology for Partial Volumes of Internal Curing Water Based on the Reduction of Autogenous Shrinkage," *Journal of Materials in Civil Engineering*, Vol 30, No. 7, July., 8 pp.

Moradllo, M., Qiao, C., Isgor, B., Reese, S., and Weiss, W. J. (2018). "Relating Formation Factor of Concrete to water Absorption," *ACI Materials Journal*, Vol. 115, No. 5, Nov., pp. 887-898.

Moradllo, M., Qiao, C., Hall, H., Ley, M. T., Reese, S., Weiss, W. J. (2019). "Quantifying Fluid Filling of the air Voids in Air Entrained Concrete Using Neutron Radiography," *Cement and Concrete Composites*, Vol. 102, Nov., 11 pp.

Obla, K. (2019). "Performance Criteria for Concrete Resistant to Chloride Ion Penetration," *ACI Materials Journal*, Vol. 116, No. 5, Sept., pp. 139-148.

O'Reilly, M., Darwin, D., Browning, J., and Locke, C. (2011). "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks," *SM Report* No. 100, University of Kansas Center for Research, Lawrence, KS, 535 pp.

O'Reilly, M., Sperry, J., Browning, J., and Darwin, D. (2017a). "Evaluation of Effects of Casting and Curing Conditions and Specimen Type on Concrete Strength and Permeability," *SM Report* No. 119, University of Kansas Center for Research, Lawrence, KS, 214 pp.

O'Reilly, M., Darwin, D., Sperry, J., and Browning, J. (2017b). "Variation of Concrete Strength, Permeability, and Porosity due to Specimen Type, Season, and Age," *SM Report* No. 120, University of Kansas Center for Research, Lawrence, KS, 78 pp.

Pendergrass, B., Shrestha, P., Riedel, E., Polley, G., and Darwin, D. (2013). "Crack Survey Results of Six Bridge Decks in Minnesota," *SL Report* 13-4, University of Kansas Center for Research, Lawrence, KS, Oct., 24 pp.

Pendergrass, B., and Darwin, D. (2014). "Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Shrinkage-Reducing Admixtures, Internal Curing, and Cracking Performance," *SM Report* No. 107, University of Kansas Center for Research, Lawrence, KS, Feb., 665 pp.

Philleo, R. E. (1986). "Freezing and Thawing Resistance of High Strength Concrete," *National Cooperative Highway Research Program (NCHRP) Synthesis 129*, Transportation Research Board, Washington, D.C., December, 38 pp.

Piasta, W., and Sikora, H. (2015). "Effect of Air Entrainment on Shrinkage of Blended Cements Concretes," *Construction and Building Materials*, Vol. 99, Nov., pp. 298-307.

Portland Cement Association (1970). *Durability of Concrete Bridge Decks-A Cooperative Study, Final Report*. The state highway departments of California, Illinois, Kansas, Michigan, Minnesota, Missouri, New Jersey, Ohio, Texas, and Virginia; the Bureau of Public Roads; and Portland Cement Association, 35 pp.

Powers, T. (1975). "Freezing Effects in Concrete," *Durability of Concrete*, SP 47—1, American Concrete Institute, Farmington Hills, MI, pp. 1-12.

Qiao, C., Moradllo, M., Hall, H., Ley, T., and Weiss, W. J. (2019). "Electrical Resistivity and Formation Factor of Air-Entrained Concrete," *ACI Materials Journal*, Vol. 116, No. 3, May, pp. 85-93.

Radlińska, A. (2008). *Reliability-Based Analysis of Early-Age Cracking in Concrete*. Purdue University, West Lafayette, IN, Aug. 215 pp.

Radlińska, A. and Weiss, W. J., (2011). "Toward the Development of a Performance-Related Specification for Concrete Shrinkage," *Journal of Materials in Civil Engineering,* Vol. 24, No. 1, pp. 64-71.

Reynolds, D., Darwin, D., and Browning J. (2009) "Lightweight Aggregates as an Internal Curing Agent for Low-Cracking High-Performance Concrete," *SM Report* No. 97, University of Kansas Center for Research, Lawrence, KS, Dec., 151 pp.

Rupnow, T. and Icenogle, P. (2012). "Evaluation of Surface Resistivity Measurements as an Alternative to the Rapid Chloride Permeability Test for Quality Assurance and Acceptance," TRB 91st Annual Meeting, Transportation Research Board, Washington, DC. 15 pp.

Russell, H. G. (2004). "Concrete Bridge Deck Performance," National Cooperative Highway Research Program (NCHRP) Synthesis 333, Transportation Research Board, Washington, D.C., 32 pp.

Savva, P., Petrou, M. (2018). "Highly Absorptive Normal Weight Aggregates for Internal Curing of Concrete," *Construction and Building Materials,* Vol. 179, Aug. pp. 80-88.

Schlitter, J., Henkensiefken, R., Castro, J., Raoufi, K., Weiss, W. J., and Nantung, T. (2010). "Development of Internally Cured Concrete for Increased Service Life," *Joint Transportation Research Program, 2010,* West Lafayette, IN, Oct., 269 pp.

Schlorholtz, S., and Hooton, R.D. (2008). "Deicer Scaling Resistance of Concrete Pavements, Bridge Decks, and Other Structures Containing Slag Cement, Phase 1: Site Selection and Analysis of Field Cores," Pooled Project No. *TPF-5(100),* National Concrete Pavement Technology Center, Ames, IA, Sept., 122 pp.

Schmitt, T. R. and Darwin, D. (1995). "Cracking in Concrete Bridge Decks," *SM Report* No. 39, University of Kansas Center for Research, Lawrence, KS, Apr., 151 pp.

Schmitt, T. R. and Darwin, D. (1999). "Effect of Material Properties on Cracking in Bridge Decks," *Journal of Bridge Engineering,* ASCE, Vol. 4, No. 1, Feb., pp. 8-13.

Shen, D., Liu, C., Feng, Z., Shu, S., and Liang, C. (2019). "Influence of Ground Granulated Blast Furnace Slag on the Early-Age Anti-Cracking Property of Internally Cured Concrete," *Construction and Building Materials*, Vol. 223, Oct., pp. 233-243.

Shilstone, J. M., Sr. (1990). "Concrete Mixture Optimization," *Concrete International*, Vol. 12, No. 6, June, pp. 33-39.

Shilstone, J. M., Sr. and Shilstone, J. M., Jr. (2002). "Performance-Based Concrete Mixtures and Specifications for Today," *Concrete International*. Vol. 24. No. 2, Feb., pp. 80-83.

Shrestha, P., Harley, A., Pendergrass, B., Darwin, D., and Browning, J. (2013). "Use of Innovative Concrete Mixes for Improved Constructability and Sustainability of Bridge Decks 2010-2013," *SL Report* 13-3, The University of Kansas Center for Research, Inc., Lawrence, KS, May, 104 pp.

Shideler, J. (1957). "Lightweight Aggregate Concrete for Structural Applications," ACI Journal Vol. 20, No. 4, Oct., pp. 299-328.

Spragg, R., Villani, C., Snyder, K., Bentz, D., Bullard, J. W., and Weiss, W. J. (2013). "Factors that Influence Electrical Resistivity Measurements in Cementitious Systems," *Transportation Research Record,* Vol. *2342,* No. 1, Dec. pp. 90-98.

Streeter, D., Wolfe, W., and Vaughn, R. (2012). "Field Performance of Internally Cured Concrete Bridge Decks in New York State," *The Economics, Performance, and Sustainability of Internally Cured Concrete,* SP-290—7. American Concrete Institute, Farmington Hills, MI, pp. 69-84.

Subgranon, T., Kim, K., and Tia, M. (2018). "Internally Cured Concrete for Pavement and Bridge Deck Applications," *Advances in Civil Engineering Materials*, Vol. 7, Issue 4, Sept. pp. 614-627.

Sun, Z. and Scherer, G. (2010). "Effect of Air Voids on Salt Scaling and Internal Freezing," *Cement and Concrete Research*, Vol. 40, Issue 2, Feb., pp. 260-270.

Suraneni, P., Monical, J., Unal, E., Farnam, Y., and Weiss, W. J. (2017). "Calcium Oxychloride Formation Potential in Cementitious Pastes Exposed to Blends of Deicing Salt," *ACI Materials Journal*, Vol. 114, No. 4, July-Aug., pp 631-641.

Sutter, L., Peterson, K., Julio-Betancourt, G., Hooton, R. D., Van Dam, T., and Smith, K. (2008). "The Deleterious Chemical Effects of Concentrated Deicing Solutions on Portland Cement Concrete," No. *SD2002-01-F*, South Dakota Department of Transportation Office of Research, Pierre, SD, Apr., 57 pp.

Talbot, C., Pigeon, M., and Marchand, J. (2000). "Influence of Fly Ash and Slag on Deicer Salt Scaling Resistance of Concrete," *SP192-39*, American Concrete Institute, Farmington Hills, MI, Apr., pp 645-657.

Tanesi, J. and Ardani, A. (2012). "Surface Resistivity Test Evaluation as an Indicator of the Chloride Permeability of Concrete (No. FHWA-HRT-13-024)," United States. Federal Highway Administration. Dec., 6 pp.

Taylor, P. and Wang, X. (2014). “Deicer Scaling Resistance of Concrete Mixtures Containing Slag Cement,” No. InTrans Project 10-374, Iowa State University Institute for Transportation, Jan, 22 pp.

Tazawa, E., Yonekura, A., and Tanaka, S. (1989). “Drying Shrinkage and Creep of Concrete Containing Granulated Blast Furnace Slag,” *Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, SP-114—64, American Concrete Institute, Farmington Hills, MI, pp. 1325-1343.

Tritsch, N., Darwin, D., and Browning, J. (2005). “Evaluating Shrinkage and Cracking Behavior of Concrete Using Restrained Ring and Free Shrinkage Tests,” *SM Report* No. 77, University of Kansas Center for Research, Lawrence, KS, Jan., 197 pp.

Todak, H., Lucero, C., and Weiss, W. J. (2015). “Why is the Air There? Thinking about Freeze-Thaw in Terms of Saturation,” *Concrete in Focus,* Jan. pp. OC3-OC7.

Valenza, J. and Scherer, G. (2005). “Mechanisms of Salt Scaling,” *Materials and Structures*, Vol. 38, Issue 4, Oct., pp. 259-268.

Valenza, J. and Scherer, G. (2007a). “Mechanism for Salt Scaling of a Cementitious Surface,” Materials and Structures, Vol. 40, Issue 3, May, pp. 479-488.

Valenza, J. and Scherer, G. (2007b). “A Review of Salt Scaling: I. Phenomenology,” Cement and Concrete Research, Vol. 37, Issue 7, July, pp. 1007-1021.

Valenza, J. and Scherer, G. (2007c). “A Review of Salt Scaling: I. Mechanisms,” Cement and Concrete Research, Vol. 37, Issue 7, July, pp. 1022-1034.

Virmani, Y. P., and Clemeña, G. G. (1998). “Corrosion Protection-Concrete Bridges,” *Report* No. FHWA-RD-98-088, Federal Highway Administration, Washington, D.C., 72 pp.

Vosoughi, P., Tritsch, S., Ceylan, H., and Taylor, P. (2017). “Lifecycle Cost Analysis of Internally Cured Jointed Plain Concrete Pavement,” Iowa Highway Research Board, Ames, IA, IHRB Project TR-676, Nov., 86 pp.

Wee, T. H., Suryavanshi A. K., and Tin S. S. (2000). “Evaluation of Rapid Chloride Permeability Test (RCPT) Results for Concrete Containing Mineral Admixtures,” *ACI Materials Journal,* Vol. 97, No. 2, Mar.-Apr., pp. 221-232.

West, M., Darwin, D., and Browning, J. (2010). “Effect of Materials and Curing Period on Shrinkage of Concrete,” *SM Report* No. 98, University of Kansas Center for Research, Lawrence, KS, Jan., 269 pp.

Wong, H., Pappas, A., Zimmerman, R., and Buenfeld, N. (2011). “Effect of Entrained Air Voids on the Microstructure and Mass Transport Properties of Concrete,” *Cement and Concrete Research*, Vol. 41, Issue 10, pp. 1067-1077.

Yuan, J., Darwin D., and Browning, J. (2011). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage Tests, Restrained Ring Tests, Construction Experience, and Crack Survey Results," *SM Report* No. 103, University of Kansas Center for Research, Lawrence, KS, June, 469 pp.

Yuan, J., Lindquist, W., Darwin, D., and Browning, J. (2015). "Effect of Slag Cement on Drying Shrinkage of Concrete," *ACI Materials Journal*, Vol. 112, No. 2, pp. 267-276.

Zhang, J., Hou, D., and Han, Y. (2012). "Micromechanical Modeling on Autogenous and Drying Shrinkages of Concrete," *Construction and Building Materials*, Vol. 29, pp. 230-240.

APPENDIX A: SCALING AND FREEZE-THAW TEST DATA FOR MIXTURES IN CHAPTERS 3

Table A.1: Scaling test results for mixtures in Program 1

Mixture: S-IC-5.5(1)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	1.5	6.37E-03	11.4	4.84E-02	2.0	8.49E-03	0.2	8.49E-04	0.3	1.27E-03	0.4	1.70E-03	0.1	4.25E-04
B	0.55	2.3	9.65E-03	10.3	4.32E-02	2.1	8.81E-03	1.0	4.19E-03	0.6	2.52E-03	0.8	3.35E-03	0.4	1.68E-03
C	0.53	3.5	1.52E-02	19.7	8.55E-02	3.8	1.65E-02	0.7	3.04E-03	0.6	2.60E-03	0.4	1.74E-03	0.5	2.17E-03
Average	0.54	☒	1.04E-02	☒	5.90E-02	☒	1.13E-02	☒	2.69E-03	☒	2.13E-03	☒	2.26E-03	☒	1.42E-03
Cumulative mass loss (lb/ft^2)			**1.04E-02**		**6.94E-02**		**8.07E-02**		**8.34E-02**		**8.55E-02**		**8.78E-02**		**8.92E-02**

Mixture: S-IC-5.5(2) (ASTM C672)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	1.0	4.21E-03	2.9	1.22E-02	0.8	3.37E-03	0.4	1.68E-03	0.2	8.41E-04	0.3	1.26E-03	0.2	8.41E-04
B	0.51	1.5	6.78E-03	3.5	1.58E-02	2.2	9.95E-03	1.1	4.97E-03	0.3	1.36E-03	0.1	4.52E-04	0.2	9.04E-04
C	0.53	0.5	2.15E-03	2.0	8.58E-03	1.1	4.72E-03	1.1	4.72E-03	0.3	1.29E-03	0.1	4.29E-04	0.4	1.72E-03
Average	0.53	☒	4.38E-03	☒	1.22E-02	☒	6.01E-03	☒	3.79E-03	☒	1.16E-03	☒	7.14E-04	☒	1.15E-03
Cumulative mass loss (lb/ft^2)			**4.38E-03**		**1.66E-02**		**2.26E-02**		**2.64E-02**		**2.75E-02**		**2.83E-02**		**2.94E-02**

Mixture: S-IC-5.5(2) (BNQ)

Specimen	Effective Area ft^2	Mass at 7 days		Mass at 21 days		Mass at 35 days		Mass at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	1.4	6.05E-03	10.3	4.45E-02	4.6	1.99E-02	3.9	1.69E-02
B	0.52	3.8	1.69E-02	1.1	4.90E-03	2.3	1.02E-02	5.2	2.31E-02
C	0.52	3.1	1.38E-02	2.5	1.11E-02	2.1	9.33E-03	5.6	2.49E-02
Average	0.52	☒	8.51E-05	☒	1.40E-04	☒	9.13E-05	☒	1.50E-04
Cumulative mass loss (lb/ft^2)			**1.22E-02**		**3.24E-02**		**4.56E-02**		**6.72E-02**

Mixture: S-IC-5.6(1)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	0.4	1.72E-03	3.6	1.55E-02	0.5	2.15E-03	0.5	2.15E-03	0.3	1.29E-03	0.5	2.15E-03	0.3	1.29E-03
B	0.52	0.2	8.79E-04	4.1	1.80E-02	2.0	8.79E-03	0.4	1.76E-03	0.8	3.52E-03	0.4	1.76E-03	0.4	1.76E-03
C	0.52	0.3	1.31E-03	5.7	2.50E-02	2.5	1.10E-02	0.2	8.76E-04	0.3	1.31E-03	0.4	1.75E-03	0.5	2.19E-03
Average	0.53	☒	1.30E-03	☒	1.95E-02	☒	7.30E-03	☒	1.59E-03	☒	2.04E-03	☒	1.89E-03	☒	1.75E-03
Cumulative mass loss (lb/ft^2)			**1.30E-03**		**2.08E-02**		**2.81E-02**		**2.97E-02**		**3.17E-02**		**3.36E-02**		**3.54E-02**

Mixture: S-IC-5.6(2) (ASTM C672)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	4.3	1.80E-02	3.1	1.30E-02	1.1	4.60E-03	0.3	1.25E-03	0.2	8.36E-04	0.3	1.25E-03	0.5	2.09E-03
B	0.54	4.7	1.99E-02	5.8	2.46E-02	0.9	3.81E-03	0.2	8.47E-04	0.4	1.69E-03	0.4	1.69E-03	0.3	1.27E-03
C	0.54	1.7	7.25E-03	3.0	1.28E-02	0.7	2.99E-03	0.4	1.71E-03	0.2	8.53E-04	0.4	1.71E-03	0.2	8.53E-04
Average	0.54	☒	1.50E-02	☒	1.68E-02	☒	3.80E-03	☒	1.27E-03	☒	1.13E-03	☒	1.55E-03	☒	1.41E-03
Cumulative mass loss (lb/ft^2)			**1.50E-02**		**3.18E-02**		**3.56E-02**		**3.69E-02**		**3.80E-02**		**3.96E-02**		**4.10E-02**

Table A.1 (con't): Scaling test results for mixtures in Program 1

Mixture: S-IC-5.6(2) (BNQ)

Specimen	Effective Area ft^2	Mass at 7 days		Mass at 21 days		Mass at 35 days		Mass at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	5.1	2.20E-02	3.2	1.38E-02	4.7	2.03E-02	10.8	4.67E-02
B	0.52	3.4	1.51E-02	1.6	7.12E-03	2.2	9.79E-03	2.6	1.16E-02
C	0.52	1.6	7.11E-03	2.0	8.89E-03	4.3	1.91E-02	1.6	7.11E-03
Average	0.52		1.48E-02		9.95E-03		1.64E-02		2.18E-02
Cumulative mass loss (lb/ft^2)			**1.48E-02**		**2.47E-02**		**4.11E-02**		**6.29E-02**

Mixture: S-IC-6.6

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	0.4	1.70E-03	0.6	2.54E-03	0.2	8.48E-04	0.7	2.97E-03	0.2	8.48E-04	0.1	4.24E-04	0.3	1.27E-03
B	0.54	0.2	8.48E-04	2.7	1.14E-02	0.1	4.24E-04	0.6	2.54E-03	0.2	8.48E-04	0.2	8.48E-04	0.2	8.48E-04
C	0.54	0.3	1.27E-03	1.6	6.78E-03	0.2	8.48E-04	0.5	2.12E-03	0.1	4.24E-04	0.1	4.24E-04	0.2	8.48E-04
Average	0.54		1.27E-03		6.92E-03		7.06E-04		2.54E-03		7.06E-04		5.65E-04		9.89E-04
Cumulative mass loss (lb/ft^2)			**1.27E-03**		**8.19E-03**		**8.90E-03**		**1.14E-02**		**1.21E-02**		**1.27E-02**		**1.37E-02**

Mixture: S-IC-7.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	4.7	1.97E-02	16.8	7.05E-02	4.2	1.76E-02	2.3	9.65E-03	1.2	5.03E-03	8.0	3.35E-02	4.9	2.05E-02
B	0.52	5.3	2.32E-02	16.5	7.23E-02	3.3	1.45E-02	1.9	8.33E-03	1.8	7.89E-03	6.0	2.63E-02	5.2	2.28E-02
C	0.53	7.2	3.10E-02	14.2	6.12E-02	3.9	1.68E-02	2.0	8.61E-03	1.5	6.46E-03	7.0	3.02E-02	6.9	2.97E-02
Average	0.53		2.46E-02		6.80E-02		1.63E-02		8.86E-03		6.46E-03		3.00E-02		2.44E-02
Cumulative mass loss (lb/ft^2)			**2.46E-02**		**9.26E-02**		**1.09E-01**		**1.18E-01**		**1.24E-01**		**1.54E-01**		**1.79E-01**

Mixture: S-IC-9.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	11.1	4.64E-02	14.3	5.98E-02	1.1	4.60E-03	0.6	2.51E-03	6.2	2.59E-02	6.8	2.84E-02	4.5	1.88E-02
B	0.55	11.5	4.79E-02	14.6	6.08E-02	1.6	6.66E-03	1.0	4.16E-03	8.1	3.37E-02	7.3	3.04E-02	5.0	2.08E-02
C	0.54	15.7	6.68E-02	17.9	7.61E-02	1.2	5.10E-03	1.7	7.23E-03	11.1	4.72E-02	9.9	4.21E-02	5.9	2.51E-02
Average	0.55		5.37E-02		6.56E-02		5.45E-03		4.63E-03		3.56E-02		3.36E-02		2.16E-02
Cumulative mass loss (lb/ft^2)			**8.76E-03**		**3.10E-02**		**3.63E-02**		**3.90E-02**		**4.24E-02**		**4.40E-02**		**4.68E-02**

Mixture: C-IC-5.7

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	6.4	2.65E-02	2.8	1.16E-02	1.5	6.21E-03	1.3	5.38E-03	0.4	1.65E-03	0.2	8.27E-04	0.3	1.24E-03
B	0.55	0.6	2.51E-03	2.9	1.21E-02	2.7	1.13E-02	0.9	3.76E-03	0.2	8.36E-04	0.4	1.67E-03	0.3	1.25E-03
C	0.55	0.5	2.08E-03	2.3	9.55E-03	2.1	8.72E-03	1.9	7.89E-03	0.2	8.30E-04	0.7	2.91E-03	0.2	8.30E-04
Average	0.55		1.04E-02		1.11E-02		8.74E-03		5.68E-03		1.11E-03		1.80E-03		1.11E-03
Cumulative mass loss (lb/ft^2)			**1.04E-02**		**2.14E-02**		**3.02E-02**		**3.58E-02**		**3.70E-02**		**3.88E-02**		**3.99E-02**

Table A.1 (con't): Scaling test results for mixtures in Program 1

Mixture: T-IC-8.2

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	19.2	8.13E-02	5.6	2.37E-02	1.5	6.35E-03	1.3	5.50E-03	0.6	2.54E-03	2.6	1.10E-02	16.4	6.94E-02
B	0.53	26.5	1.15E-01	4.7	2.05E-02	1.7	7.40E-03	1.6	6.97E-03	0.3	1.31E-03	3.7	1.61E-02	9.2	4.01E-02
C	0.53	23.1	1.00E-01	6.5	2.83E-02	1.4	6.09E-03	2.6	1.13E-02	0.4	1.74E-03	2.6	1.13E-02	13.2	5.74E-02
Average	0.53		9.91E-02		2.41E-02		6.61E-03		7.93E-03		1.86E-03		1.28E-02		5.56E-02
Cumulative mass loss (lb/ft^2)			**9.91E-02**		**1.23E-01**		**1.30E-01**		**1.38E-01**		**1.40E-01**		**1.52E-01**		**2.08E-01**

Mixture: T-IC-8.3(1)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	9.1	3.92E-02	14.0	6.03E-02	4.0	1.72E-02	1.8	7.76E-03	1.0	4.31E-03	1.3	5.60E-03	4.8	2.07E-02
B	0.54	7.5	3.19E-02	13.2	5.61E-02	8.0	3.40E-02	1.7	7.23E-03	1.8	7.65E-03	0.7	2.98E-03	4.7	2.00E-02
C	0.53	17.6	7.64E-02	11.1	4.82E-02	5.1	2.21E-02	1.9	8.25E-03	1.2	5.21E-03	0.8	3.47E-03	3.2	1.39E-02
Average	0.53		4.92E-02		5.49E-02		2.45E-02		7.75E-03		5.72E-03		4.02E-03		1.82E-02
Cumulative mass loss (lb/ft^2)			**4.92E-02**		**1.04E-01**		**1.29E-01**		**1.36E-01**		**1.42E-01**		**1.46E-01**		**1.64E-01**

Mixture: S-IC-7.1

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	6.5	2.81E-02	11.9	5.14E-02	2.0	8.65E-03	19.2	8.30E-02	5.9	2.55E-02	6.9	2.98E-02	6.6	2.85E-02
B	0.53	12.0	5.15E-02	8.9	3.82E-02	1.0	4.30E-03	13.6	5.84E-02	7.3	3.14E-02	5.3	2.28E-02	5.3	2.28E-02
C	0.57	1.4	5.68E-03	7.5	3.04E-02	0.4	1.62E-03	19.2	7.79E-02	6.9	2.80E-02	6.7	2.72E-02	6.6	2.68E-02
Average	0.54		2.84E-02		4.00E-02		4.86E-03		7.31E-02		2.83E-02		2.66E-02		2.60E-02
Cumulative mass loss (lb/ft^2)			**2.84E-02**		**6.85E-02**		**7.33E-02**		**1.46E-01**		**1.75E-01**		**2.01E-01**		**2.27E-01**

Mixture: S-IC-7.2

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	0.5	2.15E-03	0.6	2.58E-03	1.1	4.72E-03	14.8	6.35E-02	3.2	1.37E-02	2.9	1.25E-02	2.5	1.07E-02
B	0.53	0.9	3.88E-03	0.6	2.58E-03	1.0	4.31E-03	8.9	3.83E-02	2.1	9.05E-03	4.4	1.90E-02	1.9	8.18E-03
C	0.54	1.0	4.25E-03	0.8	3.40E-03	1.2	5.10E-03	9.1	3.87E-02	2.5	1.06E-02	2.7	1.15E-02	1.6	6.80E-03
Average	0.54		3.43E-03		2.85E-03		4.71E-03		4.69E-02		1.11E-02		1.43E-02		8.57E-03
Cumulative mass loss (lb/ft^2)			**3.43E-03**		**6.28E-03**		**1.10E-02**		**5.78E-02**		**6.90E-02**		**8.33E-02**		**9.19E-02**

Mixture: S-IC-9.1

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	11.0	4.67E-02	4.4	1.87E-02	2.5	1.06E-02	1.3	5.52E-03	0.1	4.25E-04	1.8	7.64E-03	1.8	7.64E-03
B	0.53	8.0	3.48E-02	4.9	2.13E-02	2.4	1.04E-02	0.9	3.92E-03	0.3	1.31E-03	1.1	4.79E-03	1.4	6.09E-03
C	0.52	6.5	2.86E-02	9.8	4.31E-02	3.8	1.67E-02	1.4	6.16E-03	0.2	8.80E-04	1.8	7.92E-03	1.3	5.72E-03
Average	0.53		3.67E-02		2.77E-02		1.26E-02		5.20E-03		8.70E-04		6.78E-03		6.49E-03
Cumulative mass loss (lb/ft^2)			**3.67E-02**		**6.44E-02**		**7.70E-02**		**8.22E-02**		**8.31E-02**		**8.99E-02**		**9.64E-02**

Table A.1 (con't): Scaling test results for mixtures in Program 1

Mixture: S-IC-9.4(1)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	10.5	4.39E-02	8.9	3.72E-02	1.6	6.70E-03	19.5	8.16E-02	6.9	2.89E-02	6.5	2.72E-02	6.5	2.72E-02
B	0.55	11.7	4.85E-02	9.6	3.98E-02	1.3	5.39E-03	20.1	8.33E-02	5.8	2.40E-02	5.0	2.07E-02	5.0	2.07E-02
C	0.55	7.8	3.24E-02	7.3	3.04E-02	1.9	7.90E-03	17.1	7.11E-02	7.0	2.91E-02	5.8	2.41E-02	6.0	2.49E-02
Average	0.55	╳	4.16E-02	╳	3.58E-02	╳	6.66E-03	╳	7.87E-02	╳	2.73E-02	╳	2.40E-02	╳	2.43E-02
Cumulative mass loss (lb/ft^2)			**4.16E-02**		**7.74E-02**		**8.41E-02**		**1.63E-01**		**1.90E-01**		**2.14E-01**		**2.38E-01**

Mixture: S-IC-7.0

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	2.5	1.08E-02	6.5	2.80E-02	1.3	5.60E-03	0.6	2.58E-03	0.2	8.61E-04	0.5	2.15E-03	0.2	8.61E-04
B	0.53	2.7	1.17E-02	3.7	1.61E-02	1.7	7.38E-03	2.2	9.55E-03	0.3	1.30E-03	0.4	1.74E-03	0.4	1.74E-03
C	0.52	2.3	1.02E-02	3.7	1.64E-02	1.4	6.22E-03	1.0	4.44E-03	0.1	4.44E-04	0.4	1.78E-03	0.2	8.88E-04
Average	0.53	╳	1.09E-02	╳	2.02E-02	╳	6.40E-03	╳	5.52E-03	╳	8.69E-04	╳	1.89E-03	╳	1.16E-03
Cumulative mass loss (lb/ft^2)			**1.09E-02**		**3.11E-02**		**3.75E-02**		**4.30E-02**		**4.39E-02**		**4.57E-02**		**4.69E-02**

Mixture: S-IC-9.4(2)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	1.7	7.37E-03	5.6	2.43E-02	1.5	6.50E-03	0.9	3.90E-03	0.3	1.30E-03	0.5	2.17E-03	0.2	8.67E-04
B	0.53	2.0	8.65E-03	7.0	3.03E-02	2.2	9.51E-03	0.6	2.59E-03	0.5	2.16E-03	0.7	3.03E-03	0.4	1.73E-03
C	0.55	1.5	6.30E-03	4.8	2.01E-02	1.0	4.20E-03	0.5	2.10E-03	0.7	2.94E-03	0.7	2.94E-03	0.2	8.40E-04
Average	0.54	╳	7.44E-03	╳	2.49E-02	╳	6.74E-03	╳	2.86E-03	╳	2.13E-03	╳	2.71E-03	╳	1.15E-03
Cumulative mass loss (lb/ft^2)			**7.44E-03**		**3.23E-02**		**3.91E-02**		**4.19E-02**		**4.41E-02**		**4.68E-02**		**4.79E-02**

Table A.2: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 1

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**S-IC-5.5(1)[a]**	**S-IC-5.5(2)[a]**	**S-IC-5.6(1)[a]**	**S-IC-5.6(2)[a]**	**S-IC-6.6[a]**	**C-IC-5.7[a]**	**S-IC-7.3**	**S-IC-9.3**	**T-IC-8.2**	**T-IC-8.3(1)**	**S-IC-7.1**	**S-IC-7.2**	**S-IC-9.1**	**S-IC-9.4(1)**	**S-IC-7.0**	**S-IC-9.4(2)**
		0.089	0.029	0.035	0.041	0.014	0.040	0.179	0.220	0.208	0.164	0.227	0.092	0.096	0.237	0.047	0.048
S-IC-5.5(1)[a]	0.089		**0.038**	0.051	0.076	**0.016**	0.069	**0.009**	**0.013**	**0.003**	**0.020**	**0.005**	0.758	0.653	**0.002**	0.099	0.108
S-IC-5.5(2)[a]	0.029			**0.038**	0.276	0.054	0.294	**1.6×10^{-5}**	**0.005**	**1.6×10^{-5}**	**1.1×10^{-4}**	**3.5×10^{-4}**	0.112	0.068	**4.1×10^{-5}**	0.150	0.183
S-IC-5.6(1)[a]	0.035				0.563	**0.024**	0.620	**1.5×10^{-5}**	**0.002**	**1.6×10^{-5}**	**1.1×10^{-4}**	**3.8×10^{-4}**	**0.006**	**0.002**	**4.9×10^{-5}**	0.102	0.142
S-IC-5.6(2)[a]	0.041					**0.024**	0.917	**0.005**	**0.008**	**0.002**	**0.009**	**0.003**	0.210	0.167	**0.001**	0.509	0.533
S-IC-6.6[a]	0.014						**0.021**	**0.001**	**0.001**	**3.3×10^{-6}**	**3.0×10^{-5}**	**2.2×10^{-4}**	**0.001**	**4.8×10^{-4}**	**2.2×10^{-5}**	**0.001**	**0.004**
C-IC-5.7[a]	0.040							**4.4×10^{-5}**	**0.002**	**3.5×10^{-5}**	**2.1×10^{-4}**	**4.7×10^{-4}**	**0.010**	**0.005**	**7.3×10^{-5}**	0.334	0.360
S-IC-7.3	0.179								0.139	**0.006**	0.122	**0.032**	**0.001**	**0.001**	**0.003**	**6.3×10^{-6}**	**2.7×10^{-5}**
S-IC-9.3	0.220									0.597	0.081	0.835	**0.010**	**0.009**	0.537	**0.002**	**0.003**
T-IC-8.2	0.208										**0.006**	0.280	**0.001**	**2.5×10^{-4}**	**0.039**	**1.0×10^{-5}**	**2.5×10^{-5}**
T-IC-8.3(1)	0.164											**0.019**	**0.005**	**0.003**	**0.002**	**1.0×10^{-4}**	**1.8×10^{-4}**
S-IC-7.1	0.227												**0.002**	**0.002**	0.575	**4.4×10^{-4}**	**0.001**
S-IC-7.2	0.092													0.836	**0.002**	**0.011**	**0.014**
S-IC-9.1	0.096														**0.002**	**0.004**	**0.006**
S-IC-9.4(1)	0.237															**4.8×10^{-5}**	**6.7×10^{-5}**
S-IC-7.0	0.047																0.932
S-IC-9.4(2)	0.048																

[a] Mixture contains cement C1(a), cement C1(b) used otherwise

Table A.3: Scaling test results for mixtures in Program 2

Mixture: S-Control(1)

Specimen	Effective Area ft²	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
A	0.52	8.4	3.70E-02	16.9	7.44E-02	3.9	1.72E-02	1.1	4.84E-03	0.4	1.76E-03	0.3	1.32E-03	0.4	1.76E-03
B	0.55	5.2	2.17E-02	11.2	4.67E-02	2.3	9.60E-03	1.1	4.59E-03	0.2	8.34E-04	0.6	2.50E-03	0.1	4.17E-04
C	0.55	26.1	1.10E-01	15.4	6.48E-02	3.6	1.51E-02	1.7	7.15E-03	0.2	8.41E-04	0.5	2.10E-03	0.3	1.26E-03
Average	0.54		5.62E-02		6.20E-02		1.40E-02		5.53E-03		1.15E-03		1.98E-03		1.15E-03
Cumulative mass loss (lb/ft²)			**5.62E-02**		**1.18E-01**		**1.32E-01**		**1.38E-01**		**1.39E-01**		**1.41E-01**		**1.42E-01**

Mixture: S-IC-6.9

Specimen	Effective Area ft²	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
A	0.55	3.2	1.34E-02	6.8	2.85E-02	2.3	9.66E-03	1.0	4.20E-03	0.1	4.20E-04	0.4	1.68E-03	0.2	8.40E-04
B	0.52	23.4	1.03E-01	6.5	2.85E-02	1.9	8.34E-03	0.9	3.95E-03	0.1	4.39E-04	0.4	1.75E-03	0.5	2.19E-03
C	0.52	11.7	5.15E-02	6.9	3.04E-02	1.9	8.36E-03	1.1	4.84E-03	0.2	8.80E-04	0.6	2.64E-03	0.5	2.20E-03
Average	0.53		5.59E-02		2.91E-02		8.78E-03		4.33E-03		5.80E-04		2.03E-03		1.74E-03
Cumulative mass loss (lb/ft²)			**5.59E-02**		**8.50E-02**		**9.38E-02**		**9.81E-02**		**9.87E-02**		**1.01E-01**		**1.02E-01**

Mixture: S-IC-8.3(1)

Specimen	Effective Area ft²	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
A	0.55	15.8	6.65E-02	6.2	2.61E-02	1.6	6.74E-03	0.6	2.53E-03	0.2	8.42E-04	0.5	2.11E-03	0.1	4.21E-04
B	0.53	15.5	6.77E-02	7.1	3.10E-02	1.6	6.99E-03	1.0	4.37E-03	0.2	8.74E-04	0.3	1.31E-03	0.1	4.37E-04
C	0.54	19.6	8.39E-02	5.5	2.35E-02	1.9	8.13E-03	0.6	2.57E-03	0.4	1.71E-03	0.4	1.71E-03	0.2	8.56E-04
Average	0.54		7.27E-02		2.69E-02		7.29E-03		3.15E-03		1.14E-03		1.71E-03		5.71E-04
Cumulative mass loss (lb/ft²)			**7.27E-02**		**9.96E-02**		**1.07E-01**		**1.10E-01**		**1.11E-01**		**1.13E-01**		**1.13E-01**

Mixture: S-IC-8.4(1)

Specimen	Effective Area ft²	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
A	0.53	14.2	6.12E-02	6.2	2.67E-02	2.0	8.62E-03	0.6	2.59E-03	1.6	6.90E-03	0.4	1.72E-03	0.3	1.29E-03
B	0.52	6.4	2.81E-02	6.7	2.94E-02	1.0	4.38E-03	0.7	3.07E-03	1.0	4.38E-03	0.1	4.38E-04	0.1	4.38E-04
C	0.53	13.4	5.78E-02	6.9	2.97E-02	2.3	9.91E-03	0.2	8.62E-04	1.0	4.31E-03	0.2	8.62E-04	0.1	4.31E-04
Average	0.53		4.90E-02		2.86E-02		7.64E-03		2.17E-03		5.20E-03		1.01E-03		7.21E-04
Cumulative mass loss (lb/ft²)			**4.90E-02**		**7.76E-02**		**8.53E-02**		**8.74E-02**		**9.26E-02**		**9.37E-02**		**9.44E-02**

Mixture: S-IC-8.4(2) -- 14-day cure

Specimen	Effective Area ft²	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
A	0.53	2.3	9.94E-03	6.6	2.85E-02	2.1	9.07E-03	1.0	4.32E-03	0.3	1.30E-03	0.4	1.73E-03	0.5	2.16E-03
B	0.53	2.8	1.21E-02	5.7	2.46E-02	3.6	1.55E-02	1.4	6.05E-03	0.5	2.16E-03	0.4	1.73E-03	0.5	2.16E-03
C	0.54	1.8	7.60E-03	5.2	2.19E-02	1.8	7.60E-03	0.8	3.38E-03	0.4	1.69E-03	0.4	1.69E-03	0.4	1.69E-03
Average	0.54		9.88E-03		2.50E-02		1.07E-02		4.58E-03		1.71E-03		1.71E-03		2.00E-03
Cumulative mass loss (lb/ft²)			**9.88E-03**		**3.49E-02**		**4.56E-02**		**5.02E-02**		**5.19E-02**		**5.37E-02**		**5.57E-02**

Table A.3 (con't): Scaling test results for mixtures in Program 2

Mixture: S-IC-8.4(2) --28-day cure

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.52	1.6	7.01E-03	2.8	1.23E-02	1.2	5.26E-03	1.8	7.89E-03	0.8	3.51E-03	0.5	2.19E-03	0.4	1.75E-03
B	0.51	1.1	4.91E-03	2.1	9.38E-03	1.3	5.81E-03	1.1	4.91E-03	0.9	4.02E-03	0.4	1.79E-03	0.5	2.23E-03
C	0.51	1.7	7.59E-03	2.5	1.12E-02	1.1	4.91E-03	1.1	4.91E-03	1.4	6.25E-03	0.4	1.79E-03	0.6	2.68E-03
Average	0.52		6.50E-03		1.09E-02		5.33E-03		5.90E-03		4.59E-03		1.92E-03		2.22E-03
Cumulative mass loss (lb/ft^2)			**6.50E-03**		**1.74E-02**		**2.28E-02**		**2.87E-02**		**3.33E-02**		**3.52E-02**		**3.74E-02**

Mixture: S-IC-8.4(2) -- 14-day cure, underside surface tested

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	1.0	4.24E-03	0.4	1.70E-03	0.5	2.12E-03	0.3	1.27E-03	0.1	4.24E-04	0.1	4.24E-04	0.2	8.48E-04
B	0.55	0.9	3.77E-03	0.3	1.26E-03	0.2	8.38E-04	0.2	8.38E-04	0.1	4.19E-04	0.1	4.19E-04	0.2	8.38E-04
C	0.54	0.6	2.54E-03	0.5	2.12E-03	0.4	1.70E-03	0.3	1.27E-03	0.1	4.24E-04	0.1	4.24E-04	0.2	8.48E-04
Average	0.54		3.52E-03		1.69E-03		1.55E-03		1.13E-03		4.22E-04		4.22E-04		8.45E-04
Cumulative mass loss (lb/ft^2)			**3.52E-03**		**5.21E-03**		**6.76E-03**		**7.89E-03**		**8.31E-03**		**8.73E-03**		**9.58E-03**

Mixture: S-IC-9.4

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	3.0	1.27E-02	3.5	1.49E-02	1.4	5.95E-03	0.8	3.40E-03	0.6	2.55E-03	0.5	2.12E-03	0.1	4.25E-04
B	0.53	5.0	2.18E-02	4.2	1.83E-02	0.9	3.92E-03	0.9	3.92E-03	0.6	2.61E-03	0.2	8.71E-04	0.1	4.35E-04
C	0.54	3.6	1.53E-02	4.7	2.00E-02	1.7	7.22E-03	0.9	3.82E-03	0.5	2.12E-03	0.2	8.50E-04	0.1	4.25E-04
Average	0.54		1.66E-02		1.77E-02		5.70E-03		3.71E-03		2.43E-03		1.28E-03		4.28E-04
Cumulative mass loss (lb/ft^2)			**1.66E-02**		**3.43E-02**		**4.00E-02**		**4.37E-02**		**4.62E-02**		**4.74E-02**		**4.79E-02**

Mixture: S-IC-7.2(1)

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	75.4	4.1	1.80E-02	4.1	1.80E-02	1.4	6.14E-03	0.8	3.51E-03	0.4	1.75E-03	0.3	1.32E-03	0.1	4.38E-04
B	76.5	14.1	6.10E-02	6.1	2.64E-02	2.2	9.51E-03	1.1	4.76E-03	0.9	3.89E-03	0.2	8.65E-04	0.1	4.32E-04
C	76.7	11.9	5.13E-02	6.1	2.63E-02	2.0	8.62E-03	1.0	4.31E-03	0.8	3.45E-03	0.2	8.62E-04	0.2	8.62E-04
Average	76.2		4.34E-02		2.36E-02		8.09E-03		4.19E-03		3.03E-03		1.01E-03		5.78E-04
Cumulative mass loss (lb/ft^2)			**4.34E-02**		**6.70E-02**		**7.51E-02**		**7.93E-02**		**8.23E-02**		**8.33E-02**		**8.39E-02**

Mixture: S-IC-8.3(2)

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.44	0.8	4.18E-03	4.9	2.56E-02	2.0	1.04E-02	1.5	7.83E-03	0.2	1.04E-03	0.1	5.22E-04	0.5	2.61E-03
B	0.54	0.5	2.12E-03	5.2	2.21E-02	2.4	1.02E-02	1.1	4.67E-03	0.5	2.12E-03	0.7	2.97E-03	0.1	4.25E-04
C	0.52	0.9	3.96E-03	7.0	3.08E-02	2.6	1.14E-02	0.8	3.52E-03	0.4	1.76E-03	0.2	8.79E-04	0.7	3.08E-03
Average	0.50		3.42E-03		2.62E-02		1.07E-02		5.34E-03		1.64E-03		1.46E-03		2.04E-03
Cumulative mass loss (lb/ft^2)			**3.42E-03**		**2.96E-02**		**4.03E-02**		**4.56E-02**		**4.73E-02**		**4.87E-02**		**5.07E-02**

Table A.3 (con’t): Scaling test results for mixtures in Program 2

Mixture: S-Control(2)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.55	8.0	3.35E-02	8.8	3.69E-02	3.8	1.59E-02	0.9	3.77E-03	0.3	1.26E-03	0.4	1.68E-03	4.5	1.89E-02
B	0.53	23.3	1.00E-01	8.6	3.70E-02	4.3	1.85E-02	1.7	7.31E-03	0.8	3.44E-03	0.2	8.60E-04	2.7	1.16E-02
C	0.53	15.1	6.49E-02	7.1	3.05E-02	2.8	1.20E-02	1.3	5.59E-03	0.7	3.01E-03	0.3	1.29E-03	3.6	1.55E-02
Average	0.54		6.62E-02		3.48E-02		1.55E-02		5.56E-03		2.57E-03		1.28E-03		1.53E-02
Cumulative mass loss (lb/ft^2)			**6.62E-02**		**1.01E-01**		**1.16E-01**		**1.22E-01**		**1.25E-01**		**1.26E-01**		**1.41E-01**

Mixture: S-IC-7.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	3.2	1.37E-02	5.1	2.18E-02	2.0	8.56E-03	0.3	1.28E-03	1.1	4.71E-03	0.4	1.71E-03	0.2	8.56E-04
B	0.54	8.4	3.55E-02	10.4	4.39E-02	3.1	1.31E-02	1.1	4.65E-03	1.4	5.91E-03	0.3	1.27E-03	0.1	4.22E-04
C	0.53	3.5	1.51E-02	11.0	4.76E-02	3.1	1.34E-02	0.8	3.46E-03	0.8	3.46E-03	0.2	8.66E-04	0.1	4.33E-04
Average	0.54		2.14E-02		3.78E-02		1.17E-02		3.13E-03		4.69E-03		1.28E-03		5.70E-04
Cumulative mass loss (lb/ft^2)			**2.14E-02**		**5.92E-02**		**7.09E-02**		**7.41E-02**		**7.88E-02**		**8.00E-02**		**8.06E-02**

Mixture: S-IC-8.9(1)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.52	8.6	3.78E-02	10.9	4.79E-02	2.2	9.68E-03	1.1	4.84E-03	0.3	1.32E-03	0.4	1.76E-03	1.6	7.04E-03
B	0.54	15.9	6.80E-02	8.5	3.64E-02	3.0	1.28E-02	1.1	4.71E-03	0.5	2.14E-03	0.2	8.56E-04	2.0	8.56E-03
C	0.52	14.5	6.43E-02	7.6	3.37E-02	1.9	8.43E-03	0.9	3.99E-03	0.2	8.87E-04	1.3	5.77E-03	0.7	3.11E-03
Average	0.53		5.67E-02		3.93E-02		1.03E-02		4.51E-03		1.45E-03		2.79E-03		6.23E-03
Cumulative mass loss (lb/ft^2)			**5.67E-02**		**9.61E-02**		**1.06E-01**		**1.11E-01**		**1.12E-01**		**1.15E-01**		**1.21E-01**

Mixture: S-IC-8.9(2)

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	26.2	1.11E-01	5.1	2.16E-02	0.9	3.81E-03	0.9	3.81E-03	0.2	8.47E-04	0.6	2.54E-03	0.7	2.97E-03
B	0.54	19.1	8.18E-02	5.6	2.40E-02	6.1	2.61E-02	0.7	3.00E-03	0.1	4.28E-04	0.5	2.14E-03	0.3	1.28E-03
C	0.54	18.7	8.00E-02	5.4	2.31E-02	0.3	1.28E-03	1.0	4.28E-03	0.2	8.55E-04	0.8	3.42E-03	0.8	3.42E-03
Average	0.54		9.09E-02		2.29E-02		1.04E-02		3.70E-03		7.10E-04		2.70E-03		2.56E-03
Cumulative mass loss (lb/ft^2)			**9.09E-02**		**1.14E-01**		**1.24E-01**		**1.28E-01**		**1.29E-01**		**1.31E-01**		**1.34E-01**

Mixture: S-IC-9.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	4.7	2.03E-02	5.6	2.41E-02	0.8	3.45E-03	0.2	8.62E-04	0.2	8.62E-04	0.1	4.31E-04	0.2	8.62E-04
B	0.52	6.0	2.63E-02	1.0	4.38E-03	0.5	2.19E-03	0.3	1.32E-03	0.3	1.32E-03	0.8	3.51E-03	0.4	1.75E-03
C	0.53	4.0	1.72E-02	1.0	4.31E-03	1.4	6.03E-03	0.4	1.72E-03	0.1	4.31E-04	0.7	3.02E-03	0.4	1.72E-03
Average	0.53		2.13E-02		1.09E-02		3.89E-03		1.30E-03		8.70E-04		2.32E-03		1.45E-03
Cumulative mass loss (lb/ft^2)			**2.13E-02**		**3.22E-02**		**3.61E-02**		**3.74E-02**		**3.83E-02**		**4.06E-02**		**4.20E-02**

Table A.3 (con't): Scaling test results for mixtures in Program 2

Mixture: S-IC-14.1

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	15.8	6.76E-02	4.1	1.75E-02	2.0	8.56E-03	1.5	6.42E-03	0.9	3.85E-03	0.9	3.85E-03	0.4	1.71E-03
B	0.54	34.8	1.47E-01	6.6	2.79E-02	3.4	1.44E-02	3.0	1.27E-02	1.0	4.23E-03	1.4	5.93E-03	0.4	1.69E-03
C	0.54	27.6	1.18E-01	7.1	3.04E-02	3.7	1.58E-02	2.3	9.83E-03	10.3	4.40E-02	1.8	7.70E-03	1.1	4.70E-03
Average	0.54		1.11E-01		2.53E-02		1.29E-02		9.65E-03		1.74E-02		5.82E-03		2.70E-03
Cumulative mass loss (lb/ft^2)			**1.11E-01**		**1.36E-01**		**1.49E-01**		**1.59E-01**		**1.76E-01**		**1.82E-01**		**1.85E-01**

Mixture: S-Control(3)

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	14.1	6.09E-02	6.2	2.68E-02	1.7	7.35E-03	1.5	6.48E-03	0.4	1.73E-03	0.4	1.73E-03	0.3	1.30E-03
B	0.55	9.8	4.11E-02	5.3	2.22E-02	1.3	5.46E-03	1.1	4.62E-03	0.8	3.36E-03	1.0	4.20E-03	1.2	5.04E-03
C	0.55	12.7	5.32E-02	5.4	2.26E-02	2.4	1.01E-02	1.1	4.61E-03	0.3	1.26E-03	0.5	2.10E-03	0.7	2.93E-03
Average	0.54		5.18E-02		2.39E-02		7.62E-03		5.24E-03		2.11E-03		2.67E-03		3.09E-03
Cumulative mass loss (lb/ft^2)			**5.18E-02**		**7.57E-02**		**8.33E-02**		**8.85E-02**		**9.06E-02**		**9.33E-02**		**9.64E-02**

Mixture: S-IC-7.2(2)

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	14.0	5.93E-02	21.8	9.24E-02	1.0	4.24E-03	1.2	5.09E-03	0.9	3.81E-03	0.4	1.70E-03	1.9	8.05E-03
B	0.53	35.5	1.54E-01	3.8	1.64E-02	2.2	9.52E-03	0.5	2.16E-03	0.1	4.33E-04	0.7	3.03E-03	1.2	5.19E-03
C	0.54	21.6	9.15E-02	4.0	1.70E-02	1.4	5.93E-03	0.5	2.12E-03	0.1	4.24E-04	0.6	2.54E-03	1.3	5.51E-03
Average	0.54		1.02E-01		4.19E-02		6.56E-03		3.12E-03		1.56E-03		2.42E-03		6.25E-03
Cumulative mass loss (lb/ft^2)			**1.02E-01**		**1.43E-01**		**1.50E-01**		**1.53E-01**		**1.55E-01**		**1.57E-01**		**1.63E-01**

Mixture: S-IC-9.0

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.52	13.9	6.09E-02	6.9	3.02E-02	3.6	1.58E-02	2.3	1.01E-02	0.9	3.94E-03	1.2	5.26E-03	2.0	8.76E-03
B	0.54	15.8	6.76E-02	5.3	2.27E-02	2.1	8.99E-03	0.8	3.42E-03	0.4	1.71E-03	0.8	3.42E-03	2.1	8.99E-03
C	0.55	15.7	6.56E-02	5.2	2.17E-02	3.1	1.30E-02	2.0	8.36E-03	0.9	3.76E-03	1.0	4.18E-03	2.2	9.20E-03
Average	0.54		6.47E-02		2.49E-02		1.26E-02		7.29E-03		3.14E-03		4.29E-03		8.98E-03
Cumulative mass loss (lb/ft^2)			**6.47E-02**		**8.96E-02**		**1.02E-01**		**1.09E-01**		**1.13E-01**		**1.17E-01**		**1.26E-01**

Mixture: S-IC-9.1

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.56	2.4	9.87E-03	10.0	4.11E-02	4.0	1.64E-02	3.1	1.27E-02	0.9	3.70E-03	1.1	4.52E-03	1.7	6.99E-03
B	0.52	1.2	5.26E-03	7.9	3.46E-02	2.0	8.77E-03	1.6	7.02E-03	0.6	2.63E-03	1.3	5.70E-03	1.7	7.45E-03
C	0.54	1.5	6.40E-03	8.8	3.75E-02	1.8	7.67E-03	1.6	6.82E-03	0.8	3.41E-03	1.5	6.40E-03	1.9	8.10E-03
Average	0.54		7.18E-03		3.78E-02		1.10E-02		8.86E-03		3.25E-03		5.54E-03		7.52E-03
Cumulative mass loss (lb/ft^2)			**7.18E-03**		**4.49E-02**		**5.59E-02**		**6.48E-02**		**6.80E-02**		**7.35E-02**		**8.11E-02**

Table A.3 (con’t): Scaling test results for mixtures in Program 2

Mixture: T-Control

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	6.3	2.74E-02	5.8	2.52E-02	1.8	7.83E-03	1.0	4.35E-03	0.5	2.17E-03	0.7	3.04E-03	0.6	2.61E-03
B	0.51	5.6	2.53E-02	5.6	2.53E-02	1.1	4.97E-03	1.2	5.43E-03	0.4	1.81E-03	0.7	3.16E-03	0.7	3.16E-03
C	0.51	5.8	2.59E-02	6.0	2.68E-02	1.6	7.14E-03	0.7	3.13E-03	0.7	3.13E-03	0.7	3.13E-03	0.4	1.79E-03
Average	0.52		2.62E-02		2.58E-02		6.65E-03		4.30E-03		2.37E-03		3.11E-03		2.52E-03
Cumulative mass loss (lb/ft^2)			**2.62E-02**		**5.20E-02**		**5.86E-02**		**6.29E-02**		**6.53E-02**		**6.84E-02**		**7.09E-02**

Mixture: T-IC-8.9

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	14.9	6.67E-02	6.5	2.91E-02	2.3	1.03E-02	1.2	5.37E-03	0.7	3.13E-03	0.6	2.69E-03	0.7	3.13E-03
B	0.54	16.1	6.84E-02	8.1	3.44E-02	2.9	1.23E-02	1.9	8.07E-03	0.9	3.82E-03	1.3	5.52E-03	0.8	3.40E-03
C	0.52	11.5	5.09E-02	6.2	2.74E-02	2.3	1.02E-02	1.6	7.08E-03	0.3	1.33E-03	0.7	3.10E-03	0.5	2.21E-03
Average	0.52		6.20E-02		3.03E-02		1.09E-02		6.84E-03		2.76E-03		3.77E-03		2.91E-03
Cumulative mass loss (lb/ft^2)			**6.20E-02**		**9.23E-02**		**1.03E-01**		**1.10E-01**		**1.13E-01**		**1.17E-01**		**1.20E-01**

Mixture: C-Control(1)

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	0.4	1.79E-03	0.8	3.57E-03	1.8	8.04E-03	1.3	5.81E-03	0.9	4.02E-03	0.9	4.02E-03	0.3	1.34E-03
B	0.51	1.4	6.35E-03	2.6	1.18E-02	1.3	5.90E-03	0.9	4.08E-03	1.4	6.35E-03	0.5	2.27E-03	0.3	1.36E-03
C	0.53	1.1	4.80E-03	2.8	1.22E-02	3.3	1.44E-02	2.4	1.05E-02	0.8	3.49E-03	1.7	7.42E-03	0.6	2.62E-03
Average	0.52		4.31E-03		9.19E-03		9.45E-03		6.79E-03		4.62E-03		4.57E-03		1.77E-03
Cumulative mass loss (lb/ft^2)			**4.31E-03**		**1.35E-02**		**2.30E-02**		**2.97E-02**		**3.44E-02**		**3.89E-02**		**4.07E-02**

Mixture: C-IC-8.8

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.50	0.8	3.64E-03	0.9	4.10E-03	0.4	1.82E-03	0.6	2.73E-03	0.4	1.82E-03	0.7	3.19E-03	0.5	2.28E-03
B	0.52	0.4	1.77E-03	0.9	3.99E-03	0.7	3.10E-03	1.2	5.32E-03	0.5	2.22E-03	1.5	6.65E-03	1.0	4.43E-03
C	0.53	0.2	8.61E-04	1.3	5.60E-03	0.7	3.02E-03	0.5	2.15E-03	0.4	1.72E-03	0.6	2.58E-03	1.0	4.31E-03
Average	0.52		2.09E-03		4.56E-03		2.65E-03		3.40E-03		1.92E-03		4.14E-03		3.67E-03
Cumulative mass loss (lb/ft^2)			**2.09E-03**		**6.65E-03**		**9.30E-03**		**1.27E-02**		**1.46E-02**		**1.88E-02**		**2.24E-02**

Mixture: FA-Control

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.49	2.9	1.35E-02	14.6	6.80E-02	14.6	6.80E-02	5.3	2.47E-02	4.6	2.14E-02	6.0	2.79E-02	5.1	2.37E-02
B	0.51	0.8	3.58E-03	6.4	2.87E-02	12.6	5.64E-02	4.0	1.79E-02	3.8	1.70E-02	4.1	1.84E-02	2.7	1.21E-02
C	0.51	0.7	3.13E-03	2.7	1.21E-02	6.0	2.68E-02	2.3	1.03E-02	1.9	8.48E-03	1.6	7.14E-03	1.2	5.36E-03
Average	0.51		6.74E-03		3.62E-02		5.04E-02		1.76E-02		1.56E-02		1.78E-02		1.37E-02
Cumulative mass loss (lb/ft^2)			**6.74E-03**		**4.30E-02**		**9.34E-02**		**1.11E-01**		**1.27E-01**		**1.44E-01**		**1.58E-01**

Table A.3 (con't): Scaling test results for mixtures in Program 2

Mixture: **FA-IC-8.9**

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	1.0	4.36E-03	18.3	7.99E-02	4.2	1.83E-02	0.5	2.18E-03	1.4	6.11E-03	1.8	7.86E-03	1.2	5.24E-03
B	0.50	1.0	4.58E-03	18.6	8.53E-02	4.9	2.25E-02	1.3	5.96E-03	1.1	5.04E-03	1.2	5.50E-03	0.9	4.13E-03
C	0.53	1.1	4.81E-03	16.4	7.17E-02	3.6	1.57E-02	1.8	7.87E-03	1.0	4.37E-03	1.0	4.37E-03	0.7	3.06E-03
Average	0.52	☒	4.59E-03	☒	7.89E-02	☒	1.88E-02	☒	5.34E-03	☒	5.17E-03	☒	5.91E-03	☒	4.14E-03
Cumulative mass loss (lb/ft^2)			**4.59E-03**		**8.35E-02**		**1.02E-01**		**1.08E-01**		**1.13E-01**		**1.19E-01**		**1.23E-01**

Table A.4: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing *w/cm* ratios of 0.45 and 0.44

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**S-Control(1)**	**S-IC-6.9**	**S-IC-8.3(1)**	**S-IC-8.4(1)**	**S-IC-8.4(2)**	**S-IC-9.4**	**S-IC-7.2(1)**	**S-IC-8.3(2)**
		0.142	0.102	0.113	0.094	0.056	0.048	0.084	0.051
S-Control(1)	0.142		0.401	0.444	0.250	0.062	**0.048**	0.198	0.052
S-IC-6.9	0.102			0.697	0.790	0.150	0.103	0.583	0.117
S-IC-8.3(1)	0.113				0.221	**0.001**	**3.4×10^{-4}**	0.182	**4.4×10^{-4}**
S-IC-8.4(1)	0.094					**0.044**	**0.021**	0.650	**0.026**
S-IC-8.4(2)	0.056						0.278	0.202	0.481
S-IC-9.4	0.048							0.115	0.545
S-IC-7.2(1)	0.084								0.139
S-IC-8.3(2)	0.051								

Table A.5: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for S-IC-8.4(2) in Program 2 (varied curing duration and test surface)

S-IC-8.4(2)	**Average mass loss through 50 cycles (lb/ft^2)**	**14-day cure**	**28-day cure**	**14-day (bottom surface)**
		0.056	0.037	0.010
14-day cure (top surface)	0.056		**0.036**	**0.001**
28-day cure (top surface)	0.037			**2.8×10^{-4}**
14-day cure (underside surface)	0.010			

Table A.6: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing a *w/cm* ratio of 0.43

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**S-Control(2)**	**S-IC-7.3**	**S-IC-8.9(1)**	**S-IC-8.9(2)**	**S-IC-9.3**	**S-IC-14.1**	**C-Control(1)**	**C-IC-8.8**	**T-Control**	**T-IC-8.9**
		0.141	0.081	0.121	0.134	0.042	0.185	0.041	0.022	0.071	0.120
S-Control(2)	0.141		0.072	0.753	0.396	**0.008**	0.366	**0.009**	**0.004**	**0.024**	0.381
S-IC-7.3	0.081			**0.039**	0.070	0.072	0.062	**0.080**	**0.019**	0.559	0.097
S-IC-8.9(1)	0.121				0.330	**0.001**	0.262	**0.001**	**1.6×10^{-4}**	**0.002**	0.342
S-IC-8.9(2)	0.134					**0.001**	0.175	**0.001**	**2.9×10^{-4}**	**0.002**	0.883
S-IC-9.3	0.042						**0.020**	0.891	**0.022**	**0.004**	**0.002**
S-IC-14.1	0.185							**0.020**	**0.013**	**0.040**	0.171
C-Control(1)	0.041								0.091	**0.019**	**0.003**
C-IC-8.8	0.022									**5.8×10^{-5}**	**0.001**
T-Control	0.071										**0.008**
T-IC-8.9	0.120										

Table A.7: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing 100% portland cement, ternary binder system, or 35% Class F fly ash

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**C-Control(1)**	**C-IC-8.8**	**T-Control**	**T-IC-8.9**	**FA-Control**	**FA-IC-8.9**
		0.041	0.022	0.071	0.120	0.158	0.123
C-Control(1)	0.041		0.091	**0.019**	**0.003**	0.077	**0.001**
C-IC-8.8	0.022			**5.8×10^{-5}**	**0.001**	0.054	**1.1×10^{-4}**
T-Control	0.158				**0.008**	0.158	**0.001**
T-IC-8.9	0.123					0.492	0.783
FA-Control	0.158						0.525
FA-IC-8.9	0.123						

Table A.8: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing a *w/cm* ratio of 0.41

Mixture	Average mass loss through 50 cycles (lb/ft^2)	S-Control(3)	S-IC-7.2(2)	S-IC-9.0	S-IC-9.1
		0.096	0.163	0.126	0.081
S-Control(3)	0.096		**0.031**	**0.020**	0.177
S-IC-7.2(2)	0.163			0.140	**0.017**
S-IC-9.0	0.126				**0.008**
S-IC-9.1	0.081				

Table A.9: *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing similar IC water contents: (a) Control mixtures, (b) 6.9 to 7.3% IC, (c) 8.3 to 9.4% IC

(a)

Mixture	Average mass loss through 50 cycles (lb/ft^2)	S-Control(1)	S-Control(2)	S-Control(3)
		0.142	0.141	0.096
S-Control(1)	0.142		0.987	0.248
S-Control(2)	0.141			0.096
S-Control(3)	0.096			

(b)

Mixture	Average mass loss through 50 cycles (lb/ft^2)	S-IC-6.9	S-IC-7.2(1)	S-IC-7.3	S-IC-7.2(2)
		0.102	0.084	0.081	0.163
S-IC-6.9	0.102		0.583	0.505	0.133
S-IC-7.2(1)	0.084			0.895	**0.040**
S-IC-7.3	0.081				**0.029**
S-IC-7.2(2)	0.163				

Table A.9 (con't): *p* values obtained from Student's t-test for the differences in cumulative scaling mass loss for mixtures in Program 2 containing similar IC water contents: (a) Control mixtures, (b) 6.9 to 7.3% IC, (c) 8.3 to 9.4% IC

(c)

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**S-IC-8.3(1)**	**S-IC-8.4(1)**	**S-IC-8.4(2)**	**S-IC-9.4(1)**	**S-IC-8.3(2)**	**S-IC-8.9(1)**	**S-IC-8.9(2)**	**S-IC-9.3**	**S-IC-9.0**	**S-IC-9.1**
		0.113	0.094	0.056	0.048	0.051	0.121	0.134	0.042	0.126	0.081
S-IC-8.3(1)	0.113		0.221	**0.001**	**5.8×10^{-5}**	**3.4×10^{-4}**	0.119	0.395	**4.9×10^{-4}**	0.160	**0.021**
S-IC-8.4(1)	0.094			**0.044**	**0.021**	**0.026**	0.060	0.124	**0.016**	0.077	0.402
S-IC-8.4(2)	0.056				0.278	0.481	**0.002**	**0.002**	0.134	**0.001**	0.050
S-IC-9.4(1)	0.048					0.545	**0.001**	**0.001**	0.359	**2.0×10^{-4}**	**0.014**
S-IC-8.3(2)	0.051						**0.001**	**0.001**	0.205	**2.6×10^{-4}**	**0.019**
S-IC-8.9(1)	0.121							0.330	**0.001**	0.487	**0.011**
S-IC-8.9(2)	0.134								**0.001**	0.626	**0.015**
S-IC-9.3	0.042									**2.9×10^{-4}**	**0.011**
S-IC-9.0	0.126										**0.008**
S-IC-9.1	0.081										

Table A.10: Scaling test results for mixtures in Program 3

Mixture: S-Control

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	2.6	1.17E-02	6.1	2.76E-02	1.4	6.32E-03	0.3	1.35E-03	0.4	1.81E-03	0.2	9.03E-04	0.6	2.71E-03
B	0.52	1.6	7.01E-03	4.1	1.80E-02	1.0	4.38E-03	0.4	1.75E-03	1.1	4.82E-03	0.5	2.19E-03	0.7	3.07E-03
C	0.52	1.7	7.52E-03	4.8	2.12E-02	1.2	5.31E-03	1.1	4.86E-03	0.8	3.54E-03	0.4	1.77E-03	0.6	2.65E-03
Average	0.52	☒	8.76E-03	☒	2.22E-02	☒	5.34E-03	☒	2.66E-03	☒	3.39E-03	☒	1.62E-03	☒	2.81E-03
Cumulative mass loss (lb/ft^2)			**8.76E-03**		**3.10E-02**		**3.63E-02**		**3.90E-02**		**4.24E-02**		**4.40E-02**		**4.68E-02**

Mixture: S-IC-6.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	1.6	6.82E-03	2.9	1.24E-02	1.0	4.26E-03	0.5	2.13E-03	0.0	#######	0.4	1.71E-03	0.4	1.71E-03
B	0.54	2.0	8.56E-03	4.6	1.97E-02	1.3	5.56E-03	0.3	1.28E-03	0.5	2.14E-03	0.3	1.28E-03	0.7	2.99E-03
C	0.54	2.2	9.41E-03	3.0	1.28E-02	0.8	3.42E-03	0.5	2.14E-03	0.1	4.28E-04	0.3	1.28E-03	0.5	2.14E-03
Average	0.54	☒	8.26E-03	☒	1.50E-02	☒	4.42E-03	☒	1.85E-03	☒	8.56E-04	☒	1.42E-03	☒	2.28E-03
Cumulative mass loss (lb/ft^2)			**8.26E-03**		**2.32E-02**		**2.76E-02**		**2.95E-02**		**3.03E-02**		**3.18E-02**		**3.41E-02**

Mixture: S-IC-6.6

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	1.6	6.86E-03	3.6	1.54E-02	0.8	3.43E-03	0.9	3.86E-03	0.7	3.00E-03	0.9	3.86E-03	0.5	2.14E-03
B	0.50	0.8	3.68E-03	4.2	1.93E-02	0.2	9.20E-04	0.4	1.84E-03	0.0	#######	0.5	2.30E-03	0.5	2.30E-03
C	0.53	0.8	3.43E-03	3.8	1.63E-02	0.9	3.86E-03	0.7	3.01E-03	0.2	8.59E-04	0.5	2.15E-03	0.3	1.29E-03
Average	0.52	☒	4.66E-03	☒	1.70E-02	☒	2.74E-03	☒	2.90E-03	☒	1.29E-03	☒	2.77E-03	☒	1.91E-03
Cumulative mass loss (lb/ft^2)			**4.66E-03**		**2.17E-02**		**2.44E-02**		**2.73E-02**		**2.86E-02**		**3.14E-02**		**3.33E-02**

Table A.10 (con't): Scaling test results for mixtures in Program 3

Mixture: **S-IC-6.8**

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.52	0.9	3.96E-03	2.8	1.23E-02	0.7	3.08E-03	0.4	1.76E-03	0.7	3.08E-03	0.2	8.80E-04	0.5	2.20E-03
B	0.50	1.1	5.07E-03	3.4	1.57E-02	1.0	4.61E-03	0.4	1.84E-03	0.2	9.22E-04	0.4	1.84E-03	0.4	1.84E-03
C	0.54	1.2	5.08E-03	1.9	8.05E-03	0.3	1.27E-03	0.1	4.23E-04	0.2	8.47E-04	0.3	1.27E-03	0.5	2.12E-03
Average	0.52		4.70E-03		1.20E-02		2.99E-03		1.34E-03		1.62E-03		1.33E-03		2.05E-03
Cumulative mass loss (lb/ft^2)			**4.70E-03**		**1.67E-02**		**1.97E-02**		**2.10E-02**		**2.27E-02**		**2.40E-02**		**2.61E-02**

Mixture: **S-IC-8.0**

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	0.5	2.25E-03	2.4	1.08E-02	0.5	2.25E-03	0.4	1.80E-03	0.0	#######	0.1	4.49E-04	0.2	8.98E-04
B	0.54	0.7	2.99E-03	2.5	1.07E-02	0.5	2.14E-03	0.2	8.55E-04	0.1	4.28E-04	0.3	1.28E-03	0.3	1.28E-03
C	0.51	0.7	3.14E-03	3.1	1.39E-02	0.9	4.04E-03	0.4	1.80E-03	0.3	1.35E-03	0.4	1.80E-03	0.3	1.35E-03
Average	0.52		2.79E-03		1.18E-02		2.81E-03		1.48E-03		5.92E-04		1.18E-03		1.18E-03
Cumulative mass loss (lb/ft^2)			**2.79E-03**		**1.46E-02**		**1.74E-02**		**1.89E-02**		**1.95E-02**		**2.07E-02**		**2.18E-02**

Mixture: **S-IC-10.2**

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	1.4	6.05E-03	3.5	1.51E-02	0.7	3.03E-03	0.5	2.16E-03	0.5	2.16E-03	0.2	8.65E-04	0.4	1.73E-03
B	0.51	0.8	3.59E-03	1.7	7.64E-03	0.3	1.35E-03	0.1	4.49E-04	0.1	4.49E-04	0.1	4.49E-04	0.2	8.98E-04
C	0.53	1.4	6.09E-03	2.9	1.26E-02	0.9	3.91E-03	0.3	1.30E-03	0.4	1.74E-03	0.2	8.70E-04	0.2	8.70E-04
Average	0.52		5.25E-03		1.18E-02		2.76E-03		1.31E-03		1.45E-03		7.28E-04		1.17E-03
Cumulative mass loss (lb/ft^2)			**5.25E-03**		**1.70E-02**		**1.98E-02**		**2.11E-02**		**2.26E-02**		**2.33E-02**		**2.45E-02**

Mixture: **S-IC-12.1**

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	3.0	1.35E-02	4.2	1.89E-02	0.5	2.25E-03	0.5	2.25E-03	0.3	1.35E-03	0.0	#######	0.1	4.51E-04
B	0.51	1.6	7.23E-03	3.9	1.76E-02	0.4	1.81E-03	0.6	2.71E-03	0.3	1.36E-03	0.2	9.04E-04	0.4	1.81E-03
C	0.51	3.8	1.72E-02	5.1	2.31E-02	0.5	2.27E-03	0.5	2.27E-03	0.4	1.82E-03	0.2	9.08E-04	0.1	4.54E-04
Average	0.51		1.27E-02		1.99E-02		2.11E-03		2.41E-03		1.51E-03		6.04E-04		9.04E-04
Cumulative mass loss (lb/ft^2)			**1.27E-02**		**3.26E-02**		**3.47E-02**		**3.71E-02**		**3.86E-02**		**3.92E-02**		**4.01E-02**

Mixture: **C-Control**

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.54	1.7	7.18E-03	3.1	1.31E-02	2.0	8.45E-03	0.5	2.11E-03	1.5	6.34E-03	1.8	7.60E-03	2.1	8.87E-03
B	0.58	4.0	1.59E-02	7.4	2.94E-02	2.4	9.53E-03	1.5	5.96E-03	1.0	3.97E-03	5.0	1.99E-02	7.3	2.90E-02
C	0.52	1.2	5.33E-03	3.3	1.47E-02	1.1	4.89E-03	0.5	2.22E-03	1.6	7.11E-03	1.1	4.89E-03	1.4	6.22E-03
Average	0.55		9.47E-03		1.90E-02		7.62E-03		3.43E-03		5.81E-03		1.08E-02		1.47E-02
Cumulative mass loss (lb/ft^2)			**9.47E-03**		**2.85E-02**		**3.61E-02**		**3.96E-02**		**4.54E-02**		**5.62E-02**		**7.09E-02**

Table A.10 (con't): Scaling test results for mixtures in Program 3

Mixture: C-IC-3.8

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.50	0.9	4.10E-03	0.8	3.65E-03	0.4	1.82E-03	0.1	4.56E-04	0.2	9.12E-04	0.5	2.28E-03	0.3	1.37E-03
B	0.48	0.5	2.38E-03	1.3	6.18E-03	0.5	2.38E-03	0.2	9.50E-04	0.4	1.90E-03	0.9	4.28E-03	1.1	5.23E-03
C	0.49	1.2	5.60E-03	1.1	5.13E-03	0.7	3.27E-03	0.1	4.67E-04	0.4	1.87E-03	0.2	9.33E-04	0.7	3.27E-03
Average	0.49		4.03E-03		4.99E-03		2.49E-03		6.24E-04		1.56E-03		2.50E-03		3.29E-03
Cumulative mass loss (lb/ft^2)			**4.03E-03**		**9.01E-03**		**1.15E-02**		**1.21E-02**		**1.37E-02**		**1.62E-02**		**1.95E-02**

Mixture: C-IC-7.3

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.53	0.5	2.18E-03	0.8	3.49E-03	0.7	3.05E-03	0.7	3.05E-03	0.2	8.71E-04	1.2	5.23E-03	0.2	8.71E-04
B	0.53	1.4	6.12E-03	1.4	6.12E-03	1.1	4.81E-03	0.6	2.62E-03	0.4	1.75E-03	0.5	2.19E-03	0.1	4.37E-04
C	0.53	1.0	4.36E-03	2.3	1.00E-02	0.9	3.92E-03	0.2	8.72E-04	0.2	8.72E-04	0.4	1.74E-03	0.1	4.36E-04
Average	0.53		4.22E-03		6.54E-03		3.93E-03		2.18E-03		1.16E-03		3.05E-03		5.81E-04
Cumulative mass loss (lb/ft^2)			**4.22E-03**		**1.08E-02**		**1.47E-02**		**1.69E-02**		**1.80E-02**		**2.11E-02**		**2.17E-02**

Mixture: C-IC-9.8

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.48	1.4	6.64E-03	1.2	5.70E-03	0.7	3.32E-03	0.4	1.90E-03	0.4	1.90E-03	0.6	2.85E-03	0.4	1.90E-03
B	0.51	0.9	4.07E-03	1.3	5.87E-03	0.5	2.26E-03	0.7	3.16E-03	0.4	1.81E-03	0.4	1.81E-03	0.5	2.26E-03
C	0.52	1.7	7.47E-03	1.8	7.91E-03	0.4	1.76E-03	0.6	2.64E-03	0.4	1.76E-03	0.5	2.20E-03	0.6	2.64E-03
Average	0.50		6.06E-03		6.49E-03		2.45E-03		2.57E-03		1.82E-03		2.28E-03		2.27E-03
Cumulative mass loss (lb/ft^2)			**6.06E-03**		**1.26E-02**		**1.50E-02**		**1.76E-02**		**1.94E-02**		**2.17E-02**		**2.39E-02**

Mixture: C-IC-11.8

Specimen	Effective Area ft^2	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
A	0.51	1.3	5.88E-03	2.8	1.27E-02	1.4	6.33E-03	1.5	6.78E-03	0.9	4.07E-03	2.0	9.04E-03	1.3	5.88E-03
B	0.51	1.4	6.28E-03	3.0	1.35E-02	2.2	9.86E-03	1.2	5.38E-03	0.9	4.04E-03	0.9	4.04E-03	1.0	4.48E-03
C	0.49	1.1	5.10E-03	2.2	1.02E-02	0.8	3.71E-03	0.8	3.71E-03	0.6	2.78E-03	0.3	1.39E-03	1.0	4.64E-03
Average	0.50		5.75E-03		1.21E-02		6.64E-03		5.29E-03		3.63E-03		4.82E-03		5.00E-03
Cumulative mass loss (lb/ft^2)			**5.75E-03**		**1.79E-02**		**2.45E-02**		**2.98E-02**		**3.34E-02**		**3.82E-02**		**4.32E-02**

Table A.11: *p* values obtained from Student’s t-test for the differences in cumulative scaling mass loss for mixtures in Program 3

Mixture	**Average mass loss through 50 cycles (lb/ft^2)**	**S-Control**	**S-IC-6.3**	**S-IC-6.6**	**S-IC-6.8**	**S-IC-8.0**	**S-IC-10.2**	**S-IC-12.1**	**C-Control**	**C-IC-3.8**	**C-IC-7.3**	**C-IC-9.8**	**C-IC-11.8**
		0.047	0.034	0.033	0.026	0.022	0.025	0.040	0.071	0.020	0.022	0.024	0.043
S-Control	0.047		0.063	**0.032**	**0.014**	**0.004**	**0.019**	0.280	0.331	**0.003**	**0.002**	**0.003**	0.624
S-IC-6.3	0.034			0.877	0.207	0.061	0.198	0.380	0.167	0.033	0.039	0.068	0.261
S-IC-6.6	0.033				0.189	**0.041**	0.190	0.248	0.158	**0.020**	**0.020**	**0.037**	0.200
S-IC-6.8	0.026					0.417	0.809	0.069	0.109	0.220	0.339	0.627	0.070
S-IC-8.0	0.022						0.809	**0.023**	0.086	0.569	0.963	0.542	**0.031**
S-IC-10.2	0.025							0.075	0.103	0.421	0.619	0.926	0.071
S-IC-12.1	0.040								0.233	**0.014**	**0.016**	**0.024**	0.690
C-Control	0.071									0.076	0.085	0.095	0.283
C-IC-3.8	0.020										0.504	0.206	**0.021**
C-IC-7.3	0.022											0.351	**0.024**
C-IC-9.8	0.024												**0.034**
C-IC-11.8	0.043												

Table A.12: Freeze-thaw test results for mixtures in Program 1

S-IC-5.5(1)

Cycles	0			22			51			74		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2178	2141	2162	2199	2167	2178	2207	2174	2191	2210	2176	2195
Mass [g]	7523	7531.8	7512.5	7537.8	7546.9	7522.4	7538.9	7548.5	7526.5	7541.8	7549.4	7525.4
$E_{Dyn.}$ [Pa]	3.9E+10	3.7E+10	3.8E+10	3.9E+10	3.8E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.80E+10			3.89E+10			3.92E+10			3.93E+10		

S-IC-5.5(1)

Cycles	96			126			149			186		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2217	2181	2200	2219	2183	2204	2228	2190	2211	2230	2192	2215
Mass [g]	7543.1	7549	7525.5	7540.6	7545.9	7524.4	7543.1	7545	7525.9	7542.2	7545.6	7525.9
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.95E+10			3.96E+10			3.99E+10			4.00E+10		

S-IC-5.5(1)

Cycles	224			263			292			323		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2234	2201	2220	2244	2210	2229	2247	2214	2234	2250	2218	2236
Mass [g]	7543.7	7547.8	7527	7542.6	7543.8	7524.3	7542.3	7543.9	7523.3	7543.2	7544.9	7523.4
$E_{Dyn.}$ [Pa]	4.1E+10	4.0E+10	4.0E+10	4.1E+10	4.0E+10	4.1E+10	4.1E+10	4.0E+10	4.1E+10	4.1E+10	4.0E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.02E+10			4.05E+10			4.07E+10			4.08E+10		

S-IC-5.6(1)

Cycles	0			29			52			73		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2081	2119	2113	2104	2141	2134	2112	2149	2141	2117	2156	2146
Mass [g]	7287.7	7346.4	7343.1	7308.1	7362.7	7356.1	7310.8	7361.6	7362.1	7313	7364	7362.3
$E_{Dyn.}$ [Pa]	3.4E+10	3.6E+10	3.6E+10	3.5E+10	3.7E+10	3.6E+10	3.5E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.52E+10			3.60E+10			3.62E+10			3.64E+10		

S-IC-5.6(1)

Cycles	104			127			164			202		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2121	2158	2151	2131	2161	2158	2134	2167	2163	2140	2163	2168
Mass [g]	7311.7	7364.7	7363.1	7311.7	7365	7363.5	7313.3	7364.4	7367.6	7315.1	7363.7	7369.7
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.66E+10			3.68E+10			3.70E+10			3.71E+10		

S-IC-5.6(1)

Cycles	241			270			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2147	2178	2175	2151	2182	2181	2155	2181	2191
Mass [g]	7314.6	7365.3	7370.2	7316.5	7365.8	7370.6	7316.2	7369	7372.5
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.74E+10			3.76E+10			3.77E+10		

S-IC-6.6

Cycles	0			22			51			74		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2130	2107	2119	2153	2130	2142	2162	2134	2148	2161	2136	2150
Mass [g]	7233	7275.1	7265	7246.6	7293.2	7280.6	7251.1	7289.3	7283	7253.3	7293.8	7285.5
$E_{Dyn.}$ [Pa]	3.6E+10	3.5E+10	3.5E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.53E+10			3.62E+10			3.64E+10			3.64E+10		

S-IC-6.6

Cycles	96			126			149			186		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2168	2141	2154	2170	2142	2161	2175	2147	2158	2175	2150	2167
Mass [g]	7253.7	7291.7	7286.6	7255.2	7291.8	7286.8	7259	7292	7286.2	7255	7282.6	7290.6
$E_{Dyn.}$ [Pa]	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.66E+10			3.67E+10			3.68E+10			3.69E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.12 (con't): Freeze-thaw test results for mixtures in Program 1

S-IC-6.6

Cycles	224			263			292			323		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2181	2156	2176	2187	2161	2183	2192	2169	2181	2193	2170	2179
Mass [g]	7258.2	7296.5	7290.9	7258.8	7295.6	7291.9	7259	7296.5	7293.1	7260.2	7297.3	7290.9
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.72E+10			3.74E+10			3.75E+10			3.75E+10		

S-IC-7.3

Cycles	0			29			52			73		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2230	2207	2198	2239	2212	2222	2239	2234	2226	2242	2236	2230
Mass [g]	7519	7507.4	7529.6	7517.9	7474.3	7593.4	7518.7	7481.7	7541.1	7517.8	7482.8	7541.8
$E_{Dyn.}$ [Pa]	4.1E+10	4.0E+10	3.9E+10	4.1E+10	4.0E+10	4.1E+10	4.1E+10	4.0E+10	4.0E+10	4.1E+10	4.1E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.99E+10			4.04E+10			4.06E+10			4.07E+10		

S-IC-7.3

Cycles	104			127			164			202		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2246	2240	2234	2244	2245	2232	2252	2247	2240	2256	2250	2248
Mass [g]	7517.8	7487.3	7539.9	7518	7483.9	7538.1	7519.5	7484.3	7542	7519.1	7488.1	7542.9
$E_{Dyn.}$ [Pa]	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.09E+10			4.09E+10			4.11E+10			4.13E+10		

S-IC-7.3

Cycles	241			270			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2263	2256	2253	2267	2263	2260	2267	2266	2261
Mass [g]	7519.8	7486.4	7542.6	7520.9	7486.1	7542.6	7520.3	7487.2	7542.9
$E_{Dyn.}$ [Pa]	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.15E+10			4.17E+10			4.18E+10		

S-IC-9.3

Cycles	0			31			61			79		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2131	2126	2148	2151	2156	2178	2160	2157	2179	2173	2167	2187
Mass [g]	7359.9	7386.8	7434.7	7377	7405.4	7449.7	7377.8	7405.9	7453	7381.1	7406.9	7455
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.7E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.8E+10	3.8E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.65E+10			3.75E+10			3.77E+10			3.80E+10		

S-IC-9.3

Cycles	103			147			186			216		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2157	2185	2207	2149	2185	2211	2150	2191	2210	2148	2195	2217
Mass [g]	7380.8	7413.3	7460.6	7380	7415.3	7461.3	7372.5	7414.6	7461	7368.1	7415.3	7461.4
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.9E+10	3.7E+10	3.8E+10	4.0E+10	3.7E+10	3.9E+10	3.9E+10	3.7E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.83E+10			3.83E+10			3.83E+10			3.84E+10		

S-IC-9.3

Cycles	246			289			304		
`Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2147	2194	2210	2139	2199	2196	2192	2169	2181
Mass [g]	7363.5	7412.7	7459.7	7360.4	7414	7464.5	7259	7296.5	7293.1
$E_{Dyn.}$ [Pa]	3.7E+10	3.9E+10	3.9E+10	3.6E+10	3.9E+10	3.9E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.83E+10			3.81E+10			3.75E+10		

C-IC-5.7

Cycles	0			22			51			74		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2194	2156	2188	2218	2167	2204	2218	2178	2206	2217	2175	2207
Mass [g]	7499	7449.2	7447.7	7523.8	7465.6	7471.2	7519.3	7470.2	7474.6	7520	7472.2	7476
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	3.9E+10	4.0E+10	3.8E+10	3.9E+10	4.0E+10	3.8E+10	3.9E+10	4.0E+10	3.8E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.84E+10			3.91E+10			3.93E+10			3.93E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.12 (con't): Freeze-thaw test results for mixtures in Program 1

C-IC-5.7

Cycles	**96**			**126**			**149**			**186**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2221**	**2183**	**2209**	**2225**	**2186**	**2214**	**2228**	**2190**	**2220**	**2232**	**2191**	**2223**
Mass [g]	**7523.6**	**7473.3**	**7476.4**	**7521.2**	**7473.4**	**7476.8**	**7522.2**	**7473.8**	**7477.4**	**7523.9**	**7476**	**7476**
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	**3.94E+10**			**3.96E+10**			**3.97E+10**			**3.98E+10**		

C-IC-5.7

Cycles	**224**			**263**			**292**			**323**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2237**	**2196**	**2228**	**2243**	**2202**	**2234**	**2246**	**2206**	**2239**	**2249**	**2209**	**2246**
Mass [g]	**7525.1**	**7477**	**7478.1**	**7523.6**	**7476.5**	**7477.4**	**7525.9**	**7478.5**	**7477.7**	**7526.2**	**7478.7**	**7478.5**
$E_{Dyn.}$ [Pa]	4.1E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.1E+10	4.1E+10	4.0E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	**4.00E+10**			**4.02E+10**			**4.04E+10**			**4.06E+10**		

T-IC-8.2

Cycles	**0**			**22**			**51**			**74**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2159**	**2155**	**2168**	**2191**	**2184**	**2195**	**2194**	**2190**	**2200**	**2195**	**2192**	**2201**
Mass [g]	**7387.5**	**7415.5**	**7406.5**	**7398.6**	**7424**	**7416**	**7399.3**	**7429.4**	**7415.2**	**7398.7**	**7425.4**	**7413.1**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.8E+10	3.8E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.75E+10**			**3.85E+10**			**3.87E+10**			**3.87E+10**		

T-IC-8.2

Cycles	**96**			**126**			**149**			**186**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2200**	**2198**	**2205**	**2209**	**2202**	**2210**	**2210**	**2200**	**2214**	**2209**	**2211**	**2216**
Mass [g]	**7399.4**	**7425.4**	**7413.9**	**7398.5**	**7424.3**	**7412.2**	**7399**	**7424.7**	**7414.2**	**7400.7**	**7425.7**	**7413.9**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.89E+10**			**3.91E+10**			**3.92E+10**			**3.93E+10**		

T-IC-8.2

Cycles	**224**			**263**			**292**			**323**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2218**	**2217**	**2223**	**2220**	**2224**	**2230**	**2228**	**2229**	**2238**	**2230**	**2233**	**2238**
Mass [g]	**7402.1**	**7423.2**	**7413.3**	**7401**	**7423.4**	**7413.1**	**7402.6**	**7425**	**7413.5**	**7401.6**	**7425.2**	**7414.7**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	**3.96E+10**			**3.98E+10**			**4.00E+10**			**4.01E+10**		

T-IC-8.3(1)

Cycles	**0**			**22**			**51**			**74**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1979**	**1974**	**1991**	**2009**	**2000**	**2014**	**2016**	**2013**	**2025**	**2018**	**2015**	**2031**
Mass [g]	**7125.9**	**7134.4**	**7176.8**	**7146.5**	**7158**	**7194.1**	**7150.7**	**7159.2**	**7197.2**	**7152**	**7159.9**	**7198**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.04E+10**			**3.13E+10**			**3.16E+10**			**3.17E+10**		

T-IC-8.3(1)

Cycles	**96**			**126**			**149**			**186**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2024**	**2023**	**2036**	**2028**	**2025**	**2043**	**2026**	**2027**	**2042**	**2034**	**2035**	**2051**
Mass [g]	**7154.6**	**7153.1**	**7199.5**	**7154.5**	**7163.5**	**7197.9**	**7154.5**	**7164**	**7197.5**	**7150.4**	**7164.2**	**7204.2**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.19E+10**			**3.21E+10**			**3.21E+10**			**3.23E+10**		

T-IC-8.3(1)

Cycles	**224**			**263**			**292**			**323**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2043**	**2042**	**2061**	**2055**	**2053**	**2069**	**2059**	**2062**	**2075**	**2061**	**2066**	**2079**
Mass [g]	**7148.3**	**7163.9**	**7202.1**	**7150.3**	**7164.9**	**7202.2**	**7152.9**	**7164.4**	**7202**	**7153.3**	**7163.8**	**7200.2**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.26E+10**			**3.30E+10**			**3.32E+10**			**3.33E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.12 (con't): Freeze-thaw test results for mixtures in Program 1

S-IC-7.1

Cycles	0			22			51			74		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2241	2229	2246	2263	2254	2272	2272	2268	2278	2272	2268	2278
Mass [g]	7579.1	7454.5	7487	7591.4	7463.9	7500.3	7592.4	7465.3	7505	7592.4	7465.3	7505
$E_{Dyn.}$ [Pa]	4.1E+10	4.0E+10	4.1E+10	4.2E+10	4.1E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.08E+10			4.17E+10			4.21E+10			4.21E+10		

S-IC-7.1

Cycles	96			126			149			186		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2274	2171	2285	2288	2200	2291	2290	2284	2298	2290	2280	2294
Mass [g]	7590.5	7465.3	7503	7594.3	7468.2	7505.9	7597	7469.2	7506.6	7595.3	7469.8	7508
$E_{Dyn.}$ [Pa]	4.3E+10	3.8E+10	4.2E+10	4.3E+10	3.9E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.10E+10			4.16E+10			4.28E+10			4.27E+10		

S-IC-7.1

Cycles	224			263			292			323		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2297	2289	2302	2297	2286	2303	2299	2290	2302	2193	2170	2179
Mass [g]	7597.4	7470.2	7511.3	7598	7471.1	7508.3	7596	7468.9	7507.4	7260.2	7297.3	7290.9
$E_{Dyn.}$ [Pa]	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.4E+10	4.2E+10	4.3E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	4.30E+10			4.30E+10			4.30E+10			3.75E+10		

S-IC-7.2

Cycles	0			29			52			73		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2148	2181	2148	2169	2203	2168	2177	2208	2176	2178	2212	2158
Mass [g]	7386.4	7499.3	7395.3	7404.6	7512	7407.4	7406.3	7514.2	7410.4	7407.9	7517.2	7410.8
$E_{Dyn.}$ [Pa]	3.7E+10	3.9E+10	3.7E+10	3.8E+10	4.0E+10	3.8E+10	3.8E+10	4.0E+10	3.8E+10	3.8E+10	4.0E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.75E+10			3.83E+10			3.86E+10			3.84E+10		

S-IC-7.2

Cycles	104			127			164			202		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2183	2217	2182	2185	2215	2180	2191	2226	2190	2196	2229	2198
Mass [g]	7408.2	7515.9	7411.6	7408	7516.3	7412.6	7410.9	7519.5	7416.2	7411.4	7520.7	7415.5
$E_{Dyn.}$ [Pa]	3.8E+10	4.0E+10	3.8E+10	3.8E+10	4.0E+10	3.8E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.88E+10			3.88E+10			3.92E+10			3.93E+10		

S-IC-7.2

Cycles	241			270			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2204	2237	2204	2208	2244	2207	2209	2247	2208
Mass [g]	7412.7	7521.1	7417.8	7412.7	7521.3	7417.1	7414.6	7523.1	7417.5
$E_{Dyn.}$ [Pa]	3.9E+10	4.1E+10	3.9E+10	3.9E+10	4.1E+10	3.9E+10	3.9E+10	4.1E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.96E+10			3.98E+10			3.99E+10		

S-IC-9.1

Cycles	0			29			52			73		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2137	2105	2126	2162	2126	2151	2167	2130	2154	2170	2135	2158
Mass [g]	7305.4	7281.7	7225.2	7319.4	7290.9	7238.7	7320.8	7294.7	7242	7320.7	7294.5	7244.1
$E_{Dyn.}$ [Pa]	3.6E+10	3.5E+10	3.5E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.55E+10			3.64E+10			3.65E+10			3.66E+10		

S-IC-9.1

Cycles	104			127			164			202		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2174	2139	2163	2176	2138	2162	2177	2144	2167	2186	2153	2175
Mass [g]	7321.3	7295.5	7245	7322.1	7295.1	7245.9	7321.8	7294.6	7247.3	7322.9	7293.8	7247.7
$E_{Dyn.}$ [Pa]	3.7E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.68E+10			3.68E+10			3.69E+10			3.72E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.12 (con't): Freeze-thaw test results for mixtures in Program 1

S-IC-9.1

Cycles	241			270			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2191	2162	2182	2198	2162	2187	2196	2166	2190
Mass [g]	7323.3	7295	7246.6	7323.7	7295.6	7246.5	7325.2	7297.1	7247.6
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.75E+10			3.76E+10			3.77E+10		

S-IC-9.1

Cycles	0			31			61			79		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2188	2194	-	2218	2223	-	2222	2222	-	2228	2231	-
Mass [g]	7549.7	7542.3	-	7573.9	7564.6	-	7563.5	7559.2	-	7562.8	7562.2	-
$E_{Dyn.}$ [Pa]	3.6E+10	3.5E+10	-	3.6E+10	3.6E+10	-	3.7E+10	3.6E+10	-	3.7E+10	3.6E+10	-
Avg. $E_{Dyn.}$ [Pa]	3.53E+10			3.61E+10			3.63E+10			3.64E+10		

S-IC-9.1

Cycles	103			147			186			216		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2229	2238	-	2244	2251	-	2249	2253	-	2252	2252	-
Mass [g]	7564.1	7561.7	-	7566.3	7563.9	-	7567	7564.7	-	7569.5	7566.9	-
$E_{Dyn.}$ [Pa]	3.7E+10	3.6E+10	-	3.7E+10	3.6E+10	-	3.7E+10	3.6E+10	-	3.7E+10	3.6E+10	-
Avg. $E_{Dyn.}$ [Pa]	3.66E+10			3.66E+10			3.68E+10			3.68E+10		

S-IC-9.1

Cycles	246			289			289		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2255	2260	-	2256	2261	-	2258	2260	-
Mass [g]	7571.1	7568.5	-	7568.9	7565.5	-	7568.7	7566.2	-
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	-	3.8E+10	3.7E+10	-	4.2E+10	4.2E+10	-
Avg. $E_{Dyn.}$ [Pa]	3.71E+10			3.73E+10			4.18E+10		

S-IC-7.0

Cycles	0			31			61			79		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2078	2089	2052	2099	2111	2075	2099	2112	2076	2103	2117	2080
Mass [g]	7035.1	7032.5	7035.6	7047.4	7043.8	7050.7	7052.7	7047.7	7052.7	7054.3	7047.6	7054.6
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.28E+10			3.35E+10			3.36E+10			3.37E+10		

S-IC-7.0

Cycles	103			147			186			216		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2103	2123	2084	2113	2129	2093	2116	2133	2094	2120	2130	2097
Mass [g]	7053.6	7049.1	7054.8	7061.2	7055.4	7059.2	7059	7052.7	7060.3	7059.7	7057.4	7061.3
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.38E+10			3.41E+10			3.42E+10			3.42E+10		

S-IC-7.0

Cycles	246			289			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2126	2139	2100	2121	2136	2100	2124	2137	2102
Mass [g]	7061.8	7056.1	7061.7	7060.4	7055.1	7060.4	7060.3	7054.3	7060.4
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.44E+10			3.43E+10			3.44E+10		

S-IC-9.4(2)

Cycles	0			30			60			78		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2202	2179	2181	2222	2200	2201	2223	2197	2202	2229	2206	2208
Mass [g]	7287.9	7245.6	7238.9	7300.3	7254.3	7248.7	7301.2	7256.9	7249.5	7301.6	7255.7	7251.4
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.76E+10			3.84E+10			3.84E+10			3.86E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.12 (con't): Freeze-thaw test results for mixtures in Program 1

S-IC-9.4(2)

Cycles	**102**			**146**			**185**			**215**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2233**	**2210**	**2209**	**2236**	**2212**	**2218**	**2241**	**2217**	**2217**	**2244**	**2218**	**2220**
Mass [g]	**7303.5**	**7257.6**	**7252.7**	**7313.8**	**7259.7**	**7258.9**	**7305.7**	**7260.4**	**7255.9**	**7307.7**	**7262**	**7257.1**
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	3.8E+10	4.0E+10	3.8E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.87E+10**			**3.89E+10**			**3.90E+10**			**3.91E+10**		

S-IC-9.4(2)

Cycles	**245**			**288**			**303**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2247**	**2222**	**2224**	**2245**	**2219**	**2223**	**2247**	**2223**	**2223**
Mass [g]	**7306.8**	**7261.3**	**7259**	**7308.8**	**7261.4**	**7257.9**	**7307.2**	**7260.8**	**7258**
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.92E+10**			**3.92E+10**			**3.92E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13: Freeze-thaw test results for mixtures in Program 2

S-Control(1)

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2110**	**2122**	**2096**	**2129**	**2140**	**2118**	**2136**	**2150**	**2126**	**2150**	**2163**	**2136**
Mass [g]	**7279.4**	**7275.4**	**7270.6**	**7297.1**	**7294.9**	**7287**	**7298.8**	**7297.6**	**7286.4**	**7301.8**	**7301.3**	**7288.3**
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.51E+10**			**3.58E+10**			**3.61E+10**			**3.65E+10**		

S-Control(1)

Cycles	**120**			**150**			**185**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2135**	**2147**	**2120**	**2128**	**2147**	**2126**	**2134**	**2153**	**2124**	**2135**	**2157**	**2138**
Mass [g]	**7302.1**	**7300.4**	**7290.7**	**7301.6**	**7300.1**	**7290.3**	**7301.5**	**7297.3**	**7290.7**	**7299.4**	**7295.8**	**7288.7**
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.60E+10**			**3.60E+10**			**3.61E+10**			**3.63E+10**		

S-Control(1)

Cycles	**260**			**280**			**300**			**333**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2137**	**2155**	**2134**	**2140.5**	**2159**	**2136.5**	**2144**	**2163**	**2139**	**2141**	**2166**	**2140**
Mass [g]	**7300.4**	**7296.4**	**7289.1**	**7298.25**	**7295.75**	**7284.7**	**7296.1**	**7295.1**	**7280.3**	**7293.7**	**7295.5**	**7279.9**
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.63E+10**			**3.64E+10**			**3.65E+10**			**3.65E+10**		

S-Control(1)

Cycles	**363**			**386**			**423**			**493**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2153**	**2175**	**2145**	**2158**	**2177**	**2146**	**2162**	**2178**	**2152**	**2171**	**2185**	**2158**
Mass [g]	**7289.8**	**7291.2**	**7272.9**	**7284.6**	**7288.8**	**7267.6**	**7280.7**	**7283.8**	**7262.4**	**7273.5**	**7279.5**	**7252.4**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.68E+10**			**3.68E+10**			**3.69E+10**			**3.71E+10**		

S-Control(1)

Cycles	**540**			**604**			**664**			**704**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2170**	**2181**	**2157**	**2171**	**2185**	**2156**	**2177**	**2191**	**2164**	**2179**	**2194**	**2169**
Mass [g]	**7263.9**	**7264.9**	**7240.1**	**7259.9**	**7263.9**	**7236.1**	**7254.6**	**7257.4**	**7230.3**	**7249.2**	**7256.5**	**7220**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.70E+10**			**3.70E+10**			**3.72E+10**			**3.73E+10**		

S-Control(1)

Cycles	**735**			**785**			**839**			**880**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2175**	**2193**	**2162**	**2179**	**2197**	**2168**	**2188**	**2200**	**2172**	**2185**	**2200**	**2172**
Mass [g]	**7244.4**	**7251.8**	**7215.2**	**7243.4**	**7249.4**	**7210.2**	**7241.5**	**7250**	**7207**	**7233.8**	**7244**	**7196**
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.72E+10**			**3.73E+10**			**3.75E+10**			**3.74E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con’t): Freeze-thaw test results for mixtures in Program 2

S-Control(1)

Cycles	917			967			1017			1066		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2186	2197	2173	2188	2201	2169	2185	2205	2172	2184	2200	2169
Mass [g]	7233.9	7246.2	7197.8	7229.3	7238.5	7189.7	7221.4	7234	7178.5	7218.7	7231.5	7174.1
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.74E+10			3.74E+10			3.74E+10			3.73E+10		

S-Control(1)

Cycles	1120			1156			1192			1225		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2181	2200	2170	2179	2195	2166	2180	2147	2166	2185	2151	2169
Mass [g]	7222.7	7227	7167	7208.1	7218	7156.1	7207.7	7221.3	7156.1	7199.6	7213.3	7143.2
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.72E+10			3.71E+10			3.65E+10			3.66E+10		

S-Control(1)

Cycles	1256			1296			1338			1368		
Specimen	A	A	B	C	A	B	C	A	B	C	B	C
Frequency [Hz]	2180	2178	2201	2169	2178	2201	2169	2178	2201	2169	2189	2162
Mass [g]	7196.4	7192.5	7204.1	7135	7192.5	7204.1	7135	7192.5	7204.1	7135	7191.8	7115.4
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.68E+10			3.71E+10			3.68E+10			3.66E+10		

S-IC-6.9

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2066	2076	2051	2056	2061	2033	2062	2068	2039	2066	2079	2048
Mass [g]	7145.5	7114.3	7046.2	7170.5	7140.6	7070.2	7168.4	7139.5	7074.9	7172.6	7141.8	7076.3
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.28E+10			3.25E+10			3.27E+10			3.29E+10		

S-IC-6.9

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2074	2084	2053	2080	2091	2059	2086	2097	2064	2090	2100	2068
Mass [g]	7170.5	7139.1	7075.2	7167.5	7136.8	7074.3	7166.6	7140.6	7073.8	7159.4	7133.2	7070.2
$E_{Dyn.}$ [Pa]	3.3E+10	3.4E+10	3.2E+10	3.4E+10	3.4E+10	3.2E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.31E+10			3.33E+10			3.35E+10			3.36E+10		

S-IC-6.9

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2093	2103	2074	2095	2105	2070	2098	2111	2076	2108	2123	2098
Mass [g]	7163.3	7136.6	7072.7	7160.4	7133.5	7072.6	7157.3	7128.5	7066.9	7149.8	7118.3	7061.1
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.37E+10			3.37E+10			3.39E+10			3.43E+10		

S-IC-6.9

Cycles	482			536			577			614		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2107	2122	2085	2119	2126	2091	2114	2125	2091	2109	2123	2091
Mass [g]	7145	7116.8	7058.3	7146.6	7116.7	7059.9	7138.4	7108.6	7051.8	7138.2	7107.4	7053.1
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.3E+10	3.4E+10	3.5E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.41E+10			3.44E+10			3.43E+10			3.42E+10		

S-IC-6.9

Cycles	664			714			763			817		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2113	2123	2090	2117	2126	2094	2112	2122	2092	2108	2114	2086
Mass [g]	7128.9	7104.1	7050.5	7120.2	7095.8	7044.7	7115.9	7089	7037.5	7111.3	7086.4	7033
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.3E+10	3.4E+10	3.5E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.42E+10			3.43E+10			3.41E+10			3.39E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-6.9

Cycles	**853**			**889**			**922**			**953**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2100**	**2110**	**2084**	**2101**	**2104**	**2084**	**2102**	**2103**	**2085**	**2100**	**2096**	**2087**
Mass [g]	**7107.5**	**7078.7**	**7026.2**	**7109.2**	**7078.1**	**7020.9**	**7108.5**	**7069.1**	**7016**	**7097.4**	**7066**	**7015.9**
E$_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. E$_{Dyn.}$ [Pa]	**3.37E+10**			**3.37E+10**			**3.37E+10**			**3.36E+10**		

S-IC-6.9

Cycles	**993**			**1035**			**1065**			**1111**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2077**	**2035**	**2056**	**1990**	**1901**	**1990**	**1929**	**1742**	**1946**	**1715**	**1442**	**1735**
Mass [g]	**7092.6**	**7067.4**	**7014.4**	**7101.7**	**7075.8**	**7015.1**	**7090.2**	**7067.4**	**7007.2**	**7086.6**	**7064.2**	**7007.5**
E$_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.0E+10	2.8E+10	3.0E+10	2.9E+10	2.3E+10	2.9E+10	2.3E+10	1.6E+10	2.3E+10
Avg. E$_{Dyn.}$ [Pa]	**3.23E+10**			**2.94E+10**			**2.69E+10**			**2.05E+10**		

S-IC-6.9

Cycles	**1129**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1627**	**1320**	**1640**
Mass [g]	**7082.1**	**7057.8**	**7004.7**
E$_{Dyn.}$ [Pa]	2.0E+10	1.3E+10	2.0E+10
Avg. E$_{Dyn.}$ [Pa]	**1.80E+10**		

S-IC-8.3(1)

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1991**	**1987**	**2013**	**2020**	**2017**	**2042**	**2029**	**2021**	**2048**	**2036**	**2031**	**2056**
Mass [g]	**7000.1**	**6989.6**	**7004.8**	**7009.5**	**7000.2**	**7015.9**	**7012.8**	**7003.4**	**7018.9**	**7014.2**	**7005**	**7019.4**
E$_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10
Avg. E$_{Dyn.}$ [Pa]	**3.02E+10**			**3.12E+10**			**3.14E+10**			**3.17E+10**		

S-IC-8.3(1)

Cycles	**120**			**150**			**185**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2044**	**2036**	**2062**	**2053**	**2048**	**2074**	**2059**	**2054**	**2079**	**2064**	**2053**	**2090**
Mass [g]	**7014.6**	**7006.5**	**7021.3**	**7018.7**	**7011.8**	**7025.8**	**7018.2**	**7012.1**	**7025.8**	**7018.2**	**7012.4**	**7026.1**
E$_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. E$_{Dyn.}$ [Pa]	**3.19E+10**			**3.22E+10**			**3.24E+10**			**3.26E+10**		

S-IC-8.3(1)

Cycles	**260**			**280**			**300**			**333**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2072**	**2053**	**2087**	**2073**	**2054**	**2089**	**2074**	**2067**	**2091**	**2044**	**2036**	**2062**
Mass [g]	**7016**	**7013.3**	**7025.8**	**7012.3**	**7012.1**	**7024.1**	**7010.5**	**7010.5**	**7024.2**	**7014.6**	**7006.5**	**7021.3**
E$_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.2E+10	3.1E+10	3.2E+10
Avg. E$_{Dyn.}$ [Pa]	**3.26E+10**			**3.26E+10**			**3.28E+10**			**3.19E+10**		

S-IC-8.3(1)

Cycles	**363**			**386**			**423**			**493**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2053**	**2048**	**2074**	**2059**	**2054**	**2079**	**2064**	**2053**	**2090**	**2072**	**2053**	**2087**
Mass [g]	**7018.7**	**7011.8**	**7025.8**	**7018.2**	**7012.1**	**7025.8**	**7018.2**	**7012.4**	**7026.1**	**7016**	**7013.3**	**7025.8**
E$_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. E$_{Dyn.}$ [Pa]	**3.22E+10**			**3.24E+10**			**3.26E+10**			**3.26E+10**		

S-IC-8.3(1)

Cycles	**578**			**604**			**664**			**704**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2073**	**2054**	**2089**	**2074**	**2067**	**2091**	**2044**	**2036**	**2062**	**2053**	**2048**	**2074**
Mass [g]	**7012.3**	**7012.1**	**7024.1**	**7010.5**	**7010.5**	**7024.2**	**7014.6**	**7006.5**	**7021.3**	**7018.7**	**7011.8**	**7025.8**
E$_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10
Avg. E$_{Dyn.}$ [Pa]	**3.26E+10**			**3.28E+10**			**3.19E+10**			**3.22E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-8.3(1)

Cycles	423			493			578			604		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2064	2053	2090	2072	2053	2087	2073	2054	2089	2074	2067	2091
Mass [g]	7018.2	7012.4	7026.1	7016	7013.3	7025.8	7012.3	7012.1	7024.1	7010.5	7010.5	7024.2
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.26E+10			3.26E+10			3.26E+10			3.28E+10		

S-IC-8.3(1)

Cycles	664			704			735			785		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2044	2036	2062	2053	2048	2074	2059	2054	2079	2064	2053	2090
Mass [g]	7014.6	7006.5	7021.3	7018.7	7011.8	7025.8	7018.2	7012.1	7025.8	7018.2	7012.4	7026.1
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.19E+10			3.22E+10			3.24E+10			3.26E+10		

S-IC-8.3(1)

Cycles	839		
Specimen	A	B	C
Frequency [Hz]	2072	2053	2087
Mass [g]	7016	7013.3	7025.8
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.26E+10		

S-IC-8.4(1)

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2004	2020	2011	1995	2002	1997	2003	2008	2004	2006	2013	2009
Mass [g]	6980.8	6976.8	7030.2	7003.4	6998.9	7052	7004.8	7003.7	7053.3	7007.4	7006.1	7054.8
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.07E+10			3.04E+10			3.06E+10			3.07E+10		

S-IC-8.4(1)

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2011	2019	2014	2020	2026	2021	2026	2032	2020	2026	2032	2030
Mass [g]	7004.4	7003.3	7052.6	7001.8	6998.9	7051.1	7003.7	7001.6	7050.7	6995.3	6996.2	7044.2
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.09E+10			3.11E+10			3.12E+10			3.13E+10		

S-IC-8.4(1)

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2030	2040	2034	2030	2037	2026	2032	2042	2032	2036	2046	2043
Mass [g]	6997.3	6991.3	7044.1	6994.1	6989.9	7046	6987.7	6981.4	7036.3	6976.4	6969.2	7029.9
$E_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.15E+10			3.13E+10			3.14E+10			3.16E+10		

S-IC-8.4(1)

Cycles	482			536			577			614		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2038	2050	2046	2036	2056	2042	2036	2055	2047	2035	2057	2047
Mass [g]	6969.4	6965.7	7022.4	6968.4	6964	7022.1	6956.9	6955.6	7011.3	6955.6	6955.3	7006.5
$E_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.16E+10			3.16E+10			3.16E+10			3.16E+10		

S-IC-8.4(1)

Cycles	664			714			763			817		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2029	2053	2046	2034	2056	2047	2028	2056	2041	2010	2040	2035
Mass [g]	6948	6945.3	6996.8	6938.2	6937	6988.4	6932.5	6931.5	6979.9	6912.8	6918.7	6970
$E_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.15E+10			3.15E+10			3.14E+10			3.09E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-8.4(1)

Cycles	**853**			**889**			**922**			**953**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1990**	**2035**	**2025**	**1975**	**2030**	**2024**	**1945**	**2025**	**2026**	**1890**	**2015**	**2029**
Mass [g]	**6909.7**	**6908.6**	**6961.7**	**6904.6**	**6900.8**	**6954.8**	**6895**	**6889.7**	**6942.9**	**6894.8**	**6887**	**6937.9**
E$_{\text{Dyn.}}$ [Pa]	3.0E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.8E+10	3.1E+10	3.1E+10	2.7E+10	3.0E+10	3.1E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.05E+10**			**3.03E+10**			**2.99E+10**			**2.93E+10**		

S-IC-8.4(1)

Cycles	**993**			**1035**			**1065**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1730**	**1952**	**2004**	**1564**	**1758**	**1980**	**1292**	**1560**	**1560**
Mass [g]	**6890.5**	**6886.8**	**6934**	**6888**	**6884.7**	**6930.3**	**6877**	**6897.1**	**6918.7**
E$_{\text{Dyn.}}$ [Pa]	2.2E+10	2.8E+10	3.0E+10	1.8E+10	2.3E+10	2.9E+10	1.2E+10	1.8E+10	1.8E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**2.70E+10**			**2.36E+10**			**1.63E+10**		

S-IC-9.4

Cycles	**0**			**31**			**61**			**79**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1991**	**1987**	**2013**	**2020**	**2017**	**2042**	**2029**	**2021**	**2048**	**2036**	**2031**	**2056**
Mass [g]	**7000.1**	**6989.6**	**7004.8**	**7009.5**	**7000.2**	**7015.9**	**7012.8**	**7003.4**	**7018.9**	**7014.2**	**7005**	**7019.4**
E$_{\text{Dyn.}}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.02E+10**			**3.12E+10**			**3.14E+10**			**3.17E+10**		

S-IC-9.4

Cycles	**103**			**147**			**186**			**216**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2044**	**2036**	**2062**	**2053**	**2048**	**2074**	**2059**	**2054**	**2079**	**2064**	**2053**	**2090**
Mass [g]	**7014.6**	**7006.5**	**7021.3**	**7018.7**	**7011.8**	**7025.8**	**7018.2**	**7012.1**	**7025.8**	**7018.2**	**7012.4**	**7026.1**
E$_{\text{Dyn.}}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.19E+10**			**3.22E+10**			**3.24E+10**			**3.26E+10**		

S-IC-9.4

Cycles	**246**			**289**			**304**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2072**	**2053**	**2087**	**2073**	**2054**	**2089**	**2074**	**2067**	**2091**
Mass [g]	**7016**	**7013.3**	**7025.8**	**7012.3**	**7012.1**	**7024.1**	**7010.5**	**7010.5**	**7024.2**
E$_{\text{Dyn.}}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.26E+10**			**3.26E+10**			**3.28E+10**		

S-IC-7.2(1)

Cycles	**0**			**31**			**61**			**79**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1990**	**1992**	**2019**	**2013**	**2020**	**2045**	**2021**	**2029**	**2051**	**2025**	**2034**	**2058**
Mass [g]	**6963.9**	**6984.6**	**7108.3**	**6974.9**	**6996**	**7120**	**6975.7**	**6996.7**	**7122.6**	**6977.9**	**6998.8**	**7122.3**
E$_{\text{Dyn.}}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.3E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.04E+10**			**3.13E+10**			**3.15E+10**			**3.17E+10**		

S-IC-7.2(1)

Cycles	**103**			**147**			**186**			**216**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2034**	**2042**	**2066**	**2047**	**2058**	**2080**	**2052**	**2061**	**2090**	**2056**	**2069**	**2090**
Mass [g]	**6979.4**	**7000.1**	**7123.5**	**6986.4**	**6998.7**	**7124.9**	**6983.3**	**6996.1**	**7118.4**	**6986.1**	**6999.8**	**7118.4**
E$_{\text{Dyn.}}$ [Pa]	3.1E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.4E+10	3.2E+10	3.2E+10	3.4E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.20E+10**			**3.24E+10**			**3.26E+10**			**3.27E+10**		

S-IC-7.2(1)

Cycles	**246**			**289**			**304**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2061**	**2070**	**2096**	**2061**	**2072**	**2096**	**2064**	**2072**	**2098**
Mass [g]	**6987.3**	**6998.5**	**7118.5**	**6984.4**	**6997.1**	**7115.2**	**6982.3**	**6994.4**	**7112.9**
E$_{\text{Dyn.}}$ [Pa]	3.2E+10	3.2E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10
Avg. E$_{\text{Dyn.}}$ [Pa]	**3.28E+10**			**3.29E+10**			**3.29E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-8.3(2)

Cycles	0			31			61			79		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2170	2144	2145	2193	2172	2170	2198	2174	2175	2204	2180	2181
Mass [g]	7236.3	7266.2	7232.4	7547.3	7275.1	7242.1	7249.7	7277.9	7246.6	7250.6	7282.6	7249.9
$E_{Dyn.}$ [Pa]	3.7E+10	3.6E+10	3.6E+10	3.9E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.64E+10			3.78E+10			3.75E+10			3.77E+10		

S-IC-8.3(2)

Cycles	103			147			186			216		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2213	2190	2191	2223	2195	2200	2227	2206	2207	2231	2211	2212
Mass [g]	7252.6	7282.3	7250.2	7256	7283	7253.9	7256.1	7285	7252.3	7257.6	7287	7252.7
$E_{Dyn.}$ [Pa]	3.8E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.80E+10			3.83E+10			3.86E+10			3.87E+10		

S-IC-8.3(2)

Cycles	246			289			304		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2236	2213	2214	2238	2217	2217	2239	2218	2219
Mass [g]	7257.9	7286.6	7251.4	7254.8	7285.7	7249.2	7255.9	7286	7247.3
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.88E+10			3.89E+10			3.90E+10		

S-Control(2)

Cycles	0			30			60			90		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2131	2142	2097	2136	2163	2119	2145	2168	2128	2158	2181	2134
Mass [g]	7266	7313.4	7181	7283.1	7332.3	7202.3	7286.1	7335.4	7199.2	7289.5	7339.2	7204
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.4E+10	3.6E+10	3.7E+10	3.5E+10	3.6E+10	3.7E+10	3.5E+10	3.7E+10	3.8E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.54E+10			3.61E+10			3.63E+10			3.67E+10		

S-Control(2)

Cycles	120			150			185			230		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2147	2163	2118	2141	2160	2117	2150	2172	2124	2158	2173	2120
Mass [g]	7290.9	7337.2	7204.8	7292.1	7339.2	7205	7283.8	7338.6	7204.8	7293.3	7340	7205.7
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.5E+10	3.6E+10	3.7E+10	3.5E+10	3.6E+10	3.8E+10	3.5E+10	3.7E+10	3.8E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.62E+10			3.61E+10			3.64E+10			3.65E+10		

S-Control(2)

Cycles	260			280			300		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2160	2172	2126	2159	2177	2130	2158	2181	2133
Mass [g]	7286.7	7340.4	7204.6	7290.2	7339.3	7203.7	7293.6	7338.3	7202.7
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.5E+10	3.7E+10	3.8E+10	3.5E+10	3.7E+10	3.8E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.66E+10			3.66E+10			3.67E+10		

S-IC-7.3

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2132	2148	2136	2130	2144	2128	2136	2150	2133	2144	2157	2141
Mass [g]	7139.7	7128.3	7122	7161.9	7154.7	7143.8	7162.4	7158.7	7147.1	7164.6	7159.1	7150.3
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.53E+10			3.53E+10			3.55E+10			3.58E+10		

S-IC-7.3

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2147	2163	2146	2156	2168	2153	2161	2171	2159	2163	2173	2159
Mass [g]	7166	7159.7	7148.5	7165.5	7157.2	7146.9	7165.2	7158.1	7147.6	7156	7153.4	7140.4
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.59E+10			3.61E+10			3.63E+10			3.63E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-7.3

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2168	2179	2166	2168	2181	2167	2172	2188	2170	2178	2194	2174
Mass [g]	7162.3	7156.5	7141	7160.4	7153	7138	7156.8	7149.4	7130.3	7155.8	7140	7122.4
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.65E+10			3.66E+10			3.67E+10			3.68E+10		

S-IC-7.3

Cycles	482			536			614			664		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2180	2200	2179	2188	2207	2183	2190	2205	2183	2189	2205	2185
Mass [g]	7140.8	7135.4	7115.4	7135.7	7127.2	7111.1	7126.7	7117.1	7101.6	7115.3	7111.6	7089.9
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.69E+10			3.71E+10			3.71E+10			3.70E+10		

S-IC-7.3

Cycles	714			763			817			853		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2194	2206	2181	2192	2206	2178	2191	2204	2177	2190	2200	2168
Mass [g]	7109.4	7103.6	7076.3	7102.5	7100.9	7071.7	7095.3	7090.8	7066.4	7087.6	7080.4	7058.6
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.70E+10			3.69E+10			3.68E+10			3.66E+10		

S-IC-7.3

Cycles	889			922			953			993		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2191	2197	2166	2192	2194	2150	2182	2199	2110	2178	2115	2079
Mass [g]	7080.6	7045.6	7046.6	7071.9	7020.4	7037.5	7069.9	7015.4	7029.9	7064.8	7014.4	7026.7
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.5E+10	3.6E+10	3.7E+10	3.4E+10	3.6E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.65E+10			3.62E+10			3.57E+10			3.44E+10		

S-IC-7.3

Cycles	1035			1065			1111			1129		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2153	2001	1984	2133	1901	1896	1993	1570	1580	1909	1440	1450
Mass [g]	7066.5	7064.2	7024.8	7056.8	7053.8	7019.8	7053.9	7044.2	7001.3	7046.5	7037.5	6991.4
$E_{Dyn.}$ [Pa]	3.5E+10	3.1E+10	3.0E+10	3.5E+10	2.8E+10	2.7E+10	3.0E+10	1.9E+10	1.9E+10	2.8E+10	1.6E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.20E+10			2.99E+10			2.27E+10			1.99E+10		

S-IC-8.9(1)

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2092	2084	2078	2087	2074	2070	2090	2078	2078	2100	2088	2078
Mass [g]	7087.4	7119.1	7068.9	7121.4	7153.3	7094.7	7126.9	7158.9	7098.9	7127	7157.6	7100
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.34E+10			3.33E+10			3.35E+10			3.37E+10		

S-IC-8.9(1)

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2106	2091	2083	2113	2098	2087	2115	2104	2090	2117	2108	2100
Mass [g]	7130	7157.3	7100.4	7127	7156.2	7099.5	7124.1	7155.7	7097.1	7116.7	7146.7	7090.4
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.39E+10			3.40E+10			3.42E+10			3.43E+10		

S-IC-8.9(1)

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2122	2112	2100	2120	2109	2103	2126	2111	2102	2133	2117	2107
Mass [g]	7120	7150.4	7091.3	7121.6	7148.1	7092.4	7113.7	7141.1	7083.2	7107.3	7138.1	7073.6
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.44E+10			3.44E+10			3.44E+10			3.46E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-8.9(1)

Cycles	**482**			**536**			**614**			**664**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2131**	**2118**	**2108**	**2135**	**2122**	**2109**	**2136**	**2119**	**2112**	**2133**	**2115**	**2104**
Mass [g]	**7104.4**	**7120.9**	**7068.7**	**7099.4**	**7113.3**	**7064.9**	**7090.9**	**7097.2**	**7050**	**7082.1**	**7080.8**	**7043.3**
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.45E+10**			**3.46E+10**			**3.46E+10**			**3.43E+10**		

S-IC-8.9(1)

Cycles	**714**			**763**			**817**			**853**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2127**	**2114**	**2104**	**2122**	**2109**	**2096**	**2115**	**2090**	**2090**	**2113**	**2076**	**2080**
Mass [g]	**7073.8**	**7069.2**	**7036.2**	**7062.4**	**7059.5**	**7026.1**	**7058.2**	**7050**	**6999.8**	**7058.6**	**7037**	**6998.9**
$E_{Dyn.}$ [Pa]	3.5E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.42E+10**			**3.40E+10**			**3.36E+10**			**3.33E+10**		

S-IC-8.9(1)

Cycles	**889**			**922**			**953**			**993**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2105**	**2035**	**2061**	**2097**	**2009**	**2056**	**2056**	**1950**	**2005**	**1985**	**1700**	**1890**
Mass [g]	**7042.2**	**7004.9**	**6999.4**	**7020.7**	**6910.9**	**7000.4**	**7004.5**	**6917.1**	**6988.2**	**7004.5**	**7004.3**	**6988.2**
$E_{Dyn.}$ [Pa]	3.4E+10	3.1E+10	3.2E+10	3.3E+10	3.0E+10	3.2E+10	3.2E+10	2.9E+10	3.0E+10	3.0E+10	2.2E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.25E+10**			**3.19E+10**			**3.03E+10**			**2.63E+10**		

S-IC-8.9(1)

Cycles	**1035**			**1065**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1814**	**1370**	**1683**	**1699**	**1122**	**1560**
Mass [g]	**7001.8**	**7002.3**	**6986.6**	**6993.8**	**6979.5**	**6974.3**
$E_{Dyn.}$ [Pa]	2.5E+10	1.4E+10	2.1E+10	2.2E+10	9.5E+09	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	**2.02E+10**			**1.66E+10**		

S-IC-8.9(2)

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080**	**2062**	**2049**	**2096**	**2079**	**2074**	**2103**	**2089**	**2083**	**2115**	**2096**	**2092**
Mass [g]	**7219.9**	**7024.1**	**7076**	**7238.9**	**7043.8**	**7092.9**	**7241**	**7044.7**	**7094.8**	**7247.4**	**7051.1**	**7101.6**
$E_{Dyn.}$ [Pa]	3.4E+10	3.2E+10	3.2E+10	3.4E+10	3.3E+10	3.3E+10	3.5E+10	3.3E+10	3.3E+10	3.5E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.28E+10**			**3.35E+10**			**3.38E+10**			**3.41E+10**		

S-IC-8.9(2)

Cycles	**120**			**150**			**185**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2090**	**2074**	**2071**	**2090**	**2067**	**2070**	**2091**	**2069**	**2072**	**2085**	**2072**	**2075**
Mass [g]	**7244.2**	**7049.1**	**7098.9**	**7245.1**	**7051.9**	**7099.4**	**7245.1**	**7054.7**	**7100**	**7243.5**	**7048.7**	**7099.8**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.34E+10**			**3.33E+10**			**3.34E+10**			**3.33E+10**		

S-IC-8.9(2)

Cycles	**260**			**280**			**300**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2087**	**2072**	**2074**	**2088**	**2073**	**2069**	**2088**	**2074**	**2065**
Mass [g]	**7244.6**	**7053.6**	**7100**	**7240.8**	**7050**	**7096**	**7237**	**7046.3**	**7091.9**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.34E+10**			**3.33E+10**			**3.33E+10**		

S-IC-9.3

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2056**	**2024**	**2029**	**2085**	**2051**	**2054**	**2094**	**2058**	**2060**	**2102**	**2064**	**2068**
Mass [g]	**7006.6**	**7052.6**	**6971.8**	**7025**	**7073.7**	**6988.8**	**7022.7**	**7070.4**	**6992.2**	**7028.7**	**7076.3**	**6998.7**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.4E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.15E+10**			**3.24E+10**			**3.27E+10**			**3.29E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-9.3

Cycles	120			150			185			230		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2086**	**2045**	**2050**	**2070**	**2040**	**2045**	**2083**	**2045**	**2049**	**2083**	**2045**	**2054**
Mass [g]	**7029.5**	**7076.9**	**6999.7**	**7031.3**	**7079.4**	**6996.3**	**7030.6**	**7077.5**	**6992.2**	**7029.5**	**7073.9**	**6987.7**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.24E+10**			**3.21E+10**			**3.23E+10**			**3.24E+10**		

S-IC-9.3

Cycles	260			280			300		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2081**	**2047**	**2050**	**2083**	**2048**	**2049**	**2085**	**2048**	**2048**
Mass [g]	**7027.8**	**7073.1**	**6984.6**	**7026.1**	**7071.7**	**6984.2**	**7024.3**	**7070.3**	**6983.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.23E+10**			**3.23E+10**			**3.23E+10**		

S-IC-14.1

Cycles	0			30			60			90		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050**	**2020**	**1990**	**2064**	**2007**	**2031**	**2074**	**2020**	**2042**	**2089**	**2034**	**2048**
Mass [g]	**6977.6**	**6947.7**	**6976.8**	**7006.2**	**6967.2**	**6983**	**7005.9**	**6968.9**	**6985.2**	**7013**	**6974.4**	**6989.6**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.0E+10	3.1E+10	3.3E+10	3.1E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.08E+10**			**3.13E+10**			**3.17E+10**			**3.21E+10**		

S-IC-14.1

Cycles	120			150			185			230		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2061**	**2006**	**2026**	**2057**	**2003**	**2017**	**2067**	**2008**	**2015**	**2065**	**2007**	**2006**
Mass [g]	**7011.9**	**6978.3**	**6991.3**	**7011.4**	**6976.8**	**6993.1**	**7011.5**	**6978.5**	**6993.3**	**7008.7**	**6980.5**	**6988.4**
$E_{Dyn.}$ [Pa]	3.2E+10	3.0E+10	3.1E+10	3.2E+10	3.0E+10	3.1E+10	3.2E+10	3.0E+10	3.1E+10	3.2E+10	3.0E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	**3.13E+10**			**3.11E+10**			**3.12E+10**			**3.11E+10**		

S-IC-14.1

Cycles	260			280			300			333		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2067**	**2000**	**1982**	**2068**	**1992**	**1878**	**2068**	**1984**	**1769**	**2072**	**1968**	**1555**
Mass [g]	**7032.6**	**6980.8**	**6978.1**	**7020.2**	**6980.2**	**6979.1**	**7007.7**	**6979.6**	**6980.1**	**7001.3**	**6975.2**	**6969.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.0E+10	3.0E+10	3.3E+10	3.0E+10	2.7E+10	3.2E+10	3.0E+10	2.4E+10	3.3E+10	2.9E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	**3.08E+10**			**2.97E+10**			**2.86E+10**			**2.67E+10**		

S-IC-14.1

Cycles	363			386			423			463		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2074**	**1913**	**1200**	**2076**	**1829**	**1018**	**2073**	**1680**	**1001**	**2076**	**1355**	**1001**
Mass [g]	**6998.7**	**6972.1**	**6960.4**	**6996.8**	**6971.3**	**6952.3**	**6986.7**	**6971.1**	**6952.3**	**6982.5**	**6973.3**	**6952.3**
$E_{Dyn.}$ [Pa]	3.3E+10	2.8E+10	1.1E+10	3.3E+10	2.5E+10	7.8E+09	3.3E+10	2.1E+10	7.5E+09	3.3E+10	1.4E+10	7.5E+09
Avg. $E_{Dyn.}$ [Pa]	**2.37E+10**			**2.19E+10**			**2.05E+10**			**1.80E+10**		

S-IC-14.1

Cycles	493			550		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2076**	**1150**	**1001**	**2059**	**1001**	**1001**
Mass [g]	**6979.4**	**6973.2**	**6952.3**	**6969.6**	**6950.5**	**6952.3**
$E_{Dyn.}$ [Pa]	3.3E+10	1.0E+10	7.5E+09	3.2E+10	7.5E+09	7.5E+09
Avg. $E_{Dyn.}$ [Pa]	**1.67E+10**			**1.57E+10**		

T-Control

Cycles	0			30			60			90		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167**	**2189**	**2145**	**2174**	**2202**	**2159**	**2185**	**2213**	**2168**	**2194**	**2218**	**2180**
Mass [g]	**7233.9**	**7353.3**	**7281.6**	**7244.4**	**7362.8**	**7286.4**	**7245.6**	**7363.9**	**7289.1**	**7248.9**	**7364.9**	**7292.5**
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.9E+10	3.7E+10	3.7E+10	3.9E+10	3.7E+10	3.8E+10	3.9E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	**3.71E+10**			**3.75E+10**			**3.79E+10**			**3.82E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

T-Control

Cycles	120			150			185			230		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2177	2202	2164	2174	2202	2162	2179	2208	2167	2183	2210	2168
Mass [g]	7246.9	7364.6	7290.2	7248.3	7364.6	7291.3	7245.8	7362.9	7290.9	7244	7359.5	7287.5
$E_{Dyn.}$ [Pa]	3.7E+10	3.9E+10	3.7E+10	3.7E+10	3.9E+10	3.7E+10	3.7E+10	3.9E+10	3.7E+10	3.7E+10	3.9E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.76E+10			3.76E+10			3.78E+10			3.78E+10		

T-Control

Cycles	260			280			300		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2182	2211	2167	2186	2213	2168	2189	2215	2169
Mass [g]	7243.4	7356.4	7288	7242.7	7353.1	7286.1	7242	7349.7	7284.2
$E_{Dyn.}$ [Pa]	3.7E+10	3.9E+10	3.7E+10	3.8E+10	3.9E+10	3.7E+10	3.8E+10	3.9E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.78E+10			3.79E+10			3.79E+10		

T-IC-8.9

Cycles	0			30			60			90		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2031	2036	2050	2042	2047	2062	2051	2057	2075	2060	2064	2080
Mass [g]	6944.3	6903.3	6942.7	6958.8	6919.8	6960.2	6957.9	6921.1	6969.2	6968.2	6921.9	6968.9
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.12E+10			3.16E+10			3.20E+10			3.22E+10		

T-IC-8.9

Cycles	120			150			185			230		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2041	2049	2069	2036	2047	2062	2043	2054	2064	2037	2053	2064
Mass [g]	6962.3	6923.2	6968	6962.3	6924.3	6972.7	6960.1	6925.3	6971.8	6958.7	6924.5	6968.2
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.17E+10			3.16E+10			3.18E+10			3.17E+10		

T-IC-8.9

Cycles	260			280			300		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2037	2053	2068	2038	2054	2071	2038	2054	2073
Mass [g]	6955.7	6920.9	6967.2	6952.6	6921.2	6964.2	6949.4	6921.5	6961.1
$E_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.17E+10			3.18E+10			3.18E+10		

C-Control(1)

Cycles	0			30			60			90		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2170	2190	2167	2184	2200	2173	2191	2208	2174	2189	2216	2176
Mass [g]	7039.5	7333.7	7347.7	7319.1	7345.6	7358.4	7321	7346.4	7359.2	7324.2	7350.2	7362.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.8E+10	3.7E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.71E+10			3.80E+10			3.82E+10			3.83E+10		

C-Control(1)

Cycles	120			150			185			230		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2203	2191	2170	2189	2206	2170	2196	2213	2174	2196	2212	2192
Mass [g]	7323.6	7340.6	7360.7	7324.2	7340.4	7361.7	7321	7338.9	7357.7	7315.2	7328.8	7348.5
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.81E+10			3.81E+10			3.83E+10			3.84E+10		

C-Control(1)

Cycles	260			280			300			364		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2197	2216	2196	2199	2216	2214	2201	2216	2214	2200	2213	2201
Mass [g]	7313.8	7326.1	7344.1	7311.3	7322.1	7334.9	7308.7	7318.1	7325.7	7297.8	7306.6	7308.2
$E_{Dyn.}$ [Pa]	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.85E+10			3.87E+10			3.87E+10			3.85E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

C-Control(1)

Cycles	424			464			495			545		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2213**	**2223**	**2170**	**2220**	**2231**	**2152**	**2217**	**2232**	**2147**	**2220**	**2234**	**2151**
Mass [g]	**7299.8**	**7308.6**	**7308.8**	**7302.6**	**7308.3**	**7307.2**	**7300.1**	**7306.7**	**7304.2**	**7302.8**	**7309.1**	**7305.7**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.7E+10	3.9E+10	3.9E+10	3.7E+10	3.9E+10	3.9E+10	3.6E+10	3.9E+10	4.0E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.84E+10**			**3.84E+10**			**3.83E+10**			**3.84E+10**		

C-Control(1)

Cycles	599			677			727			777		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2227**	**2242**	**2156**	**2229**	**2245**	**2162**	**2233**	**2250**	**2163**	**2235**	**2249**	**2166**
Mass [g]	**7305.4**	**7310.1**	**7303.9**	**7306.3**	**7311.7**	**7303.6**	**7305.5**	**7310.5**	**7302.1**	**7304.8**	**7309.6**	**7299.8**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	3.7E+10	3.9E+10	4.0E+10	3.7E+10	3.9E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.86E+10**			**3.88E+10**			**3.89E+10**			**3.89E+10**		

C-Control(1)

Cycles	826			880			916			952		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2236**	**2252**	**2158**	**2240**	**2250**	**2153**	**2236**	**2251**	**2152**	**2235**	**2251**	**2158**
Mass [g]	**7311.3**	**7307.7**	**7304.3**	**7311**	**7313.2**	**7300.4**	**7310.8**	**7313.7**	**7300.7**	**7313.5**	**7321.2**	**7299.2**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.89E+10**			**3.88E+10**			**3.88E+10**			**3.89E+10**		

C-Control(1)

Cycles	985			1016			1098			1128		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2242**	**2252**	**2157**	**2241**	**2256**	**2160**	**2246**	**2257**	**2156**	**2244**	**2255**	**2150**
Mass [g]	**7308.9**	**7314.3**	**7295.8**	**7308.8**	**7310.1**	**7294.9**	**7310.1**	**7319**	**7298.9**	**7311.4**	**7317.6**	**7297.6**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.89E+10**			**3.90E+10**			**3.90E+10**			**3.89E+10**		

C-Control(1)

Cycles	1174			1223			1277			1308		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2241**	**2255**	**2149**	**2240**	**2257**	**2150**	**2238**	**2253**	**2137**	**2238**	**2253**	**2137**
Mass [g]	**7313.5**	**7316.4**	**7294.9**	**7312.8**	**7313.7**	**7295.9**	**7313.5**	**7314.4**	**7293.5**	**7312.5**	**7312.6**	**7293.4**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.7E+10	4.0E+10	4.0E+10	3.6E+10	4.0E+10	4.0E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.89E+10**			**3.89E+10**			**3.87E+10**			**3.87E+10**		

C-Control(1)

Cycles	1349			1380			1410			1440		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2244**	**2261**	**2131**	**2246**	**2263**	**2109**	**2246**	**2263**	**2100**	**2250**	**2262**	**2094**
Mass [g]	**7312.9**	**7314.1**	**7287.1**	**7311.5**	**7310.6**	**7284.6**	**7311.1**	**7310.9**	**7283.6**	**7312.1**	**7309.7**	**7282.5**
$E_{Dyn.}$ [Pa]	4.0E+10	4.1E+10	3.6E+10	4.0E+10	4.1E+10	3.5E+10	4.0E+10	4.1E+10	3.5E+10	4.0E+10	4.1E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	**3.88E+10**			**3.85E+10**			**3.84E+10**			**3.84E+10**		

C-Control(1)

Cycles	1475			1550			1601			1678		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2247**	**2262**	**2092**	**2260**	**2268**	**2079**	**2252**	**2267**	**2086**	**2253**	**2260**	**2069**
Mass [g]	**7310.9**	**7310.1**	**7281.1**	**7311.8**	**7309.1**	**7275.8**	**7311.1**	**7308.3**	**7272.2**	**7311.3**	**7308.2**	**7270.8**
$E_{Dyn.}$ [Pa]	4.0E+10	4.1E+10	3.5E+10	4.0E+10	4.1E+10	3.4E+10	4.0E+10	4.1E+10	3.4E+10	4.0E+10	4.0E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.84E+10**			**3.84E+10**			**3.84E+10**			**3.81E+10**		

C-Control(1)

Cycles	1757			1802			1866			1932		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2253**	**2267**	**2052**	**2257**	**2260**	**2058**	**2255**	**2262**	**2036**	**2252**	**2265**	**2014**
Mass [g]	**7311.7**	**7307.1**	**7267.3**	**7311.3**	**7307**	**7264.3**	**7311**	**7305.4**	**7260.7**	**7304**	**7301.2**	**7252.6**
$E_{Dyn.}$ [Pa]	4.0E+10	4.1E+10	3.3E+10	4.0E+10	4.0E+10	3.3E+10	4.0E+10	4.1E+10	3.3E+10	4.0E+10	4.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.80E+10**			**3.80E+10**			**3.78E+10**			**3.75E+10**		

C-Control(1)

Cycles	2002			2100		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2255**	**2271**	**2017**	**2255**	**2272**	**1990**
Mass [g]	**7308.8**	**7301.6**	**7274.9**	**7306.1**	**7298.8**	**7220.5**
$E_{Dyn.}$ [Pa]	4.0E+10	4.1E+10	3.2E+10	4.0E+10	4.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	**3.77E+10**			**3.74E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

C-IC-8.8

Cycles	0			30			60			90		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2069	2053	2061	2081	2068	2075	2086	2073	2084	2097	2084	2090
Mass [g]	7006.6	7018.6	7021.7	7015.2	7011.2	7031.4	7015.6	7007	7030.6	7021.5	7007.2	7033.9
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.23E+10			3.27E+10			3.29E+10			3.32E+10		

C-IC-8.8

Cycles	120			150			185			230		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2087	2074	2078	2084	2071	2078	2087	2074	2079	2084	2072	2079
Mass [g]	7018.8	7009.8	7034.1	7019.7	7007.4	7034.6	7017.3	7005	7033.6	7011.4	7003	7027.2
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.29E+10			3.28E+10			3.29E+10			3.28E+10		

C-IC-8.8

Cycles	260			280			300			333		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2087	2075	2077	2087	2074	2078	2086	2073	2080	2088	2071	2080
Mass [g]	7015.4	7003.5	7028.4	7005.7	7000.3	7017.8	6996	6997.1	7007.2	6997.4	6999.4	6997.6
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.29E+10			3.28E+10			3.28E+10			3.28E+10		

C-IC-8.8

Cycles	363			386			423			493		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2092	2075	2073	2090	2077	2073	2089	2078	2073	2091	2080	2074
Mass [g]	6984.1	6992.6	6994.1	6980.6	6990	6985.5	6973.8	6985.8	6979.1	6959	6978.5	6961.5
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.28E+10			3.27E+10			3.27E+10			3.27E+10		

C-IC-8.8

Cycles	578			604			664			704		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2085	2075	2068	2089	2074	2062	2087	2074	2060	2089	2075	2051
Mass [g]	6928.7	6971	6929.9	6921.2	6969.2	6922	6909.1	6965.6	6910.6	6894	6959.7	6897.7
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.24E+10			3.24E+10			3.23E+10			3.22E+10		

C-IC-8.8

Cycles	735			785			839			880		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2084	2065	2048	2087	2067	2039	2090	2065	2037	2086	2063	2020
Mass [g]	6880.3	6955.5	6886.6	6867.2	6953.6	6877.3	6862.7	6954.1	6871.7	6840.4	6946.3	6847.6
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.19E+10			3.19E+10			3.18E+10			3.15E+10		

C-IC-8.8

Cycles	917			967			1017			1066		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2081	2056	1992	2075	2058	1996	2079	2053	1970	2060	2040	1840
Mass [g]	6834.8	6947.4	6840.4	6820.5	6921.1	6815.9	6794.1	6917.3	6804.8	6789.5	6925.3	6793.6
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	2.9E+10	3.2E+10	3.2E+10	2.9E+10	3.2E+10	3.2E+10	2.9E+10	3.1E+10	3.1E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.11E+10			3.10E+10			3.07E+10			2.91E+10		

C-IC-8.8

Cycles	1120			1156			1192			1225		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2060	2040	1750	2050	2020	1650	2051	2014	1630	2050	2003	1600
Mass [g]	6774.7	6910.3	6765.4	6789	6903.1	6755.5	6753	6899.3	6751.7	6936.9	6891.4	6731.2
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	2.2E+10	3.1E+10	3.1E+10	2.0E+10	3.1E+10	3.0E+10	1.9E+10	3.2E+10	3.0E+10	1.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.83E+10			2.71E+10			2.68E+10			2.67E+10		

C-IC-8.8

Cycles	1256			1296			1338			1368		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2030	1999	1530	2010	1987	1370	1980	1959	1195	1975	1949	1080
Mass [g]	6904.5	6889.4	6720	6707.7	6883.7	6705.7	6696.7	6873.2	6692	6683.9	6875.2	6684.4
$E_{Dyn.}$ [Pa]	3.1E+10	3.0E+10	1.7E+10	2.9E+10	2.9E+10	1.4E+10	2.8E+10	2.9E+10	1.0E+10	2.8E+10	2.8E+10	8.4E+09
Avg. $E_{Dyn.}$ [Pa]	2.59E+10			2.42E+10			2.25E+10			2.17E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con’t): Freeze-thaw test results for mixtures in Program 2

C-IC-8.8

Cycles	1414			1432		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1935	1915	800	1890	1890	500
Mass [g]	6671.9	6864.6	6000	6661.8	6863.3	5000
$E_{Dyn.}$ [Pa]	2.7E+10	2.7E+10	4.2E+09	2.6E+10	2.7E+10	1.4E+09
Avg. $E_{Dyn.}$ [Pa]	1.95E+10			1.79E+10		

FA-Control

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2234	2231	2228	2222	2220	2215	2225	2229	2225	2236	2240	2238
Mass [g]	7496.5	7480	7487.7	7540.7	7579.6	7523.4	7544.2	7526	7525.8	7547.1	7528.7	7530.2
$E_{Dyn.}$ [Pa]	4.1E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.1E+10	4.0E+10	4.1E+10	4.1E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.04E+10			4.03E+10			4.05E+10			4.09E+10		

FA-Control

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2240	2240	2240	2250	2252	2250	2251	2256	2252	2253	2260	2255
Mass [g]	7548.7	7530.6	7531.1	7547.5	7530.5	7530.5	7549.3	7529	7530.8	7544.2	7525.6	7529.6
$E_{Dyn.}$ [Pa]	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.10E+10			4.14E+10			4.15E+10			4.15E+10		

FA-Control

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2262	2265	2262	2262	2266	2268	2263	2270	2265	2272	2278	2275
Mass [g]	7548.3	7531.5	7533.8	7544.9	7531.2	7532.2	7543.3	7529.3	7533	7541.2	7527.2	7527.2
$E_{Dyn.}$ [Pa]	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.18E+10			4.19E+10			4.19E+10			4.22E+10		

FA-Control

Cycles	482			536			614			664		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2277	2281	2278	2280	2290	2286	2286	2290	2284	2286	2292	2288
Mass [g]	7539.6	7526.3	7526.9	7542	7528.2	7528.6	7540.8	7526.5	7529.9	7540.3	7525.1	7521.8
$E_{Dyn.}$ [Pa]	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.24E+10			4.26E+10			4.27E+10			4.27E+10		

FA-Control

Cycles	714			763			817			853		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2288	2296	2289	2291	2297	2292	2290	2296	2291	2290	2295	2292
Mass [g]	7536.6	7522.7	7520.4	7537.1	7520.6	7520.6	7535.5	7520.4	7518.4	7534.4	7519.8	7514.5
$E_{Dyn.}$ [Pa]	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.28E+10			4.29E+10			4.28E+10			4.28E+10		

FA-Control

Cycles	889			922			953			993		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2292	2297	2293	2295	2300	2295	2290	2300	2298	2286	2296	2292
Mass [g]	7530.4	7518.7	7510.6	7523.3	7514.4	7507.4	7520.5	7512.6	7505.5	7519.7	7511.3	7503.3
$E_{Dyn.}$ [Pa]	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.29E+10			4.30E+10			4.29E+10			4.27E+10		

FA-Control

Cycles	1035			1065			1111			1160		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2289	2302	2289	2287	2301	2289	2286	2300	2289	2286	2300	2290
Mass [g]	7516.4	7509.5	7501.9	7510.4	7506.3	7499.4	7507.3	7502.5	7493.7	7501.9	7499.3	7489.3
$E_{Dyn.}$ [Pa]	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.28E+10			4.27E+10			4.27E+10			4.27E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

FA-Control

Cycles	1214			1245			1286			1317		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2285	2301	2288	2290	2305	2296	2286	2301	2294	2285	2302	2294
Mass [g]	7497.2	7498	7482.9	7487.3	7488.2	7479.6	7481.8	7483.7	7472	7477	7478	7466.1
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.26E+10			4.28E+10			4.26E+10			4.26E+10		

FA-Control

Cycles	1347			1377			1412			1447		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2286	2308	2295	2285	2307	2295	2285	2300	2295	2285	2295	2295
Mass [g]	7473.3	7476.4	7463.9	7468.6	7472.1	7460.2	7463.1	7468.3	7456.8	7454.5	7463.1	7450.2
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10
Avg. $E_{Dyn.}$ [Pa]	4.27E+10			4.26E+10			4.25E+10			4.24E+10		

FA-Control

Cycles	1487			1538			1615			1694		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2283	2307	2297	2288	2310	2299	2283	2311	2308	2270	2313	2296
Mass [g]	7451.4	7459.3	7446.9	7442.1	7451.9	7438.6	7426.4	7442.5	7427.1	7414.2	7432.3	7416.9
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.2E+10	4.3E+10	4.3E+10	4.1E+10	4.3E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.26E+10			4.26E+10			4.26E+10			4.23E+10		

FA-Control

Cycles	1739			1803			1869			1939		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2279	2307	2292	2279	2310	2299	2269	2310	2292	2260	2310	2290
Mass [g]	7407	7425.6	7408.3	7399.3	7418.4	7400.9	7382.8	7406.2	7388.1	7371.6	7402.5	7379.2
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	4.2E+10	4.2E+10	4.3E+10	4.2E+10	4.1E+10	4.3E+10	4.2E+10	4.1E+10	4.3E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.22E+10			4.23E+10			4.20E+10			4.18E+10		

FA-Control

Cycles	2037			2171		
Specimen	A	B	C	A	B	C
Frequency [Hz]	2257	2315	2290	2273	2318	2294
Mass [g]	7351.7	7392.4	7361.4	7325.6	7375.8	7343.1
$E_{Dyn.}$ [Pa]	4.1E+10	4.3E+10	4.2E+10	4.1E+10	4.3E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.18E+10			4.19E+10		

FA-IC-8.9

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2062	2072	2076	2060	2066	2072	2064	2071	2076	2071	2080	2085
Mass [g]	7278.3	7155.8	7087.7	7327	7208	7141.3	7329.6	7214.1	7146	7331.9	7215.4	7150
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.33E+10			3.34E+10			3.36E+10			3.39E+10		

FA-IC-8.9

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2077	2086	2083	2084	2090	2095	2091	2097	2102	2091	2097	2104
Mass [g]	7332.5	7217	7149.3	7331.2	7215.3	7147.6	7330.8	7215.3	7146	7325.3	7213	7142.2
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.40E+10			3.42E+10			3.44E+10			3.44E+10		

FA-IC-8.9

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2097	2103	2106	2099	2104	2111	2101	2104	2110	2109	2112	2125
Mass [g]	7330.1	7216.2	7146.5	7327	7215.7	7144	7322.6	7213.7	7141.3	7318	7210.1	7139.7
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.47E+10			3.47E+10			3.50E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

FA-IC-8.9

Cycles	482			536			614			664		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2112	2119	2122	2115	2120	2125	2115	2125	2128	2120	2126	2130
Mass [g]	7313.9	7209.8	7137.6	7313.1	7212.1	7135.5	7304.6	7209.7	7135.7	7294.9	7206.5	7132.5
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.51E+10			3.52E+10			3.52E+10			3.53E+10		

FA-IC-8.9

Cycles	714			763			817			853		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2120	2134	2130	2122	2130	2135	2124	2133	2135	2125	2133	2135
Mass [g]	7288.2	7202.9	7129	7284	7202.1	7127.3	7279.4	7200.4	7124.4	7270	7197.8	7123.4
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.54E+10			3.54E+10			3.54E+10			3.54E+10		

FA-IC-8.9

Cycles	889			922			953			993		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124	2134	2136	2124	2136	2139	2119	2130	2135	2113	2126	2131
Mass [g]	7266	7192.4	7119.6	7261.7	7188.7	7116.7	7255.5	7187.5	7113.4	7248.5	7187.5	7110.2
$E_{Dyn.}$ [Pa]	3.6E+10	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.54E+10			3.54E+10			3.53E+10			3.51E+10		

FA-IC-8.9

Cycles	1035			1065			1111			1160		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2115	2128	2133	2112	2128	2132	2110	2129	2131	2102	2130	2128
Mass [g]	7247.1	7186	7109.1	7230.5	7172.2	7100	7213.9	7169.4	7085.8	7201.6	7157	7075
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.51E+10			3.50E+10			3.50E+10			3.48E+10		

FA-IC-8.9

Cycles	1214			1245			1286			1317		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2091	2128	2125	2079	2130	2131	2076	2125	2130	2071	2128	2124
Mass [g]	7182.6	7148.7	7065.8	7169.8	7141.1	7056.4	7157.2	7128.7	7045.8	7146.8	7120.2	7040.6
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.3E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.45E+10			3.43E+10			3.42E+10		

FA-IC-8.9

Cycles	1347			1377			1412			1487		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2061	2125	2122	2041	2120	2122	1989	2120	2120	1950	2115	2113
Mass [g]	7140.9	7112	7034.5	7128.6	7101.3	7027.5	7119	7108.1	7018	7105.6	7085.1	7009.3
$E_{Dyn.}$ [Pa]	3.3E+10	3.5E+10	3.4E+10	3.2E+10	3.5E+10	3.4E+10	3.1E+10	3.5E+10	3.4E+10	2.9E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.40E+10			3.37E+10			3.31E+10			3.25E+10		

FA-IC-8.9

Cycles	1487			1538			1615			1694		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1870	2111	2109	1870	2102	2106	1747	2090	2094	1560	2073	2065
Mass [g]	7099	7078.2	7004.8	7086.1	7069.3	6995.3	7065.7	7050.7	6981.8	7047.8	7033.4	6964.2
$E_{Dyn.}$ [Pa]	2.7E+10	3.4E+10	3.4E+10	2.7E+10	3.4E+10	3.4E+10	2.3E+10	3.3E+10	3.3E+10	1.9E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.16E+10			3.14E+10			3.00E+10			2.78E+10		

FA-IC-8.9

Cycles	1739			1803			1869			1939		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1480	2036	2043	1320	1920	2006	1207	1831	1906	1001	1707	1740
Mass [g]	7043.3	7025	6957	7021.8	7009.4	6942.9	7006.1	6991.1	6928.5	6985.9	6973.3	6914.4
$E_{Dyn.}$ [Pa]	1.7E+10	3.2E+10	3.1E+10	1.3E+10	2.8E+10	3.0E+10	1.1E+10	2.5E+10	2.7E+10	7.6E+09	2.2E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.66E+10			2.38E+10			2.12E+10			1.74E+10		

FA-IC-8.9

Cycles	2037		
Specimen	A	B	C
Frequency [Hz]	-	1327	1400
Mass [g]	-	6942.4	6887.4
$E_{Dyn.}$ [Pa]	-	1.3E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	1.39E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-Control(3)

Cycles	0			30			60			83		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2175	2156	2201	2166	2147	2189	2168	2150	2193	2177	2157	2194
Mass [g]	7266	7321.8	7322	7301.6	7351.6	7347.8	7307.5	7356.3	7348.9	7309	7358.6	7352.3
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.75E+10			3.73E+10			3.75E+10			3.77E+10		

S-Control(3)

Cycles	120			160			190			237		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2184	2160	2207	2189	2172	2210	2195	2174	2217	2200	2174	2227
Mass [g]	7310	7359.7	7353.8	7309.9	7358.6	7351.2	7310.1	7360.3	7351.1	7304.1	7354.1	7344.2
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.79E+10			3.82E+10			3.83E+10			3.85E+10		

S-Control(3)

Cycles	275			301			361			432		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2205	2180	2233	2203	2180	2228	2213	2188	2231	2222	2194	2239
Mass [g]	7309	7361.5	7350	7308.6	7359.5	7347.4	7306.5	7357.3	7342.8	7303	7352.1	7335.3
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	4.0E+10	3.8E+10	3.8E+10	4.0E+10	3.9E+10	3.8E+10	4.0E+10	3.9E+10	3.8E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.87E+10			3.86E+10			3.88E+10			3.91E+10		

S-Control(3)

Cycles	482			536			614			664		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2224	2197	2244	2220	2206	2247	2231	2206	2253	2235	2206	2253
Mass [g]	7301.8	7352.7	7333.3	7301.3	7347.5	7330.8	7297.1	7353	7321.9	7293.3	7342.4	7313.8
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.92E+10			3.93E+10			3.95E+10			3.95E+10		

S-Control(3)

Cycles	714			763			817			853		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2238	2200	2235	2239	2200	2257	2237	2204	2256	2236	2207	2256
Mass [g]	7288.6	7343.3	7306.3	7286.2	7341.4	7301.9	7282.4	7320.4	7300.1	7275.4	7275.3	7287.7
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.8E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.92E+10			3.95E+10			3.94E+10			3.93E+10		

S-Control(3)

Cycles	889			922			953			993		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2242	2212	2261	2247	2214	2261	2248	2215	2262	2250	2215	2263
Mass [g]	7272.1	7330.4	7281.4	7264.7	7322.9	7273.4	7260.4	7319.4	7270	7253.2	7313.7	7266.9
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.96E+10			3.96E+10			3.97E+10			3.97E+10		

S-Control(3)

Cycles	1035			1065			1111			1160		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2255	2216	2263	2255	2215	2262	2255	2212	2261	2252	2214	2260
Mass [g]	7266.5	7311.8	7261.7	7249.6	7310.6	7255.1	7238	7300.7	7247.1	7228.3	7291.9	7236.8
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.97E+10			3.97E+10			3.96E+10			3.95E+10		

S-Control(3)

Cycles	1214			1245			1286			1317		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2251	2216	2255	2261	2220	2264	2261	2217	2260	2257	2219	2259
Mass [g]	7218.4	7281.4	7223.8	7209.2	7273.6	7215.3	7202.6	7266.8	7207.5	7195.4	7258.5	7199.2
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.94E+10			3.96E+10			3.95E+10			3.94E+10		

S-Control(3)

Cycles	1347			1377			1412			1487		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2261	2219	2262	2262	2218	2262	2262	2217	2264	2263	2213	2262
Mass [g]	7191.8	7255.8	7195	7186.7	7250.5	7185.6	7180.3	7241.9	7176.3	7167.8	7231.4	7158.6
$E_{Dyn.}$ [Pa]	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.8E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.95E+10			3.94E+10			3.94E+10			3.93E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-Control(3)

Cycles	**1497**			**1615**			**1694**			**1739**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2263**	**2217**	**2264**	**2263**	**2214**	**2263**	**2263**	**2213**	**2264**	**2262**	**2212**	**2261**
Mass [g]	**7155**	**7219.1**	**7138.3**	**7141.6**	**7202.6**	**7122.3**	**7125.6**	**7186.3**	**7099.8**	**7115.3**	**7179.2**	**7089.9**
$E_{Dyn.}$ [Pa]	4.0E+10	3.8E+10	4.0E+10	4.0E+10	3.8E+10	4.0E+10	4.0E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.93E+10**			**3.91E+10**			**3.90E+10**			**3.89E+10**		

S-Control(3)

Cycles	**14803**			**1869**			**1939**			**2037**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2264**	**2216**	**2263**	**2258**	**2211**	**2260**	**2260**	**2211**	**2260**	**2260**	**2211**	**2260**
Mass [g]	**7104.5**	**7165.8**	**7073.4**	**7085.7**	**7145.5**	**7055.5**	**7074**	**7130.3**	**7043.3**	**7054.4**	**7102.7**	**7019.8**
$E_{Dyn.}$ [Pa]	3.9E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10	3.9E+10	3.8E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.89E+10**			**3.87E+10**			**3.86E+10**			**3.85E+10**		

S-Control(3)

Cycles	**2171**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**2258**	**2205**	**2261**
Mass [g]	**7021.1**	**7069.1**	**6992**
$E_{Dyn.}$ [Pa]	3.9E+10	3.7E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	**3.83E+10**		

S-IC-7.2(2)

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2103**	**2100**	**2096**	**2123**	**2113**	**2103**	**2130**	**2123**	**2109**	**2148**	**2140**	**2120**
Mass [g]	**7123.4**	**7062.2**	**7056.6**	**7139.3**	**7078.1**	**7075.6**	**7143.7**	**7081.6**	**7077.4**	**7147.8**	**7087**	**7080.8**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.6E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.38E+10**			**3.43E+10**			**3.46E+10**			**3.51E+10**		

S-IC-7.2(2)

Cycles	**120**			**150**			**185**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2130**	**2121**	**2100**	**2125**	**2120**	**2103**	**2134**	**2130**	**2110**	**2137**	**2130**	**2112**
Mass [g]	**7147**	**7089.5**	**7083.5**	**7149.6**	**7086.8**	**7082.6**	**7151.3**	**7087.3**	**7083.9**	**7146.9**	**7086.4**	**7080.8**
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.45E+10**			**3.45E+10**			**3.48E+10**			**3.48E+10**		

S-IC-7.2(2)

Cycles	**260**			**280**			**300**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2137**	**2129**	**2115**	**2137**	**2131**	**2115**	**2136**	**2133**	**2115**
Mass [g]	**7147**	**7084.1**	**7080.1**	**7145**	**7084.6**	**7079.5**	**7143**	**7085.1**	**7078.9**
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	**3.48E+10**			**3.48E+10**			**3.49E+10**		

S-IC-9.0

Cycles	**0**			**30**			**60**			**90**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2086**	**2076**	**2062**	**2093**	**2082**	**2078**	**2102**	**2094**	**2080**	**2113**	**2106**	**2092**
Mass [g]	**6967.3**	**6909.5**	**6947.2**	**6980.8**	**6926.4**	**6966.4**	**6983.7**	**6932.2**	**6968.3**	**6988.6**	**6934.5**	**6970.2**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.24E+10**			**3.28E+10**			**3.30E+10**			**3.34E+10**		

S-IC-9.0

Cycles	**120**			**150**			**185**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094**	**2086**	**2074**	**2095**	**2086**	**2071**	**2100**	**2094**	**2075**	**2100**	**2097**	**2074**
Mass [g]	**6988.8**	**6935.1**	**6971.6**	**6990.4**	**6935**	**6974.9**	**6992.2**	**6934.3**	**6974.7**	**6990.4**	**6926.8**	**6971.3**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.28E+10**			**3.28E+10**			**3.30E+10**			**3.30E+10**		

S-IC-9.0

Cycles	**260**			**280**			**300**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2097**	**2096**	**2075**	**2099**	**2099**	**2075**	**2100**	**2101**	**2076**
Mass [g]	**6992.8**	**6925.4**	**6972.5**	**6989.6**	**6924.2**	**6969**	**6986.3**	**6922.9**	**6965.5**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.29E+10**			**3.30E+10**			**3.30E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.13 (con't): Freeze-thaw test results for mixtures in Program 2

S-IC-9.1

Cycles	0			30			60			90		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2079**	**2047**	**2064**	**2070**	**2037**	**2056**	**2076**	**2034**	**2059**	**2081**	**2047**	**2068**
Mass [g]	**6914.3**	**6931.9**	**6898.4**	**6951.5**	**6956.1**	**6930.3**	**6955.1**	**6962.6**	**6936.3**	**6959.6**	**6965.3**	**6940.4**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.19E+10**			**3.18E+10**			**3.19E+10**			**3.21E+10**		

S-IC-9.1

Cycles	120			160			190			237		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2087**	**2053**	**2075**	**2096**	**2057**	**2081**	**2102**	**2063**	**2087**	**2098**	**2065**	**2089**
Mass [g]	**6957.7**	**6966**	**6938.4**	**6955.8**	**6967**	**6937.7**	**6957**	**6967.9**	**6937.9**	**6952.4**	**6960.2**	**6934.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.23E+10**			**3.25E+10**			**3.27E+10**			**3.27E+10**		

S-IC-9.1

Cycles	275			301			361			432		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2105**	**2073**	**2091**	**2109**	**2073**	**2091**	**2113**	**2075**	**2095**	**2115**	**2078**	**2101**
Mass [g]	**6958.6**	**6968.6**	**6939.3**	**6955.4**	**6965.5**	**6938.7**	**6955.9**	**6963.3**	**6940.9**	**6951.4**	**6959.2**	**6933.5**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.29E+10**			**3.29E+10**			**3.31E+10**			**3.31E+10**		

S-IC-9.1

Cycles	482			536			614			664		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2117**	**2085**	**2106**	**2122**	**2087**	**2106**	**2120**	**2084**	**2107**	**2120**	**2084**	**2106**
Mass [g]	**6948.5**	**6953.1**	**6929.8**	**6950.2**	**6956.4**	**6930.6**	**6998**	**6952.3**	**6930.3**	**6944**	**6943.1**	**6922**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.33E+10**			**3.34E+10**			**3.34E+10**			**3.33E+10**		

S-IC-9.1

Cycles	714			763			817			853		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2123**	**2086**	**2107**	**2125**	**2091**	**2108**	**2124**	**2099**	**2109**	**2123**	**2102**	**2110**
Mass [g]	**6936.7**	**6936.8**	**6918.9**	**6933.6**	**6931.9**	**6919.7**	**6930.4**	**6932.2**	**6912.4**	**6924.7**	**6932.2**	**6907**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.33E+10**			**3.34E+10**			**3.34E+10**			**3.34E+10**		

S-IC-9.1

Cycles	889			922			953			993		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2097**	**2096**	**2075**	**2099**	**2099**	**2075**	**2100**	**2101**	**2076**	**2095**	**2086**	**2071**
Mass [g]	**6992.8**	**6925.4**	**6972.5**	**6989.6**	**6924.2**	**6969**	**6986.3**	**6922.9**	**6965.5**	**6990.4**	**6935**	**6974.9**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.29E+10**			**3.30E+10**			**3.30E+10**			**3.28E+10**		

S-IC-9.1

Cycles	1035			1065			1111			1160		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2136**	**2098**	**2119**	**2125**	**2087**	**2101**	**2122**	**2060**	**2096**	**2122**	**2050**	**2096**
Mass [g]	**6920.9**	**6920.6**	**6905.6**	**6914.8**	**6910.9**	**6899.2**	**6914.9**	**6909.7**	**6896.6**	**6911.1**	**6907.5**	**6893.9**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.1E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.28E+10**			**3.28E+10**			**3.25E+10**			**3.19E+10**		

S-IC-9.1

Cycles	1214			1245			1286			1317		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2074**	**2036**	**1992**	**2057**	**2023**	**1958**	**2010**	**1974**	**1860**	**1953**	**1905**	**1752**
Mass [g]	**6871.4**	**6863.3**	**6855.5**	**6862.2**	**6854.5**	**6845.9**	**6856.5**	**6849.8**	**6832.1**	**6861**	**6842.2**	**6830.7**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	2.9E+10	3.1E+10	3.0E+10	2.8E+10	3.0E+10	2.9E+10	2.6E+10	2.8E+10	2.7E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	**3.08E+10**			**3.01E+10**			**2.82E+10**			**2.60E+10**		

S-IC-9.1

Cycles	1347			1377			1412		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1900**	**1800**	**1647**	**1780**	**1675**	**1500**	**1680**	**1531**	**1290**
Mass [g]	**6844.7**	**6836.6**	**6814.6**	**6839**	**6826.3**	**6805.7**	**6824.2**	**6816.9**	**6795.5**
$E_{Dyn.}$ [Pa]	2.7E+10	2.4E+10	2.0E+10	2.3E+10	2.1E+10	1.7E+10	2.1E+10	1.7E+10	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	**2.36E+10**			**2.03E+10**			**1.68E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.14: *p* values obtained from Student’s t-test for the differences in freeze-thaw cycles to drop specimens below 90% of the initial E_{Dyn} for mixtures in Program 2 containing a *w/cm* ratio of 0.45

Mixture	**Average No. of cycles to 90% E_{Dyn}**	**S-Control(1)**	**S-IC-6.9**	**S-IC-8.3(1)**	**S-IC-8.4(1)**
		1569	1034	709	982
S-Control(1)	1569		**3.4×10^{-5}**	**6.9×10^{-6}**	**3.1×10^{-5}**
S-IC-6.9	1034			**4.8×10^{-4}**	0.161
S-IC-8.3(1)	709				**0.001**
S-IC-8.4(1)	982				

Table A.15: *p* values obtained from Student’s t-test for the differences in freeze-thaw cycles to drop specimens below 90% of the initial EDyn for mixtures in Program 2 containing *w/cm* ratios of 0.41 to 0.43

Mixture	**Average No. of cycles to 90% E_{Dyn}**	**S-IC-7.3**	**S-IC-8.9(1)**	**S-IC-14.1**	**C-Control(1)**	**C-IC-8.8**	**FA-Control**	**FA-IC-8.9**	**S-Control-3**	**S-IC-9.1**
		1038	956	315	>2000	1070	>2000	1615	>2000	1275
S-IC-7.3	1038		0.063	**0.001**	**-**	0.098	**-**	**0.007**	**-**	**0.002**
S-IC-8.9(1)	956			**4.1×10^{-4}**	**-**	0.070	**-**	**0.004**	**-**	**4.1×10^{-4}**
S-IC-14.1	315				**-**	**0.009**	**-**	**0.003**	**-**	**1.6×10^{-4}**
C-Control(1)	>2000					**-**	**-**	**-**	**-**	**-**
C-IC-8.8	1070						**-**	0.066	**-**	0.842
FA-Control	>2000							**-**	**-**	**-**
FA-IC-8.9	1615								**-**	**0.032**
S-Control-3	>2000									**-**
S-IC-9.1	1275									

- Specimens did not exhibit damage through more than 2000 freeze-thaw cycles

Table A.16: Freeze-thaw test results for mixtures in Program 3

S-Control

Cycles	0			32			55			87		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2074	2067	2081	2078	2076	2084	2080	2077	2088	2085	2085	2095
Mass [g]	7374.3	7466.4	7422.5	7386.4	7476.8	7433.2	7385.7	7477.8	7433	7384.8	7479	7431.9
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.48E+10			3.49E+10			3.51E+10		

S-Control

Cycles	112			154			186			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2085	2083	2090	2094	2096	2103	2097	2098	2106	2098	2105	2108
Mass [g]	7383.6	7476.3	7429	7380.6	7473.8	7425	7376.6	7467.3	7418	7372.7	7463.3	7411.2
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.50E+10			3.54E+10			3.55E+10			3.56E+10		

S-Control

Cycles	241			266			292			328		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2104	2107	2109	2109	2112	2115	2111	2116	2114	2114	2120	2118
Mass [g]	7367.1	7461.5	7409.2	7361	7455	7404.8	7356.1	7450.5	7396.5	7347.8	7442	7389.7
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.56E+10			3.58E+10			3.58E+10			3.59E+10		

S-Control

Cycles	352			380			411			446		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2118	2119	2120	2116	2124	2116	2125	2129	2117	2124	2129	2122
Mass [g]	7344.6	7438.8	7381	7342.8	7434.9	7377.8	7332.6	7436.1	7372.7	7327.2	7423	7363
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.59E+10			3.59E+10			3.61E+10			3.61E+10		

S-Control

Cycles	474			514			540			579		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124	2131	2117	2134	2134	2122	2135	2135	2125	2134	2137	2122
Mass [g]	7322.4	7420.9	7355.9	7311.1	7410.9	7342.5	7301.1	7405.1	7334.4	7299.4	7402.6	7330.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.60E+10			3.62E+10			3.62E+10			3.61E+10		

S-Control

Cycles	629			700			734			756		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2136	2140	2120	2131	2135	2107	2136	2123	2089	2126	2114	2076
Mass [g]	7289.5	7395.5	7318.4	7282.8	7389.2	7318.1	7279.9	7386.5	7301.2	7271.1	7382.1	7297.1
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.61E+10			3.58E+10			3.55E+10			3.51E+10		

S-Control

Cycles	786			816			846			867		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2130	2111	2060	2120	2090	2035	2113	2080	2008	2092	2040	1946
Mass [g]	7264.5	7373.3	7290.5	7265.4	7380.5	7300.9	7262.7	7377.2	7289.7	7258.6	7376.7	7284.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.4E+10	3.5E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.2E+10	3.4E+10	3.3E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.49E+10			3.44E+10			3.39E+10			3.25E+10		

S-Control

Cycles	901			934			967			1000		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2060	1965	1775	2010	1900	1695	1950	1700	1508	1850	1570	1405
Mass [g]	7247.7	7375.6	7284.9	7255.9	7371.1	7291.3	7252.3	7356	7282.7	7247.5	7350.3	7274.9
$E_{Dyn.}$ [Pa]	3.3E+10	3.1E+10	2.5E+10	3.2E+10	2.9E+10	2.3E+10	3.0E+10	2.3E+10	1.8E+10	2.7E+10	2.0E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.97E+10			2.78E+10			2.36E+10			2.07E+10		

S-Control

Cycles	1035			1070		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1741	1241	1001	1606	1001	-
Mass [g]	7240.7	7344.4	7268.8	7235.7	7337.1	-
$E_{Dyn.}$ [Pa]	2.4E+10	1.2E+10	7.9E+09	2.0E+10	8.0E+09	
Avg. $E_{Dyn.}$ [Pa]	1.46E+10			1.20E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

S-IC-6.3

Cycles	0			32			55			87		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2052	2049	2028	2052	2050	2032	2053	2053	2034	2059	2056	2039
Mass [g]	7336.8	7401.2	7399.3	7346.9	7414.2	7413.8	7351.1	7412.6	7411.8	7347.8	7412.1	7410.5
$E_{Dyn.}$ [Pa]	3.3E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.34E+10			3.35E+10			3.36E+10			3.37E+10		

S-IC-6.3

Cycles	112			154			186			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2052	2052	2031	2051	2056	2041	2046	2047	2034	2039	2041	2029
Mass [g]	7349.8	7410.3	7410.3	7341.7	7409.3	7407.4	7332.1	7401.8	7394.7	7323.6	7396.5	7390.7
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.35E+10			3.36E+10			3.33E+10			3.31E+10		

S-IC-6.3

Cycles	241			266			292			328		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2029	2031	2018	2034	2020	2008	1970	2008	1973	1884	1970	1912
Mass [g]	7319	7391.3	7388.9	7308.8	7281.3	7382.3	7304.3	7374.4	7376.3	7291.4	7368.6	7366.7
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.1E+10	2.8E+10	3.1E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.28E+10			3.24E+10			3.14E+10			2.94E+10		

S-IC-6.3

Cycles	352			380			411		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1819	1929	1818	1625	1777	1708	1360	1629	1515
Mass [g]	7288.5	7360.7	7360.1	7282.3	7357.9	7358.1	7278.5	7346.7	7356.8
$E_{Dyn.}$ [Pa]	2.6E+10	3.0E+10	2.6E+10	2.1E+10	2.5E+10	2.3E+10	1.5E+10	2.1E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.74E+10			2.31E+10			1.80E+10		

S-IC-6.6

Cycles	0			46			95			125		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2065	2032	2035	2063	2030	2030	2072	2038	2033	2064	2034	2028
Mass [g]	7309	7249.1	7271.2	7321.7	7263	7283.3	7325.5	7266.8	7287.2	7325.9	7271.9	7291.3
$E_{Dyn.}$ [Pa]	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.29E+10			3.29E+10			3.31E+10			3.30E+10		

S-IC-6.6

Cycles	150			181			222			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2061	2030	2023	2064	2032	2023	2023	2052	2006	2036	2008	1975
Mass [g]	7326.7	7268.9	7288.8	7326.2	7267.5	7287.9	7325.1	7268	7291.1	7322	7269.6	7291.7
$E_{Dyn.}$ [Pa]	3.4E+10	3.2E+10	3.2E+10	3.4E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.3E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.28E+10			3.29E+10			3.25E+10			3.18E+10		

S-IC-6.6

Cycles	253			283			313			348		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2020	1995	1948	2000	1945	1880	1965	1862	1725	1897	1659	1420
Mass [g]	7321.1	7272	7291.6	7321.7	7275.3	7286.4	7319.5	7279.2	7286.9	7316.5	7277.6	7276.3
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.0E+10	2.8E+10	3.1E+10	2.7E+10	2.3E+10	2.9E+10	2.2E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.12E+10			2.98E+10			2.72E+10			2.20E+10		

S-IC-6.6

Cycles	383		
Specimen	A	B	C
Frequency [Hz]	1810	1450	1200
Mass [g]	7312.2	7275.2	7272.3
$E_{Dyn.}$ [Pa]	2.6E+10	1.7E+10	1.1E+10
Avg. $E_{Dyn.}$ [Pa]	1.80E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

S-IC-6.8

Cycles	0			32			55			87		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2026	1996	2029	2032	2002	2037	2031	2003	2037	2036	2009	2041
Mass [g]	7232.3	7193.7	7245.8	7244.8	7208.2	7261.7	7246.1	7209.2	7260.4	7245.8	7206.8	7258
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.3E+10	3.2E+10	3.1E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.18E+10			3.21E+10			3.21E+10			3.23E+10		

S-IC-6.8

Cycles	112			154			186			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2032	2007	2030	2044	2015	2049	2045	2014	2051	2040	2014	2047
Mass [g]	7242.8	7204.8	7258.8	7243.8	7205.2	7254.2	7237.4	7195.6	7245.3	7234.3	7190.2	7236.1
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.21E+10			3.25E+10			3.25E+10			3.24E+10		

S-IC-6.8

Cycles	241			266			292			328		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2040	2014	2050	2039	2012	2053	2030	2007	2053	2035	2002	2053
Mass [g]	7230.3	7187.3	7234.6	7222.2	7180.3	7230.5	7212.8	7172.5	7221.6	7202.6	7164.9	7211.3
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.1E+10	3.3E+10	3.2E+10	3.1E+10	3.3E+10	3.2E+10	3.1E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.24E+10			3.24E+10			3.22E+10			3.21E+10		

S-IC-6.8

Cycles	352			380			411			446		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2039	1997	2046	1992	1984	2040	1925	1964	2029	1833	1942	2007
Mass [g]	7142.7	7159.3	7206.8	7097.5	7155	7200.4	7066.6	7147.6	7197.7	7054.7	7141.2	7202
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.2E+10	2.8E+10	3.0E+10	3.2E+10	2.6E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.19E+10			3.12E+10			3.01E+10			2.88E+10		

S-IC-6.8

Cycles	474			514			540		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1634	1906	1984	1315	1775	1912	1189	1602	1780
Mass [g]	7022.5	7137.4	7183.5	6953.6	7132.8	7170	6947.6	7128.8	7169.7
$E_{Dyn.}$ [Pa]	2.0E+10	2.8E+10	3.1E+10	1.3E+10	2.4E+10	2.8E+10	1.1E+10	2.0E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.64E+10			2.19E+10			1.84E+10		

S-IC-7.0

Cycles	0			14			38			75		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1931	1929	1926	1921	1920	1919	1924	1918	1921	1928	1924	1925
Mass [g]	6946.3	6942.4	6939.3	6953.6	6949.1	6945.1	6955	6951.4	6948.1	6955.8	6950	6946.8
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.80E+10			2.78E+10			2.78E+10			2.79E+10		

S-IC-7.0

Cycles	115			150			185			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1930	1926	1927	1932	1929	1934	1932	1925	1934	1927	1923	1930
Mass [g]	6952.3	6945.6	6944.2	6944	6938.4	6941.2	6940.3	6929.1	6936.4	6931.8	6919.1	6926.6
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.80E+10			2.81E+10			2.80E+10			2.79E+10		

S-IC-7.0

Cycles	244			278			311			344		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1932	1920	1936	1932	1919	1936	1930	1915	1929	1925	1900	1915
Mass [g]	6931	6913.1	6923	6915	6900.9	6911.3	6902.5	6888.8	6904.5	6886.8	6876.2	6893.1
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.79E+10			2.79E+10			2.77E+10			2.73E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

S-IC-7.0

Cycles	377			412			447			475		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1918	1890	1915	1899	1852	1890	1875	1835	1875	1850	1775	1825
Mass [g]	6861	6853.4	6869.8	6840.2	6839.6	6856.3	6820.2	6826.5	6844.9	6788.5	6792.6	6815.1
$E_{Dyn.}$ [Pa]	2.7E+10	2.7E+10	2.7E+10	2.7E+10	2.5E+10	2.7E+10	2.6E+10	2.5E+10	2.6E+10	2.5E+10	2.3E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.71E+10			2.62E+10			2.57E+10			2.43E+10		

S-IC-7.0

Cycles	511			545			587		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1803	1660	1699	1737	1525	1610	1607	1355	1504
Mass [g]	6766.7	6781	6798.8	6728.8	6726.4	6767.1	6696.1	6680.7	6723.3
$E_{Dyn.}$ [Pa]	2.4E+10	2.0E+10	2.1E+10	2.2E+10	1.7E+10	1.9E+10	1.9E+10	1.3E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.18E+10			1.93E+10			1.62E+10		

S-IC-7.7

Cycles	0			35			55			75		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2015	2018	2008	2004	2014	2002	2004	2013	2001	2006	2014	2002
Mass [g]	7124.9	7089.5	7103.4	7129.3	7095.8	7107	7128.4	7095.1	7107.5	7124.6	7093.9	7107.2
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.12E+10			3.10E+10			3.10E+10			3.10E+10		

S-IC-7.7

Cycles	92			127			158			190		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1998	2012	1997	2001	2018	2003	1995	2014	1995	1992	2013.5	1988
Mass [g]	7121.1	7091.1	7103.3	7110.8	7080.8	7091.2	7101.4	7069.2	7077.3	7085	7060.6	7063.9
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.09E+10			3.10E+10			3.07E+10			3.06E+10		

S-IC-7.7

Cycles	204			224			254			283		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1989	2013	1981	1990	2007	1974	1974	2003	1950	1955	1990	1925
Mass [g]	7068.6	7052	7050.4	7053.6	7036.6	7037.7	7033.9	7022.2	7018.5	7017.2	7006.2	6997.9
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10	2.9E+10	2.9E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.04E+10			3.02E+10			2.97E+10			2.91E+10		

S-IC-7.7

Cycles	311			328			352			390		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1941	1982	1885	1918	1978	1874	1881	1956	1801	1836	1890	1660
Mass [g]	6998	6992.9	6976.4	6979	6980.7	6961.2	6957.9	6954.7	6939.3	6931.6	6932.4	6901.9
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	2.7E+10	2.8E+10	3.0E+10	2.6E+10	2.7E+10	2.9E+10	2.4E+10	2.5E+10	2.7E+10	2.1E+10
Avg. $E_{Dyn.}$ [Pa]	2.84E+10			2.80E+10			2.66E+10			2.43E+10		

S-IC-7.7

Cycles	428			458		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1718	1800	1525	1550	1684	1420
Mass [g]	6893.7	6905.9	6864.2	6846.4	6865.7	6813.1
$E_{Dyn.}$ [Pa]	2.2E+10	2.4E+10	1.7E+10	1.8E+10	2.1E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.12E+10			1.79E+10		

S-IC-7.8

Cycles	0			25			61			85		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2023	2020	2026	2018	2020	2014	2016	2018	2014	2013	2020	2018
Mass [g]	7337	7297.9	7210.8	7344.9	7305.9	7217.5	7345	7298.1	7211.6	7340.9	7291.4	7200
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.23E+10			3.21E+10			3.21E+10			3.21E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

S-IC-7.8

Cycles	114			145			180			208		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2004	2013	2008	2017	2018	2019	2001	2003	2008	1969	1994	1991
Mass [g]	7329.8	7279.3	7185.8	7327.6	7250.8	7169.3	7292.4	7220.2	7136.9	7259.5	7199.6	7115
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.18E+10			3.20E+10			3.14E+10			3.07E+10		

S-IC-7.8

Cycles	248			274			300			313		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1920	1931	1950	1825	1835	1865	1653	1676	1783	1481	1517	1700
Mass [g]	7236.6	7166.5	7082.2	7212.9	7137.2	7062.7	7185.8	7111	7046.3	7158.3	7085	7029.9
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.6E+10	2.6E+10	2.7E+10	2.1E+10	2.2E+10	2.4E+10	1.7E+10	1.8E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.90E+10			2.62E+10			2.24E+10			1.89E+10		

S-IC-8.0

Cycles	0			33			64			93		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1920	1931	1927	1915	1934	1930	1893	1930	1926	1889	1930	1920
Mass [g]	7089.7	7108.9	7121.3	7105.4	7124.6	7136.1	7110.9	7130.2	7141.5	7111.1	7132.6	7145.6
$E_{Dyn.}$ [Pa]	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.7E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.86E+10			2.86E+10			2.84E+10			2.83E+10		

S-IC-8.0

Cycles	118			141			173			197		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1874	1930	1914	1848	1920	1889	1798	1910	1888	1705	1866	1854
Mass [g]	7109.9	7131.9	7145.3	7110.2	7127.9	7144.3	7106.9	7125	7145.6	7106.4	7123.4	7143.3
$E_{Dyn.}$ [Pa]	2.7E+10	2.9E+10	2.8E+10	2.6E+10	2.8E+10	2.8E+10	2.5E+10	2.8E+10	2.8E+10	2.2E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.81E+10			2.75E+10			2.69E+10			2.53E+10		

S-IC-8.0

Cycles	224			254			271			305		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1624	1843	1797	1470	1750	1710	1065	1685	1640	1008	1480	1410
Mass [g]	7105	7122.2	7148.3	7108	7126	7154.3	7099.7	7122.9	7147.4	7090.2	7135.5	7147.6
$E_{Dyn.}$ [Pa]	2.0E+10	2.6E+10	2.5E+10	1.7E+10	2.4E+10	2.3E+10	8.7E+09	2.2E+10	2.1E+10	7.8E+09	1.7E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.38E+10			2.10E+10			1.72E+10			1.34E+10		

S-IC-10.2

Cycles	0			32			55			87		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1993	1959	1995	1997	1958	2001	1997	1962	2001	1989	1956	1993
Mass [g]	7238.4	7317.4	7227.9	7254.3	7332.3	7225	7256.5	7333.5	7226.7	7260.9	7335.8	7227.1
$E_{Dyn.}$ [Pa]	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.09E+10			3.11E+10			3.11E+10			3.09E+10		

S-IC-10.2

Cycles	112			154			186			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1963	1947	1979	1916	1933	1961	1786	1875	1903	1608	1783	1814
Mass [g]	7262.4	7337.7	7225.6	7274.2	7354.4	7232.7	7281.4	7345.8	7237.3	7281.2	7343.5	7231.7
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	2.9E+10	3.0E+10	3.0E+10	2.5E+10	2.8E+10	2.8E+10	2.0E+10	2.5E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.04E+10			2.96E+10			2.72E+10			2.38E+10		

S-IC-10.2

Cycles	241			266		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1391	1650	1727	1080	1450	1600
Mass [g]	7283.9	7346.7	7232	7283.5	7348	7231.9
$E_{Dyn.}$ [Pa]	1.5E+10	2.2E+10	2.3E+10	9.2E+09	1.7E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.01E+10			1.53E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

S-IC-10.7

Cycles	0			35			55			75		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2015	2013	1970	1985	1995	1934	1970	1986	1930	1970	1980	1910
Mass [g]	7243.6	7276.5	7100.6	7257	7288.4	7110.4	7260.9	7290.3	7115.7	7259	7291.3	7113.2
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.0E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.12E+10			3.04E+10			3.01E+10			2.99E+10		

S-IC-10.7

Cycles	92			127			158			190		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1950	1964	1890	1920	1920	1830	1800	1825	1680	1612.5	1627.5	1407.5
Mass [g]	7257.8	7293.9	7113.1	7244.7	7287.3	7103.5	7235.2	7278.4	7092.2	7226.6	7271.8	7082.8
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.8E+10	2.9E+10	2.9E+10	2.6E+10	2.5E+10	2.6E+10	2.2E+10	2.0E+10	2.1E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.93E+10			2.79E+10			2.45E+10			1.88E+10		

S-IC-10.7

Cycles	204		
Specimen	A	B	C
Frequency [Hz]	1425	1430	1135
Mass [g]	7218	7265.2	7073.4
$E_{Dyn.}$ [Pa]	1.6E+10	1.6E+10	9.9E+09
Avg. $E_{Dyn.}$ [Pa]	1.40E+10		

S-IC-11.6

Cycles	0			14			38			75		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1949	1974	1957	1937	1963	1948	1930	1959	1946	1915	1935	1930
Mass [g]	7183	7129.9	7115.4	7189.8	7138	7122.2	7194.3	7141.5	7125.7	7194.6	7144.4	7126.6
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.97E+10			2.94E+10			2.93E+10			2.88E+10		

S-IC-11.6

Cycles	115			150			185			220		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1890	1910	1910	1850	1869	1869	1716	1720	1720	1390	1395	1520
Mass [g]	7187.4	7138.6	7120	7173.1	7137.3	7105.2	7162.4	7135.5	7083.7	7141.3	7125.9	7050.9
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.8E+10	2.7E+10	2.7E+10	2.7E+10	2.3E+10	2.3E+10	2.3E+10	1.5E+10	1.5E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.81E+10			2.68E+10			2.28E+10			1.59E+10		

S-IC-12.1

Cycles	0			32			55			87		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1968	1935	1935	1956	1921	1916	1942	1912	1881	1890	1852	1812
Mass [g]	7087.4	7026	7096	7109.9	7046.5	7118.3	7112.5	7049.7	7122.6	7117.4	7056.6	7136.2
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	2.9E+10	2.9E+10	2.8E+10	2.8E+10	2.9E+10	2.8E+10	2.7E+10	2.8E+10	2.6E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.90E+10			2.87E+10			2.81E+10			2.64E+10		

S-IC-12.1

Cycles	112			139			169		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1670	1685	1403	1238	1394	1001	1000	1000	1000
Mass [g]	7130	7063	7146.2	7148.6	7065	7142	7128.1	7061.3	7107.3
$E_{Dyn.}$ [Pa]	2.2E+10	2.2E+10	1.5E+10	1.2E+10	1.5E+10	7.8E+09	7.7E+09	7.7E+09	7.7E+09
Avg. $E_{Dyn.}$ [Pa]	1.95E+10			1.15E+10			7.69E+09		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

C-Control

Cycles	0			31			61			85		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2113**	**2112**	**2116**	**2112**	**2114**	**2115**	**2108**	**2114**	**2125**	**2109**	**2112**	**2113**
Mass [g]	**7557.1**	**7562.8**	**7523.5**	**7566.7**	**7573**	**7593.1**	**7564.3**	**7571.5**	**7592**	**7559.7**	**7570.7**	**7589.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.65E+10**			**3.67E+10**			**3.67E+10**			**3.66E+10**		

C-Control

Cycles	117			154			189			219		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2117**	**2122**	**2119**	**2122**	**2126**	**2126**	**2125**	**2126**	**2125**	**2128**	**2130**	**2126**
Mass [g]	**7550.6**	**7564.7**	**7580.5**	**7536.1**	**7554.8**	**7566.6**	**7521.6**	**7545.3**	**7554.9**	**7515.7**	**7537.8**	**7548.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.68E+10**			**3.69E+10**			**3.69E+10**			**3.70E+10**		

C-Control

Cycles	249			284			319			359		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2131**	**2136**	**2129**	**2131**	**2139**	**2130**	**2129**	**2139**	**2133**	**2133**	**2142**	**2129**
Mass [g]	**7502.3**	**7527.5**	**7533.9**	**7488.3**	**7513.6**	**7521.5**	**7468.7**	**7493.3**	**7498.3**	**7454.5**	**7482.3**	**7488.3**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.70E+10**			**3.70E+10**			**3.69E+10**			**3.69E+10**		

C-Control

Cycles	375			410			441			487		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2136**	**2142**	**2130**	**2136**	**2148**	**2134**	**2139**	**2148**	**2131**	**2142**	**2155**	**2138**
Mass [g]	**7451.5**	**7445.9**	**7479.2**	**7429**	**7456.5**	**7463.8**	**7420**	**7442.9**	**7448.7**	**7400.5**	**7426.3**	**7429.8**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.69E+10**			**3.69E+10**			**3.69E+10**			**3.70E+10**		

C-Control

Cycles	507			540			575			611		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2142**	**2155**	**2135**	**2142**	**2155**	**2120**	**2151**	**2167**	**2139**	**2152**	**2170**	**2136**
Mass [g]	**7398.8**	**7424.4**	**7426.4**	**7381.5**	**7405.7**	**7407**	**7375.6**	**7395.3**	**7398**	**7366.5**	**7382.7**	**7392.1**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	**3.69E+10**			**3.67E+10**			**3.71E+10**			**3.71E+10**		

C-Control

Cycles	645			667			703			738		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2156**	**2122**	**2139**	**2157**	**2177**	**2136**	**2158**	**2177**	**2134**	**2157**	**2174**	**2126**
Mass [g]	**7359.7**	**7377.4**	**7384.7**	**7353**	**7365.1**	**7375**	**7343.7**	**7360.1**	**7371.1**	**7336.7**	**7353.7**	**7367.3**
$E_{Dyn.}$ [Pa]	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.66E+10**			**3.71E+10**			**3.71E+10**			**3.69E+10**		

C-Control

Cycles	773			797			831			863		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2153**	**2174**	**2120**	**2157**	**2174**	**2122**	**2156**	**2177**	**2122**	**2155**	**2175**	**2121**
Mass [g]	**7328.5**	**7346.4**	**7361**	**7325.4**	**7341.3**	**7358.4**	**7318.8**	**7334.5**	**7347.5**	**7310.1**	**7325.5**	**7341.5**
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.68E+10**			**3.68E+10**			**3.68E+10**			**3.67E+10**		

C-Control

Cycles	897			930			965			1000		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2159**	**2177**	**2111**	**2158**	**2178**	**2112**	**2151**	**2169**	**2097**	**2153**	**2173**	**2108**
Mass [g]	**7303**	**7321.9**	**7334.4**	**7290**	**7309.5**	**7320.3**	**7277.9**	**7301.9**	**7310.7**	**7268.3**	**7292.4**	**7301.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.8E+10	3.5E+10	3.7E+10	3.8E+10	3.5E+10	3.6E+10	3.7E+10	3.5E+10	3.7E+10	3.7E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	**3.66E+10**			**3.66E+10**			**3.62E+10**			**3.63E+10**		

C-Control

Cycles	1028			1064			1098			1140		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2148**	**2163**	**2085**	**2145**	**2155**	**2065**	**2143**	**2153**	**2050**	**2131**	**2129**	**2013**
Mass [g]	**7252.2**	**7280.4**	**7290.2**	**7244.7**	**7262.6**	**7277**	**7214.6**	**7247.9**	**7260.8**	**7194**	**7223.4**	**7237.3**
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.4E+10	3.6E+10	3.7E+10	3.4E+10	3.6E+10	3.6E+10	3.3E+10	3.5E+10	3.5E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.58E+10**			**3.54E+10**			**3.51E+10**			**3.42E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

C-Control

Cycles	1186			1218			1254			1280		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124	2100	1962	2080	2098	1958	2074	2072	1915	2062	2070	1910
Mass [g]	7175.2	7209.3	7223.4	7159.6	7196.6	7209	7145.8	7187.4	7194.2	7134.6	7179.9	7189.2
$E_{Dyn.}$ [Pa]	3.5E+10	3.4E+10	3.0E+10	3.4E+10	3.4E+10	3.0E+10	3.3E+10	3.3E+10	2.9E+10	3.3E+10	3.3E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.32E+10			3.26E+10			3.18E+10			3.15E+10		

C-Control

Cycles	1300			1328			1346			1397		
Specimen	0	B	C	0	B	C	A	B	C	A	B	C
Frequency [Hz]	2036	2038	1850	2027	2015	1841	2030	2018	1838	2020	2018	1814
Mass [g]	7127	7171	7179	7110.1	7147	7151.6	7106.7	7136.5	7150.1	7077	7132.6	7132.2
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	2.7E+10	3.2E+10	3.2E+10	2.6E+10	3.2E+10	3.1E+10	2.6E+10	3.1E+10	3.1E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.03E+10			3.00E+10			2.98E+10			2.94E+10		

C-Control

Cycles	1432			1472			1498			1520		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006	2002	1810	1966	1966	1767	1718	1710	1630	-	1320	1038
Mass [g]	7065	7120.2	7110.1	7039.1	7105.2	7092.3	6961.6	7086.7	7071.4	-	7007.8	7010.3
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	2.5E+10	2.9E+10	3.0E+10	2.4E+10	2.2E+10	2.2E+10	2.0E+10	-	1.3E+10	8.2E+09
Avg. $E_{Dyn.}$ [Pa]	2.90E+10			2.77E+10			2.17E+10			1.07E+10		

C-IC-3.8

Cycles	0			31			61			85		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2074	2067	2081	2078	2076	2084	2080	2077	2088	2085	2085	2095
Mass [g]	7374.3	7466.4	7422.5	7386.4	7476.8	7433.2	7385.7	7477.8	7433	7384.8	7479	7431.9
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.48E+10			3.49E+10			3.51E+10		

C-IC-3.8

Cycles	117			154			189			219		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2085	2083	2090	2094	2096	2103	2097	2098	2106	2098	2105	2108
Mass [g]	7383.6	7476.3	7429	7380.6	7473.8	7425	7376.6	7467.3	7418	7372.7	7463.3	7411.2
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.50E+10			3.54E+10			3.55E+10			3.56E+10		

C-IC-3.8

Cycles	249			284			319			359		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2104	2107	2109	2109	2112	2115	2111	2116	2114	2114	2120	2118
Mass [g]	7367.1	7461.5	7409.2	7361	7455	7404.8	7356.1	7450.5	7396.5	7347.8	7442	7389.7
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.56E+10			3.58E+10			3.58E+10			3.59E+10		

C-IC-3.8

Cycles	375			410			441			487		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2118	2119	2120	2116	2124	2116	2125	2129	2117	2124	2129	2122
Mass [g]	7344.6	7438.8	7381	7342.8	7434.9	7377.8	7332.6	7436.1	7372.7	7327.2	7423	7363
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.59E+10			3.59E+10			3.61E+10			3.61E+10		

C-IC-3.8

Cycles	507			540			575			611		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124	2131	2117	2134	2134	2122	2135	2135	2125	2134	2137	2122
Mass [g]	7322.4	7420.9	7355.9	7311.1	7410.9	7342.5	7301.1	7405.1	7334.4	7299.4	7402.6	7330.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.60E+10			3.62E+10			3.62E+10			3.61E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

C-IC-3.8

Cycles	645			667			703			738		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2136	2140	2120	2131	2135	2107	2136	2123	2089	2126	2114	2076
Mass [g]	7289.5	7395.5	7318.4	7282.8	7389.2	7318.1	7279.9	7386.5	7301.2	7271.1	7382.1	7297.1
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.61E+10			3.58E+10			3.55E+10			3.51E+10		

C-IC-3.8

Cycles	773			797			831			863		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2130	2111	2060	2120	2090	2035	2113	2080	2008	2092	2040	1946
Mass [g]	7264.5	7373.3	7290.5	7265.4	7380.5	7300.9	7262.7	7377.2	7289.7	7258.6	7376.7	7284.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.4E+10	3.5E+10	3.5E+10	3.3E+10	3.5E+10	3.5E+10	3.2E+10	3.4E+10	3.3E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.49E+10			3.44E+10			3.39E+10			3.25E+10		

C-IC-3.8

Cycles	897			930			965			1000		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2060	1965	1775	2010	1900	1695	1950	1700	1508	1850	1570	1405
Mass [g]	7247.7	7375.6	7284.9	7255.9	7371.1	7291.3	7252.3	7356	7282.7	7247.5	7350.3	7274.9
$E_{Dyn.}$ [Pa]	3.3E+10	3.1E+10	2.5E+10	3.2E+10	2.9E+10	2.3E+10	3.0E+10	2.3E+10	1.8E+10	2.7E+10	2.0E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.97E+10			2.78E+10			2.36E+10			2.07E+10		

C-IC-3.8

Cycles	1035			1070		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1741	1241	1001	1606	1001	-
Mass [g]	7240.7	7344.4	7268.8	7235.7	7337.1	-
$E_{Dyn.}$ [Pa]	2.4E+10	1.2E+10	7.9E+09	2.0E+10	8.0E+09	-
Avg. $E_{Dyn.}$ [Pa]	1.46E+10			1.20E+10		

C-IC-7.3

Cycles	0			35			75			91		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2073	2045	2092	2070	2036	2095	2073	2039	2095	2073	2040	2097
Mass [g]	7403.2	7336.7	7339.5	7411.3	7343.5	7343.8	7410.4	7342	7342.1	7409	7341.8	7340.6
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.48E+10			3.49E+10			3.51E+10		

C-IC-7.3

Cycles	127			158			204			224		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2072	2042	2103	2074	2042	2105	2074	2059	2107	2074	2036	2108
Mass [g]	7401.8	7331.4	7336.4	7394.6	7325	7332.5	7382.9	7316.8	7320.5	7367.4	7309.5	7313.1
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.50E+10			3.54E+10			3.55E+10			3.56E+10		

C-IC-7.3

Cycles	254			283			311			328		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2067	2029	2097	2065	2014	2098	2059	2007	2098	2057	1995	2098
Mass [g]	7364.1	7301.4	7305.5	7353.3	7294.3	7293.8	7345.6	7288.3	7285.5	7337	7282	7282.4
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.56E+10			3.58E+10			3.58E+10			3.59E+10		

C-IC-7.3

Cycles	352			390			428			463		
Specimen	A	B	C	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2056	1986	2098	2040	1943	2090	2032	1910	2081	2018	1849	2064
Mass [g]	7329.4	7270.5	7266	7312	7253.9	7247.8	7289.6	7232.1	7226.5	7272.4	7212.8	7209.8
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.59E+10			3.59E+10			3.61E+10			3.61E+10		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

C-IC-7.3

Cycles	**498**			**533**			**557**			**591**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1987**	**1640**	**2041**	**1956**	**1500**	**1986**	**1930**	**1400**	**1964**	**1895**	**1110**	**1893**
Mass [g]	**7254.1**	**7200.9**	**7196.7**	**7240.7**	**7180.8**	**7179.3**	**7233**	**7137.6**	**7171.1**	**7207.9**	**7149.2**	**7154.5**
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.60E+10**			**3.62E+10**			**3.62E+10**			**3.61E+10**		

C-IC-7.3

Cycles	**624**			**657**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1820**	**1001**	**1700**	**1620**	**-**	**1600**
Mass [g]	**7194.5**	**7135.5**	**7140.9**	**7174.3**	**-**	**7125**
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.6E+10	3.6E+10	-	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	**3.61E+10**			**3.55E+10**		

C-IC-9.8

Cycles	**0**			**25**			**51**			**87**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1996**	**1995**	**2000**	**1997**	**1993**	**1997**	**2000**	**1996**	**1999**	**2003**	**2000**	**2002**
Mass [g]	**7336.8**	**7141.7**	**7113.2**	**7344.6**	**7148.9**	**7119.6**	**7344.8**	**7147.5**	**7118.8**	**7345**	**7148.8**	**7111**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	**3.11E+10**			**3.11E+10**			**3.12E+10**			**3.13E+10**		

C-IC-9.8

Cycles	**112**			**140**			**171**			**206**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2003**	**2002**	**2007**	**2002**	**2000**	**2000**	**2007**	**2003**	**2007**	**2007**	**2006**	**2006**
Mass [g]	**7341**	**7136.1**	**7105**	**7337.7**	**7129**	**7095.2**	**7327.7**	**7117.8**	**7078.7**	**7322.2**	**7105.9**	**7069.5**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	**3.13E+10**			**3.12E+10**			**3.13E+10**			**3.13E+10**		

C-IC-9.8

Cycles	**234**			**274**			**300**			**339**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2012**	**2004**	**2001**	**2013**	**2013**	**2003**	**2012**	**2012**	**2000**	**2015**	**2010**	**2001**
Mass [g]	**7313**	**7094.3**	**7060.5**	**7304.8**	**7071.9**	**7046.2**	**7294.4**	**7062.2**	**7036.9**	**7280.3**	**7045.3**	**7022**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	**3.12E+10**			**3.13E+10**			**3.12E+10**			**3.11E+10**		

C-IC-9.8

Cycles	**356**			**386**			**415**			**443**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2014**	**2012**	**1996**	**2000**	**1987**	**1955**	**1972**	**1970**	**1890**	**1959**	**1953**	**1867**
Mass [g]	**7277.6**	**7036.6**	**7019.6**	**7268.9**	**7033.7**	**7025.7**	**7255.8**	**7016.7**	**7002**	**7252.2**	**7005**	**6988.6**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.0E+10	2.9E+10	3.1E+10	3.0E+10	2.7E+10	3.0E+10	2.9E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	**3.11E+10**			**3.02E+10**			**2.91E+10**			**2.85E+10**		

C-IC-9.8

Cycles	**460**			**484**			**522**			**560**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1947**	**1927**	**1800**	**1910**	**1905**	**1712**	**1796**	**1801**	**1430**	**1590**	**1666**	**1260**
Mass [g]	**7241.3**	**6993.5**	**6984.4**	**7226.3**	**6980.9**	**6973.6**	**7208.9**	**6954.5**	**6966.6**	**7185.6**	**6913.9**	**6942.8**
$E_{Dyn.}$ [Pa]	3.0E+10	2.8E+10	2.5E+10	2.9E+10	2.7E+10	2.2E+10	2.5E+10	2.4E+10	1.5E+10	2.0E+10	2.1E+10	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	**2.75E+10**			**2.61E+10**			**2.17E+10**			**1.75E+10**		

C-IC-11.8

Cycles	**0**			**25**			**51**			**87**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2011**	**1996**	**2026**	**2004**	**1992**	**2025**	**2002**	**1991**	**2020**	**1998**	**1995**	**2026**
Mass [g]	**7186.1**	**7136.6**	**7166**	**7193.6**	**7141.3**	**7171.7**	**7190.9**	**7141.8**	**7173.2**	**7182.5**	**7135.2**	**7166.9**
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	**3.14E+10**			**3.13E+10**			**3.12E+10**			**3.12E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.16 (con't): Freeze-thaw test results for mixtures in Program 3

C-IC-11.8

Cycles	112			140			171			206		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2001**	**1993**	**2025**	**1985**	**1989**	**2019**	**1970**	**1990**	**2017**	**1960**	**1990**	**2010**
Mass [g]	**7172.3**	**7124.6**	**7156.3**	**7163.4**	**7114.6**	**7142.9**	**7142.6**	**7093.3**	**7121.1**	**7117.8**	**7070.2**	**7098.9**
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.0E+10	3.0E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	**3.12E+10**			**3.09E+10**			**3.06E+10**			**3.03E+10**		

C-IC-11.8

Cycles	234			274			300			339		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1930**	**1984**	**2013**	**1830**	**1957**	**2004**	**1772**	**1930**	**1970**	**1585**	**1899**	**1930**
Mass [g]	**7100.5**	**7053.5**	**7078.9**	**7064.3**	**7035.3**	**7053.7**	**7035.7**	**7017.3**	**7032.8**	**7001.6**	**7003.4**	**7007**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	3.1E+10	2.6E+10	2.9E+10	3.1E+10	2.4E+10	2.8E+10	3.0E+10	1.9E+10	2.7E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	**2.99E+10**			**2.85E+10**			**2.73E+10**			**2.49E+10**		

C-IC-11.8

Cycles	356			389			424		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1410**	**1864**	**1903**	**1001**	**1755**	**1753**	**1001**	**1460**	**1540**
Mass [g]	**6923.5**	**6989.3**	**6996.2**	**6858.7**	**6973.7**	**6975**	**6800**	**6925.6**	**6944.1**
$E_{Dyn.}$ [Pa]	1.5E+10	2.6E+10	2.7E+10	7.4E+09	2.3E+10	2.3E+10	7.4E+09	1.6E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	**2.29E+10**			**1.80E+10**			**1.37E+10**		

Note: 1 Pa = 1.45×10^{-4} psi

Table A.17: *p* values obtained from Student's t-test for the differences in freeze-thaw cycles to drop specimens below 90% of the initial E_{Dyn} for mixtures in Program 3 containing 28% slag cement

Mixture	Average No. of cycles to 90% E_{Dyn}	S-Control	S-IC-6.3	S-IC-6.6	S-IC-6.8	S-IC-7.0[a]	S-IC-7.7[a]	S-IC-7.8	S-IC-8.0	S-IC-10.2	S-IC-10.7	S-IC-11.6	S-IC-12.1
		884	316	315	447	456	321	247	191	178	123	151	88
S-Control	884		**4.8×10^{-5}**	**6.5×10^{-5}**	**0.001**	**1.5×10^{-4}**	**1.0×10^{-4}**	**2.3×10^{-5}**	**3.8×10^{-5}**	**1.9×10^{-5}**	**1.3×10^{-5}**	**1.3×10^{-5}**	**9.6×10^{-6}**
S-IC-6.3	316			0.952	**0.029**	**0.001**	0.641	**0.005**	**0.007**	**4.8×10^{-5}**	**1.7×10^{-4}**	**1.4×10^{-4}**	**5.0×10^{-5}**
S-IC-6.6	315				**0.032**	**0.002**	0.644	**0.018**	**0.011**	**0.002**	**0.001**	**0.001**	**4.8×10^{-5}**
S-IC-6.8	447					0.718	0.054	**0.006**	**0.004**	**0.002**	**0.001**	**0.001**	**0.001**
S-IC-7.0[a]	456						**0.006**	**5.0×10^{-5}**	**3.3×10^{-4}**	**4.8×10^{-5}**	**1.7×10^{-5}**	**1.0×10^{-5}**	**6.4×10^{-6}**
S-IC-7.7[a]	321							**0.023**	**0.011**	**0.004**	**0.001**	**0.001**	**4.3×10^{-4}**
S-IC-7.8	247								0.061	**0.002**	**0.023**	**3.6×10^{-6}**	**4.8×10^{-6}**
S-IC-8.0	191									0.493	**0.027**	0.082	**0.006**
S-IC-10.2	178										**0.011**	**0.042**	**0.001**
S-IC-10.7	123											**0.011**	**0.020**
S-IC-11.6	151												**1.8×10^{-4}**
S-IC-12.1	88												

[a] FLWA soaked for 5 minutes instead of 72 hours

Table A.18: *p* values obtained from Student's t-test for the differences in freeze-thaw cycles to drop specimens below 90% of the initial E_{Dyn} for mixtures in Program 3 containing 100% portland cement

Mixture	**Average No. of cycles to 90% E_{Dyn}**	**C-Control**	**C-IC-3.8**	**C-IC-7.3**	**C-IC-9.8**	**C-IC-11.8**
		1193	540	460	451	279
C-Control	1193		**0.016**	**0.001**	**0.001**	**0.001**
C-IC-3.8	540			0.075	0.250	0.075
C-IC-7.3	460				0.724	**0.036**
C-IC-9.8	451					0.075
C-IC-11.8	279					

APPENDIX B: SURFACE RESISTIVITY MEASUREMENTS AND RAPID CHLORIDE PERMEABILITY RESULTS FOR MIXTURES IN CHAPTER 3

Table B.1: Surface resistivity measurements (kΩ-cm) for mixtures in Program 1

S-IC-5.5(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	21.3	21.2	20.2	20.2	21.4	21.0	20.5	20.5	**20.8**
B	22.2	21.0	23.5	22.7	21.6	22.1	23.7	22.9	**22.5**
C	20.9	21.1	20.4	22.2	20.8	21.1	20.2	20.6	**20.9**

Average: 21.4

S-IC-5.5(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.6	19.7	19.8	18.9	18.4	19.8	18.6	19.5	**19.2**
B	20.9	19.2	19.5	19.9	19.9	19.4	19.6	18.6	**19.6**
C	19.0	19.3	18.6	16.6	19.4	18.6	19.6	16.8	**18.5**

Average: 19.1

S-IC-5.6(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.7	21.8	21.5	21.4	20.4	20.7	21.2	21.6	**21.2**
B	23.4	21.8	21.2	20.0	23.2	21.3	20.6	21.2	**21.6**
C	22.8	22.0	21.8	22.1	22.0	21.9	22.0	22.4	**22.1**

Average: 21.6

S-IC-5.6(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	16.7	16.6	15.9	17.2	17.0	15.8	16.4	17.0	**16.6**
B	16.3	14.8	16.2	15.9	16.4	15.5	16.6	15.7	**15.9**
C	17.1	16.8	17.4	16.1	17.5	16.4	18.1	16.8	**17.0**

Average: 16.5

S-IC-6.6

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	17.5	18.3	17.9	16.6	17.6	18.1	17.7	16.7	**17.6**
B	17.4	18.7	17.9	19.6	17.1	18.9	18.2	19.5	**18.4**
C	19.5	19.8	18.6	18.9	19.2	19.4	18.5	19.2	**19.1**

Average: 18.4

S-IC-7.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	16.2	16.2	17.0	17.6	16.3	16.3	17.6	16.5	**16.7**
B	17.7	17.6	19.2	19.6	18.0	18.0	19.2	19.6	**18.6**
C	17.2	17.6	18.2	18.0	17.2	17.9	18.9	18.9	**18.0**

Average: 17.8

S-IC-9.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.9	19.1	18.7	19.2	19.0	19.1	18.6	19.4	**19.0**
B	18.4	19.1	19.3	19.3	18.7	19.5	18.5	18.8	**19.0**
C	19.5	19.8	18.7	20.1	19.2	19.3	18.8	19.9	**19.4**

Average: 19.1

Table B.1 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 1

C-IC-5.7

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	11.4	11.4	11.5	11.8	11.4	11.2	11.1	11.8	**11.5**
B	11.2	11.3	11.8	12.7	11.3	11.2	11.7	12.6	**11.7**
C	10.9	11.5	10.7	11.4	11.1	11.5	10.5	10.9	**11.1**

Average: 11.4

T-IC-8.2

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	29.1	29.8	27.3	30.8	29.5	29.6	27.4	30.1	**29.2**
B	29.6	29.4	27.7	30.0	30.0	29.7	27.7	30.1	**29.3**
C	30.8	35.2	28.0	29.7	31.8	34.8	29.0	29.7	**31.1**

Average: 29.9

T-IC-8.3(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.2	20.9	19.2	19.7	19.1	20.8	18.7	19.7	**19.8**
B	19.3	20.2	20.6	19.6	19.6	20.0	20.5	19.9	**20.0**
C	19.6	19.5	18.5	20.7	19.9	19.5	17.7	20.6	**19.5**

Average: 19.8

T-IC-8.3(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	33.0	27.4	29.3	29.8	33.0	28.4	31.3	28.8	**30.1**
B	27.9	28.9	29.9	28.7	27.6	28.9	29.4	28.4	**28.7**
C	29.4	28.2	29.4	28.4	29.7	27.9	28.4	28.4	**28.7**

Average: 29.2

T-IC-8.3(3)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	30.4	32.7	34.7	32.9	31.2	32.6	35.3	32.8	**32.8**
B	29.3	32.1	32.3	31.5	30.2	29.3	33.0	30.0	**31.0**
C	33.9	34.1	34.2	32.3	32.9	32.5	33.2	32.9	**33.3**

Average: 32.3

S-IC-7.1

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
M12-A	23.9	22.6	22.9	23.0	23.1	22.4	22.6	23.6	**23.0**
M12-B	26.7	26.9	25.0	27.4	25.6	26.8	24.8	27.1	**26.3**
M12-C	25.6	24.6	23.5	22.8	26.0	24.1	23.6	22.2	**24.1**

Average: 24.5

S-IC-7.2

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	21.1	22.2	23.6	21.6	20.7	22.5	23.5	21.6	**22.1**
B	22.4	22.0	22.1	23.1	22.0	22.0	22.1	22.9	**22.3**
C	21.4	22.1	22.5	22.1	21.2	22.1	22.8	22.2	**22.1**

Average: 22.2

Table B.1 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 1

S-IC-9.1

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.9	22.8	21.7	21.8	21.2	21.6	21.9	21.5	**21.7**
B	21.1	20.6	21.4	22.5	21.3	19.9	21.5	22.9	**21.4**
C	22.0	22.0	21.7	23.1	22.5	22.1	21.3	23.4	**22.3**
Average:	**21.8**								

S-IC-9.4(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	22.7	23.4	26.6	22.2	22.5	23.2	22.6	23.0	**23.3**
B	24.8	22.6	22.6	23.1	23.8	22.0	23.1	23.5	**23.2**
C	21.2	23.3	22.4	22.8	21.3	23.3	22.6	22.4	**22.4**
Average:	**23.0**								

S-IC-7.0

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	22.5	23.7	24.3	23.9	23.2	24.6	24.1	24.6	**23.9**
B	21.1	20.0	21.2	21.4	21.6	20.2	21.3	21.6	**21.1**
C	25.9	25.0	24.9	23.5	25.9	25.4	24.8	23.5	**24.9**
Average:	**23.3**								

S-IC-9.4(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	32.6	29.6	28.6	29.0	32.5	29.8	28.5	28.5	**29.9**
B	31.8	35.7	33.9	30.9	31.6	35.8	33.4	31.2	**33.0**
C	31.2	29.2	28.9	29.8	30.8	29.1	29.0	29.3	**29.7**
Average:	**30.9**								

Table B.2: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 1

Mixture	**Average 28-day SRM (kΩ-cm)**	**S-IC-5.5(1)[a]**	**S-IC-5.5(2)[a]**	**S-IC-5.6(1)[a]**	**S-IC-5.6(2)[a]**	**S-IC-6.6[a]**	**C-IC-5.7[a]**	**S-IC-7.3**	**S-IC-9.3**	**T-IC-8.2**	**T-IC-8.3(1)**	**T-IC-8.3(2)**	**T-IC-8.3(3)**	**S-IC-7.1**	**S-IC-7.2**	**S-IC-9.1**	**S-IC-9.4(1)**	**S-IC-7.0**	**S-IC-9.4(2)**
		21.4	19.1	21.6	16.5	18.4	11.4	17.8	19.1	29.9	19.8	29.2	32.3	24.5	22.5	21.8	23.0	23.3	30.9
S-IC-5.5(1)[a]	21.4		**0.023**	0.721	**0.002**	**0.012**	**5.5×10^{-5}**	**0.010**	**0.016**	**0.001**	**0.046**	**4.2×10^{-4}**	**2.4×10^{-4}**	0.051	0.239	0.548	0.065	0.207	**0.001**
S-IC-5.5(2)[a]	19.1			**0.004**	**0.005**	0.246	**5.9×10^{-5}**	0.108	0.928	**1.0×10^{-4}**	0.132	**5.9×10^{-5}**	**6.3×10^{-5}**	**0.006**	**0.001**	**0.003**	**0.001**	**0.024**	**4.6×10^{-4}**
S-IC-5.6(1)[a]	21.6				**2.7×10^{-4}**	**0.003**	**7.2×10^{-6}**	**0.003**	**0.001**	**2.5×10^{-4}**	**2.5×10^{-4}**	**1.5×10^{-4}**	**1.3×10^{-4}**	**0.048**	0.118	0.677	**0.026**	0.226	**0.001**
S-IC-5.6(2)[a]	16.5					**0.026**	**1.7×10^{-4}**	0.122	**0.002**	**4.3×10^{-5}**	**0.001**	**2.4×10^{-4}**	**3.1×10^{-5}**	**0.001**	**6.6×10^{-5}**	**2.2×10^{-4}**	**1.1×10^{-4}**	**0.005**	**2.1×10^{-4}**
S-IC-6.6[a]	18.4						**1.5×10^{-4}**	0.445	0.166	**1.1×10^{-4}**	**0.038**	**7.1×10^{-5}**	**6.7×10^{-5}**	**0.005**	**0.001**	**0.002**	**0.001**	**0.015**	**4.1×10^{-4}**
C-IC-5.7[a]	11.4							**4.2×10^{-4}**	**4.1×10^{-6}**	**8.8×10^{-6}**	**8.4×10^{-6}**	**3.4×10^{-6}**	**8.7×10^{-6}**	**1.9×10^{-4}**	**8.7×10^{-7}**	**5.3×10^{-6}**	**4.2×10^{-6}**	**0.001**	**6.1×10^{-5}**
S-IC-7.3	17.8								**0.012**	**1.4×10^{-4}**	**0.026**	**9.7×10^{-5}**	**8.4×10^{-5}**	**0.004**	**0.001**	**0.003**	**0.001**	**0.012**	**4.3×10^{-4}**
S-IC-9.3	19.1									**0.001**	**0.033**	**3.3×10^{-5}**	**5.1×10^{-5}**	**0.006**	**5.7×10^{-5}**	**0.001**	**2.5×10^{-4}**	**0.022**	**4.4×10^{-4}**
T-IC-8.2	29.9										**9.6×10^{-5}**	0.417	0.055	**0.009**	**2.6×10^{-4}**	**2.8×10^{-4}**	**0.001**	**0.007**	0.463
T-IC-8.3(1)	19.8											**4.2×10^{-5}**	**6.1×10^{-5}**	**0.009**	**1.1×10^{-4}**	**0.003**	**0.001**	**0.037**	**0.001**
T-IC-8.3(2)	29.2												**0.019**	**0.012**	**1.2×10^{-4}**	**1.6×10^{-4}**	**3.3×10^{-4}**	**0.009**	0.218
T-IC-8.3(3)	32.3													**0.003**	**1.4×10^{-4}**	**1.5×10^{-4}**	**2.4×10^{-4}**	**0.002**	0.308
S-IC-7.1	24.5														0.077	0.057	0.212	0.479	**0.011**
S-IC-7.2	22.5															0.250	0.052	0.376	**0.001**
S-IC-9.1	21.8																**0.040**	0.268	**0.001**
S-IC-9.4(1)	23.0																	0.790	**0.002**
S-IC-7.0	23.3																		**0.008**
S-IC-9.4(2)	30.9																		

[a] Mixture contains cement C1(a), cement C1(b) used otherwise

Table B.3: Surface resistivity measurements (kΩ-cm) for mixtures in Program 2

S-Control(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	14.9	14.7	16.1	15.2	14.9	14.6	16	14.9	**15.2**
B	14.7	14.3	15.1	14.9	14.7	14.6	15.1	14.8	**14.8**
C	14.6	14.5	15	14.7	14.4	14.5	15.3	14.6	**14.7**

Average: 14.9

S-IC-6.9

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	14	14.6	13.6	14.7	14.1	14.8	13.9	14.6	**14.3**
B	15	14.7	14.8	15.2	14.9	14.6	14.7	15.2	**14.9**
C	14	15.5	15	14.8	14.2	14.7	14.7	15	**14.7**

Average: 14.6

S-IC-8.3(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.5	18.1	19.1	19.5	18.1	18.4	19.4	19.5	**18.8**
B	18.4	18.1	19.5	18.3	18.4	18.1	19.2	18.1	**18.5**
C	18.8	18.4	19.2	19.6	19	18.6	19.6	19.4	**19.1**

Average: 18.8

S-IC-8.4(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	14.1	14.8	13.4	15.1	14.4	14.6	13.7	15.5	**14.5**
B	16	15.1	15.4	15.6	15.8	15.1	15.5	15.5	**15.5**
C	15.3	15.4	15.9	15.2	15.1	15.4	15.5	15.5	**15.4**

Average: 15.1

S-IC-8.4(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15	15.9	15.9	14.9	14.9	15.7	15.7	14.7	**15.3**
B	16.5	16.6	15.3	14.3	16.1	16.4	15.8	14.6	**15.7**
C	14.3	15	15.2	15.1	14.5	15.2	15	15.2	**14.9**

Average: 15.3

S-IC-8.4(3)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15.4	15.2	15.1	15	15.6	15.3	15	15.1	**15.2**
B	15.8	15.6	15.6	15.4	15.6	15.2	15.5	15.4	**15.5**
C	17	15.5	15.5	15	17.4	15.3	15.8	15.4	**15.9**

Average: 15.5

S-IC-9.4

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15	15	15	14.8	14.8	14.7	15.3	14.5	**14.9**
B	14.1	14.8	15.8	15.1	14.1	14.4	15.8	15.1	**14.9**
C	15.4	15.3	15.1	15	15.5	15.4	15.1	15.1	**15.2**

Average: 15.0

Table B.3 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 2

S-IC-7.2(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	16	15.5	16	17.2	16.3	15.9	15.9	17.1	**16.2**
B	16.6	16.1	16.6	17.3	16.5	16.4	16.9	16.7	**16.6**
C	15.7	16.7	16.8	16.5	15.8	16.7	17	16.9	**16.5**

Average: 16.5

S-IC-8.3(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	22.5	21.9	21.9	20.8	22.3	21.7	22.1	21	**21.8**
B	22.2	23	24.8	20.9	22.4	22.9	24.9	20.6	**22.7**
C	22.5	22.6	22.4	22.4	22.7	22.5	22.3	22.1	**22.4**

Average: 22.3

S-Control(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	17	17.5	17.5	15.6	17.4	17.5	17.5	15.5	**16.9**
B	16.5	16.5	16.7	17.7	17	16	16.7	17.5	**16.8**
C	17.6	17.2	17.3	18.7	17.9	17.2	17.3	18.6	**17.7**

Average: 17.2

S-IC-7.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	22.2	22.2	22.5	22.5	22.7	22.1	22.5	22.2	**22.4**
B	21.5	21.3	21.6	21.3	20.6	21.6	23.2	21.6	**21.6**
C	19.6	22	20.5	21.5	20	22.2	20.3	20.9	**20.9**

Average: 21.6

S-IC-8.9(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.7	18.5	19	19.2	18.4	18.6	19.1	19	**18.8**
B	20.3	18	19.3	18.9	20.4	17.9	19.6	18	**19.1**
C	19.5	18.8	19.6	19.2	19.4	19	19.3	19.5	**19.3**

Average: 19.1

S-IC-8.9(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15.7	16.4	15.8	16	15.9	16.3	16.1	15.9	**16.0**
B	15.9	17.5	17	17	15.8	17.5	17.5	17.1	**16.9**
C	16.3	15.7	15.9	16.5	16.3	15.7	15.7	15.9	**16.0**

Average: 16.3

S-IC-9.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15.4	18.4	17.1	19.1	15.6	18.6	17.5	18.8	**17.6**
B	17.4	17.3	18.1	17	18.8	17.3	18	17.1	**17.6**
C	17.3	18.5	17	16.3	17.2	19	16.6	16.6	**17.3**

Average: 17.5

Table B.3 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 2

S-IC-14.1

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	15.7	17.5	16.9	16.1	15.8	17.4	17	16.2	**16.6**
B	16.8	17.2	15.9	18.2	16.9	17.1	15.7	18.1	**17.0**
C	16.3	17.1	17.5	16.3	16.1	17	17.4	16.3	**16.8**

Average: **16.8**

T-Control

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	29	33	33.4	34	29.1	33	33.7	34.2	**32.4**
B	31.6	31	30.2	31.3	31.3	31.2	30.3	31.1	**31.0**
C	30.1	28.8	30.5	30.1	29.9	29.1	30.6	31	**30.0**

Average: **31.1**

T-IC-9.9

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	27.7	27	27.5	26.9	28	27.8	27.7	27.5	**27.5**
B	26.6	26	27	27.8	26.9	25.6	27.3	27.7	**26.9**
C	29.2	27.6	25.9	28.1	29.2	27.9	25.6	27.9	**27.7**

Average: **27.4**

C-Control(1)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	9.9	9.6	9.9	9.3	9.8	9.8	10	9.3	**9.7**
B	9.6	9.3	9.3	9.6	9.7	9.1	9.2	9.8	**9.5**
C	9.7	10.5	10.3	9.6	9.9	10.5	10.2	9.9	**10.1**

Average: **9.7**

C-Control(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	8.6	8	7.8	6.8	8.6	8.2	8	7	**7.9**
B	8.5	7.8	7.8	8	8.6	7.8	7.8	8.2	**8.1**
C	7.5	7.5	8	8	7.7	7.7	8	8	**7.8**

Average: **7.9**

C-IC-8.7

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	8.6	9.3	8.5	9.1	8.6	9.2	8.6	9.1	**8.9**
B	8.9	8.8	9	9.1	9	8.9	9	9.2	**9.0**
C	8.7	9.4	9	8.8	8.8	9.4	8.7	8.8	**9.0**

Average: **8.9**

C-IC-8.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	9	9.5	10.2	9.4	9.2	9.6	10.4	9.6	**9.6**
B	10	10.2	10	10.2	10.1	10.6	10.1	10.2	**10.2**
C	9	9.5	8.8	9.5	9.3	9.8	8.8	9.7	**9.3**

Average: **9.7**

Table B.3 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 2

FA-Control

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	6	6.2	6.9	6	6	6.3	7.2	6.3	**6.4**
B	7	7	7.2	7	6.9	6.9	7.2	6.8	**7.0**
C	7.4	7.3	6.9	7.1	7.4	7.3	6.8	7	**7.2**

Average: 6.8

FA-IC-8.9

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	7.3	7.4	7.8	7.7	7.2	7.7	7.6	8	**7.6**
B	9	8.6	7.8	7.9	8.9	8.7	7.7	7.7	**8.3**
C	8.5	8	7.9	7.9	8.5	8	8	8	**8.1**

Average: 8.0

FA-IC-9.0

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	9	9.4	9.6	8.8	8.8	9.6	9.4	8.4	**9.1**
B	7.7	7.8	7.8	7.7	7.7	8.1	8.1	7.7	**7.8**
C	7.6	7.5	7.2	7.1	7.6	7.6	7.3	7.2	**7.4**

Average: 8.1

S-Control(3)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	19.6	18.5	18.9	19.4	19.8	18.3	19	19.5	**19.1**
B	18.4	18.8	17.6	18	18.4	18.5	17.5	18.1	**18.2**
C	18.4	18.9	19.1	18.9	18.7	19.1	19.6	19.2	**19.0**

Average: 18.8

S-IC-7.2(2)

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	19.2	19.7	18.2	19	19.6	19.7	18.2	19.3	**19.1**
B	20.4	20.8	18.4	20.2	20.5	21.2	18.6	20.1	**20.0**
C	20	20.5	20.6	20.3	19.9	20.3	20.6	20	**20.3**

Average: 19.8

S-IC-9.0

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	21.7	19.7	19.5	20.7	21.6	19.3	19.3	20.9	**20.3**
B	21.1	19.5	19.4	21	20.8	19.6	19.3	21.3	**20.3**
C	19.3	19.3	18.1	18.5	19.8	19.5	18	19.2	**19.0**

Average: 19.9

S-IC-9.1

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.6	20.2	21.2	20.9	20.9	20.2	21.2	21	**20.8**
B	20.4	19.8	21.1	20.9	19.9	19.6	21.2	20.9	**20.5**
C	21.8	20.4	20.9	21	21.4	20.4	20.9	21.1	**21.0**

Average: 20.7

Table B.3 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 2

S-IC-9.2

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	19.5	18.4	19.5	19.2	19.6	18.5	19.4	19.6	**19.2**
B	18.1	17.8	18.4	19	18.8	17.7	18.5	19	**18.4**
C	17.4	18.2	19.4	18.7	17.4	18.4	19.3	18.6	**18.4**
Average:	**18.7**								

Table B.4: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 2 containing *w/cm* ratios of 0.45 and 0.44

Mixture	**Average 28-day SRM (kΩ-cm)**	**S-Control(1)**	**S-IC-6.9**	**S-IC-8.3(1)**	**S-IC-8.4(1)**	**S-IC-8.4(2)**	**S-IC-8.4(3)**	**S-IC-9.4**	**S-IC-7.2(1)**	**S-IC-8.3(2)**
		14.9	14.6	18.8	15.1	15.2	15.5	15.0	16.5	22.3
S-Control(1)	14.9		0.317	**5.5×10^{-5}**	0.544	0.222	0.067	0.613	**0.001**	**1.9×10^{-5}**
S-IC-6.9	14.6			**6.8×10^{-5}**	0.241	0.083	**0.029**	0.145	**0.001**	**2.1×10^{-5}**
S-IC-8.3(1)	18.8				**0.001**	**2.2×10^{-4}**	**1.9×10^{-4}**	**4.5×10^{-5}**	**3.1×10^{-4}**	**4.1×10^{-4}**
S-IC-8.4(1)	15.1					0.693	0.349	0.710	**0.019**	**8.0×10^{-5}**
S-IC-8.4(2)	15.2						0.490	0.299	**0.012**	**3.9×10^{-5}**
S-IC-8.4(3)	15.5							0.078	**0.019**	**3.5×10^{-5}**
S-IC-9.4	15.0								**0.001**	**1.7×10^{-5}**
S-IC-7.2(1)	16.5									**4.2×10^{-5}**
S-IC-8.3(2)	22.3									

Table B.5: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 2 containing slag cement with a *w/cm* ratio of 0.43

Mixture	**Average 28-day SRM (kΩ-cm)**	**S-Control(2)**	**S-IC-7.3**	**S-IC-8.9(1)**	**S-IC-8.9(2)**	**S-IC-9.3**	**S-IC-14.1**	**C-Control(1)**	**C-Control(2)**	**C-IC-8.7**	**C-IC-8.8**	**T-Control**	**T-IC-8.9**
		17.2	21.6	19.1	16.3	17.5	16.8	9.7	7.9	8.9	9.7	31.1	27.4
S-Control(2)	17.2		**0.001**	0.114	0.004	0.291	0.339	**2.5×10^{-5}**	**6.1×10^{-6}**	**8.6×10^{-6}**	**4.0×10^{-5}**	**5.0×10^{-5}**	**0.019**
S-IC-7.3	21.6			**0.001**	**0.005**	**0.001**	**4.1×10^{-4}**	**1.4×10^{-5}**	**6.2×10^{-6}**	**8.0×10^{-6}**	**1.8×10^{-5}**	**3.1×10^{-4}**	**0.044**
S-IC-8.9(1)	19.1				**0.001**	**0.019**	**2.3×10^{-4}**	**2.1×10^{-6}**	**2.4×10^{-7}**	**2.3×10^{-7}**	**5.5×10^{-6}**	**7.1×10^{-5}**	**0.020**
S-IC-8.9(2)	16.3					**0.001**	**0.228**	**4.9×10^{-5}**	**1.1×10^{-5}**	**1.7×10^{-5}**	**7.5×10^{-5}**	**4.1×10^{-5}**	**0.010**
S-IC-9.3	17.5						**0.010**	**2.9×10^{-6}**	**1.6×10^{-7}**	**1.2×10^{-7}**	**8.9×10^{-6}**	**4.2×10^{-5}**	**0.013**
S-IC-14.1	16.8							**5.5×10^{-6}**	**4.0×10^{-7}**	**3.8×10^{-7}**	**1.5×10^{-5}**	**3.5×10^{-5}**	**0.011**
C-Control(1)	9.7								**0.001**	**0.011**	0.844	**7.8×10^{-6}**	**0.003**
C-Control(2)	7.9									0.051	**0.003**	**5.0×10^{-6}**	**0.002**
C-IC-8.7	8.9										0.061	**5.9×10^{-6}**	**0.002**
C-IC-8.8	9.7											**8.7×10^{-6}**	**0.003**
T-Control	31.1												0.898
T-IC-8.9	27.4												

Table B.6: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 2 slag cement with a *w/cm* ratio of 0.41

Mixture	**Average 28-day SRM (kΩ-cm)**	**S-Control(3)**	**S-IC-7.2(2)**	**S-IC-9.0**	**S-IC-9.1**	**S-IC-9.2**
		18.8	19.8	19.9	20.7	18.7
S-Control(3)	18.8		0.088	0.088	0.101	0.810
S-IC-7.2(2)	19.8			0.912	0.068	0.065
S-IC-9.0	19.9				0.120	0.078
S-IC-9.1	20.7					**0.002**
S-IC-9.2	18.7					

Table B.7: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 2 containing 100% portland cement or 35% Class F fly ash

Mixture	**Average 28-day SRM (kΩ-cm)**	**C-Control(1)**	**C-IC-8.8**	**FA-Control**	**FA-IC-8.9**
		10.7	10.7	7.5	8.8
C-Control(1)	10.7		0.844	**0.001**	**0.003**
C-IC-8.8	10.7			**0.002**	**0.007**
FA-Control	7.5				**0.023**
FA-IC-8.9	8.8				

Table B.8: Surface resistivity measurements (kΩ-cm) for mixtures in Program 3

S-Control

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	17.3	18.8	18.3	19.2	17.4	18.7	18.7	19.5	**18.5**
B	19.3	18.8	17.7	18.8	19.2	18.9	17.5	19.0	**18.7**
C	17.8	18.0	19.2	19.3	17.7	18.0	18.9	19.1	**18.5**

Average: **18.5**

S-IC-6.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.0	19.2	19.5	19.1	19.9	19.0	19.4	19.2	**19.4**
B	19.2	18.6	19.7	19.7	19.1	18.7	19.6	19.7	**19.3**
C	18.7	19.3	20.4	19.4	18.8	19.9	20.1	19.4	**19.5**

Average: **19.4**

S-IC-6.6

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.8	21.2	20.4	19.9	20.4	20.9	20.3	19.7	**20.5**
B	19.0	19.8	19.7	18.7	18.8	19.5	19.7	19.0	**19.3**
C	18.9	18.7	18.8	19.0	18.9	18.6	18.7	18.8	**18.8**

Average: **19.5**

S-IC-6.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.3	19.8	19.7	18.6	18.0	20.2	20.2	18.8	**19.2**
B	19.7	19.6	20.1	20.4	19.8	19.7	20.1	20.4	**20.0**
C	18.6	19.8	19.7	19.2	18.8	19.6	19.9	19.0	**19.3**

Average: **19.5**

S-IC-7.0

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	21.7	22.5	22.1	21.5	21.4	22.7	22.2	24.2	**22.3**
B	21.7	22.3	21.3	20.7	21.7	21.4	19.4	20.3	**21.1**
C	21.4	22.0	22.9	22.2	21.7	22.7	22.9	22.2	**22.3**

Average: **21.9**

S-IC-7.7

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	23.5	24.2	22.4	22.8	23.5	24.4	22.2	22.7	**23.2**
B	24.2	24.0	25.4	25.3	24.4	24.3	25.8	25.3	**24.8**
C	23.1	23.7	22.0	23.9	23.4	23.9	22.3	23.8	**23.3**

Average: **23.8**

S-IC-7.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	18.0	18.7	18.9	18.7	17.8	18.5	18.8	18.6	**18.5**
B	19.6	22.2	20.3	19.2	20.0	22.1	20.1	19.6	**20.4**
C	19.3	19.7	18.8	19.7	19.4	20.0	18.7	19.7	**19.4**

Average: **19.4**

Table B.8 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 3

S-IC-8.0

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	17.1	17.4	17.4	17.5	17.4	17.6	17.7	17.6	**17.5**
B	16.7	16.5	15.5	16.7	16.9	16.8	15.9	16.7	**16.5**
C	15.6	15.4	16.8	17.0	15.8	15.7	17.0	17.2	**16.3**

Average: **16.7**

S-IC-10.2

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	16.9	17.0	17.4	17.5	16.9	17.1	17.4	14.4	**16.8**
B	16.9	17.6	17.4	16.7	17.4	18.0	17.7	17.0	**17.3**
C	18.0	18.4	17.9	18.0	19.0	18.8	18.4	18.2	**18.3**

Average: **17.5**

S-IC-10.7

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.1	20.7	20.4	20.3	20.3	20.9	20.3	20.2	**20.4**
B	20.8	19.5	19.1	19.7	20.6	19.4	19.2	19.8	**19.8**
C	21.3	20.4	20.5	20.0	21.5	20.6	20.8	19.8	**20.6**

Average: **20.3**

S-IC-11.6

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	26.1	25.2	25.9	27.3	26.1	25.4	25.9	27.1	**26.1**
B	24.5	23.9	22.9	24.1	24.7	23.7	23.1	24.3	**23.9**
C	25.2	26.2	24.1	22.7	25.4	26.2	24.3	22.4	**24.6**

Average: **24.9**

S-IC-12.1

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	20.2	20.1	19.1	19.3	20.5	20.4	19.1	19.6	**19.8**
B	20.6	19.6	19.3	19.2	20.4	19.5	19.2	19.3	**19.6**
C	20.2	19.2	19.6	19.5	20.3	19.4	19.9	19.7	**19.7**

Average: **19.7**

C-Control

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	11.1	11.0	11.7	11.8	10.9	10.6	11.5	11.3	**11.2**
B	10.6	11.2	10.6	11.1	10.7	11.2	10.6	10.9	**10.9**
C	10.4	10.4	10.8	10.5	10.6	10.8	10.8	10.7	**10.6**

Average: **10.9**

C-IC-3.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	10.4	10.8	10.6	11.0	10.3	10.7	10.6	11.3	**10.7**
B	10.4	10.4	10.7	10.6	10.6	10.5	10.9	10.6	**10.6**
C	10.5	10.8	11.2	10.0	10.8	11.0	11.0	10.2	**10.7**

Average: **10.7**

Table B.8 (con't): Surface resistivity measurements (kΩ-cm) for mixtures in Program 3

C-IC-7.3

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	11.8	12.4	13.0	11.9	11.6	12.8	13.0	11.8	**12.3**
B	12.5	11.8	12.4	11.9	12.4	11.6	12.6	11.8	**12.1**
C	12.6	11.4	10.6	10.2	12.4	11.2	11.0	10.6	**11.3**

Average: 11.9

C-IC-9.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	10.5	10.5	10.6	10.6	10.6	10.5	10.4	10.5	**10.5**
B	11.0	11.1	11.2	10.2	11.0	11.1	11.0	10.4	**10.9**
C	11.0	11.3	11.7	10.6	11.2	11.5	11.5	10.6	**11.2**

Average: 10.9

C-IC-11.8

Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	11.2	11.7	11.1	11.0	11.1	11.8	11.2	11.0	**11.3**
B	11.0	11.9	11.3	10.6	11.0	11.9	11.4	11.6	**11.3**
C	11.1	11.4	10.6	11.7	10.9	11.5	10.7	11.6	**11.2**

Average: 11.3

Table B.9: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 3 containing 28% slag cement

Mixture	**Average 28-day SRM (kΩ-cm)**	**S-Control**	**S-IC-6.3**	**S-IC-6.6**	**S-IC-6.8**	**S-IC-7.0**	**S-IC-7.7**	**S-IC-7.8**	**S-IC-8.0**	**S-IC-10.2**	**S-IC-10.7**	**S-IC-11.6**	**S-IC-12.1**
		18.5	19.4	19.5	19.5	21.9	23.8	19.4	16.7	17.5	20.3	24.9	19.7
S-Control	18.5		**0.001**	0.130	0.192	**0.001**	**0.001**	0.192	**0.009**	0.069	**0.002**	**0.001**	**6.7×10^{-5}**
S-IC-6.3	19.4			0.806	0.718	**0.003**	**0.001**	0.955	**0.002**	**0.012**	**0.025**	**0.001**	**0.021**
S-IC-6.6	19.5				0.956	**0.021**	**0.004**	0.900	**0.012**	**0.037**	0.260	**0.003**	0.759
S-IC-6.8	19.5					**0.007**	**0.002**	0.917	**0.016**	**0.049**	0.092	**0.002**	0.654
S-IC-7.0	21.9						**0.046**	**0.022**	**0.001**	**0.002**	**0.025**	**0.018**	**0.006**
S-IC-7.7	23.8							**0.005**	**4.0×10^{-4}**	**0.001**	**0.004**	0.256	**0.001**
S-IC-7.8	19.4								**0.016**	**0.049**	0.237	**0.003**	0.654
S-IC-8.0	16.7									0.291	**0.001**	**4.2×10^{-4}**	**0.001**
S-IC-10.2	17.5										**0.005**	**0.001**	**0.007**
S-IC-10.7	20.3											**0.003**	0.084
S-IC-11.6	24.9												**0.001**
S-IC-12.1	19.7												

Table B.10: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program 3 containing 100% portland cement

Mixture	**Average 28-day SRM (kΩ-cm)**	**C-Control**	**C-IC-3.8**	**C-IC-7.3**	**C-IC-9.8**	**C-IC-11.8**
		10.9	10.7	11.9	10.9	11.3
C-Control	10.9		0.256	**0.047**	0.907	0.106
C-IC-3.8	10.7			**0.016**	0.386	**4.8×10^{-4}**
C-IC-7.3	11.9				**0.048**	0.108
C-IC-9.8	10.9					0.123
C-IC-11.8	11.3					

Table B.11: Rapid chloride permeability test results (Coulombs) for mixtures in Program 1

Mix ID	S-IC-5.5(1)			
	A	B	C	Average
28-Day	1615	1572	1911	1700
56-Day	1119	1179	1096	1130

Mix ID	S-IC-5.6(1)			
	A	B	C	Average
28-Day	1782	1500	2125	1800
56-Day	887	984	930	930

Mix ID	S-IC-6.6			
	A	B	C	Average
28-Day	2008	1654	1430	1700
56-Day	1225	1233	1216	1220

Mix ID	S-IC-7.3			
	A	B	C	Average
28-Day	2285	2151	2120	2190
56-Day	1554	1616	1679	1620

Mix ID	S-IC-9.3			
	A	B	C	Average
28-Day	2056	1999	1971	2010
56-Day	1308	1309	1450	1360

Mix ID	C-IC-5.7			
	A	B	C	Average
28-Day	3202	3332	3129	3220
56-Day	2561	2428	2693	2560

Mix ID	T-IC-8.2			
	A	B	C	Average
28-Day	2565	2813	2607	2660
56-Day	1753	1942	1780	1830

Mix ID	T-IC-8.3(1)			
	A	B	C	Average
28-Day	1586	1354	1331	1420
56-Day	784	846	727	790

Mix ID	S-IC-7.1			
	A	B	C	Average
28-Day	1717	1925	1627	1760
56-Day	1345	1169	1100	1200

Mix ID	S-IC-7.2			
	A	B	C	Average
28-Day	1729	1883	1874	1830
56-Day	1418	1404	1400	1410

Table B.11 (con't): Rapid chloride permeability test results (Coulombs) for mixtures in Program 1

Mix ID	S-IC-9.1			
	A	B	C	Average
28-Day	1885	2000	1787	1890
56-Day	1304	1315	1279	1300

Mix ID	S-IC-9.4(1)			
	A	B	C	Average
28-Day	1517	1467	1542	1510
56-Day	1104	1179	1264	1180

Mix ID	S-IC-7.0			
	A	B	C	Average
28-Day	1936	1731	1785	1820
56-Day	1438	1324	1226	1330

Mix ID	S-IC-9.4(2)			
	A	B	C	Average
28-Day	1344	1180	1431	1320
56-Day	1003	928	902	940

Table B.12: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 1

Mixture	Average 56-day RCP (Coulombs)	S-IC-5.5(1)[a]	S-IC-5.6(1)[a]	S-IC-6.6[a]	C-IC-5.7[a]	S-IC-7.3	S-IC-9.3	T-IC-8.2	T-IC-8.3(1)	S-IC-7.1	S-IC-7.2	S-IC-9.1	S-IC-9.4(1)	S-IC-7.0	S-IC-9.4(2)
		1130	930	1220	2560	1620	1360	790	1830	1200	1410	1300	1180	1330	940
S-IC-5.5(1)[a]	1130		**0.006**	**0.021**	**5.9×10^{-5}**	**3.8×10^{-4}**	**0.014**	**0.001**	**4.1×10^{-4}**	0.395	**4.0×10^{-4}**	**0.003**	0.386	**0.040**	**0.009**
S-IC-5.6(1)[a]	930			**0.001**	**3.7×10^{-5}**	**1.2×10^{-4}**	**0.002**	**0.029**	**1.7×10^{-4}**	**0.026**	**7.8×10^{-5}**	**2.6×10^{-4}**	**0.010**	**0.004**	0.809
S-IC-6.6[a]	1220				**6.4×10^{-5}**	**4.2×10^{-4}**	0.051	**2.3×10^{-4}**	**0.001**	0.798	**1.5×10^{-5}**	**0.003**	0.414	0.164	**0.001**
C-IC-5.7[a]	2560					**3.7×10^{-4}**	**2.1×10^{-4}**	**2.9×10^{-5}**	**0.002**	**2.1×10^{-4}**	**1.1×10^{-4}**	**8.2×10^{-5}**	**1.0×10^{-4}**	**2.3×10^{-4}**	**4.0×10^{-5}**
S-IC-7.3	1620						**0.012**	**0.039**	**0.039**	**0.007**	**0.005**	**0.001**	**0.002**	**0.016**	**1.4×10^{-4}**
S-IC-9.3	1360							**0.001**	**0.003**	0.157	0.338	0.309	0.059	0.751	**0.002**
T-IC-8.2	790								**1.1×10^{-4}**	**0.007**	**0.002**	**0.001**	**0.002**	**0.002**	**0.026**
T-IC-8.3(1)	1830									**0.003**	**0.002**	**0.001**	**0.001**	**0.004**	**0.026**
S-IC-7.1	1200										**0.050**	0.268	0.809	0.261	**0.030**
S-IC-7.2	1410											0.050	**0.008**	0.273	**1.1×10^{-4}**
S-IC-9.1	1300												0.069	0.655	**3.8×10^{-4}**
S-IC-9.4(1)	1180													0.128	**0.013**
S-IC-7.0	1330														**0.005**
S-IC-9.4(2)	940														

[a] Mixture contains cement C1(a), cement C1(b) used otherwise

Table B.13: Rapid chloride permeability test results (Coulombs) for mixtures in Program 2

Mix ID	S-Control(1)			
	A	B	C	Average
28-Day	-	2079	1762	1920
56-Day	1425	1326	1462	1400

Mix ID	S-IC-6.9			
	A	B	C	Average
28-Day	2140	2235	2700	2360
56-Day	1160	1277	1246	1230

Mix ID	S-IC-8.3(1)			
	A	B	C	Average
28-Day	1790	2005	1730	1840
56-Day	966	968	1166	1030

Mix ID	S-IC-8.4(1)			
	A	B	C	Average
28-Day	1982	1857	1873	1900
56-Day	1283	1216	1128	1210

Table B.13 (con't): Rapid chloride permeability test results (Coulombs) for mixtures in Program 2

Mix ID	S-Control(2)			
	A	B	C	Average
28-Day	1929	1923	1747	1870
56-Day	1839	1722	1582	1710

Mix ID	S-IC-7.3			
	A	B	C	Average
28-Day	1427	1396	1350	1390
56-Day	1204	1119	1147	1160

Mix ID	S-IC-8.9(1)			
	A	B	C	Average
28-Day	1395	1427	1437	1420
56-Day	1085	1150	1149	1130
Mix ID	S-IC-9.3			
	A	B	C	Average
28-Day	1886	1622	1546	1680
56-Day	999	1050	1005	1020

Mix ID	S-IC-8.9(2)			
	A	B	C	Average
28-Day	1860	1805	1912	1860
56-Day	1296	1273	1444	1340
Mix ID	S-IC-14.1			
	A	B	C	Average
28-Day	1866	2010	1782	1890
56-Day	1143	1179	1141	1150

Mix ID	T-Control			
	A	B	C	Average
28-Day	1188	1243	1348	1260
56-Day	984	915	949	950

Mix ID	T-IC-8.9			
	A	B	C	Average
28-Day	1608	1501	1346	1490
56-Day	831	805	843	830

Mix ID	C-Control(1)			
	A	B	C	Average
28-Day	4544	4685	4330	4520
56-Day	4097	3948	4340	4130

Mix ID	C-IC-8.8			
	A	B	C	Average
28-Day	4473	4192	4565	4410
56-Day	3396	3314	3792	3500

Mix ID	FA-Control			
	A	B	C	Average
28-Day	5693	5114	6175	5660
56-Day	4063	4067	3800	3980

Mix ID	FA-IC-8.9			
	A	B	C	Average
28-Day	5667	4856	5534	5350
56-Day	3294	3223	3169	3230

Mix ID	S-Control(3)			
	A	B	C	Average
28-Day	1688	1856	1373	1640
56-Day	1571	1555	1596	1570

Mix ID	S-IC-7.2(2)			
	A	B	C	Average
28-Day	1527	1420	1447	1460
56-Day	1171	1003	1161	1110

Mix ID	S-IC-9.0			
	A	B	C	Average
28-Day	1591	1517	1356	1490
56-Day	1224	1257	1104	1200

Mix ID	S-IC-9.1			
	A	B	C	Average
28-Day	1526	1535	1657	1570
56-Day	1232	1072	1173	1160

Table B.14: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 2 containing slag cement with a *w/cm* ratio of 0 .45

Mixture	**Average 56-day RCP (Coulombs)**	**S-Control(1)**	**S-IC-6.9**	**S-IC-8.3(1)**	**S-IC-8.4(1)**
		1400	1230	1030	1210
S-Control(1)	1400		**0.030**	**0.009**	**0.032**
S-IC-6.9	1230			0.061	0.759
S-IC-8.3(1)	1030				0.093
S-IC-8.4(1)	1210				

Table B15: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 2 containing slag cement with a *w/cm* ratio of 0.43

Mixture	**Average 56-day RCP (Coulombs)**	**S-Control(2)**	**S-IC-7.3**	**S-IC-8.9(1)**	**S-IC-8.9(2)**	**S-IC-9.3**	**S-IC-14.1**	**C-Control(1)**	**C-IC-8.8**	**T-Control**	**T-IC-8.9**
		1710	1160	1130	1340	1020	1150	4130	3500	950	830
S-Control(2)	1710		**0.002**	**0.015**	**0.002**	**0.001**	**0.002**	**6.0×10^{-5}**	**4.2×10^{-4}**	**0.001**	**2.9×10^{-4}**
S-IC-7.3	1160			**0.038**	0.434	**0.001**	0.937	**1.4×10^{-5}**	**9.7×10^{-5}**	**0.003**	**2.7×10^{-4}**
S-IC-8.9(1)	1130				**0.022**	**0.005**	0.348	**1.3×10^{-5}**	**9.1×10^{-5}**	**0.002**	**0.001**
S-IC-8.9(2)	1340					**0.015**	0.348	**2.5×10^{-5}**	**1.6×10^{-4}**	**0.004**	**2.4×10^{-4}**
S-IC-9.3	1020						**0.003**	**1.1×10^{-5}**	**7.5×10^{-5}**	0.055	**0.001**
S-IC-14.1	1150							**1.3×10^{-5}**	**9.3×10^{-5}**	**0.001**	**3.9×10^{-5}**
C-Control(1)	4130								**0.028**	**1.1×10^{-5}**	**8.7×10^{-6}**
C-IC-8.8	3500									**6.8×10^{-5}**	**5.5×10^{-5}**
T-Control	950										**0.006**
T-IC-8.9	830										

Table B.16: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 2 containing slag cement with a *w/cm* ratio of 0.41

Mixture	**Average 56-day RCP (Coulombs)**	**S-Control(3)**	**S-IC-7.2(2)**	**S-IC-9.0**	**S-IC-9.1**
		1570	1110	1200	1160
S-Control(3)	1570		**0.001**	**0.002**	**0.001**
S-IC-7.2(2)	1110			0.309	0.545
S-IC-9.0	1200				0.614
S-IC-9.1	1160				

Table B.17: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 2 containing 100% portland cement or 35% Class F fly ash

Mixture	**Average 56-day RCP (Coulombs)**	**C-Control(1)**	**C-IC-8.8**	**FA-Control**	**FA-IC-8.9**
		4130	3500	3980	3230
C-Control(1)	4130		**0.028**	0.353	**0.002**
C-IC-8.8	3500			0.050	0.148
FA-Control	3980				**0.001**
FA-IC-8.9	3230				

Table B.18: Rapid chloride permeability test results (Coulombs) for mixtures in Program 3

Mix ID	S-Control			
	A	B	C	Average
28-Day	1522	1586	1536	1550
56-Day	1094	1076	1168	1110

Mix ID	S-IC-6.3			
	A	B	C	Average
28-Day	1488	1445	1534	1490
56-Day	1052	911	1069	1010

Mix ID	S-IC-6.8			
	A	B	C	Average
28-Day	1615	2061	1687	1790
56-Day	1015	1093	1172	1090

Mix ID	S-IC-8.0			
	A	B	C	Average
28-Day	1542	1963	1779	1760
56-Day	1129	1234	1212	1190

Mix ID	S-IC-10.2			
	A	B	C	Average
28-Day	1789	1702	1762	1750
56-Day	1162	1045	1189	1130

Mix ID	S-IC-12.1			
	A	B	C	Average
28-Day	1397	1336	1226	1320
56-Day	1020	891	988	970

Mix ID	C-Control			
	A	B	C	Average
28-Day	3469	3474	3389	3440
56-Day	3583	3037	2673	3100

Mix ID	C-IC-3.8			
	A	B	C	Average
28-Day	3169	3058	3459	3230
56-Day	2814	2771	2909	2830

Mix ID	C-IC-7.3			
	A	B	C	Average
28-Day	3372	3208	3054	3210
56-Day	2559	2629	2931	2710

Mix ID	C-IC-9.8			
	A	B	C	Average
28-Day	3711	3414	3625	3580
56-Day	2634	2682	2530	2620

Mix ID	C-IC-11.8			
	A	B	C	Average
28-Day	3323	3290	3143	3250
56-Day	2566	2363	2543	2490

Table B.19: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 3 containing 28% slag cement

Mixture	Average 56-day RCP (Coulombs)	S-Control	S-IC-6.3	S-IC-6.8	S-IC-8.0	S-IC-10.2	S-IC-12.1
		1110	1010	1090	1190	1130	970
S-Control	1110		0.150	0.735	0.137	0.731	**0.038**
S-IC-6.3	1010			0.288	**0.038**	0.143	0.523
S-IC-6.8	1090				0.151	0.574	0.100
S-IC-8.0	1190					0.335	**0.011**
S-IC-10.2	1130						**0.048**
S-IC-12.1	970						

Table B.20: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program 3 containing 100% portland cement

Mixture	Average 56-day RCP (Coulombs)	C-Control	C-IC-3.8	C-IC-7.3	C-IC-9.8	C-IC-11.8
		3100	2830	2710	2620	2490
C-Control	3100		0.376	0.246	0.147	**0.090**
C-IC-3.8	2830			0.530	**0.024**	**0.011**
C-IC-7.3	2710				0.275	0.175
C-IC-9.8	2620					0.187
C-IC-11.8	2490					

APPENDIX C: MINNESOTA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE

SB-10 STRUCTURAL CONCRETE – INTERNALLY CURED HIGH PERFORMANCE CONCRETE BRIDGE DECKS (CONTRACTOR CONCRETE MIX DESIGN)

Delete the contents of 2401.2.A, "Concrete," and replace with the following:

Design an internally cured concrete mixture that will minimize cracking by incorporating saturated lightweight fine aggregate. Perform the work in accordance with the applicable requirements of MnDOT 2401, "Concrete Bridge Construction," 2461, "Structural Concrete," and the following:

2.A.1 Fine Aggregate Requirements

Provide fine aggregates complying with quality requirements of 3126.2.D, "Deleterious Material," 3126.2.E, "Organic Impurities," and 3126.2.F, "Structural Strength."

2.A.1.a Fine Aggregate Lightweight Requirements

Incorporate fine lightweight aggregate as a means to provide internal curing water for concrete. The requirements of ASTM C1761 and C330 shall apply, except as modified in this specification.

(1) Size all lightweight aggregate to pass a 3/8 in. sieve.
(2) Proportion the volume of lightweight aggregate such that is does not exceed 10 percent of total aggregate volume. Lightweight aggregate used as a replacement for normal weight aggregate shall be made on a volume basis.
(3) Pre-wet lightweight aggregate prior to adding at the time of batching. Recommendations for pre-wetting made by the lightweight aggregate supplier shall be followed to ensure that the lightweight aggregate has achieved an acceptable absorbed moisture content at the time of batching. Mixture proportions shall not be adjusted based on the absorbed water in the lightweight aggregate.
(4) Handling and Stockpiling Lightweight Aggregates:

Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.

Transport aggregate in a manner that insures uniform grading.

Do not use aggregates that have become mixed with earth or foreign material.

Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.

Provide additional stockpiling or binning in cases of high or non-uniform moisture.

2.A.1.b Fine Aggregate Alkali Silica Reactivity (ASR) Requirements

The Department will routinely test fine aggregate sources for alkali silica reactivity (ASR) in accordance with the following:

(1) Multiple sources of certified portland cement in accordance with ASTM C 1260 MnDOT Modified; and
(2) Multiple combinations of certified portland cement and supplementary cementitious materials in accordance with ASTM C 1567 MnDOT Modified.

The Concrete Engineer, in conjunction with the Engineer, will review the 14-day fine aggregate expansion test results to determine the acceptability of the proposed fine aggregate and cement combination in accordance with the following:

(1) For fine aggregate and cement combinations previously tested by the Department, the Concrete Engineer will use the average of all 14-day unmitigated test results for an individual source to determine necessary mitigation in accordance with Table HPC-1.

(2) If the previously tested proposed fine aggregate and cement combination requires less mitigation than the average 14-day unmitigated test result, the Concrete Engineer will allow mitigation at the lesser rate in accordance with Table HPC-1.

(3) Alkali silica reactivity (ASR) ASTM C1260 and ASTM C1567 test results are available on the MnDOT Concrete Engineering Unit website.

Table HPC-1
Fine Aggregate ASR Mitigation Requirements

14-day Fine Aggregate Unmitigated Expansion Limits	**Class F Fly Ash**	**Class C Fly Ash**	**Slag**	**Slag/Class F Fly Ash**	**Slag/Class C Fly Ash**	**IS(20)/Class F Fly Ash**	**IS(20)/Class C Fly Ash**
≤ 0.150	No mitigation required						
>0.150 - 0.200	Not Allowed	Not Allowed	35%	Not Allowed	Not Allowed	Not Allowed	Not Allowed
> 0.200 – 0.300	Not Allowed	Not Allowed	35%				
> 0.300	The Department will reject the fine aggregate						

The Concrete Engineer may reject the fine aggregate if mortar bar specimens exhibit an indication of external or internal distress not represented by the expansion results. The Concrete Engineer will make the final acceptance of the aggregate.

2.A.2 Intermediate Aggregate Requirements

Provide intermediate aggregates complying with the quality requirements of 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure," except as modified in Table HPC-2. If the intermediate aggregate is from the same source as the ¾ in- fraction, the aggregate quality is determined based upon the composite of the ¾ in- and intermediate aggregate.

The Concrete Engineer classifies intermediate aggregate in accordance with Table HPC-2.

Table HPC-2
Intermediate Aggregate for Use in Concrete

If the gradation meets the following:	Classify material type as:	Gradation Test Procedures	Quality Test Requirements
100% passing the 1/2" and ≤90% passing #4	Intermediate Aggregate	Coarse Aggregate (+4 Portion)	Spec. 3137.2.D.2 except 3137.2.D.2(i) modified to maximum 40% carbonate
		Fine Aggregate (-4 Portion)	Shale in Sand (-4 Portion)
100% passing the 1/2" and >90% passing #4	Intermediate Aggregate	Fine Aggregate (Minimum 1000 g sample)	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)
100% passing the 3/8" and ≤90% passing #4	Coarse Sand	Fine Aggregate	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)

For any intermediate aggregate size not previously tested by the Department, the Concrete Engineer reserves the right to test for alkali silica reactivity, in accordance with ASTM C1260, prior to allowing incorporation into the concrete mix design.

2.A.3 Coarse Aggregate Requirements

Provide Class A, B or C coarse aggregate meeting the quality requirements in accordance with 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure."

When providing Class B aggregate, the maximum absorption percent by weight is 1.10%.

2.A.3.a Coarse Aggregate Alkali Silica Reactivity (ASR) Requirements

When using coarse aggregate identified as quartzite or gneiss, the Concrete Engineer will review ASTM C1293 testing to determine the necessary ASR mitigation requirements in accordance with Table HPC-3.

ASR ASTM C1293 test results are available on the MnDOT Concrete Engineering Unit website.

Table HPC-3
Coarse Aggregate ASR Mitigation Requirements*

ASTM C1293 Expansion Results	Class F Fly Ash	Class C Fly Ash	Slag	Slag/Class F Fly Ash	Slag/Class C Fly Ash	IS(20)/Class F Fly Ash	IS(20)/Class C Fly Ash
≤ 0.040	No mitigation required						
>0.040	Not Allowed	Not Allowed	35%	Not Allowed	Not Allowed	Not Allowed	Not Allowed

* The Engineer will allow the Contractor to substitute a portion of the minimum required supplementary cementitious material with up to 2% silica fume by weight for mitigation purposes.

2.A.4 Cementitious Materials

Provide only cementitious materials from the Approved/Qualified Products List.

2.A.4.a Cement

Use Type I or Type I/II cement complying with Specification 3101, "Portland Cement," or blended cement in accordance with Specification 3103, "Blended Hydraulic Cement."

(1) Total alkalis (Na_2Oe) no greater than 0.60 percent in the portland cement, and
(2) Total alkalis (Na_2Oe) no greater than 3.0 lb per yd^3 of concrete resulting from the portland cement.

2.A.4.b Ground Granulated Blast Furnace Slag

Use ground granulated blast furnace slag conforming to Specification 3102, "Ground Granulated Blast-Furnace Slag."

2.A.4.c Silica Fume

Use silica fume conforming to ASTM C 1240.

2.A.4.d Ternary Mixes

Ternary mixes are defined as portland cement and two other supplementary cementitious materials, or blended cement and one other supplementary cementitious material with a maximum replacement of 40% by weight.

2.A.5 Allowable Admixtures

Use any of the following admixtures on the MnDOT Approved/Qualified Products as listed under "Concrete Admixtures A-S":

(A) Type A, Water Reducing Admixture,
(B) Type B, Retarding Admixture,
(C) Type C, Accelerating Admixture,
(D) Type D, Water Reducing and Retarding Admixture,
(E) Type F, High Range Water Reducing Admixture, and
(F) Type S, Specific Performance Based Admixture

Obtain a written statement from the manufacturer of the admixtures verifying:

(1) Compatibility of the combination of materials, and
(2) Manufacturer recommended sequence of incorporating the admixtures into the concrete.

The manufacturer will further designate a technical representative to dispense the admixture products.

Utilize the technical representative in an advisory capacity and have them report to the Contractor any operations or procedures which are considered as detrimental to the integrity of the placement. Verify with the Engineer whether the Manufacturer’s technical representative’s presence is required during the concrete placement.

2.A.6 Concrete Mix Design Requirements

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department’s website at least 21 calendar days before the initial concrete placement. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

2.A.6.a Concrete Mix Design Requirements

Design and produce 3YHPCIC-M or 3YPHCIC-S concrete mixes based on an absolute volume of 27.0 ft^3 [1.0 m^3] in accordance with the Table HPC-4 and the following requirements:

Table HPC-4
High Performance Bridge Deck Concrete Mix Design Requirements

Concrete Grade	**Mix Number ***	**Intended Use**	**w/c ratio**	**Target Air Content**	**Maximum %SCM (Fly Ash/Slag/ Silica Fume/ Ternary) ‖**	**Slump Range †, *inches***	**Minimum/Maximum Compressive Strength, f’c (28-day)**	**3137 Spec.**
HPC	3YHPCIC-M	Bridge Deck – Monolithic	0.43-0.45	6.5% to 10%	0/28/2/30	1 1/2" to 4 "	4000psi/5500 psi	2.D.2
	3YHPCIC-S	Bridge – Structural Slab						

* Provide a Job Mix Formula in accordance with 2401.2.A.7. Use any good standard practice to develop a job mix formula and gradation working range by using procedures such as but not limited to 8-18, 8-20 gradation control, Shilstone process, FHWA 0.45 power chart or any other performance related gradation control to produce a workable and pumpable concrete mixture meeting all the requirements of this contract.

‖ The individual limits of each SCM shall apply to ternary mixtures.

† Keep the consistency of the concrete uniform during entire placement.

Limit volume of water plus cementitious materials to a maximum of 27% of total concrete volume.

Add all mix water at the plant. No water will be allowed to be added on site.

2.A.6.b Required Preliminary Testing

Prior to placement of any 3YHPCIC-M or 3YHPCIC-S Concrete, the Engineer will require preliminary batching and testing of the concrete mix design.

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department’s website at least 14 calendar days prior to the beginning of preliminary laboratory mixing and testing of the proposed mix designs. Any changes or adjustments to the material or mix design require a new Contractor mix design submittal. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

Batch the concrete and place in mixing truck for the max anticipated delivery time. Test the concrete for the following hardened concrete properties in accordance with Table HPC-5:

Table HPC-5 Required Hardened Concrete Properties for Mixes 3YHPCIC-M and 3YHPCIC-S		
Test	Requirement	Test Method
Required Strength (Average of 3 cylinders)	4000 psi min. at 28 days, 5500 psi max. at 28 days	ASTM C31
Rapid Chloride Permeability	≤ 2500 coulombs at 28 days (For Preliminary Approval) ≤ 1500 coulombs at 56 days	ASTM C1202
Freeze-Thaw Durability	Greater than 90% at 300 cycles	ASTM C666 Procedure A
Shrinkage	No greater than 0.040 percent at 28 days	ASTM C157
Scaling	Visual rating not greater than 1 at 50 cycles	ASTM C672

The Engineer will allow the maturity method for subsequent strength determination. Perform all maturity testing in accordance with ASTM C1074 and the MnDOT Concrete Manual.

If a mix is approved, the Concrete Engineer will consider the mix design and testing as acceptable for a period of 5 years provided the actual concrete mixed and placed in the field meets the Contract Requirements. The Concrete Engineer will not require new testing within that 5-year period as long as all the constituents (including the aggregates) of the proposed mix design are the same as the original mix design.

The Engineer determines final acceptance of concrete for payment based on satisfactory field placement and performance.

2.A.7 Job Mix Formula

A Job Mix Formula (JMF) contains the following:

(a) Proportions for each aggregate fraction,
(b) Individual gradations for each aggregate fraction, and
(c) Composite gradation of the combined aggregates including working ranges on each sieve in accordance with Table HPC-6.

Table HPC-6 Job Mix Formula Working Range	
Sieve Sizes	**Working Range, %***
1 in [25 mm] and larger	±5
¾ in [19 mm]	±5
½ in [12.5 mm]	±5
⅜ in [9.5 mm]	±5
No.4 [4.75 mm]	±5
No.8 [2.36 mm]	±4
No.16 [1.18 mm]	±4
No.30 [600 µm]	±4
No.50 [300 µm]	±3
No.100 [150 µm]	±2
No.200 [75 µm]	≤ 1.6

* Working range limits of the composite gradation based on a moving average of 4 tests (N=4).

2.A.7.a Verification of JMF

Prior to beginning placements of bridge deck concrete, perform gradation testing to ensure current materials comply with the approved JMF. Perform gradation testing in accordance with the Schedule of Materials Control.

(1) Take samples at the belt leading to the weigh hopper or other locations close to the incorporation of the work as approved by the Engineer.
(2) Add fill-in sieves as needed during the testing process to prevent overloading.

The Producer and Engineer will test and record the individual gradation results using the Concrete Aggregate Worksheet.

(1) Using the JMF Moving Average Summary Worksheet, calculate the moving average of Producer aggregate gradation test results during production.
(2) The Engineer will randomly verify Producer combined aggregate gradation results as defined in the Schedule of Materials Control.

If, during production, the approved JMF falls outside of the allowable working range immediately sample and test additional gradation and continue production.

2.A.7.b JMF Adjustment

If it is determined that the current aggregates do not meet the approved JMF, submit a new mix design including JMF to the Concrete Engineer in accordance with 2401.2.A.7.

2.A.7.c JMF Acceptance

The Engineer will make monetary adjustments for the quantity of bridge deck concrete represented by the JMF Working Range failure, from the failing test to the next passing test, at a minimum rate of $500.00 or $5.00 per cubic yard, whichever is greater.

2.A.8 Laboratory batching, testing requirements and submittals:

To determine the characteristics of the Contractor proposed mix design, the Concrete Engineer will require the Contractor to prepare test batches and do laboratory testing. Conduct all batching and testing of concrete at a **single** AMRL certified laboratory using the exact materials proposed in the mix design.

Lab testing requirements:

(a) Slump and air content at <5 minutes, 15 minutes, and 30 minutes after the completion of mixing,
(b) Compressive strength (Make cylinders in accordance with AASHTO T126 and tested in accordance with AASHTO T22) at 1, 3, 7, 28, 56 days (sets of 3),
(c) Hardened air content (ASTM C457) at a minimum of 7 days,
(d) Rapid chloride permeability (ASTM C1202) at 28 days and 56 days (2 specimens for 28 day test and 2 test specimens for 56 day test (Take 2 specimens from each batch of a 2 batch mix)),
(e) Concrete Durability (ASTM C666, Procedure A) at 300 cycles, and
(f) Concrete Shrinkage (ASTM C157) at 28 days.

The Contractor is required to contact the MnDOT Concrete Engineering Unit a minimum of 2-days prior to any mixing so that a MnDOT representative can observe the process. This same 2-day notification is required prior to any physical testing on hardened concrete samples. Additionally, retain any hardened concrete test specimens for a minimum of 90 days and make available for MnDOT to examine.

Perform all testing for plastic concrete after all admixtures additions to the concrete mixture.

After completion of the laboratory testing specified herein and, at least, 15 working days prior to the trial placement, submit the laboratory test data to the MnDOT for review and acceptance.

Include the following information in the laboratory reports of the design mixes:

(a) Exact batch weights and properties of all ingredients used and all aggregate gradations
(b) Slump and air content
(c) Cylinder identification, including mix designation
(d) Date and time of cylinder preparation
(e) Date and time cylinder specimen was tested
(f) Compressive strength of each cylinder specimen at 1, 3, 7, 28, and 56 day (sets of 3)
(g) A graphic plot of age, from 0 to 56 days, vs. strength for each mix design
(h) Hardened air content at a minimum of 7 days
(i) Rapid chloride permeability at 28 days and 56 days
(j) Concrete Durability at 300 cycles and
(k) Concrete Shrinkage at 28 days.

2.A.9 Prior to Actual Bridge Deck Placement

2.A.9.a Trial Placement

A minimum of 14 calendar days prior to the actual placement of the bridge deck slab concrete, successfully complete a separate trial placement utilizing a minimum of two (2) - 10 yd^3 loads.

The Engineer may allow the incorporation of the concrete for trial batches into the bridge footings, abutments or end diaphragms. The Contractor may also choose to incorporate the trial batches into residential /commercial construction in the immediate vicinity of the project. In any case, the Engineer will require mixing, transporting, and placing the concrete using the same methods as the actual placement of the bridge deck.

If the concrete is incorporated into the permanent work, the Engineer will test the plastic concrete in accordance with the Schedule of Materials Control. The Engineer may require additional trial batches if the concrete delivered to the project does not comply with the plastic concrete requirements of the Contract.

The concrete mix design, laboratory batching and mixing, and the trial placement is incidental to the concrete furnished and placed.

Use the same materials, same supplier, and same supplier's manufacturing plant, and proportions in the permanent work as in the trial placement. Strength requirements specified for each mix are applicable to the cylinder tests taken during the production work.

2.A.9.b Slab Placement and Curing Plan

At least 14 calendar days prior to slab placement, provide a slab placement and curing plan for each bridge to the Engineer for approval. Include the following information in the placement and curing plan:

(1) Anticipated concrete delivery rates
(2) Estimated start and finish time
(3) Material, labor and equipment proposed for placing, finishing, and curing including placement of wet burlap, soaker hose, or other system to maintain the deck in a moist condition during the curing period
(4) Number of work bridges proposed for use
(5) Number of people responsible for the various tasks and
(6) Bulkheading methods and materials proposed for use if the Contractor cannot maintain the proposed concrete placement rates.

For full depth monolithic decks, the finishing machine will consist of a cylindrical finisher mated with horizontal adjustable augers, both of which are mounted on a transversely moving carriage unless otherwise approved by the State Bridge Construction Engineer.

A 10 ft [3 m] bull float is required for full-depth decks prior to carpet dragging regardless of whether texture planing is specified for the final ride surface. Float slab in accordance with MnDOT Construction Manual 5-393.358 to ensure the final surface does not vary by greater than ⅛ in [3 mm] within a 10 ft [3 m] straightedge laid longitudinally on the final surface. This surface tolerance includes areas near expansion devices and other breaks in the continuity of the bridge slab.

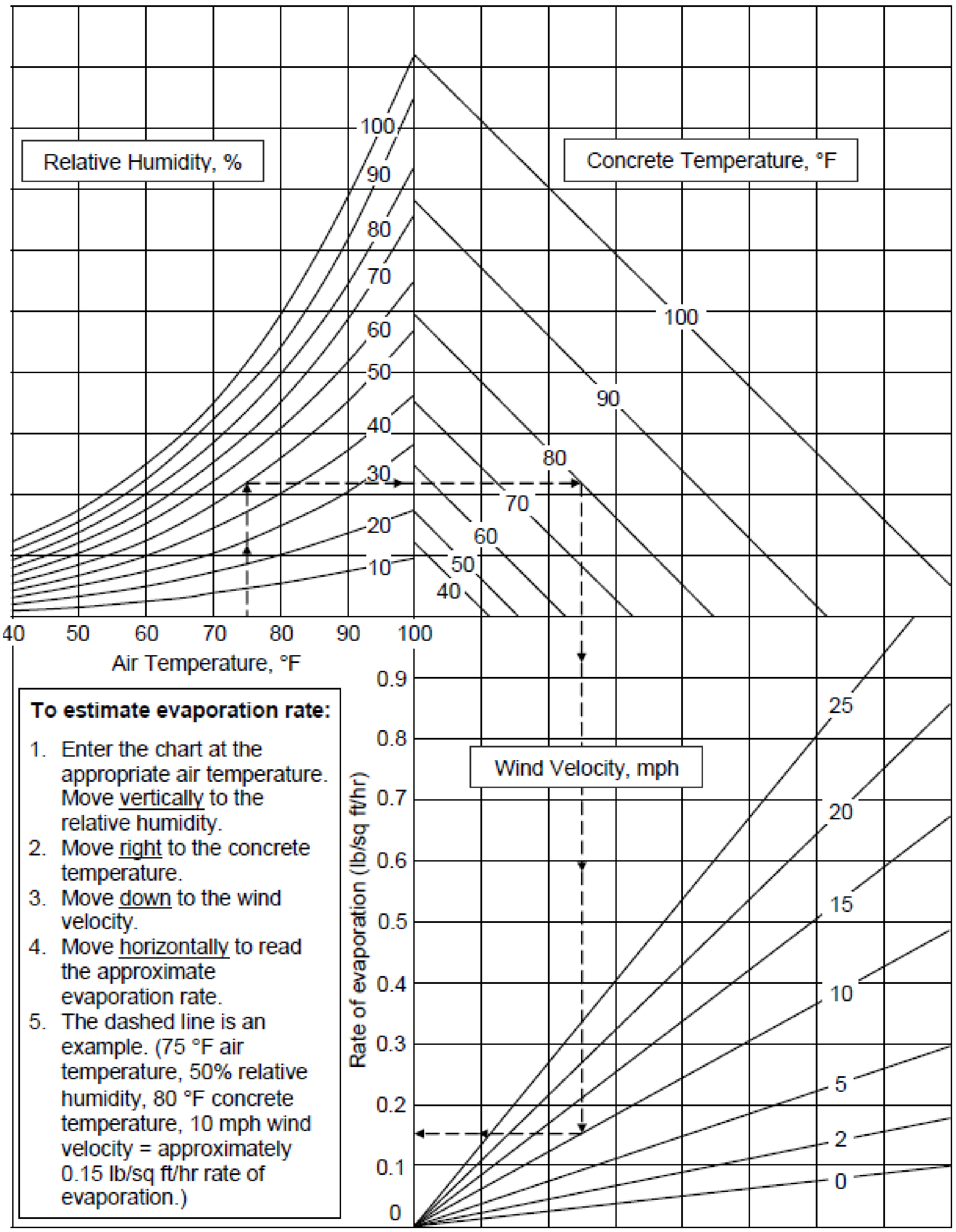
Attend a pre-placement meeting 10 days to 15 days before the slab placement to review the information and details provided in the placement and curing plan. The following project personnel are required to attend the pre-placement meeting:

(1) Contractor
(2) Engineer
(3) Concrete supplier and
(4) If required by the Engineer, the concrete pump supplier.

2.A.9.c Three (3) Hours Prior to Beginning Bridge Deck Concrete Placement

The Engineer requires the Contractor to comply with <u>all</u> of the following conditions prior to allowing the Contractor to begin the bridge deck concrete placement:

(1) Provide a forecast to the Engineer three (3) hours before placement. The Engineer will review the forecast for the following:
    (a) No forecasted precipitation two (2) hours prior to the scheduled placement duration, nor up to two (2) hours after the anticipated completion of the placement, and
    (b) Less than 30% chance of precipitation for the entire placement window and
(2) Only if the combination of air temperature, relative humidity, concrete temperature and wind velocity produces an evaporation rate of less than 0.20 pounds per square foot of surface area per hour, according Figure HPC-1:



To estimate evaporation rate:

1. Enter the chart at the appropriate air temperature. Move vertically to the relative humidity.
2. Move right to the concrete temperature.
3. Move down to the wind velocity.
4. Move horizontally to read the approximate evaporation rate.
5. The dashed line is an example. (75 °F air temperature, 50% relative humidity, 80 °F concrete temperature, 10 mph wind velocity = approximately 0.15 lb/sq ft/hr rate of evaporation.)

[1] Based on ACI 305 R, "Hot Weathering Concreting"

FIGURE HPC-1

SB-10.1 Delete the 16th paragraph through 18th paragraphs of 2401.3.G, "Concrete Curing and Protection," and replace with the following:9

2.A.9.d Actual Bridge Deck Placement and Curing Requirements

In addition to the requirements set forth in 2461.3.G.4, "Field Adjustments," if any adjustments are necessary on site, comply with the following:

(1) The Engineer will only allow the addition of admixtures originally incorporated into the mix, except Viscosity Modifying Admixture (VMA) is allowed to adjust slump even if they were not used in the original testing
(2) The Engineer will allow a maximum of 1 gal of water additions per yd^3 of concrete on site provided additional water is available to add per the Certificate of Compliance, including any water necessary to dilute admixtures and
(3) Mix the load a minimum of 5 minutes or 50 revolutions after any additions.

The Engineer will not allow finishing aids or evaporation retarders for use in finishing of the concrete.

The Contractor is fully responsible for curing methods. Comply with the following curing methods unless other methods are approved by the Engineer in writing.

Table HPC-7
Required Curing Method Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Required Curing Method ‖
Bridge structural slab curing (3YHPCIC-S)	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks (3YHPCIC-M)	Epoxy Chip Seal Wearing Course or Premixed Polymer Wearing Course	Conventional wet curing after carpet drag
	Bridge Deck Planing	Conventional wet curing after carpet drag.
	Tined Texturing*	Conventional wet curing after tine texturing AMS curing Compound after wet cure period
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)*	Conventional wet curing after applying transverse broom finish AMS curing Compound after wet cure period

‖ Apply conventional wet curing to bridge slabs following the finishing machine or air screed.
* Prevent marring of broomed finish or tined textured surface by careful placement of wet curing.

Use conventional wet curing consisting of pre-wetted burlap covered with white plastic sheeting in accordance with the following. Presoak the burlap for a minimum of 12 hours prior to application:

(1) Place the burlap to cover 100 percent of the deck area without visible openings
(2) Place the wet curing within 20 min after the finishing machine completes the final strike-off of the concrete surface
(3) If the Contractor fails to place the wet curing within 20 min, the Department will monetarily deduct $500 for every 5 min period, or any portion thereof, after the initial time period until the Contractor places the wet curing as approved by the Engineer, the Department may assess the deduction more than once
(4) Keep the slab surface continuously wet for an initial curing period of at least 7 calendar days

(5) Use a work bridge to follow the finish machine and
(6) Provide an additional center rail on wide bridges, if necessary.

Where marring of the broomed finish or tined texturing surface finish is a concern, the Engineer may authorize curing as follows:

(1) Apply a membrane curing compound meeting the requirements of 3754, "Poly-Alpha Methylsytrene (AMS) Membrane Curing Compound"
(2) Apply curing compound using approved power-operated spray equipment
(3) Provide a uniform, solid white, opaque coverage of membrane cure material on exposed concrete surfaces (equal to a white sheet of paper)
(4) Place the membrane cure within 30 min of concrete placement unless otherwise directed by the Engineer
(5) Provide curing compound for moisture retention until the placement of a conventional wet curing
(6) Apply conventional wet curing when walking on the concrete will not produce imprints deeper than $^{1}/_{16}$ in [1.6 mm]
(7) Keep the deck slab surface continuously wet for an initial curing period of at least 7 calendar days including weekends, holidays, or both if these fall within the 7-calendar-day curing period
(8) The Engineer will not allow placement of membrane curing compound on any concrete surface that expects future placement of additional concrete on that surface and
(9) If the Contractor fails to meet these requirements, the Department may reduce the contract unit price for the concrete item in accordance with 1512, "Conformity with Contract Documents."

SB-10.2 Delete 2401.3.I.2, "Crack Sealing," and replace with the following:

The Contractor is fully responsible for crack sealing all cracks identified by the Engineer in accordance with Table HPC-8.

Table HPC-8
Required Crack Sealing Requirements Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Crack Sealing Requirements
Bridge structural slab (3YHPCIC-S) *	Low Slump Wearing Course	Seal cracks in accordance with 2401.3.I.2
Bridge deck slab for full-depth decks (3YHPCIC-M)	Epoxy Chip Seal Wearing Course or Premixed Polymer Wearing Course	See wearing course special provision
	Bridge Deck Texture Planing	Seal cracks in accordance with 2401.3.I.2 after texture planing
	Tined Texturing	Seal cracks in accordance with 2401.3.I.2
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)	Seal cracks in accordance with 2401.3.I.2

* Shotblast the surface in preparation for low slump wearing course. Prior to placing the low slump wearing course, the Engineer will visually inspect the bridge structural slab, and will mark cracks that require sealing appearing on the top surface. Control the application of the crack sealer such that the maximum width of crack sealant does not exceed 1 in [25 mm]. If exceeding the permitted width of 1 in [25 mm], remove excess by means of surface grinding to prevent debonding of concrete wearing course. The Engineer requires the sealer to cure completely prior to pre-wetting of the deck, as required for placement of a low slump concrete wearing course.

SB-10.3 Method of Measurement

If measuring bridge slab concrete by area, the Engineer will base the measurement on end-of-slab stationing and out-to-out transverse dimensions of the slab.

SB-10.4 Basis of Payment

Payment for Item No. 2401.618 "BRIDGE SLAB CONCRETE (3YHPCIC-M)" will be made at the Contract price per square foot and shall be compensation in full for all costs of forming, placing, finishing, curing, crack sealing, and all associated incidentals necessary to construct the bridge deck and end diaphragms as detailed in the Plans in accordance with these specifications.

APPENDIX D: DETERMINING THE ABSPORPTION, SURFACE MOISTURE, AND TOTAL MISTURE OF FINE LIGHTWEIGHT AGGREGATES USING A CENTRIFUGE

The centrifuge used is the Houghton HM-E5 Centrifuge Extractor with a 9 in. bowl diameter. Note that similar models with variable speed control and the same bowl diameter are expected to yield the same results*. To obtain the absorption using centrifuge, the following series of steps should be performed:

1. Soak the aggregates for 72 hours and drain a sample using a No. 200 sieve before testing. After aggregates are drained, mix them with a scoop before taking the sample.
2. Measure the mass of the empty centrifuge bowl and record it as $\mathbf{M_1}$.
3. Tare the scale with centrifuge bowl placed on it. Add 600 grams (± 5 grams) of drained pre-wetted lightweight aggregate to the bowl. Record the resulting mass as $\mathbf{M_2}$.
4. Make sure that the material is evenly distributed inside the bowl by shaking it horizontally. This will avoid any vibration during centrifugation. Place the bowl in the centrifuge. After the filter paper ring and the lid are placed on top of the bowl, secure the assembly.
5. Run the centrifuge selecting 2000 rpm for the testing speed for a period of three minutes.
6. Remove the centrifuge bowl measure the mass of centrifuge bowl plus the aggregate inside (which now is in pre-wetted surface-dry condition), record it as $\mathbf{M_3}$.
7. By subtracting the mass of empty centrifuge bowl ($\mathbf{M_3}$) from $\mathbf{M_1}$, obtain the mass of pre-wetted surface-dry aggregate (PSD), record it as $\mathbf{M_4}$.
8. Record the weight of an empty pan for oven drying the aggregate, record it as $\mathbf{M_5}$.
9. Carefully transfer all the material to the pan, place it in an oven at 110 ± 5 ˚C (230 ± 10 ˚F) until constant mass is reached. Once aggregate is oven-dried, measure the mass of pan plus oven-dried aggregate and record it as $\mathbf{M_6}$.
10. By subtracting $\mathbf{M_5}$ from $\mathbf{M_6}$ obtain the mass of oven-dried aggregate, call it $\mathbf{M_7}$.
11. Using the equations in the results section of the provided spreadsheet, obtain the surface moisture and 72-hour absorption.

Note: The attached excel spreadsheet will automatically calculate $\mathbf{M_4}$, $\mathbf{M_7}$, Absorption, Surface Moisture, and Total Moisture when $\mathbf{M_1}$, $\mathbf{M_2}$, $\mathbf{M_3}$, $\mathbf{M_5}$, and $\mathbf{M_6}$ are entered in the cells highlighted yellow.

*****If the centrifuge has a different bowl radius, keeping the spinning time at 3 minutes, the appropriate spinning speed can be calculated from the formula below with a known bowl radius (*R*):

$$R\omega^2 = 5000 \text{ (m·radians/sec.)}$$

Where,

R= bowl radius (meters), ω= spinning speed (radians/sec), 1 radian/sec=9.55 RPM

Absorption, Surface Moisture, and Total Moisture

Procedure	Measurement	Value
Measure mass of empty centrifuge bowl	M_1	
Measure mass of pre-wetted LWA added tared centrifuge bowl (600±5 g)	M_{WET}	
Measure mass of centrifuge bowl and PSD aggregate after centrifugation	M_2	
Calculate mass of PSD, M_{PSD}	$M_{PSD}= M_2-M_1$	
Measure mass of empty pan used for oven drying aggregate	M_3	
Measure mass of pan and oven-dry aggregate	M_4	
Calculate mass of oven dry aggregate, M_{OD}	$M_{OD}=M_4-M_3$	

Results

Calculate desired properties	Result	Value
Absorption (%)= $(M_{PSD}-M_{OD})/M_{OD}*100$	Absorption	
Surface Moisture(%)= $(M_{WET}-M_{PSD})/M_{PSD}*100$	Surface Moisture	
Total Moisture(%)= $(M_{WET}-M_{OD})/M_{OD}*100$	Total Moisture	
Water Content(%)= $(M_{PSD}-M_{OD})/M_{PSD}*100$	Water Content	

Relative Density

Procedure	Measurement	Value
Measure mass of filled pycnometer	M_{PW}	
Measure mass of PSD LWA added to tared empty pycnometer (600±5 g)	M_{PSD}	
Measure mass of pycnometer and PSD aggregate filled with water	M_{PS}	
Measure mass of empty pan used for oven drying aggregate	M_5	
Measure mass of pan and oven-dry aggregate	M_6	
Calculate mass of oven dry aggregate, M_{OD}	$M_{OD}=M_6-M_5$	

Results

Calculate desired properties	Result	Value
Relative Density (PSD)= $M_{PSD}/(M_{PW}+M_{PSD}-M_{PS})$	(PSD) Relative Density	
Relative Density (OD)= $M_{OD}/(M_{PW}+M_{PSD}-M_{PS})$	(OD) Relative Density	

APPENDIX E: TRIP TICKETS AND PLASTIC CONCRETE TEST RESULTS FOR MNDOT IC-LC-HPC AND CONTROL DECK PLACEMENTS

Table E.1: Trip Tickets and Plastic Concrete Properties for IC-LC-HPC-1

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water[*]	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1[†]	384	163	216	1680	1146	203	0.437	24.8%	6	65	7
2	388	163	216	1651	1104	191	0.449	25.4%	2½	65	7
3	385	164	216	1651	1104	191	0.423	24.4%	3½	68	7.5
4	388	165	225	1651	1097	189	0.440	25.2%	-	-	-
5	390	165	227	1649	1100	189	0.432	25.0%	4	-	8.1
6	386	165	216	1647	1098	189	0.435	24.9%	-	-	-
7	386	165	221	1650	1102	190	0.444	25.2%	-	-	-
8	384	163	220	1649	1105	189	0.440	24.9%	-	-	-

[*] Water include free-surface moisture from aggregates

[†] Truck rejected

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table E.2: Trip Tickets and Plastic Concrete Properties for MN-Control-1

Truck	Material Proportions, SSD Basis (lb/yd^3)					*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Class F Fly Ash	Water[*]	Coarse Agg.	Fine Agg.			Slump (in.)	Temp. (°F)	Air (%)
1	445	150	216	1714	1356	0.364	25.0%	4	62	5.8
2	443	147	216	1716	1358	0.367	24.8%	-	-	-
3	445	149	216	1716	1358	0.365	24.9%	-	-	-
4	444	148	225	1716	1360	0.380	25.4%	-	-	-
5	446	150	227	1703	1360	0.381	25.6%	-	-	6.0
6	444	151	216	1718	1362	0.364	24.9%	-	-	-
7	447	149	221	1718	1358	0.372	25.2%	-	-	-
8	444	147	220	1718	1358	0.373	25.1%	-	-	-
9	445	148	221	1720	1360	0.374	25.2%	-	-	-
10	445	150	221	1718	1358	0.373	25.2%	3¾	70	5.6
11	447	149	220	1719	1360	0.370	25.2%	-	-	6.8

[*] Water include free-surface moisture from aggregates

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table E.3: Trip Tickets and Plastic Concrete Properties for IC-LC-HPC-2

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water*	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	412	156	229	1413	1146	241	0.403	24.6%	3½	76	9.1
2	412	153	237	1417	1142	240	0.420	25.0%	-	-	-
3	413	154	245	1417	1144	243	0.432	25.5%	-	-	-
4	410	154	248	1415	1146	243	0.439	25.6%	-	-	-
5	410	155	247	1415	1142	243	0.437	25.6%	-	-	-
6	413	154	237	1413	1142	243	0.418	25.1%	-	-	-
7	410	152	246	1417	1144	240	0.437	25.5%	-	-	-
8	410	152	244	1415	1141	243	0.435	25.4%	-	-	-
9	410	154	245	1417	1144	240	0.433	25.4%	-	-	-
10	416	153	245	1415	1142	243	0.430	25.5%	-	-	-
11	410	154	246	1417	1142	240	0.436	25.5%	3½	81	9.0
12	417	154	246	1419	1144	241	0.431	25.7%	-	-	-
13	410	155	246	1417	1140	243	0.435	25.5%	-	-	-
14	410	154	246	1415	1144	241	0.436	25.5%	-	-	-
15	410	154	246	1413	1144	241	0.437	25.5%	-	-	-
16	411	154	242	1413	1142	241	0.429	25.3%	-	-	-
17	411	153	244	1415	1144	243	0.433	25.4%	-	-	-
18	410	155	246	1415	1144	243	0.435	25.5%	-	-	-
19	414	154	244	1417	1142	240	0.429	25.5%	-	-	-
20	411	154	246	1413	1144	243	0.435	25.5%	3½	78	9.3
21	411	154	245	1417	1146	240	0.434	25.5%	-	-	-
22	410	154	247	1415	1142	243	0.437	25.6%	-	-	-
23	410	154	247	1416	1143	250	0.438	25.6%	-	-	-
24	411	154	244	1416	1145	251	0.432	25.4%	-	-	-
25	411	154	244	1416	1143	240	0.432	25.4%	-	-	-

* Water include free-surface moisture from aggregates

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table E.4: Trip Tickets and Plastic Concrete Properties for MN-Control-2

Truck	Material Proportions, SSD Basis (lb/yd^3)					*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	**Class F Fly Ash**	**Water[*]**	**Coarse Agg.**	**Fine Agg.**			**Slump (in.)**	**Temp. (°F)**	**Air (%)**
1	378	202	234	1738	1276	0.403	26.0%	3½	72	7.2
2	378	203	231	1740	1278	0.398	25.9%	-	-	-
3	381	204	226	1738	1278	0.387	25.6%	-	-	-
4	379	202	226	1738	1278	0.390	25.6%	-	-	-
5	378	202	228	1742	1280	0.393	25.6%	-	-	-
6	380	204	228	1742	1268	0.391	25.7%	-	-	-
7	379	205	226	1738	1278	0.388	25.6%	-	-	-
8	378	203	223	1738	1278	0.384	25.3%	-	-	-
9	381	205	226	1740	1280	0.386	25.7%	-	-	-
10	377	203	228	1738	1278	0.393	25.7%	3¼	75	6.1
11	386	202	229	1740	1280	0.389	25.8%	-	-	-
12	385	203	223	1738	1278	0.379	25.5%	-	-	-
13	378	205	234	1740	1280	0.401	26.0%	-	-	-
14	382	202	227	1738	1280	0.389	25.7%	-	-	-
15	378	203	231	1738	1276	0.397	25.8%	-	-	-
16	378	205	237	1742	1276	0.407	26.2%	-	-	-
17	381	203	226	1738	1278	0.387	25.6%	-	-	-
18	379	204	238	1738	1278	0.409	26.3%	-	-	-
19	380	202	229	1738	1278	0.395	25.8%	-	-	-
20	379	205	230	1738	1278	0.394	25.8%	-		
21	382	202	231	1740	1280	0.396	25.9%	3	73	5.5
22	377	205	236	1742	1276	0.405	26.1%	-	-	-
23	380	204	229	1744	1276	0.393	25.8%	-	-	-
24	378	204	233	1742	1276	0.400	26.0%	-	-	-
25	378	203	231	1738	1276	0.398	25.9%	-	-	-
26	377	201	238	1740	1276	0.412	26.2%	-	-	-
27	378	202	227	1760	1276	0.391	25.6%	-	-	-

[*] Water include free-surface moisture from aggregates

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table E.5: Trip Tickets and Plastic Concrete Properties for IC-LC-HPC-3

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water*	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	410	154	237	1409	1140	243	0.420	25.0%	3¾	77	9.1
2	416	155	227	1407	1140	241	0.398	24.5%	2½	77	8.5
3	411	156	237	1405	1142	241	0.419	25.0%	-	-	-
4	410	155	237	1405	1144	245	0.420	25.0%	-	-	-
5	411	154	237	1439	1146	241	0.420	25.0%	-	-	-
6	410	155	237	1415	1144	245	0.420	25.0%	-	-	-
7	411	155	237	1415	1142	243	0.420	25.0%	-	-	-
8	410	154	241	1413	1140	247	0.428	25.2%	-	-	-
9	412	154	245	1403	1144	243	0.434	25.5%	-	-	-
10	410	155	243	1415	1142	245	0.430	25.4%	-	-	-
11	412	153	241	1413	1146	241	0.428	25.2%	-	-	-
12	413	155	244	1417	1140	241	0.430	25.4%	-	-	-
13	424	154	240	1417	1146	243	0.417	25.4%	-	-	-
14	428	156	240	1417	1144	241	0.411	25.5%	3¾	74	8
15	419	154	240	1413	1146	241	0.419	25.3%	-	-	-
16	410	155	233	1415	1144	245	0.413	24.8%	-	-	-
17	414	153	240	1415	1144	243	0.424	25.2%	-	-	-
18	438	153	239	1415	1144	241	0.405	25.6%	4	73	8.8
19	411	155	235	1415	1144	241	0.415	24.9%	-	-	-
20	411	155	241	1419	1142	250	0.427	25.3%	-	-	-
21	410	154	244	1413	1146	245	0.432	25.4%	3¾	74	8
22	411	155	245	1421	1144	245	0.434	25.5%	-	-	-
23	411	153	241	1419	1146	245	0.428	25.2%	-	-	-
24	413	155	242	1419	1144	243	0.426	25.3%	-	-	-
25	411	154	235	1419	1142	243	0.416	24.8%	-	-	-
26	411	155	245	1423	1144	247	0.433	25.5%	-	-	-
27	412	154	245	1405	1140	245	0.432	25.5%	-	-	-
28	411	154	237	1407	1144	247	0.420	25.0%	-	-	-
29	414	156	236	1405	1146	245	0.415	25.0%	-	-	-
30	418	155	233	1405	1144	245	0.407	24.9%	3	74	7.5
31	411	153	240	1407	1142	243	0.425	25.1%	-	-	-
32	411	155	237	1407	1144	243	0.419	25.0%	-	-	-

* Water include free-surface moisture from aggregates

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table E.6: Trip Tickets and Plastic Concrete Properties for IC-LC-HPC-4

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water[*]	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	415	166	249	1721	974	196	0.428	25.9%	5½	68	11.0
2	420	167	250	1691	968	196	0.425	26.1%	5½	66	10.0
3[†]	418	163	248	1735	968	194	0.428	25.8%	6	66	11.2, 9.0
4	415	163	251	1700	962	196	0.434	25.9%	4½	64	7.4
5	417	165	245	1729	972	196	0.420	25.6%	-	-	-
6	418	164	243	1710	982	198	0.418	25.6%	4	-	8.2
7	417	163	243	1700	974	196	0.419	25.5%	3¾	61	9.4
8	415	164	243	1700	976	197	0.420	25.5%	-	-	-
9	415	167	244	1685	970	212	0.419	25.6%	3¾	70	8.0
10	415	168	245	1687	976	204	0.421	25.7%	-	-	-
11	417	166	244	1723	976	204	0.419	25.7%	-	-	-
12	417	163	243	1721	964	196	0.418	25.5%	-	-	-
13	417	163	245	1756	996	203	0.422	25.6%	-	-	-
14	415	168	246	1698	986	196	0.422	25.8%	-	-	-
15	418	163	244	1725	974	196	0.420	25.6%	5	59	8.0
16	416	164	245	1708	976	196	0.422	25.6%	-	-	-
17	415	166	246	1723	966	200	0.423	25.7%	-	-	-
18	417	163	247	1727	966	198	0.426	25.7%	-	-	-
19	419	164	246	1702	972	198	0.421	25.7%	4½	67	8.7
20	415	165	245	1708	976	196	0.422	25.6%	-	-	-
21	418	163	244	1706	972	196	0.421	25.6%	-	-	-
22	419	168	245	1710	964	196	0.418	25.8%	-	-	-
23[‖]	-								-	-	-
24	419	163	246	1717	972	196	0.422	25.7%	-	-	-
25[‖]	-								-	-	-
26	416	167	247	1676	1022	200	0.424	25.8%	-	-	-
27	418	165	243	1703	972	197	0.417	25.6%	4½	60	8.4
28	417	164	242	1697	968	197	0.417	25.5%	-	-	-
29	415	164	243	1701	970	197	0.420	25.5%	-	-	-
30	417	163	243	1697	966	199	0.419	25.5%	-	-	-
31	415	165	245	1699	970	197	0.422	25.6%	-	-	-
32	415	166	244	1709	968	197	0.420	25.6%	5½	58	9.5
33	413	163	245	1701	970	197	0.426	25.5%	-	-	-
34	416	164	246	1705	970	197	0.423	25.7%	-	-	-
35	417	166	247	1703	968	197	0.424	25.8%	-	-	-
36	415	168	248	1716	968	197	0.424	25.8%	-	-	-
37	419	163	247	1705	966	199	0.425	25.8%	-	-	-
38	416	163	246	1709	968	197	0.425	25.7%	-	-	-
39	415	166	244	1703	968	197	0.421	25.6%	-	-	-
40	415	166	244	1703	968	197	0.421	25.6%	-	-	-

[*] Water include free-surface moisture from aggregates

[†] Air content measured twice

[‖] Trip ticket not available

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

APPENDIX F: BRIDGE DECK SURVEY SPECIFICATION

1.0 DESCRIPTION.

This specification covers the procedures and requirements to perform bridge deck surveys of reinforced concrete bridge decks.

2.0 SURVEY REQUIREMENTS.

a. Pre-Survey Preparation.

(1) Prior to performing the crack survey, related construction documents need to be gathered to produce a scaled drawing of the bridge deck. The scale must be exactly 1 in. = 10 ft (for use with the scanning software), and the drawing only needs to include the boundaries of the deck surface.

NOTE 1 – In the event that it is not possible to produce a scaled drawing prior to arriving at the bridge deck, a hand-drawn crack map (1 in.= 10 ft) created on engineering paper using measurements taken in the field is acceptable.

(2) The scaled drawing should also include compass and traffic directions in addition to deck stationing. A scaled 5 ft by 5 ft grid is also required to aid in transferring the cracks observed on the bridge deck to the scaled drawing. The grid shall be drawn separately and attached to the underside of the crack map such that the grid can easily be seen through the crack map.

NOTE 2 – Maps created in the field on engineering paper need not include an additional grid.

(3) For curved bridges, the scaled drawing need not be curved, i.e., the curve may be approximated using straight lines.

(4) Coordinate with traffic control so that at least one side (or one lane) of the bridge can be closed during the time that the crack survey is being performed.

b. Preparation of Surface.

(1) After traffic has been closed, station the bridge in the longitudinal direction at ten feet intervals. The stationing shall be done as close to the centerline as possible. For curved bridges, the stationing shall follow the curve.

(2) Prior to beginning the crack survey, mark a 5 ft by 5 ft grid using lumber crayons or chalk on the portion of the bridge closed to traffic corresponding to the grid on the scaled drawing. Measure and document any drains, repaired areas, unusual cracking, or any other items of interest.

(3) Starting with one end of the closed portion of the deck, using a lumber crayon or chalk, begin tracing cracks that can be seen while bending at the waist. After beginning to trace cracks, continue to the end of the crack, even if this includes portions of the crack that were not initially seen while bending at the waist. Areas covered by sand or other debris need not be surveyed. Trace the cracks using a different color crayon than was used to mark the grid and stationing.

(4) At least one person shall recheck the marked portion of the deck for any additional cracks. The goal is not to mark every crack on the deck, only those cracks that can initially be seen while bending at the waist.

NOTE 3 – An adequate supply of lumber crayons or chalk should be on hand for the survey. Crayon or chalk colors should be selected to be readily visible when used to mark the concrete.

c. Weather Limitations.

(1) Surveys are limited to days when the expected temperature during the survey will not be below 60°F.

(2) Surveys are further limited to days that are forecasted to be at least mostly sunny for a majority of the day.

(3) Regardless of the weather conditions, the bridge deck must be <u>completely</u> dry before the survey can begin.

3.0 BRIDGE SURVEY.

a. Crack Surveys.

Using the grid as a guide, transfer the cracks from the deck to the scaled drawing. Areas that are not surveyed should be marked on the scaled drawing. Spalls, regions of scaling, and other areas of special interest need not be included on the scale drawings but should be noted.

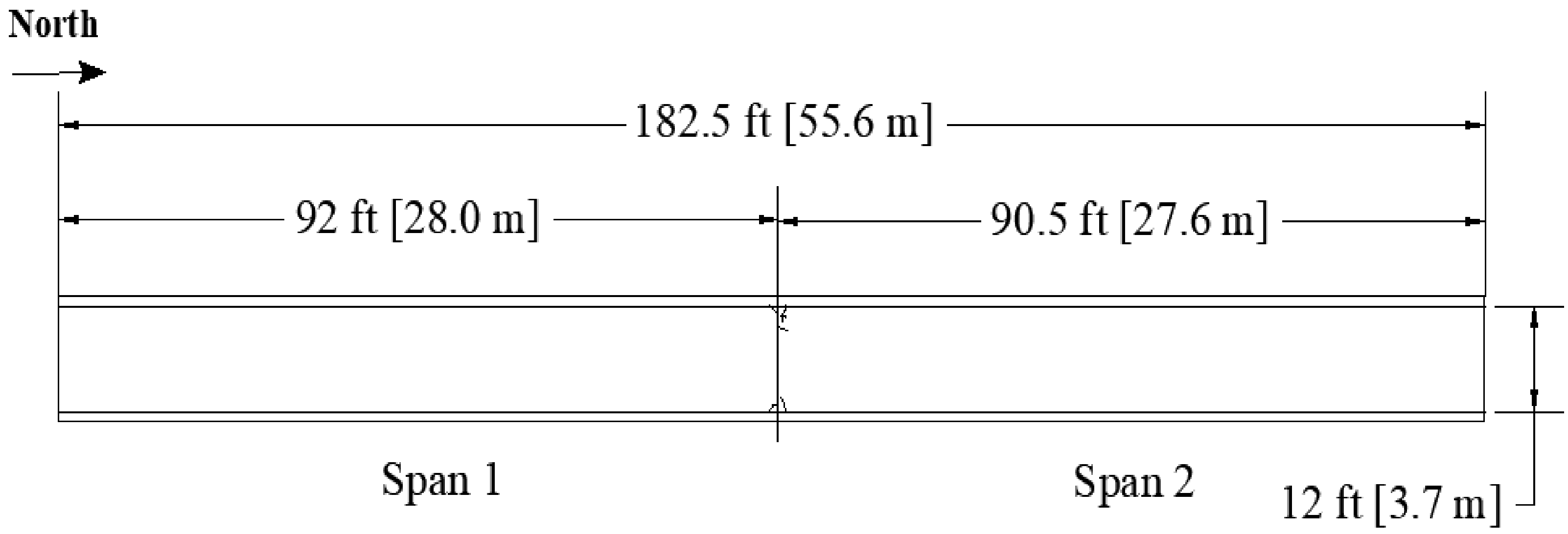
b. Delamination Survey.

At any time during or after the crack survey, bridge decks shall be checked for delamination. Any areas of delamination shall be noted and drawn on a separate drawing of the bridge. This second drawing need not be to scale.

c. Under Deck Survey.

Following the crack and delamination survey, the underside of the deck shall be examined and any unusual or excessive cracking noted.

APPENDIX G: DATA FOR EVALUATION OF BRIDGE DECK CRACKING PERFORMANCE

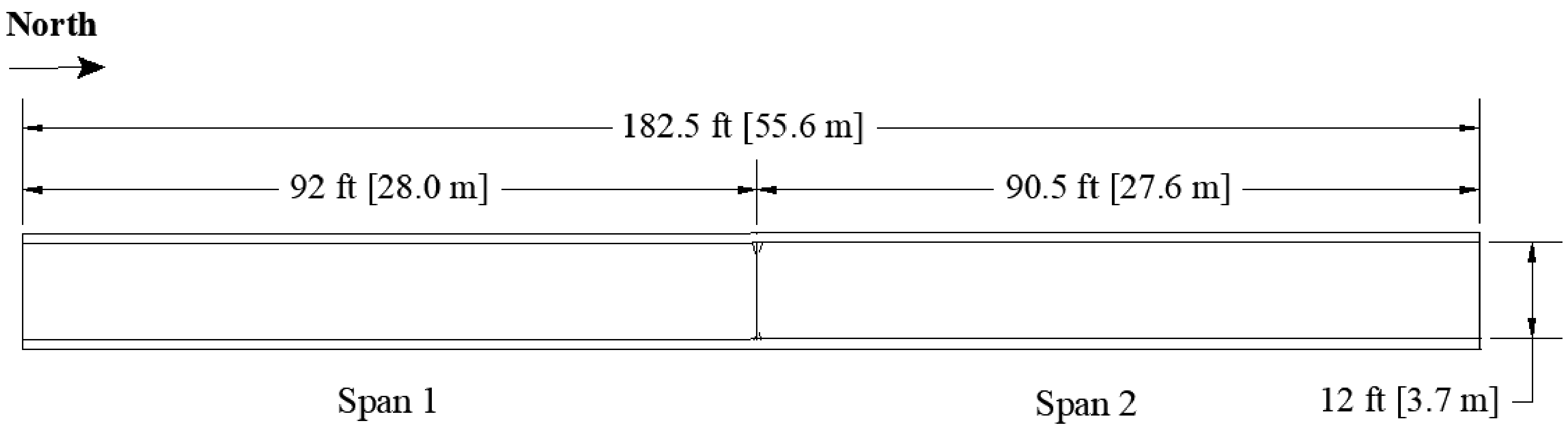


Birdge ID: IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 6/27/2017

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 9.2 months
Crack Density: 0.013 m/m^2
Span 1: 0.010 m/m^2
Span 2: 0.016 m/m^2
Crack Length: 8.7 ft
Span 1: 3.3 ft
Span 2: 5.4 ft

Figure G.1: Crack Map for IC-LC-HPC-1 (Survey 1)

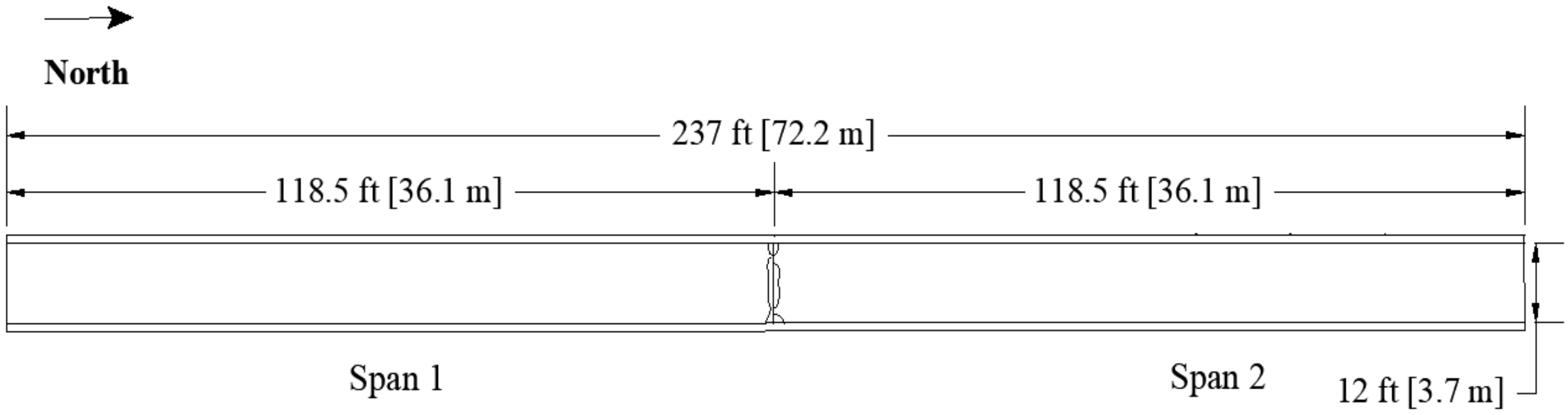


Bridge ID: IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St.
over I-94
Construction Date: 9/21/2016
Crack Survey Date: 5/8/2018

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 19.6 months
Crack Density: 0.007 m/m^2
Span 1: 0.006 m/m^2
Span 2: 0.009 m/m^2
Crack Length: 4.9 ft
Span 1: 2.1 ft
Span 2: 2.9 ft

Figure G.2: Crack Map for IC-LC-HPC-1 (Survey 2)

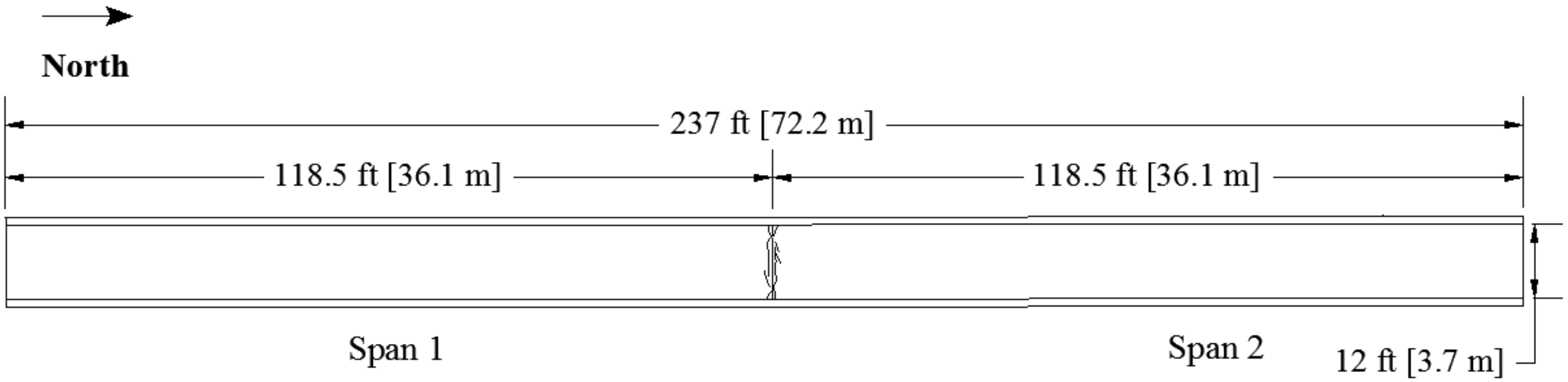


Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 6/27/2017

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
  Span 1: 118.5 ft (36.1 m)
  Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 9.2 months
Crack Density: 0.029 m/m^2
  Span 1: 0.037 m/m^2
  Span 2: 0.022 m/m^2
Crack Length: 29.2 ft
  Span 1: 16.1 ft
  Span 2: 13.1 ft

Figure G.3: Crack Map for MN-Control-1 (Survey 1)

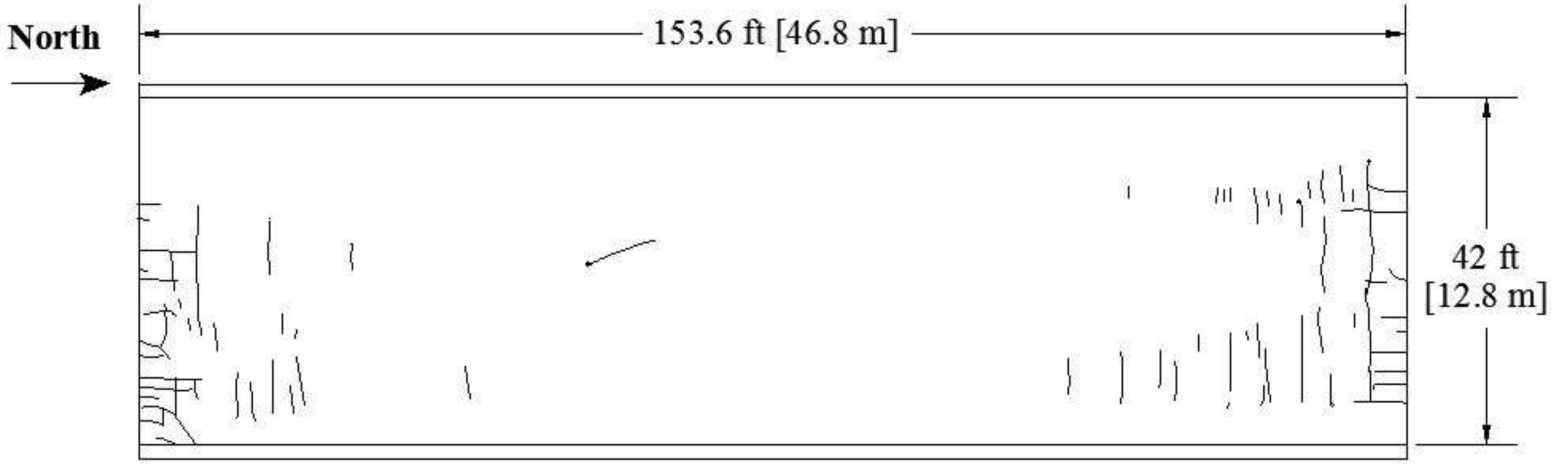


Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 5/8//2018

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 19.3 months
Crack Density: 0.032 m/m^2
Span 1: 0.031 m/m^2
Span 2: 0.034 m/m^2
Crack Length: 28.1 ft
Span 1: 13.5 ft
Span 2: 14.6 ft

Figure G.4: Crack Map for MN-Control-1 (Survey 2)

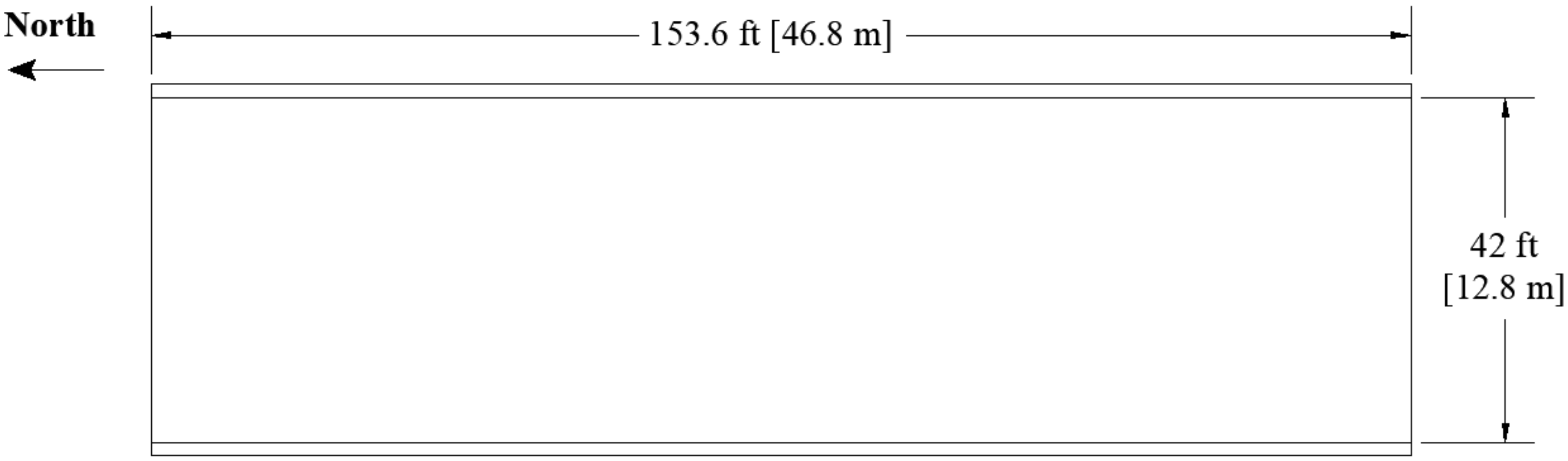


Bridge ID: IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over
Little Cannon River
Construction Date: 7/6/2017
Crack Survey Date: 5/10/2018

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 10.1 months
Crack Density: 0.165 m/m^2
Crack Length: 325.0 ft

Figure G.5: Crack Map for IC-LC-HPC-2 [w/ Overlay] (Survey 1)

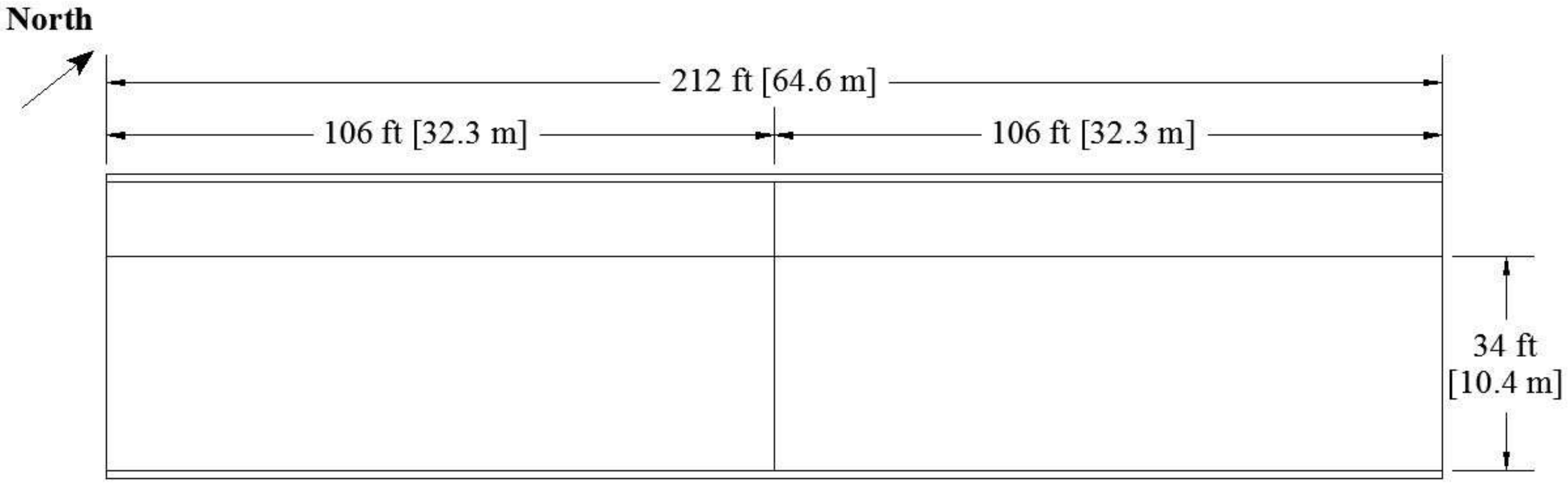


Bridge ID: MN-Control-2
Bridge Number: 25032
Bridge Location: N.B TH 52 over Little Cannon River
Construction Date: 9/15/2017
Crack Survey Date: 5/10/2018

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

Bridge Age: 7.8 months
Crack Density: 0 m/m^2
Crack Length: 0 ft

Figure G.6: Crack Map for MN-Control-2 [w/ Overlay] (Survey 1)

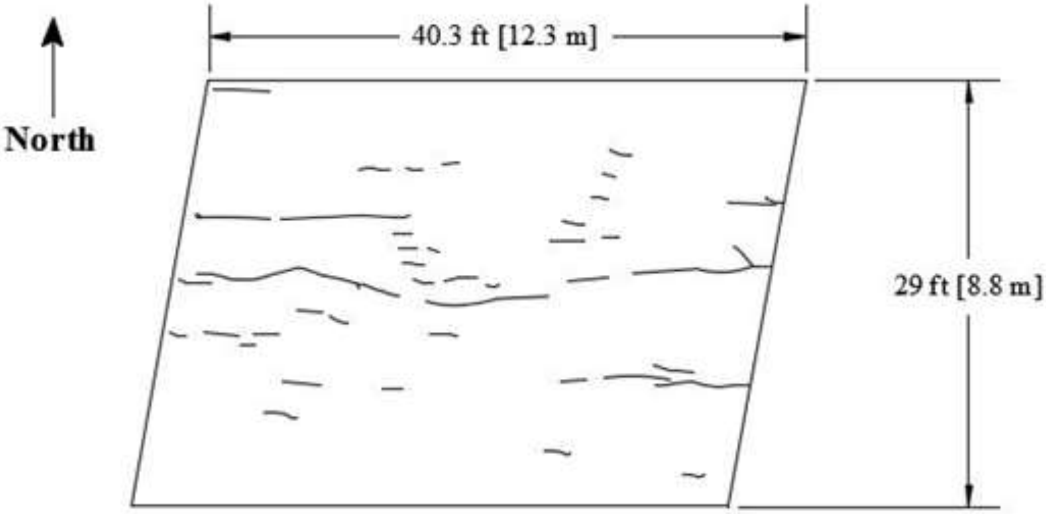


Bridge ID: IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52
Construction Date: 6/29/2017
Crack Survey Date: 5/10/2018

Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

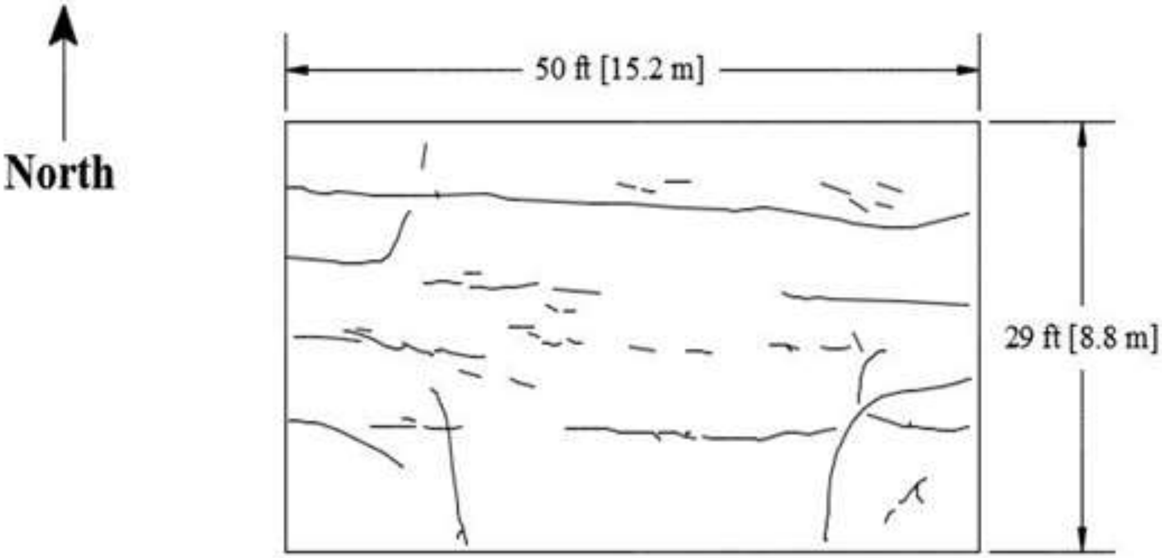
Bridge Age: 10.4 months
Crack Density: 0 m/m^2
  Span 1: 0 m/m^2
  Span 2: 0 m/m^2
Crack Length: 0 ft
  Span 1: 0 ft
  Span 2: 0 ft

Figure G.7: Crack Map for IC-LC-HPC-3 [w/ Overlay] (Survey 1)



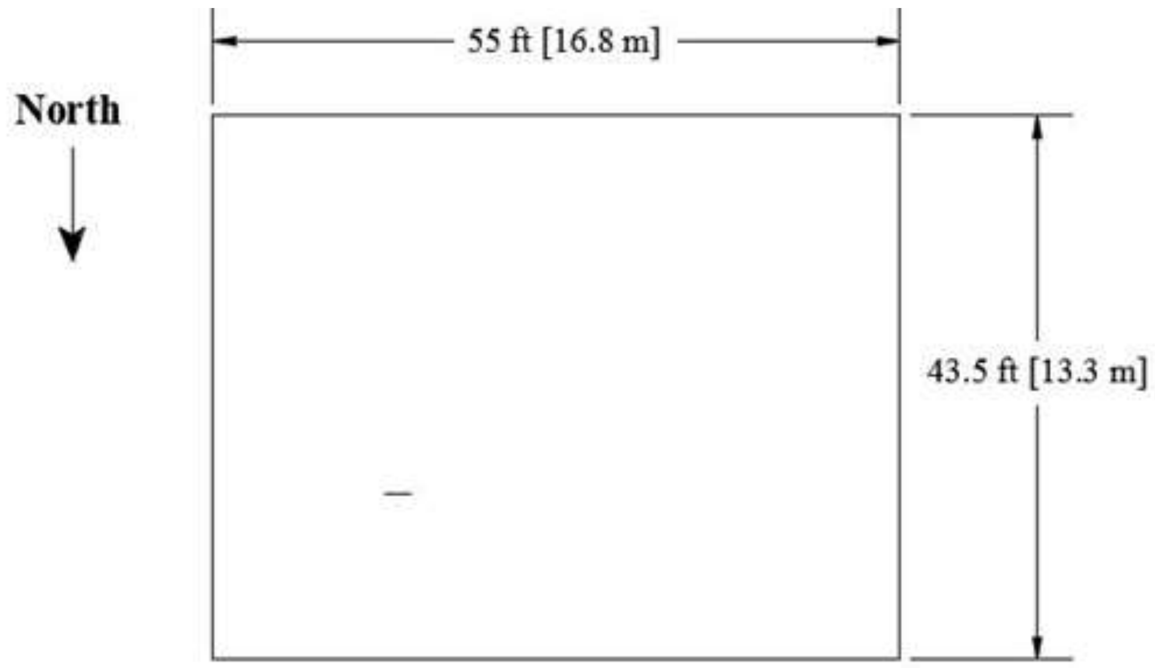
Bridge Deck Age = 71.6 months; Average crack density = 0.347 m/m^2

Figure G.8: Crack Map for IN-IC (Survey 1)



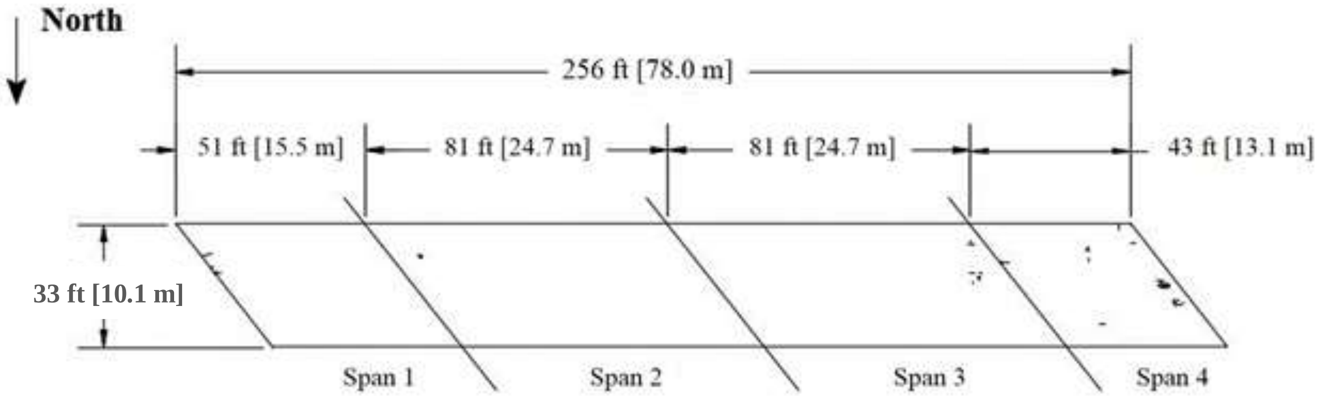
Bridge Deck Age = 71.6 months; Average crack density = 0.507 m/m^2

Figure G.9: Crack Map for IN-IC (Survey 1)



Bridge Deck Age = 34.8 months; Average crack density = 0.003 m/m^2

Figure G.10: Crack Map for IN-IC-HPC-2 (Survey 1)

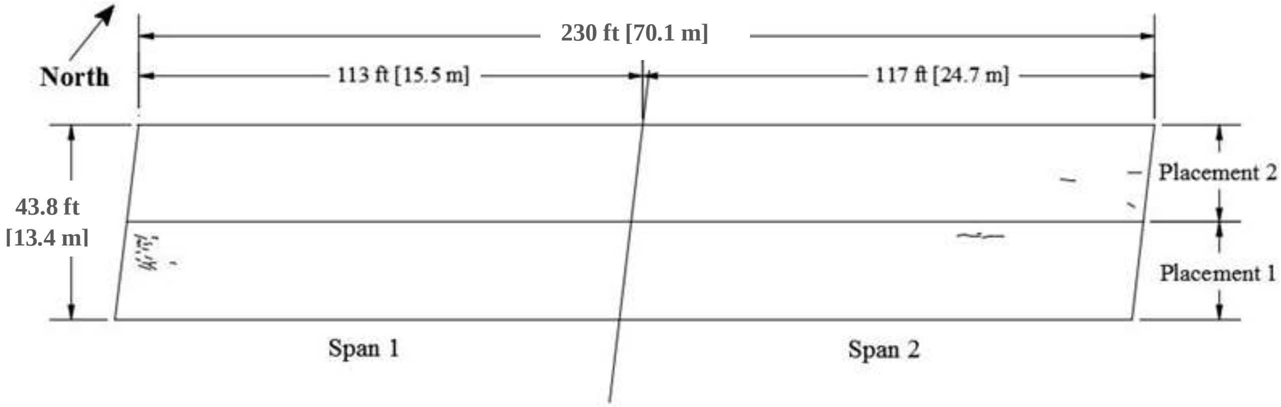


Bridge Deck Age = 21.6 months; Average crack density = 0.016 m/m^2

Span 1 crack density = 0.014 m/m^2 Span 2 crack density = 0.002 m/m^2

Span 3 crack density = 0.007 m/m^2 Span 4 crack density = 0.063 m/m^2

Figure G.11: Crack Map for IN-IC-HPC-3 (Survey 1)



Bridge Deck Age = 10.5 months (Placement 1), 15.6 months (Placement 2)
Average crack density = 0.013 m/m^2
Placement 1 crack density = 0.021 m/m^2 Placement 2 crack density = 0.005 m/m^2
Span 1 crack density = 0.014 m/m^2 Span 2 crack density = 0.012 m/m^2

Figure G.12: Crack Map for IN-IC-HPC-4 (Survey 1)

APPENDIX H: KANSAS DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC) – AGGREGATES, CONCRETE, AND CONSTRUCTION

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 2007 EDITION

Add a new SECTION to DIVISION 1100:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE – AGGREGATES

1.0 DESCRIPTION

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

2.0 REQUIREMENTS

a. Coarse Aggregates for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1-1**:

TABLE 1-1: QUALITY REQUIREMENTS FOR COARSE AGGREGATES FOR BRIDGE DECK

Concrete Classification	**Soundness (min.)**	**Wear (max.)**	**Absorption (max.)**	**Acid Insol. (min.)**
Grade 3.5 (AE) (LC-HPC) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 sieve (KT-2) 2.5%
- Shale or Shale-like material (KT-8)....................... 0.5%
- Clay lumps and friable particles (KT-7) 1.0%
- Sticks (wet) (KT-35).. 0.1%
- Coal (AASHTO T 113).. 0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 2.0c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to **subsection 2.0c**.

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.

- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 sieve (KT-2)……………. 2.0%
  - Shale or Shale-like material (KT-8) …………………… 0.5%
  - Clay lumps and friable particles (KT-7)……………….. 1.0%
  - Sticks (wet) (KT-35)…………………………..…..…… 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 sieve (KT-2)…………..... 2.0%
  - Clay lumps & friable particles (KT-7)…………………. 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 2.0c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 2.0c**.

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet **TABLE 1-2**.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under **subsection 2.0c.(2)** may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……………….0.90
- Wear, maximum (KTMR-25) …………………….50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate Concrete Modulus of Rupture:
- At 60 days, minimum………………………….550 psi
- At 365 days, minimum…..…………………….550 psi

  Expansion:
- At 180 days, maximum……………………….0.050%
- At 365 days, maximum……………………….0.070%

  Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:
- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 sieve is to be considered a Fine Aggregate described in **subsection 2.0b**. Provide material with less than 5% calcareous material retained on the ⅜" sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)…………………….50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

*Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.

- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1-2**.

TABLE 1-2: GRADING REQUIREMENTS FOR MIXED AGGREGATES FOR CONCRETE BRIDGE DECKS

Type	**Usage**	**Percent Retained on Individual Sieves - Square Mesh Sieves**										
		1½"	**1"**	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	5-18	8-18	8-18	8-18	8-18	8-18	8-15	5-15	0-10

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method. Note: Manufactured sands used to obtain optimum gradations have caused difficulties in pumping, placing or finishing. Natural coarse sands and pea gravels used to obtain optimum gradations have worked well in concretes that were pumped.

(b) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 sieve (KT-2)……………..…..2.5%
- Shale or Shale-like material (KT-8)…………………..…….0.5%
- Clay lumps and friable particles (KT-7)…………………… 1.0%
- Sticks (wet) (KT-35)………………………..……………0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.

- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

d. Lightweight Aggregates for Concrete.

Fine lightweight aggregate is permitted as a means to provide internal curing water for concrete. The requirements of ASTM C1761 and C330 shall apply, except as modified in this specification.

(1) Product Control

- Size Requirement: All lightweight aggregate shall pass 3/8 in. sieve.

(2) Proportioning.

- Volume of lightweight aggregate added to a mixture shall not exceed 10 percent of total aggregate volume. If lightweight aggregate is used as a replacement for normalweight aggregate, the replacement shall be made on a volume basis.

(3) Pre-wetting.

- Lightweight aggregate shall be pre-wetted prior to adding at the time of batching. Recommendations for pre-wetting made by the lightweight aggregate supplier shall be followed to ensure that the lightweight aggregate has achieved an acceptable absorbed moisture content at the time of batching. Mixture proportions shall not be adjusted based on the absorbed water in the lightweight aggregate.

(4) Handling and Stockpiling Lightweight Aggregates.

- Lightweight aggregates shall be handled and stockpiled in accordance with the requirements for fine aggregates in subsection 2.0b.(5)

3.0 TEST METHODS

Test aggregates according to the applicable provisions of **SECTION 1117**.

4.0 PREQUALIFICATION

Aggregates for concrete must be prequalified according to **subsection 1101.2**.

5.0 BASIS OF ACCEPTANCE

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and **subsection 1101.4**.

07-29-09 LAL
04-18-11 DD
01-27-14 BP DD
07-16-14 DD

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 2007 EDITION

Add a new SECTION to DIVISION 400:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE

1.0 DESCRIPTION

Provide the grades of low-cracking high-performance concrete (LC-HPC) specified in the Contract Documents.

2.0 MATERIALS

Coarse, Fine & Mixed Aggregate	**07-PS0165, latest version**
Admixtures	**DIVISION 1400**
Cement	**DIVISION 2000**
Water	**DIVISION 2400**

3.0 CONCRETE MIX DESIGN

a. General. Design the concrete mixes specified in the Contract Documents.

Provide aggregate gradations that comply with **07-PS0165, latest version** and Contract Documents.

If desired, contact the DME for available information to help determine approximate proportions to produce concrete having the required characteristics on the project.

Take full responsibility for the actual proportions of the concrete mix, even if the Engineer assists in the design of the concrete mix.

Submit all concrete mix designs to the Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the DME).

Do not place any concrete on the project until the Engineer approves the concrete mix designs. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval.

Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to **TABLE 1-1**.

TABLE 1-1: AIR ENTRAINED CONCRETE FOR BRIDGE DECKS

Grade of Concrete Type of Aggregate (SECTION 1100)	lb of Cementitious per cu yd of Concrete, min/max	lb of Water per lb of Cementitious*	Designated Air Content Percent by Volume**	Specified 28-day Compressive Strength Range, psi
Grade 3.5 (AE) (LC-HPC)				
MA-4	500 / 540	0.44 – 0.45	8.0 ± 1.0	3500 – 5500

*Limits of lb. of water per lb. of cementitious. Includes free water in aggregates, but excludes water of absorption of the aggregates. With approval of the Engineer, may be decreased to 0.43 on-site.

**Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected. The Engineer will sample concrete for tests at the discharge end of the conveyor, bucket or if pumped, the piping.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. Portions of portland cement may be replaced with slag cement or slag cement and silica fume if used in conjunction with internal curing using pre-wetted lightweight aggregate (see 07-PS0165 subsection 2.0d.). The replacements of portland cement are limited to 30% by volume with slag cement and 3% by volume with silica fume..

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Air-Entrainment and Water Reduction. Verify that the admixtures used are compatible and will work as intended without detrimental effects. Use the dosages recommended by the admixture manufacturers to determine the quantity of each admixture for the concrete mix design. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Set retarding or accelerating admixtures are prohibited for use in Grade 3.5 (AE) (LC-HPC) concrete. These include Type B, C, D, E, and G chemical admixtures as defined by ASTM C 494/C 494M – 08. Do not use admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture in Grade 3.5 (AE) (LC-HPC) concrete.

(1) Air-Entraining Admixture. If specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content. Use only a vinsol resin or tall oil based air-entraining admixture.

(2) Water-Reducing Admixture. Use a Type A water reducer or a dual rated Type A water reducer – Type F high-range water reducer, when necessary to obtain compliance with the specified fresh and hardened concrete properties.

Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the water-reducing admixture is added to the concrete mixture.

The manufacturer may recommend mixing revolutions beyond the limits specified in **subsection 5.0**. If necessary and with the approval of the Engineer, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Slump control may be accomplished in the field only by redosing with a water-reducing admixture. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50% of the original dose. The redosed concrete shall be retested for slump prior to deposit on the bridge deck.

(3) Adjust the mix designs during the course of the work when necessary to achieve compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining and water-reducing chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design within the limits in **TABLE 1-2**.

TABLE 1-2: DESIGNATED SLUMP*

Type of Work	Designated Slump (inches)
Grade 3.5 (AE) (LC-HPC)	1 ½ - 3

* The Engineer will obtain sample concrete at the discharge end of the conveyor, bucket or if pumped, the piping.

If potential problems are apparent at the discharge of any truck, and the concrete is tested at the truck discharge (according to **subsection 6.0**), the Engineer will reject concrete with a slump greater than 3 ½ inches at the truck discharge, 3 inches if being placed by a bucket.

4.0 REQUIREMENTS FOR COMBINED MATERIALS

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards weighing 94 pounds net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5% throughout the range of use.

(2) Water. Measure the mixing water by weight or volume. In either case, the measurement must be accurate to within 1% throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5% throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3% of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site allowing the Engineer to test the aggregates for compliance with the specified requirements.

KDOT will sample and test aggregates from each source to determine their compliance with specifications. Do not batch the concrete mixture until the Engineer has determined that the aggregates comply with the specifications. KDOT will conduct sampling at the batching site, and test samples according to the Sampling and Testing Frequency Chart in Part V. For QC/QA Contracts, establish testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. When batching, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples can not be taken from the stream, take them from approved stockpiles, or use a template and sample from the conveyor belt. If test results indicate an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates tested concurrently with production may resume.

c. Handling of Materials.

(1) Aggregate Stockpiles. Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an “Approved Materials” sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. At the plant, limit stockpiles of tested and approved coarse aggregate and fine aggregate to 250 tons each, unless approved for more by the Engineer. If mixed aggregate is used, limit the approved stockpile to 500 tons, the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer so no material foreign to the concrete or material capable of changing the desired proportions is included. When 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used for any one continuous concrete placement.

(2) Segregation. Do not use segregated aggregates. Previously segregated materials may be thoroughly re-mixed and used when representative samples taken anywhere in the stockpile indicated a uniform gradation exists.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. Provide aggregate with a moisture content of ± 0.5% from the average of that day. If the moisture content in the aggregate varies by more than the above tolerance, take whatever corrective measures are necessary to bring the moisture to a constant and uniform consistency before placing concrete. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content, or by adding moisture to the stockpiles in a manner producing uniform moisture content through all portions of the stockpile.

For plants equipped with an approved accurate moisture-determining device capable of determining the free moisture in the aggregates, and provisions made for batch to batch correction of the amount of water and the weight of aggregates added, the requirements relative to manipulating the stockpiles for moisture control will be waived. Any procedure used will not relieve the producer of the responsibility for delivery of concrete meeting the specified water-cement ratio and slump requirements.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by KDOT. If the producer elects to use KDOT Approved Materials for non-KDOT work, during the progress of a project requiring KDOT Approved Materials, inform the Engineer and agree to pay all costs for additional materials testing.

Clean all conveyors, bins and hoppers of unapproved materials before beginning the manufacture of concrete for KDOT work.

5.0 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to maintain continuous delivery at the rate required. The delivery rate of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

Seek the Engineer’s approval of the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

Clean the mixing drum before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cementitious. Uniformly flow materials into the drum throughout the batching operation. Add all mixing water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. The Engineer will allow an overload of up to 10% above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch between 1 to 5 minutes at mixing speed. Do not exceed the maximum total 60 mixing revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must comply with

Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch between 70 and 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate device indicating and controlling the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a batch slip including batch weights of every constituent of the concrete and time for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cementitious and aggregates. Include quantities, type, product name and manufacturer of all admixtures on the batch ticket.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited. Add all water at the plant. If needed, adjust slump through the addition of a water reducer according to **subsection 3.0e.(2)**.

b. Placement Limitations.

(1) Concrete Temperature. Unless otherwise authorized by the Engineer, the temperature of the mixed concrete immediately before placement is a minimum of 55°F, and a maximum of 70°F. With approval by the Engineer, the temperature of the concrete may be adjusted 5°F above or below this range.

(2) Qualification Batch. For Grade 3.5 (AE) (LC-HPC) concrete, qualify a field batch (one truckload or at least 6 cubic yards) at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Simulate haul time to the jobsite prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this specification.

(3) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(4) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, mixing and concreting operations shall not proceed once the descending ambient air temperature reaches 40°F, and may not be initiated until an ascending ambient air temperature reaches 40°F. The ascending ambient air temperature for initiating concreting operations shall increase to 45°F if the maximum ambient air temperature is expected to be between 55°F and 60°F during or within 24 hours of placement and to 50°F if the ambient air temperature is expected to equal or exceed 60°F during or within 24 hours of placement.

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is prohibited. Unless otherwise authorized, maintain the temperature of the mixed concrete between 55°F to 70°F at the time of placing it in the forms. With approval by the Engineer, the temperature of the concrete may be adjusted up to 5°F above or below this range. Do not place concrete when there is a probability of air temperatures being more than 25°F below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F.

If the ambient air temperature is 40°F or less at the time the concrete is placed, the Engineer may permit the water and the aggregates be heated to at least 70°F, but not more than 120°F.

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(5) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F, cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F and 70°F. With approval by the Engineer, the temperature of the concrete may be up to 5°F below or above this range.

Maintain the temperature of the concrete at time of placement within the specified temperature range by any combination of the following:

Shading the materials storage areas or the production equipment.

Cooling the aggregates by sprinkling with potable water.

Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.

- Liquid nitrogen injection.

6.0 INSPECTION AND TESTING

The Engineer will test the first truckload of concrete by obtaining a sample of fresh concrete at truck discharge and by obtaining a sample of fresh concrete at the discharge end of the conveyor, bucket or if pumped, the piping. The Engineer will obtain subsequent sample concrete for tests at the discharge end of the conveyor, bucket or if pumped, the discharge end of the piping. If potential problems are apparent at the discharge of any truck, the Engineer will test the concrete at truck discharge prior to deposit on the bridge deck. If a truckload is redosed with an admixture on-site or set aside to allow for concrete properties to meet the required specifications, the truckload shall be retested prior to deposit on the bridge deck. All retesting shall be performed by the Contractor or Concrete Supplier under the supervision of the Engineer.

The Engineer will cast, store, and test strength test specimens in sets of 5. See **TABLE 1-3**.

KDOT will conduct the sampling and test the samples according to **SECTION 2500** and **TABLE 1-3**. The Contractor may be directed by the Engineer to assist KDOT in obtaining the fresh concrete samples during the placement operation.

A plan will be finalized prior to the construction date as to how out-of-specification concrete will be handled.

TABLE 1-3: SAMPLING AND TESTING FREQUENCY CHART

Tests Required (Record to)	**Test Method**	**CMS**	**Verification Samples and Tests**	**Acceptance Samples and Tests**
Slump (0.25 inch)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 3 truckloads	
Temperature (1°F)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb)	KT-20	a	One of every 6 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 6 truckloads	
Cylinders (1 lbf; 0.1 in; 1 psi)	KT-22 and AASHTO T 22	VER	Make at least 2 groups of 5 cylinders per pour or major mix design change with concrete sampled from at least 2 different truckloads evenly spaced throughout the pour, with a minimum of 1 set for every 100 cu yd. Include in each group 3 test cylinders to be cured according to KT-22 and 2 test cylinders to be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	

TABLE 1-3: SAMPLING AND TESTING FREQUENCY CHART				
Tests Required (Record to)	**Test Method**	**CMS**	**Verification Samples and Tests**	**Acceptance Samples and Tests**
Density of Fresh Concrete (0.1 lb/cu ft or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 100 cu yd for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the DME on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements. If a truckload is found not to comply with the specified requirements, successive truckloads shall be tested until the requirements are met.

The Engineer will permit occasional deviations below the specified cementitious content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the maximum tolerance in the air content. Continuous operation below the specified cement content for any reason is prohibited.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

07-29-09 LAL, 04-18-11
01-27-14 BP DD
07-16-14 DD

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 2007 EDITION

Add a new SECTION to DIVISION 700:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE – CONSTRUCTION

1.0 DESCRIPTION

Construct the low-cracking high-performance concrete (LC-HPC) structures according to the Contract Documents and this specification.

BID ITEMS	**UNITS**
Qualification Slab	Cubic Yard
Concrete (*) (AE) (LC-HPC)	Cubic Yard
*Grade of Concrete	

2.0 MATERIALS

Provide materials that comply with the applicable requirements.

LC-HPC .... **07-PS0166, latest version**
Concrete Curing Materials .... **DIVISION 1400**

3.0 CONSTRUCTION REQUIREMENTS

a. Qualification Batch and Slab. For each LC-HPC bridge deck, produce a qualification batch of LC-HPC that is to be placed in the deck and complies with **07-PS0166, latest version**, and construct a qualification slab that complies with this specification to demonstrate the ability to handle, place, finish and cure the LC-HPC bridge deck.

After the qualification batch of LC-HPC complies with **07-PS0166, latest version**, construct a qualification slab 15 to 45 days prior to placing LC-HPC in the bridge deck. Construct the qualification slab to comply with the Contract Documents, using the same LC-HPC that is to be placed in the deck and that was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish and cure the qualification slab according to the Contract Documents, using the same personnel, methods and equipment (including the concrete pump, if used) that will be used on the bridge deck.

A minimum of 1 day after construction of the qualification slab, core 4 full-depth 4 inch diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of LC-HPC in the deck until approval is given by the Engineer. Approval to place concrete on the deck will be based on satisfactory placement, consolidation, finishing and curing of the qualification slab and cores, and will be given or denied within 24 hours of receiving the cores from the Contractor. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

b. Falsework and Forms. Construct falsework and forms according to **SECTION 708**.

c. Handling and Placing LC-HPC.

(1) Quality Control Plan (QCP). At a project progress meeting prior to placing LC-HPC, discuss with the Engineer the method and equipment used for deck placement. Submit an acceptable QCP according to the Contractor's Concrete Structures Quality Control Plan, Part V. Detail the equipment (for both determining and controlling the evaporation rate and LC-HPC temperature), procedures used to minimize the evaporation rate, plans for maintaining a continuous rate of finishing the deck without delaying the application of curing materials within the time specified in **subsection 3.0f.**, including maintaining a continuous supply of LC-HPC throughout the placement with an adequate quantity of LC-HPC to complete the deck and filling diaphragms and end walls in advance of deck placement, and plans for placing the curing materials within the time specified in **subsection 3.0f**. In the plan, also include input from the LC-HPC supplier as to how variations in the moisture content of the aggregate will be handled, should they occur during construction.

(2) Use a method and sequence of placing LC-HPC approved by the Engineer. Do not place LC-HPC until the forms and reinforcing steel have been checked and approved. Before placing LC-HPC, clean all forms of debris.

(3) Finishing Machine Setup. On bridges skewed greater than 10º, place LC-HPC on the deck forms across the deck on the same skew as the bridge, unless approved otherwise by State Bridge Office (SBO). Operate the bridge deck finishing machine on the same skew as the bridge, unless approved otherwise by the SBO. Before placing LP-HPC, position the finish machine throughout the proposed placement area to allow the Engineer to verify the reinforcing steel positioning.

(4) Environmental Conditions. Maintain environmental conditions on the entire bridge deck so the evaporation rate is less than 0.2 lb/sq ft/hr. The temperature of the mixed LC-HPC immediately before placement must be a minimum of 55°F and a maximum of 70°F. With approval by the Engineer, the temperature of the LC-HPC may be adjusted 5°F above or below this range. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, LC-HPC temperature, wind speed and relative humidity. The effects of any fogging required by the Engineer will not be considered in the estimation of the evaporation rate (**subsection 3.0c.(5)**).

Just prior to and at least once per hour during placement of the LC-HPC, the Engineer will measure and record the air temperature, LC-HPC temperature, wind speed, and relative humidity on the bridge deck. The Engineer will take the air temperature, wind, and relative humidity measurements approximately 12 inches above the surface of the deck. With this information, the Engineer will determine the evaporation rate using KDOT software or **FIGURE 710-1**.

When the evaporation rate is equal to or above 0.2 $\mathrm{lb/ft^2/hr}$, take actions (such as cooling the LC-HPC, installing wind breaks, sun screens etc.) to create and maintain an evaporation rate less than 0.2 $\mathrm{lb/ft^2/hr}$ on the entire bridge deck.

(5) Fogging of Deck Placements. Fogging using hand-held equipment may be required by the Engineer during unanticipated delays in the placing, finishing or curing operations. If fogging is required by the Engineer, do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

(6) Placement and Equipment. Place LC-HPC by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the Contractor can show proficiency when placing the approved mix during construction of the qualification slab using the same pump as will be used on the job. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix, using the same pump as will be used for the deck placement, at least 15 days prior to placing LC-HPC in the bridge deck. To limit the loss of air, the maximum drop from the end of a conveyor belt or from a concrete bucket is 5 feet and pumps must be fitted with an air cuff/bladder valve. Do not use chutes, troughs or pipes made of aluminum.

Place LC-HPC to avoid segregation of the materials and displacement of the reinforcement. Do not deposit LC-HPC in large quantities at any point in the forms, and then run or work the LC-HPC along the forms.

Fill each part of the form by depositing the LC-HPC as near to the final position as possible.

The Engineer will obtain sample LC-HPC for tests and cylinders at the discharge end of the conveyor, bucket, or if pumped, the piping.

(7) Consolidation.

- Accomplish consolidation of the LC-HPC on all span bridges that require finishing machines by means of a mechanical device on which internal (spud or tube type) concrete vibrators of the same type and size are mounted (**subsection 154.2**).
- Observe special requirements for vibrators in contact with epoxy coated reinforcing steel as specified in **subsection 154.2**.
- Provide stand-by vibrators for emergency use to avoid delays in case of failure.
- Operate the mechanical device so vibrator insertions are made on a maximum spacing of 12 inch centers over the entire deck surface.
- Provide a uniform time per insertion of all vibrators of 3 to 15 seconds, unless otherwise designated by the Engineer.
- Provide positive control of vibrators using a timed light, buzzer, automatic control or other approved method.
- Extract the vibrators from the LC-HPC at a rate to avoid leaving any large voids or holes in the LC-HPC.
- Do not drag the vibrators horizontally through the LC-HPC.
- Use hand held vibrators (**subsection 154.2**) in inaccessible and confined areas such as along bridge rail or curb.
- When required, supplement vibrating by hand spading with suitable tools to provide required consolidation.
- Reconsolidate any voids left by workers.

Continuously place LC-HPC in any floor slab until complete, unless shown otherwise in the Contract Documents.

d. Construction Joints, Expansion Joints and End of Wearing Surface (EWS) Treatment. Locate the construction joints as shown in the Contract Documents. If construction joints are not shown in the Contract Documents, submit proposed locations for approval by the Engineer.

If the work of placing LC-HPC is delayed and the LC-HPC has taken its initial set, stop the placement, saw the nearest construction joint approved by the Engineer, and remove all LC-HPC beyond the construction joint.

Construct keyed joints by embedding water-soaked beveled timbers of a size shown on the Contract Documents, into the soft LC-HPC. Remove the timber when the LC-HPC has set. When resuming work, thoroughly clean the surface of the LC-HPC previously placed, and when required by the Engineer, roughen the key with a steel tool. Before placing LC-HPC against the keyed construction joint, thoroughly wash the surface of the keyed joint with clean water.

e. Finishing. Strike off bridge decks with a vibrating screed or single-drum roller screed, either self-propelled or manually operated by winches and approved by the Engineer. Use a self-oscillating screed on the finish machine, and operate or finish from a position either on the skew or transverse to the bridge roadway centerline. See **subsection 3.0c.(3)**. Do not mount tamping devices or fixtures to drum roller screeds; augers are allowed.

Irregular sections may be finished by other methods approved by the Engineer and detailed in the required QCP. See **subsection 3.0c.(1)**.

Finish the surface by a burlap drag, metal pan or both, mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal pan, as necessary, to remove any local irregularities. Do not add water to the surface of LC-HPC. Do not use a finishing aid.

Tining of plastic LC-HPC is prohibited. All LC-HPC surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Finish all top surfaces, such as the top of retaining walls, curbs, abutments and rails, with a wooden float by tamping and floating, flushing the mortar to the surface and provide a uniform surface, free from pits or porous places. Trowel the surface producing a smooth surface, and brush lightly with a damp brush to remove the glazed surface.

f. Curing and Protection.

(1) General. Cure all newly placed LC-HPC immediately after finishing, and continue uninterrupted for a minimum of 14 days. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Curing compounds are prohibited during the 14 day curing period.

(2) Cover With Wet Burlap. Soak the burlap a minimum of 12 hours prior to placement on the deck. Rewet the burlap if it has dried more one hour before it is applied to the surface of bridge deck. Apply 1 layer of wet burlap within 10 minutes of LC-HPC strike-off from the screed, followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period. In the required QCP, address the rate of LC-HPC placement and finishing methods that will affect the period between strike-off and burlap placement. See **subsection 3.0c.(1)**. During times of delay expected to exceed 10 minutes, cover all concrete that has been placed, but not finished, with wet burlap.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the LC-HPC has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire LC-HPC surface. For bridge decks with superelevation, place a minimum of 1 soaker hose along the high edge of the deck to keep the entire deck wet during the curing period.

(3) Waterproof Cover. Place white polyethylene film on top of the soaker hoses, covering the entire LC-HPC surface after soaker hoses have been placed, a maximum of 12 hours after the placement of the LC-HPC. Use as wide of sheets as practicable, and overlap 2 feet on all edges to form a complete waterproof cover of the entire LC-HPC surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, use soaker hoses to keep the entire exposed area continuously wet. Replace saturated burlap and polyethylene film, resuming the specified curing conditions, as soon as possible.

Inspect the LC-HPC surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

(4) Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that the entire bridge deck is wet and all curing material is in place;
- documentation showing the time and date of all inspections and the inspector’s signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to keep the exposed area continuously wet.

(5) Cold Weather Curing. When LC-HPC is being placed in cold weather, also adhere to **07-PS0166, latest version**.

When LC-HPC is being placed and the ambient air temperature may be expected to drop below 40ºF during the curing period or when the ambient air temperature is expected to drop more than 25°F below the temperature of the LC-HPC during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the LC-HPC and girder temperatures between 40ºF and 75ºF as measured on the upper and lower surfaces of the LC-HPC. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of LC-HPC and between 40ºF and 75ºF. When artificial heating is used to maintain the LC-HPC and girder temperatures, provide adequate ventilation to limit exposure to carbon dioxide if necessary. Maintain wet burlap and polyethylene cover during the entire 14 day curing period. Heating may be stopped after the first 72 hours if the time of curing is lengthened to account for periods when the ambient air temperature is below 40ºF. For every day the ambient air temperature is below 40ºF, an additional day of curing with a minimum ambient air temperature of 50ºF will be required. After completion of the required curing period, remove the curing and protection so that the temperature of the LC-HPC during the first 24 hours does not fall more than 25°F.

(6) Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply 2 coats of an opaque curing membrane to the LC-HPC. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. Apply each coat of curing membrane according to the manufacturer’s instructions with a minimum spreading rate per coat of 1 gallon per 80 square yards of LC-HPC surface. If the LC-HPC is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a minimum of 7 days. Give any marred or disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may limit work on the deck until the 7-day period is complete. Because the purpose of the curing membrane is to allow for slow drying of the bridge deck, extension of the initial curing period beyond 14 days, while permitted, shall not be used to reduce the 7-day period during which the curing membrane is applied and protected.

(7) Construction Loads. Adhere to **TABLE 710-2**.

If the Contractor needs to drive on the bridge before the approach slabs can be placed and cured, construct a temporary bridge from the approach over the EWS capable of supporting the anticipated loads. Do not bend the reinforcing steel which will tie the approach slab to the EWS or damage the LC-HPC at the EWS. The method of bridging must be approved by the Engineer.

TABLE 710-2: CONCRETE LOAD LIMITATIONS ON BRIDGE DECKS

Days after concrete is placed	**Element**	**Allowable Loads**
1*	Subdeck, one-course deck or concrete overlay	Foot traffic only.
3*	One-course deck or concrete overlay	Work to place reinforcing steel or forms for the bridge rail or barrier.
7*	Concrete overlays	Legal Loads; Heavy stationary loads with the Engineer's approval.***
10 (15)**	Subdeck, one-course deck or post-tensioned haunched slab bridges**	Light truck traffic (gross vehicle weight less than 5 tons).****
14 (21)**	Subdeck, one-course deck or post-tensioned haunched slab bridges**	Legal Loads; Heavy stationary loads with the Engineer's approval.***Overlays on new decks.
28	Bridge decks	Overloads, only with the State Bridge Engineer's approval.***

*Maintain a 7 day wet cure at all times (14-day wet cure for decks with LC-HPC).
** Conventional haunched slabs.
*** Submit the load information to the appropriate Engineer. Required information: the weight of the material and the footprint of the load, or the axle (or truck) spacing and the width, the size of each tire (or track length and width) and their weight.
****An overlay may be placed using pumps or conveyors until legal loads are allowed on the bridge.

g. Grinding and Grooving. Correct surface variations exceeding 1/8 inch in 10 feet by use of an approved profiling device, or other methods approved by the Engineer after the curing period. Perform grinding on hardened LC-HPC after the 7 day curing membrane period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

After any required grinding is complete, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Transverse grooving of the finished surface may be done with equipment that is not self-propelled providing that the Contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing LC-HPC surface. Make the grooving approximately 3/16 inch in width at 3/4 inch centers and the groove depth approximately 1/8 inch. For bridges with drains, terminate the transverse grooving approximately 2 feet in from the gutter line at the base of the curb. Continuously remove all slurry residues resulting from the texturing operation.

h. Post Construction Conference. At the completion of the deck placement, curing, grinding and grooving for a bridge using LC-HPC, a post-construction conference will be held with all parties that participated in the planning and construction present. The Engineer will record the discussion of all problems and successes for the project.

i. Removal of Forms and Falsework. Do not remove forms and falsework without the Engineer's approval. Remove deck forms approximately 2 weeks (a maximum of 4 weeks) after the end of the curing period (removal of burlap), unless approved by the Engineer. The purpose of 4 week maximum is to limit the moisture gradient between the bottom and the top of the deck.

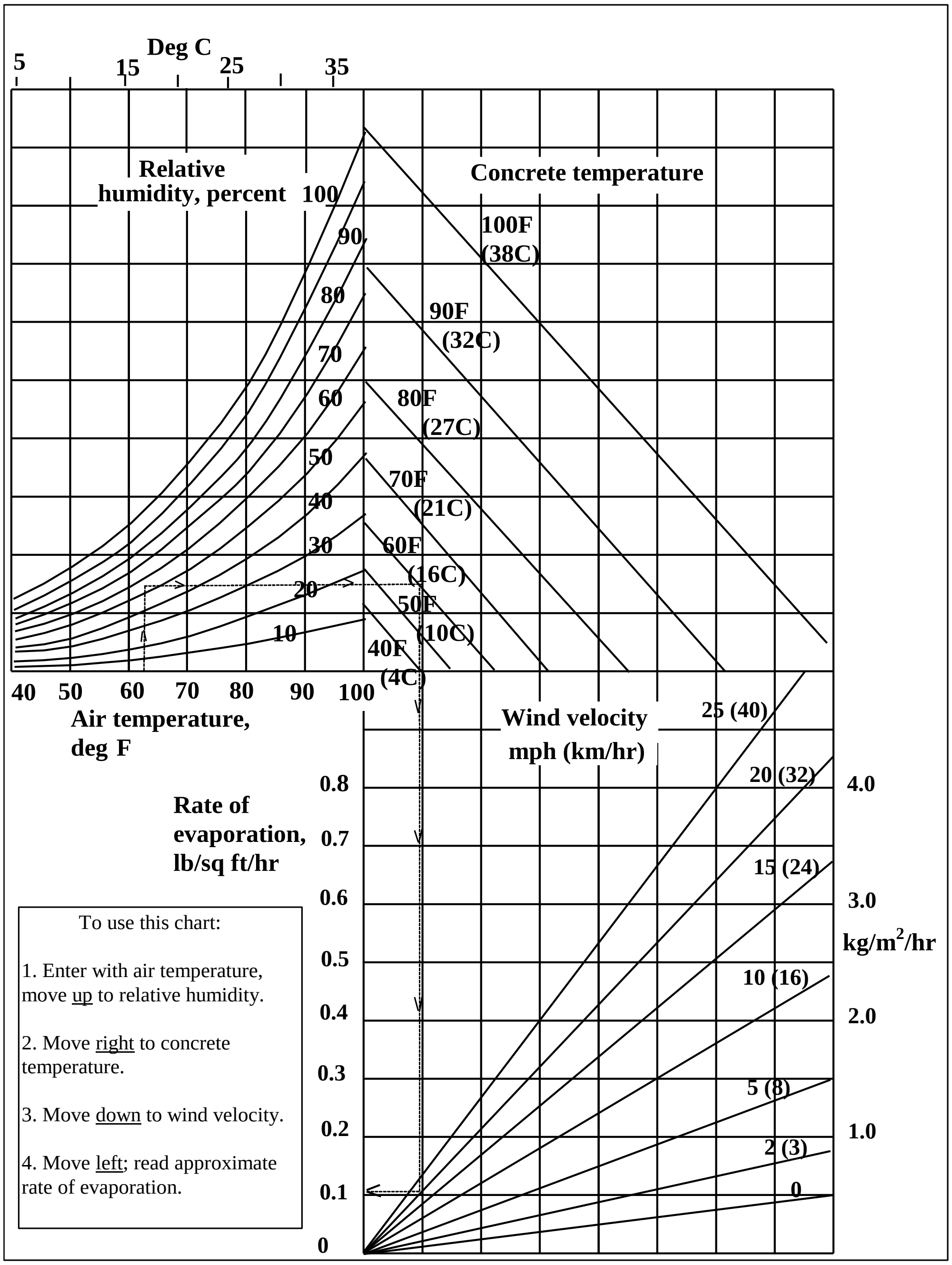
For additional requirements regarding forms and falsework, see **SECTION 708**.

4.0 MEASUREMENT AND PAYMENT

The Engineer will measure the qualification slab and the various grades of (AE) (LC-HPC) concrete placed in the structure by the cubic yard. No deductions are made for reinforcing steel and pile heads extending into the LP-HPC. The Engineer will not separately measure reinforcing steel in the qualification slab.

Payment for the "Qualification Slab" and the various grades of "(AE) (LC-HPC) Concrete" at the contract unit prices is full compensation for the specified work.

FIGURE 710-1: STANDARD PRACTICE FOR CURING CONCRETE



To use this chart:

1. Enter with air temperature, move <u>up</u> to relative humidity.

2. Move <u>right</u> to concrete temperature.

3. Move <u>down</u> to wind velocity.

4. Move <u>left</u>; read approximate rate of evaporation.

Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

07-29-09 LAL, 04-18-11 DD

*From Kansas Department of Transportation (2014a, 2014b, 2011)

APPENDIX I: INDIANA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR INTERNALLY CURED, HIGH PERFORMANCE, STRUCTURAL CONCRETE FOR BRIDGE DECKS

LAPORTE DISTRICT

ADDED 10/5/2012
Contract No. B-30496

INTERNALLY CURED, HIGH PERFORMANCE, STRUCTURAL CONCRETE FOR BRIDGE DECK

Description

This work shall consist of furnishing and placing internally cured high performance concrete (IC-HPC), for bridge deck in accordance with 105.03. IC-HPC contains portland cement and two pozzolanic materials, as well as a pre-soaked lightweight fine aggregate, to produce a concrete of high durability, low permeability, and low cracking potential. The absorbed water within the pre-soaked lightweight fine aggregate provides internal moisture that is released to the hydrating cement within the paste matrix of the placed concrete. The pre-soaked lightweight fine aggregate is intended to inhibit autogenous shrinkage by hydrating more of the cementitious materials and thereby reduce early age cracking of the bridge deck.

MATERIALS

Materials

Materials shall be in accordance with the following:

Admixtures	912.03
Castings	910.05
Cast Iron Soil Pipe	908.10
Coarse Aggregate, Class A*, Size No. 8	904
Curing Materials	912.01
Fabric For Waterproofing	913.16
Fine Aggregate, Natural Sand Size No. 23	904
Fly Ash	901.02
Ground Granulated Blast Furnace Slag	901.03
Lightweight Fine Aggregate	**
Permanent Metal Forms	910.03
Portland Cement	901.01
Reinforcing Steel, Epoxy Coated	910.01
Steel Drain Pipe	910.07
Silica Fume	901.04
Utility Asphalt, UA-1	902.01(d)
Water	913.01

* If the Contract requires stay-in-place metal forms for the bridge deck or if the Contractor elects to use such forms, the bridge deck concrete shall incorporate class AP coarse aggregate instead of Class A.

** Described Herein

Shipping and storage of cement shall be in accordance with 702.04.

Lightweight fine aggregate shall be an expanded shale meeting the requirements of ASTM C 330 except that compressive strength and splitting tensile strength testing are not required. Density Factor (Specific Gravity Factor) shall be determined by the method defined in this specification. Approval of the lightweight aggregate source will be based on a Type B Certification and the acceptance criteria stated in Job Control Testing.

Concrete Mix Design

The concrete shall be designed utilizing three cemetitious materials as part of the binder systems. Portland cement, silica fume, fly ash and lightweight fine aggregate shall be proportioned in accordance with Concrete Mix Criteria. A concrete mix design, CMD, and trial batch shall be in accordance with requirements detailed elsewhere in this special provision. The CMD shall be submitted in a format acceptable to the Engineer and include the following:

(a) list of all ingredients
(b) source of all materials
(c) gradation of the aggregates
(d) absorption of the aggregates
(e) SSD bulk specific gravity of the aggregates
(f) Specific Gravity Factor of Lighweight Fine Aggregate
(g) Specific gravity of each pozzolan
(h) batch weights (mass)
(i) names of all admixtures
(j) range of admixture dosage rates as recommended by the manufacturer

A change in material source, class or type requires a new CMD.

A CMD in accordance with this special provision may be substituted only for concrete used in the RC Bridge Approach. IC-HPC may be substituted for other Class C concrete if approved in writing by the Engineer.

Concrete Mix Criteria

The CMD shall produce workable high performance concrete mixtures having the following properties:

1. The design paste volume of total cementitious material and water shall not exceed 25.0 % of the concrete volume design value (e.g 6.75 ft^3 maximum paste volume per cubic yard concrete). Each cementitious material shall be batched within a tolerance not to exceed 1.0% in accordance with 702.06.

2. The cement content in the ternary binder system shall be at least 390 lbs (231 kg) per cubic yard (cubic meter) of concrete. Air-entraining cements will not be permitted.

3. Class F or C fly ash shall be used as part of the total cementitious content in the ternary binder system. Fly ash shall constitute 20.0 to 25.0 percent by weight (mass) of the total cementitious content in the mix design. Fly ash shall not be used in conjunction with Type IP cement. In lieu of fly ash, ground granulated blast furnace slag (ggbfs) may be used in an amount of 15.0 to 20.0 percent by weight (mass) of the total cementitious content in the mix design. Ggbfs shall not be used in conjunction with Type IS cement.

4. Silica fume shall constitute 3.0%-7.0% of the total cementitious content in the mix design.

5. The water-cementitious ratio of the delivered IC-HPC shall be within a range of ± 0.025 of the target stated in the approved mix design, and shall not exceed 0.430 nor be less than 0.360. The Contractor shall achieve this by controlling water added to the batch and water occurring as surface moisture on the aggregates.

6. The CMD target air content shall be set at 6.5 %.

7. Total fine aggregate volume shall be no less than 35% nor more than 45% of the total aggregate volume for the IC-HPC. Coarse aggregate and natural sand volumes are to be based on Bulk Specific Gravities in the saturated surface dry (ssd) condition. Lightweight fine aggregate volume is to be determined based on Specific Gravity Factor (SGF), as determined by the methodology defined in this special provision. The Contractor and Department are to have concurrence on aggregate Bulk Specific Gravities (ssd), Specific Gravity Factor (SGF) and corresponding absorptions prior to submitting the design of IC-HPC concrete for DTE review.

8. The amount of lightweight fine aggregate needed for internal curing of the concrete shall be determined as follows:

a) Proportion the mix according the preceding requirements and establish the volume of fine aggregate based on the properties of the natural sand only.

b) Determine the weight (mass) of dry lightweight fine aggregate by the following equation

$M_{DLWA} = 1.025(C_f \times 0.070) / \Phi_{LWA}$

Where: M_{DLWA} = weight of dry lightweight fine aggregate in lbs/yd³ of IC-HPC.

C_f = Cementitious content (includes cement, fly ash and silica fume)

Φ_{LWA} = Absorption, as decimal, determined by AASHTO T 84, except soaking period is 24 hours and surface dry condition is established per criteria 4 of note 2. Testing absorption will also be accomplished per ACI 211.2 Appendix B, except that the minimum weight of sample is 500 grams. This test is to be used for purposes of comparison and finalizing a value

c) Determine the Specific Gravity Factor (SGF) of the lightweight fine aggregate per Section 10 of AASHTO T 84, except that S and S_1 will be determine for the material in the condition as previously described for Φ_{LWA} in part 8.b).

d) Determine the design batch weight of soaked surface dry lightweight fine aggregate, which has absorbed water for 24 hours soak, using the following equation:

$$M_{sLWA} = M_{DLWA}(1 + \Phi_{LWA})$$

e) Determine the mix design volume of lightweight fine aggregate at ϕ_{LWA} moisture content using the following equation:

$V_{sLWA} = M_{sLWA} / (SGF \times 62.4)$

Where: M_{sLWA} = See 8.d) above

SGF = Bulk Specific Gravity as described previously in 8.c).

In no case shall V_{sLWA} be less than 20% of the total fine aggregate volume determined previously in 8.a).

f) Determine the volume of ssd natural sand for IC-HPC by subtracting V_{sLWA} from the total fine aggregate volume determined previously in part 8.a).

9. The slump shall be within a range of 2.5" to 5.5" at point of placement.

10. The CMD target compressive strength at 28-days shall be a minimum of 5000 psi.

11. The CMD Target resistance to chloride ion permeability at 56 days shall be set such that the delivered concrete will be no greater than 1500 coulombs.

Absorption and SSD bulk specific gravity for the natural sand are to be determined in accordance with AASHTO T 84. Absorption and SSD bulk specific gravity of the coarse aggregate are to be determined in accordance with AASHTO T 85, by procedures 8.2. Values agreed upon by the Contractor and Engineer shall apply when calculating target batch mass (weights) and determining water/cementitious ratio.

The IC-HPC shall contain an air entraining agent and either a water reducing, high range, admixture (type F) or a water-reducing, high range, and retarding admixture (type G) as identified in the Department's list of approved PCC Admixture and Admixture Systems. The type admixture used shall not be changed during any individual contiguous pour. The type admixture to be used shall be selected based on the expected concrete temperature, ambient temperature, initial set time, lineal rate of deck placement in ft/h (m/h), and dead load deflection of any structural members containing the concrete. When either temperature is expected to be 65°F (18°C) or above and dead load deflection is of concern; type G admixture, or a system of Type B or D combined with a Type F, shall be used. A type F admixture shall be used when both temperatures are expected to be below 65°F (18°C) or dead load deflection is not of concern. Retardation may be required due to the structure design or the proposed pour sequence in accordance with 704.04. A higher temperature restriction regulating the need to retard the concrete initial set time may be requested in writing and shall substantiate the effects of IC-HPC initial set time, lineal rate of deck placement, and dead load deflection.

The admixture addition rate shall not be reduced below the minimum, or exceed the maximum rate recommended by the manufacturer, regardless of the temperature of the concrete or ambient temperature.

There will be no calendar date restrictions as to the use of high performance concrete with a ternary binder system.

The CMD by absolute volume method shall be submitted to the Engineer for verification at least seven days prior to the trial batch demonstration. An explanation of intended use for each mix design shall be provided.

Trial Batch

A trial batch demonstration shall be conducted by the Contractor. The Engineer will be in attendance. Both parties are to verify that the IC-HPC mix design meets the requirements of this specification. A representative from the lightweight aggregate supplier shall be present for the trial batch. This representative shall have the necessary test equipment and technical expertise to measure the properties of lightweight fine aggregate for use in structural concrete. The representative shall provide testing, guidance and direction in proportioning the IC concrete per ACI 211.2.

The Contractor shall construct lightweight fine aggregate stockpile(s) at the concrete production facility so as to maintain uniform moisture throughout the pile. Prior to the IC-HPC production the lightweight fine aggregate shall undergo a period of wetting and draining. The Contractor shall wet the lightweight fine aggregate stockpile(s) utilizing a sprinkler system, approved by the DTE, to continuously and uniformly apply water to soak the stockpile(s) for a minimum of 48 hours or until the moisture content can consistently be maintained above the absorption Φ_{LWA}. If steady rain of comparable intensity occurs, the sprinkler system may be turned off, with concurrence by the DTE. At the end of the wetting period the lightweight fine aggregate stockpile(s) shall be allowed to drain for 12 to 15 hours immediately prior to being used in IC-HPC production, unless otherwise directed by the DTE. Manipulation of the lightweight fine aggregate stockpile(s) may be necessary to assure uniform wetting and drainage. The soaked and drained lightweight fine aggregate shall achieve, and maintain, an absorbed moisture content equal to or greater than Φ_{LWA} prior to use. Transfer of the lightweight fine aggregate to the storage bin in the plant shall be monitored and controlled to assure that free water does not have time to drain down into the lower lightweight fine aggregate and significantly increase the water/cementitious ratio for a batched load of IC-HPC.

The target batch weight from the soaked and drained stockpiled lightweight fine aggregate, which has been soaked and drained, will be determined as follows:

1. Obtain a representative sample in accordance with AASHTO T 84. Weigh the soaked and drained sample of lightweight fine aggregate and record the value as W_{WET}.
2. Prepare the sample, to surface dry condition, by following criteria 4 of Note 2 of AASHTO T 84 or by ACI 211.2 Appendix B, except the minimum weight of sample is 500 grams. Weigh the wet sample in the surface dry condition. Record the value as W_{SSD}. Dry the sample to a constant weight and record the value as W_{DRY}.
3. Calculate the target batch weight for the stockpiled, soaked and drained lightweight fine aggregate (TBW_{LWA}) needed to produce each cubic yard of IC-HPC as follows:

$TBW_{LWA} = M_{DLWA} \times [1.00 + (W_{WET} - W_{DRY}) / W_{DRY}]$

The wet loose unit weight of the soaked and drained lightweight aggregate shall also be determined in accordance with ACI 211.2 in order to substantiate the target batch weight. The concrete shall be batched and mixed in accordance with 702.06 and 702.07. Sufficient IC-HPC shall be produced to accurately represent the mix design and provide an amount of concrete to provide samples for all parties to perform the required testing. The Engineer will test the trial batch IC-HPC and provide the Contractor with the results. The sample of IC-HPC shall not be used for more than one test, except the unit weight specimen may be used to conduct the air content test. The IC-HPC shall be agitated for a period of time that simulates delivery to the job site.

Test results from the Contractor and Department must both validate compliance with the required plastic properties. The Department's water to cementitious ratio measurement shall not exceed ±0.015 from the value measured by the Contractor. The Contractor's air content shall measure at least 6.5% and the Department's corresponding measure is to be within ± 0.5 % points. The air content is to be measured by both AASHTO T 152 and T 196, in an effort to establish any difference between the two test methods for IC-HPC. The Departments measurement for slump is to be within a tolerance of ± 1" of the Contractor's measurement. If comparison between Contractor and Department results is out of tolerance, an investigation will be conducted to ascertain the cause and determine corrective action(s) needed to resolve the discrepancy.

The measured relative yield, Ry, is to be determined and compared to the theoretical Ry value tabulated below. The theoretical Ry is selected based on measured air content.

Air Content %	Theor. Ry	Air Content %	Theor. Ry	Air Content %	Theor. Ry	Air Content %	Theor. Ry
3.0	**0.965**	**5.0**	**0.985**	**7.0**	**1.005**	**9.0**	**1.025**
3.1	0.966	5.1	0.986	7.1	1.006	9.1	1.026
3.2	0.967	5.2	0.987	7.2	1.007	9.2	1.027
3.3	0.968	5.3	0.988	7.3	1.008	9.3	1.028
3.4	0.969	5.4	0.989	7.4	1.009	9.4	1.029
3.5	0.970	5.5	0.990	7.5	1.010	9.5	1.030
3.6	0.971	5.6	0.991	7.6	1.011	9.6	1.031
3.7	0.972	5.7	0.992	7.7	1.012	9.7	1.032
3.8	0.973	5.8	0.993	7.8	1.013	9.8	1.033
3.9	0.974	5.9	0.994	7.9	1.014	9.9	1.034
4.0	**0.975**	**6.0**	**0.995**	**8.0**	**1.015**	**10.0**	**1.035**
4.1	0.976	6.1	0.996	8.1	1.016	10.1	1.036
4.2	0.977	6.2	0.997	8.2	1.017	10.2	1.037
4.3	0.978	6.3	0.998	8.3	1.018	10.3	1.038
4.4	0.979	6.4	0.999	8.4	1.019	10.4	1.039
4.5	0.980	6.5	1.000	8.5	1.020	10.5	1.040
4.6	0.981	6.6	1.001	8.6	1.021	10.6	1.041
4.7	0.982	6.7	1.002	8.7	1.022	10.7	1.042
4.8	0.983	6.8	1.003	8.8	1.023	10.8	1.043
4.9	0.984	6.9	1.004	8.9	1.024	10.9	1.044

If a measured Ry is excessively low or high, an investigation will be conducted by the Contractor and Engineer to ascertain the cause and determine corrective action needed to resolve the discrepancy. The aggregates may need to be re-tested for bulk specific gravity (ssd), Specific Gravity Factor, absorption, or moisture content, as appropriate.

Once the IC-HPC has passed the requirements for batching, and testing the plastic concrete properties of slump and air content, specimens will be cast for testing compressive strength and permeability. Four 6"x12" cylinders will be cast for the purpose of compressive strength determination. Two cylinders will be tested at an age of 7-days and two cylinders will be tested at an age of 28-days. The compressive strength will be reported as the average of the two cylinders tested at the designated age. The compressive strength shall exceed 4400 psi at 28 days.

Two additional 6"x12" specimens will be cast for the purpose of testing the IC-HPC for resistance to chloride ion penetration at 56 days. The result will be the averaged of the two specimens cored from the cylinders. Two 4"x8" cylinders may also be cast and tested for resistance to chloride penetration at 28 days, after accelerated curing. The specimens for accelerated testing shall be cured in the same manner as the cylinders for compressive strength, for a period of 7 days, after which they will be cured at 100 °F ± 10 °F for a period of 20 days.

All molds, facilities and materials necessary to prepare and initially cure these cylinders, shall be provided.

Samples representing the natural sand, lightweight fine aggregate and coarse aggregate used in the IC-HPC production will be tested for gradation. The gradation of each aggregate shall comply with the specification. Gradation, fineness modulus and dry loose density of the lightweight fine aggregate will be determined in accordance with ASTM C 330 for material used in the IC-HPC produced at the trial batch. Specific Gravity Factor will be determined as described in this special provision.

Except for adjustments to compensate for routine aggregate moisture fluctuations, changes in target aggregate (SSD) batch weights (mass) shall be documented and submitted to the Engineer for approval, prior to implementing. Changes to the dosage rate of admixtures will be permitted. A new CMD shall be prepared and successfully demonstrated for changes in the source, type or class of a material, the amounts of cementitious materials, increase in target water/cementitious ratio, or the addition or deletion of admixtures.

Test Methods and Procedures

The following test methods and procedures apply with exceptions as listed below.

Air Test	AASHTO T 152 or T 196*
Compressive Strength	AASHTO T 22
Flexural Strength	AASHTO T 97
High Pressure Air Content of Hardened PCC	ITM 401
Making and Curing Specimens	AASHTO T 23
Moisture Content, Aggregate	AASHTO T 255
Obtaining and Testing of Drilled Cores	AASHTO T 24
Sampling Fresh Concrete	AASHTO T 141
Sampling Stockpiled Aggregates	ITM 207
Sieve Analysis of Aggregates	AASHTO T 27
Slump	AASHTO T 119
Specific Gravity and Absorption, Coarse Aggregate.	AASHTO T 85**
Specific Gravity and Absorption, Fine Aggregate.	AASHTO T 84
Resistance to Chloride Ion Penetration	AASHTO T 277
Unit Weight (Mass)	AASHTO T 121
Water-Cementitious Ratio	ITM 403

* If the use of lightweight fine aggregate is found to produce significantly different results for air content then the method and procedure for the test shall be in accordance with AASHTO T 196.

** Section 8.2

(a) Exceptions to AASHTO T 23

The **exceptions to AASHTO T** 23 for making and curing specimens in the field **shall** be as follows.

1. Initial curing of cylinders shall be no less than 16 h or more than 48 h.

2. Non-watertight beam forms (molds) will be permitted.

3. After 24 h, the molded beam specimens shall be taken to the storage location and removed from the molds.

4. Field stored beams will not require 24 ± 4 h immersion in water saturated with calcium hydroxide prior to the time of testing.

(b) Exceptions to AASHTO T 27

The exceptions to AASHTO T 27 for conducting a sieve analysis are in accordance with 904.06.

(c) Exception to AASHTO T 84

The exceptions to AASHTO T 84 for determining SSD specific gravity and absorption for the fine aggregate shall be as follows:

1. The SSD bulk specific gravity shall be reported to the nearest 0.001 and the absorption reported to the nearest and 0.01%.

(d) Exception to AASHTO T 85

The exceptions to AASHTO T 85 for determining SSD specific gravity and absorption for the coarse aggregate shall be as follows:

1. The 15 h soak period shall not be eliminated.

2. The in-water weight (mass) shall be determined following the 15 h soaking period prior to determining the SSD weight (mass).

3. The SSD bulk specific gravity shall be reported to the nearest 0.001 and the absorption reported to the nearest 0.01%.

(e) Exceptions to AASHTO T 97

The exceptions to AASHTO T 97 for conducting a flexural test shall be as follows:

1. The beam size shall be measured to the nearest 1/16 in. (1.0 mm).

2. The test result shall be discarded when the break occurs outside the middle third of the beam.

(f) Exceptions to AASHTO T 121

The exceptions to AASHTO T 121 for determining the unit weight (mass) of concrete shall be as follows:

1. Weight (mass) shall be determined to the nearest 0.01 lb (0.005 kg).

(g) Exceptions to AASHTO T 141

The exceptions to AASHTO T 141 for sampling fresh concrete in the field shall be as follows:

1. The entire sample may be obtained from one portion of the load after at least 0.25 yd^3 (0.25 m^3) of concrete has been discharged.

(h) Exceptions to AASHTO T 152

The exceptions to AASHTO T 152 for determining the air content in PCC shall be as follows:

1. The aggregate correction factor shall be determined in accordance with 6.4.3 except that the volume of water shall not be removed from the assembled and filled apparatus.

2. The aggregate correction factor test shall be re-run for confirmation if the test results for gravel is greater than 0.4% or if the test results for crushed stone is greater than 0.6%.

CONSTRUCTION

General

Construction operations as applicable shall be in accordance with 702, 703 and 704.

Ready-Mixed Concrete

Ready mixed IC-HPC shall be in accordance with 702.09. Mixing at the work site, as described in 702.08 is prohibited.

The Contractor shall construct lightweight fine aggregate stockpile(s) at the concrete production facility so as to maintain uniform moisture throughout the pile. Prior to the IC-HPC production the lightweight fine aggregate shall undergo a period of wetting and draining.

The Contractor shall wet the lightweight fine aggregate stockpile(s) utilizing a sprinkler system, approved by the DTE, to continuously and uniformly apply water to soak the stockpile(s) for a minimum of 48 hours or until the moisture content can consistently be maintained above the absorption, Φ_{LWA}. If steady rain of comparable intensity occurs, the sprinkler system may be turned off, with concurrence by the DTE. At the end of the wetting period the lightweight fine aggregate stockpile(s) shall be allowed to drain for 12 to 15 hours immediately prior to being used in IC-HPC production, unless otherwise directed by the DTE. The soaked and drained lightweight fine aggregate shall achieve, and maintain, an absorbed moisture content equal to or greater than Φ_{LWA} prior to use. Manipulation of the lightweight fine aggregate stockpile(s) may be necessary to assure uniform wetting and drainage. Transfer of the lightweight fine aggregate to the storage bin in the plant shall be monitored and controlled to assure that free water does not have time to drain down into the lower lightweight fine aggregate and significantly increase the water/cementitious ratio for a batched load of IC-HPC.

A representative from the lightweight aggregate supplier shall be present for any IC-HPC production. This representative shall have the necessary test equipment and technical expertise to measuring the properties of lightweight fine aggregate for IC-HPC. The representative shall provide guidance and direction in proportioning the IC concrete per ACI 211.2 and the experienced gained from the trial batch demonstration. The Department will determine the amount of soaked and drained lightweight aggregate by the method established at the trial batch, which shall be used to establish the target batch weight of lightweight fine aggregate.

Testing Facilities and Equipment

An easily accessible means of obtaining concrete samples at the point of placement and transporting the samples from the bridge deck for testing shall be provided. All molds, facilities, and materials necessary to prepare and initially cure quality control and acceptance cylinders shall be provided at the work site.

Job Control Testing

Prior to any IC-HPC production, newly delivered or existing stockpiles of lightweight fine aggregate will be tested for fineness modulus and dry loose bulk density to verify uniformity in accordance with ASTM C 330. The fineness and loose bulk density parameters established at the trial batch will be the basis for making the comparison.

Department acceptance of IC-HPC will be determined on the basis of tests performed by the Engineer. Any necessary labor for sampling the IC-HPC shall be furnished to the Engineer, as required. During placement, the IC-HPC will be tested for slump, relative yield and air content. Testing for plastic and hardened concrete properties will be performed on the first load of IC-HPC and every 50 cubic yards. The slump shall be in accordance with concrete mix criteria stated herein. IC-HPC that may initially exceed the maximum allowable slump can be held in reserve until the slump is determined be within specification and the load does not exceed the 90 minute time limit as stated in 702.09(c)5. Air content shall be 6.5% ± 1.5% at point of placement.

Relative yield will be determined and shared with the Contractor, through the representative from the lightweight aggregate supplier. The Contractor shall make adjustments to the aggregate batch weights, as appropriate, to correct problems with relative yield. Should the relative yield exceed the Theoretical value, for the measured air content, by 0.010; the Engineer will immediately increase the frequency of sampling and testing until the relative yield is reduced. Any increased sampling and testing will include cylinders for compressive strength and rapid permeability.

Two 6"x12" cylinders will be cast every 50 cubic yards and tested for compressive strength at an age of 28-days. Cylinders will be cured in accordance with AASHTO T 23. Compressive strength shall exceed 4000 psi.

Two 6"x12" cylinders will be cast every 50 cubic yards and tested for the purpose of testing resistance to chloride ion penetration at 56 days.

Falsework and Centering

Falsework and **arch** centering for structural elements shall be in accordance with 702.14.

Finishing

The concrete shall be finished in accordance with 702.21 and 704.05.

Wet Curing

After finishing and texturing in accordance with 704.05, the IC-HPC shall be cured in accordance with 704.06 and 702.22, except as modified herein.

An evaporation retardant shall be applied, in accordance with the manufacturer's recommendation, to the exposed concrete surface immediately after finishing or texturing operations. Reapplication of the retardant shall be performed whenever the surface is disturbed, or when drying of the surface is observed. The evaporation retardant shall be one of the products listed below. A type D certification for the evaporative retardant shall be in accordance with 516 and submitted to the Engineer prior to use.

(a) Confilm, manufactured by Master Builders Technologies; 3715 Bargetown Road, Room 214; Louisville, KY 40218

(b) Sika-Film, manufactured by Sika Corporation; 2930 Switzer Road; Columbus, OH 43219

(c) Eucobar, Euclid Chemical Company; 19218 Redwood Road; Cleveland, OH 44110

Evaporative retardant shall be applied to the finished or textured surface of IC-HPC regardless of the evaporation rate. If the evaporation rate exceeds 0.10 $lbs/ft^2/h$ (0.50 $kg/m^2/h$) during placement of concrete, fog misting, as recommended by the silica fume manufacturer, shall be initiated prior to the texturing operation. Fog misting shall not be excessive to cause water to wash the fresh concrete surface, or to stand on the surface during floating or troweling operations.

The rate of water evaporation shall be determined during concrete placement in accordance with ACI 308, Section 1.2.1. or the following English (metric) equation:

$$E = [T_c^{2.5} - (r \times T_a^{2.5})][1 + 0.4V]\times 10^{-6}$$
$$(E = 5[(T_c + 18)^{2.5} - r(T_a + 18)^{2.5}][V + 4] \times 10^{-6})$$

where:

E = Evaporation rate, lb/ft^2/h (kg/m^2/h)
T_c = Concrete temperature, °F (°C)
T_a = Ambient temperature, °F (°C)
r = (RH %)/100
V = Wind velocity, mi/h (k/h)

Measurements of T_a, r, & V shall be obtained on-site and compared for accuracy with readings from the nearest weather station monitored by the National Climatic Data Center. Measurement of T_c shall be determined from the concrete placed.

The IC-HPC shall be wet cured continuously for at least 168 h commencing immediately after the surface is able to support the protective covering without deformation. The wet cure period shall be 240 h for concrete placed in cold weather.

Membrane forming curing compound shall not be applied to IC-HPC in bridge decks or the top surface of reinforced concrete slab bridges.

Surfaces to be cured shall be protected by covering with cotton mats, burlap, or other satisfactory protective material that is kept continuously and thoroughly wet, through the use of soaker hoses, during the curing period. The protective covering shall be suitably anchored. Curbs, walls, handrails, copings, and other surfaces requiring a finish in accordance with 702.21 may have the covering temporarily removed for finishing, but the cover shall be restored as soon as possible. Water application through the soaker hoses shall be discontinued 24 hours before the cure period ends and the protective covering is removed.

Cold Weather Concrete

Cold weather concrete operations shall be in accordance with 702.11, except that immediately after a pour is completed, the freshly poured concrete and forms shall be covered so as to form a protective enclosure and the air in the enclosure kept at a temperature above 50 °F (10 °C) for at least 240 hours.

Removal and Re-use of Forms

The forms for any portion of the structure shall not be removed until IC-HPC is strong enough to withstand damage. Field operations concerning IC-HPC shall be controlled by the Department through test beams in accordance with the requirements of 702.13(h).

Application of Loads

The application of loads to IC-HPC shall be in accordance with the test beam requirements of 702.24(a). Construction activities shall not interfere with wet curing of the bridge deck throughout the period specified.

No contract time extension will be considered for delays due to additional time necessary to attain specified strengths.

Sealing

The IC-HPC deck surface shall not be sealed.

Method of Measurement

IC-HPC will be measured by the cubic yard (cubic meter) in accordance with the neat lines or as directed. However, no allowance will be made for variations in beam fillet depths, coping depths, or diaphragm depths. Reinforcing steel will be measured in accordance with 703.07. Castings and cast iron pipe will be measured in accordance with 702.27.

Basis of Payment

The accepted quantities of IC-HPC will be paid for at the contract unit price by the cubic yard (cubic meter) of concrete, complete in place. Reinforcing steel will be paid for in accordance with 703.08. Castings and cast iron pipe will be paid for in accordance with 702.28.

Payment will be made under:

Pay Item	**Pay Unit Symbol**
Concrete, C, Superstructure, Modified, IC-HPC	CYS (m3)

The cost of conducting trial batch demonstrations, performing quality control testing, and similar requirements included herein will not be paid for directly but shall be included in the cost of IC-HPC.

BRIDGE RAILING

This work shall be in accordance with 706, except that internally cured high performance concrete (IC-HPC) shall be used in lieu of Class C concrete. IC-HPC in the bridge railing shall meet the requirements of the special provision entitled Internally Cured, High Performance, Structural Concrete For Bridge Decks.