EVALUATING FREE SHRINKAGE OF CONCRETE FOR CONTROL OF CRACKING IN BRIDGE DECKS

By

Swapnil Deshpande

David Darwin

JoAnn Browning

A Report on Research Sponsored by

CONSTRUCTION OF CRACK-FREE BRIDGE DECKS
TRANSPORTATION POOLED FUND STUDY
Project No. TPF-5(051)

Structural Engineering and Engineering Materials
SM Report No. 89

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
LAWRENCE, KANSAS

January 2007

ABSTRACT

The effects of paste volume, water-cement ratio, aggregate type, cement type, curing period, and the use of mineral admixtures and superplasticizers on the free shrinkage of concrete are evaluated with the goal of establishing guidelines to reduce cracking in reinforced concrete bridge decks. Three concrete prisms were cast and tested in accordance with ASTM C 157 for each mixture up to an age of 365 days under controlled conditions of 23 ± 2°C (73 ± 3°F) and 50 ± 4 percent relative humidity. The work was organized in five test programs. The first program included mixes with water-cement ratios of 0.40, 0.45, and 0.50, and aggregate contents of 60, 70, and 80 percent, with Type I/II cement and Type II coarse-ground cement. The second program included the mixes with one of three coarse aggregate types, granite, limestone, and quartzite. The third program evaluated the effects of Class C fly ash, ground granulated blast-furnace slag, and silica fume as partial volume replacements for portland cement. The fourth and fifth programs were used, respectively, to evaluate the effect of curing period (3, 7, 14, or 28 days) and the use of different superplasticizer types and dosages.

The results indicate that concrete shrinkage decreases with an increase in the aggregate content (and a decrease in the paste content) of the mix. For a given aggregate content, no clear effect of water-cement ratio on the shrinkage is observed. In general, granite coarse aggregates result in lower shrinkage than limestone coarse aggregates. A similar conclusion cannot be made with quartzite coarse aggregate, although in some cases shrinkage of concrete containing quartzite coarse aggregate was lower than that of concrete containing limestone. The use of partial volume replacement of portland cement by Class C fly ash without changing the water or aggregate content generally leads to increased shrinkage. The use of partial volume replacement of portland cement by blast furnace slag without changing the water or aggregate content can lead to increased early-age shrinkage, although the ultimate shrinkage is not significantly affected. An increase in the curing period helps to reduce shrinkage. The use of Type II coarse ground cement results in significantly less shrinkage compared to Type I/II cement. The use of superplasticizers in concrete appears to increase in shrinkage to a certain degree. The results, however, do not present a clear picture of the effect of superplasticizer dosage on shrinkage.

Keywords: aggregates, cement fineness, concrete, cracking, curing, fly ash, paste content, shrinkage, silica fume, slag, superplasticizers

ACKNOWLEDGEMENTS

This report is based on research performed by Swapnil S. Deshpande in partial fulfillment of the requirements for the MSCE degree from the University of Kansas. This research project was sponsored by the Kansas Department of Transportation serving as the lead agency for the "Construction of Crack-Free Bridge Decks" Transportation Pooled Fund Study, Project No. TPF-5(051). The Federal Highway Administration (FHWA) of the U.S. Department of Transportation, the Delaware Department of Transportation, the Idaho Department of Transportation, the Indiana Department of Transportation, the Michigan Department of Transportation, the Minnesota Department of Transportation, the Mississippi Department of Transportation, the Missouri Department of Transportation, the Montana Department of Transportation, the New Hampshire Department of Transportation, the North Dakota Department of Transportation, the Oklahoma Department of Transportation, the South Dakota Department of Transportation, the Texas Department of Transportation, and the Wyoming Department of Transportation provided funding to the pooled fund. Representatives from each state and the FHWA served on a Technical Advisory Committee that provided advice and oversight to the project.

Maria Voelker, Will Lindquist, and Heather McLeod helped in laboratory work and data collection. Jim Weaver helped with the test setup. LRM Industries provided concrete materials.

TABLE OF CONTENTS

ABSTRACT i

ACKNOWLEDGEMENTS iii

LIST OF TABLES vii

LIST OF FIGURES xi

CHAPTER 1: INTRODUCTION 1

1.1 GENERAL 1
1.2 SHRINKAGE: DEFINITION AND CLASSIFICATION 2
1.3 FREE SHRINKAGE: MEANING AND SIGNIFICANCE 4
1.4 FREE SHRINKAGE TEST 6
1.5 PREVIOUS WORK 7
1.6 SUMMARY OF PREVIOUS WORK 31
1.7 OBJECTIVE AND SCOPE 32

CHAPTER 2: EXPERIMENTAL PROGRAM 35

2.1 GENERAL 35
2.2 FREE SHRINKAGE TEST 36
2.3 MATERIALS 36
2.4 MIX PROPORTIONING 42
2.5 MIXING EQUIPMENT 43
2.6 PROGRAM I (AGGREGATE CONTENT, WATER-CEMENT RATIO, CEMENT TYPE) 43
2.7 PROGRAM II (COARSE AGGREGATE TYPES) 44
2.8 PROGRAM III (MINERAL ADMIXTURES) 45
2.9 PROGRAM IV (CURING PERIOD) 47
2.10 PROGRAM V (SUPERPLASTICIZERS) 48
2.11 MIXING 52

2.12 CASTING 55
2.13 CURING 55
2.14 DRYING 56
2.15 DATA COLLECTION 57

CHAPTER 3: RESULTS AND EVALUATION 59

3.1 GENERAL 59
3.2 STATISTICAL ANALYSIS 60
3.3 PROGRAM I (AGGREGATE CONTENT, WATER-CEMENT RATIO, CEMENT TYPE) 61
3.4 PROGRAM II (COARSE AGGREGATE TYPES) 64
3.5 PROGRAM III (MINERAL ADMIXTURES) 67
3.6 PROGRAM IV (CURING PERIOD AND CEMENT TYPE) 73
3.7 PROGRAM V (SUPERPLASTICIZERS) 79
3.8 COMPARISON OF RESULTS WITH PREVIOUS WORK 85

CHAPTER 4: SUMMARY AND CONCLUSIONS 90

4.1 SUMMARY 90
4.2 CONCLUSIONS 93
4.3 RECOMMENDATIONS 94

REFERENCES 96

TABLES 99

FIGURES 170

APPENDIX A 223

LIST OF TABLES

Table 2.1 – Program I (Aggregate Content, Water-Cement Ratio, Cement Type) test matrix ... 99

Table 2.2 – Program II (Coarse Aggregate Types) test matrix ... 99

Table 2.3 – Program III (Mineral Admixtures) test matrix ... 100

Table 2.4 – Program IV (Curing Period) test matrix ... 100

Table 2.5 – Program V (Superplasticizers) test matrix ... 101

Table 2.6– Pea gravel gradations ... 102

Table 2.7 – Sand gradations ... 103

Table 2.8 – 19-mm (3/4-in.) Granite gradations ... 104

Table 2.9 – 25-mm (1-in.) Limestone gradations ... 104

Table 2.10 – 19-mm (3/4-in.) Limestone gradations ... 105

Table 2.11 – Quartzite gradations ... 106

Table 2.12 Chemical composition of mineral admixtures ... 107

Table 2.13 – Mix Proportions-Program I-Aggregate Content, Water-Cement Ratio, Cement Type ... 108

Table 2.14 – Mix Proportions-Program II-Aggregate Types ... 110

Table 2.15 – Mix Proportions-Program III-Mineral admixtures ... 113

Table 2.16 – Mix Proportions-Program IV-Curing Period ... 116

Table 2.17 – Mix Proportions-Program V-Superplasticizers ... 117

Table 3.1 - Summary of free shrinkage measurements for Program I ... 10525

Table 3.2 - Comparison of free shrinkage measurements for various water cement ratios for Program I ... 125

Table 3.3a - Summary of free shrinkage measurements for Program II (Non-air-entrained Batches) 126

Table 3.3b - Summary of free shrinkage measurements for Program II (Air-Entrained Batches) 127

Table 3.4 - Summary of free shrinkage measurements for Program III 128

Table 3.5 - Summary of free shrinkage measurements for Program IV 129

Table 3.6 - Summary of free shrinkage measurements for based on drying period for Program IV 130

Table 3.7a - Summary of free shrinkage measurement for Program V (Non-air-entrained concrete) 131

Table 3.7b - Summary of Free Shrinkage Measurement from Program V for air-entrained batches 133

Table 3.8-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 60% aggregate content, 30, 180, and 365 days after casting 134

Table 3.9-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 70% aggregate content, 30, 180, and 365 days after casting 135

Table 3.10-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 80% aggregate content, 30, 180, and 365 days after casting 136

Table 3.11-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 60% aggregate content, 30, 180, and 365 days after casting 137

Table 3.12-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 70% aggregate content, 30, 180, and 365 days after casting 138

Table 3.13-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 80% aggregate content, 30, 180, and 365 days after casting 139

Table 3.14-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type I/II cement, 30, 180, and 365 days after casting 140

Table 3.15-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type I/II cement, 30, 180, and 365 days after casting 141

Table 3.16-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type I/II cement, 30, 180, and 365 days after casting 142

Table 3.17-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting 143

Table 3.18-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting 144

Table 3.19-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting 145

Table 3.20a-Program II Student's t-test results for non-air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting 146

Table 3.21a-Program III Student's t-test results for concrete containing Type I/II cement with mineral admixtures by volume replacement at 30, 180, and 365 days after casting 150

Table 3.22-Program IV Student's t-test results (Batch 165) for different curing periods, for non-air-entrained concrete containing Type I/II cement 153

Table 3.23-Program IV Student's t-test (Batch 166) results for different curing periods, for non-air-entrained concrete containing Type II coarse-ground cement 154

Table 3.24 Program IV Student's t-test results (Batch 201) for different curing periods, for air-entrained concrete containing Type I/II cement 155

Table 3.25-Program IV Student's t-test (Batch 207) results for different curing periods, for air-entrained concrete containing Type II coarse-ground cement 156

Table 3.26-Program IV Student's t-test results (Batch 165 and 166) comparing cement type with curing periods, for different drying periods of non-air-entrained concrete 157

Table 3.27-Program IV Student's t-test results (Batch 201 and 207) comparing cement type with curing periods, for different drying periods of air-entrained concrete 158

Table 3.28a-Program V Student's t-test results for concrete containing Glenium 3000NS for different dosage rates, 30, 180, and 365 days after casting........ 159

Table 3.28b-Program V Student's t-test results for concrete containing Rheobuild 1000 for different dosage rates, 30, 180, and 365 days after casting........ 160

Table 3.29a-Program V Student's t-test results for concrete containing Glenium 3000NS for different dosage rates, 30, 180, and 365 days after casting, cont........ 161

Table 3.29b-Program V Student's t-test results for concrete containing Rheobuild 1000 for different dosage rates, 30, 180, and 365 days after casting, cont........ 162

Table 3.30-Program V Student's t-test results for concrete containing Adva 100 for different dosage rates, 30, 180, and 365 days after casting 163

Table 3.31a-Program V Student's t-test results for concrete containing different superplasticizers (low dosage) for different dosage rates, 30, 180, and 365 days after casting........ 165

Table 3.31b-Program V Student's t-test results for concrete containing different superplasticizers (medium dosage) for different dosage rates, 30, 180, and 365 days after casting........ 166

Table 3.31c-Program V Student's t-test results for concrete containing different superplasticizers (high dosage) for different dosage rates, 30, 180, and 365 days after casting........ 167

Table 3.32a-Program V Student's t-test results for non-air-entrained concrete containing different superplasticizers (dosage rates for same slump), 30, 180, and 365 days after casting........ 168

Table 3.32b-Program V Student's t-test results for air-entrained concrete containing different superplasticizers (dosage rates for same slump), 30, 180, and 365 days after casting........ 169

LIST OF FIGURES

Figure 2.1 Free Shrinkage Specimen Mold. 170

Figure 2.2 Cross-section of Free Shrinkage Specimen. 170

Figure 2.3 Mechanical Dial Gage Length Comparator. 171

Figure 3.1 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type I/II cement. 172

Figure 3.2 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II cement. 173

Figure 3.3 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II cement. 174

Figure 3.4 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type II CG cement. 175

Figure 3.5 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type II coarse ground (CG) cement. 176

Figure 3.6 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type II coarse ground (CG) cement. 177

Figure 3.7 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.40............ 178

Figure 3.8 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.40............ 179

Figure 3.9 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.45............ 180

Figure 3.10 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.45............ 181

Figure 3.11 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.50............ 182

Figure 3.12 Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.50............ 183

Figure 3.13 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days. ... 184

Figure 3.14 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days. ... 184

Figure 3.15 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days. ... 185

Figure 3.16 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days. ... 185

Figure 3.17 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days. ... 186

Figure 3.18 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days. ... 186

Figure 3.19 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days. ... 187

Figure 3.20 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days. ... 187

Figure 3.21 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days. ... 188

Figure 3.22 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days. ... 188

Figure 3.23 Free Shrinkage Test, Program II. Comparison of different aggregate type through 180 days. ... 189

Figure 3.24 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days. ... 189

Figure 3.25 Free Shrinkage Test, Program III. Comparing mineral admixtures through 30 days. ... 190

Figure 3.26 Free Shrinkage Test, Program III. Comparing mineral admixtures through 180 days. ... 190

Figure 3.27 Free Shrinkage Test, Program III. Comparing mineral admixtures through 365 days. ... 191

Figure 3.28 Free Shrinkage Test, Program III. Comparing mineral admixtures through 30 days. 191

Figure 3.29 Free Shrinkage Test, Program III. Comparing mineral admixtures through 180 days. 192

Figure 3.30 Free Shrinkage Test, Program III. Comparing mineral admixtures through 365 days. 192

Figure 3.31 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 30 days. 193

Figure 3.32 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 180 days. 193

Figure 3.33 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 365 days. 194

Figure 3.34 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 30 days. 194

Figure 3.35 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 30 days. Drying only. 195

Figure 3.36 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 180 days. 195

Figure 3.37 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 180 days. Drying only. 196

Figure 3.38 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 365 days. 196

Figure 3.39 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 365 days. Drying only. 197

Figure 3.40 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 30 days. Type II coarse ground (CG) cement. 197

Figure 3.41 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 30 days. Drying only. ... 198

Figure 3.42 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 180 days. Type II coarse ground (CG) cement. ... 198

Figure 3.43 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 180 days. Drying only. ... 199

Figure 3.44 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 365 days. Type II coarse ground (CG) cement. ... 199

Figure 3.45 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 365 days. Drying only. ... 200

Figure 3.46 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 30 days. ... 200

Figure 3.47 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 30 days. Drying only. ... 201

Figure 3.48 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 180 days. ... 201

Figure 3.49 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 180 days. Drying only. ... 202

Figure 3.50 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 365 days. ... 202

Figure 3.51 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 365 days. Drying only. ... 203

Figure 3.52 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 30 days. ... 203

Figure 3.53 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 30 days. Drying only. 204

Figure 3.54 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement through 180 days. Batch 207. 204

Figure 3.55 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 180 days. Drying only. 205

Figure 3.56 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 365 days. 205

Figure 3.57 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 365 days. Drying only. 206

Figure 3.58 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 3-day cure specimens. Comparing cement type through 365 days. 206

Figure 3.59 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 7-day cure specimens. Comparing cement type through 365 days. 207

Figure 3.60 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 14-day cure specimens. Comparing cement type through 365 days. 207

Figure 3.61 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 28-day cure specimens. Comparing cement type through 365 days. 208

Figure 3.62 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 3-day cure specimens. Comparing cement type through 365 days. 208

Figure 3.63 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 7-day cure specimens. Comparing cement type through 365 days. 209

Figure 3.64 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 14-day cure specimens. Comparing cement type through 365 days. 209

Figure 3.65 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 28-day cure specimens. Comparing cement type through 365 days. 210

Figure 3.66 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 30 days. 210

Figure 3.67 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 180 days. 211

Figure 3.68 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 365 days. 211

Figure 3.69 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 30 days. 212

Figure 3.70 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 180 days. 212

Figure 3.71 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 365 days. 213

Figure 3.72 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 30 days. 213

Figure 3.73 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 180 days. 214

Figure 3.74 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 365 days. 214

Figure 3.75 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 30 days. 215

Figure 3.76 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 180 days. 215

Figure 3.77 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 365 days. 216

Figure 3.78 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 30 days. 216

Figure 3.79 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 180 days. 217

Figure 3.80 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 365 days. 217

Figure 3.81 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 30 days. 218

Figure 3.82 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 180 days. 218

Figure 3.83 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 365 days. 219

Figure 3.84 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 30 days. 219

Figure 3.85 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 180 days. 220

Figure 3.86 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 365 days. 220

Figure 3.87 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 30 days. 221

Figure 3.88 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 180 days. 221

Figure 3.89 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 365 days. 222

Figure A3.1 - Free Shrinkage, Batch 62. 80% Aggregate, 0.40 w/c. Type I/II cement. Drying begins at 3 days.. 223

Figure A3.2 - Free Shrinkage, Batch 63. 80% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days.. 223

Figure A3.3 - Free Shrinkage, Batch 64. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days.. 224

Figure A3.4 - Free Shrinkage, Batch 65. 70% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3. 224

Figure A3.5 - Free Shrinkage, Batch 66. 70% Aggregate, 0.40 w/c. Type I/II cement. Drying begins on day 3. ... 225

Figure A3.6 - Free Shrinkage, Batch 67. 80% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3. ... 225

Figure A3.7 - Free Shrinkage, Batch 68. 60% Aggregate, 0.40 w/c. Type I/II cement. Drying begins on day 3. ... 226

Figure A3.8 - Free Shrinkage, Batch 69. 60% Aggregate, 0.45 w/c., Type I/II cement. Drying begins on day 3. ... 226

Figure A3.9- Free Shrinkage, Batch 70. 60% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3. ... 227

Figure A3.10 - Free Shrinkage, Batch 71. 80% Aggregate, 0.40 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 227

Figure A3.11 - Free Shrinkage, Batch 72. 80% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 228

Figure A3.12 - Free Shrinkage, Batch 73. 80% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 228

Figure A3.13 - Free Shrinkage, Batch 74. 70% Aggregate, 0.40 w/c. Type II CG cement. Drying begins on day 3. ... 229

Figure A3.14 - Free Shrinkage, Batch 75. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 229

Figure A3.15 - Free Shrinkage, Batch 76. 70% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 230

Figure A3.16 - Free Shrinkage, Batch 77. 60% Aggregate, 0.40 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 230

Figure A3.17 - Free Shrinkage, Batch 78. 60% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 231

Figure A3.18 - Free Shrinkage, Batch 79. 60% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3. ... 231

Figure A3.19 - Free Shrinkage, Batch 94. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite. 232

Figure A3.20 - Free Shrinkage, Batch 95. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone. 232

Figure A3.21 - Free Shrinkage, Batch 187. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite. 233

Figure A3.22 - Free Shrinkage, Batch 188. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone. 233

Figure A3.23 - Free Shrinkage, Batch 189. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Granite. 234

Figure A3.24 - Free Shrinkage, Batch 198. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite. 234

Figure A3.25 - Free Shrinkage, Batch 199. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone. 235

Figure A3.26 - Free Shrinkage, Batch 200. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Granite. 235

Figure A3.27 - Free Shrinkage, Batch 262. 68.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Quartzite. 236

Figure A3.28 - Free Shrinkage, Batch 263. 68.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Limestone. 236

Figure A3.29 - Free Shrinkage, Batch 264. 68.8% Aggregate, 0.45 w/c., Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Granite. 237

Figure A3.30 - Free Shrinkage, Batch 85. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures. 237

Figure A3.31 - Free Shrinkage, Batch 86. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% slag replacement. 238

Figure A3.32 - Free Shrinkage, Batch 87. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Class C Fly Ash replacement. 238

Figure A3.33 - Free Shrinkage, Batch 88. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% silica fume replacement. 239

Figure A3.34 - Free Shrinkage, Batch 194. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures. 239

Figure A3.35 - Free Shrinkage, Batch 195. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Replacement by Slag. 240

Figure A3.36 - Free Shrinkage, Batch 196. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Replacement by Class C Fly Ash. 240

Figure A3.37 - Free Shrinkage, Batch 197. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% Replacement by Silica Fume. 241

Figure A3.38 - Free Shrinkage, Batch 202. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures. 241

Figure A3.39 - Free Shrinkage, Batch 203. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures. Adva superplasticizer. 242

Figure A3.40 - Free Shrinkage, Batch 204. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% Replacement by Silica Fume. Adva superplasticizer 242

Figure A3.41 - Free Shrinkage, Batch 165, 3-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 243

Figure A3.42 - Free Shrinkage, Batch 165, 7-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 7 days. 243

Figure A3.43 - Free Shrinkage, Batch 165, 14-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 14 days. 244

Figure A3.44 - Free Shrinkage, Batch 165, 28-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 28 days. 244

Figure A3.45 - Free Shrinkage, Batch 166, 3-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 3 days. 245

Figure A3.46 - Free Shrinkage, Batch 166, 7-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 7 days. 245

Figure A3.47 - Free Shrinkage, Batch 166, 14-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 14 days. 246

Figure A3.48 - Free Shrinkage, Batch 166, 28-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 28 days. 246

Figure A3.49 Free Shrinkage, Batch 201(3-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement Drying begins at 3 days. 247

Figure A3.50 Free Shrinkage, Batch 201(7-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement Drying begins at 7 days. 247

Figure A3.51 Free Shrinkage, Batch 201(14-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement Drying begins at 14 days. 248

Figure A3.52 Free Shrinkage, Batch 201(28-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement Drying begins at 28 days. 248

Figure A3.53 Free Shrinkage, Batch 207(3-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 3 days. 249

Figure A3.54 Free Shrinkage, Batch 207(7-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 7 days. 249

Figure A3.55 Free Shrinkage, Batch 207(14-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 14 days. 250

Figure A3.56 Free Shrinkage, Batch 207(28-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 28 days. 250

Figure A3.57 - Free Shrinkage, Batch 167. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures...................... 251

Figure A3.58 - Free Shrinkage, Batch 168. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Glenium 3000NS. 251

Figure A3.59 - Free Shrinkage, Batch 169. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Glenium 3000NS. 252

Figure A3.60 - Free Shrinkage, Batch 170. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS. 252

Figure A3.61 - Free Shrinkage, Batch 171. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Rheobuild 1000........................ 253

Figure A3.62 - Free Shrinkage, Batch 172. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Rheobuild 1000. 253

Figure A3.63 - Free Shrinkage, Batch 173. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000. 254

Figure A3.64 - Free Shrinkage, Batch 174. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS. 254

Figure A3.65 - Free Shrinkage, Batch 175. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures...................... 255

Figure A3.66 - Free Shrinkage, Batch 176. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Glenium 3000NS. 255

Figure A3.67 - Free Shrinkage, Batch 177. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Glenium 3000NS. 256

Figure A3.68 - Free Shrinkage, Batch 178. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS. 256

Figure A3.69 - Free Shrinkage, Batch 179. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Rheobuild 1000. 257

Figure A3.70 - Free Shrinkage, Batch 180. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Rheobuild 1000. 257

Figure A3.71 - Free Shrinkage, Batch 181. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000. 258

Figure A3.72 - Free Shrinkage, Batch 182. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000. 258

Figure A3.73 - Free Shrinkage, Batch 183. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures...................... 259

Figure A3.74 - Free Shrinkage, Batch 184. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Adva 100. 259

Figure A3.75 - Free Shrinkage, Batch 185. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Adva 100. 260

Figure A3.76 - Free Shrinkage, Batch 186. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Adva 100. 260

Figure A3.77 - Free Shrinkage, Batch 190. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Adva 100. 261

Figure A3.78 - Free Shrinkage, Batch 191. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Adva 100. 261

Figure A3.79 - Free Shrinkage, Batch 192. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Adva 100. 262

Figure A3.80 - Free Shrinkage, Batch 193. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixture. 262

Figure A3.81 - Free Shrinkage, Batch 208. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures. 263

Figure A3.82 - Free Shrinkage, Batch 209. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Adva 100. 263

Figure A3.83 - Free Shrinkage, Batch 210. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Glenium 3000 NS. 264

Figure A3.84 - Free Shrinkage, Batch 211. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Rheobuild 1000. 264

Figure A3.85 - Free Shrinkage, Batch 260. 63.5% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Control, no superplasticizer, increased paste content for same slump. 265

Figure A3.86- Free Shrinkage, Batch 249. 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Glenium 3000 NS. 265

Figure A3.87 - Free Shrinkage, Batch 256. 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Rheobuild 1000. 266

Figure A3.88 - Free Shrinkage, Batch 259 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Adva 100. 266

CHAPTER 1: INTRODUCTION

1.1 GENERAL

Cracking in the concrete bridge decks is a well documented problem. Cracking contributes to the deterioration of bridge decks and allows the ingress of water to the reinforcement, which may lead to corrosion. Cracking increases the maintenance costs, reduces the service life, and may result in disruptive and costly repairs. Experience shows that a combination of shrinkage and thermal stresses causes most deck cracking. Efforts have been made to reduce the cracking by designing concrete mixes for minimal shrinkage and improving methods of construction, placement, and finishing. Many departments of transportation in United States provide strict specifications regarding mix design, construction, and curing procedures, but bridge deck cracking remains a problem. According to a study conducted by Federal Highway Administration (FHWA) in 2005, 27 percent of the bridges in the United States are structurally inefficient or functionally obsolete. Although these classifications are not based exclusively on the condition of bridge decks, the bridge decks are the primary factors affecting this rating. According to infrastructure report card of 2005 (American Society of Civil Engineers), it will cost $9.4 billion a year for 20 years to eliminate all bridge deficiencies in United States.

Among the other factors that effect cracking on bridge decks are age, type of construction, girder type, ambient air temperature, and compressive strength (Lindquist, Darwin, Browning 2005). This study, however, focuses only on the reduction of cracking through the development of concrete mixes with minimal shrinkage.

Various researchers have studied the effect of different factors that affect restrained and unrestrained shrinkage of concrete. This report reviews some of that work and describes an experimental study that evaluates the effect of various ingredients and admixtures in concrete on the unrestrained (free) shrinkage of concrete.

1.2 SHRINKAGE: DEFINITION AND CLASSIFICATION

Shrinkage is a reduction in volume, and in concrete, it is mainly caused by the loss of water. In most cases, shrinkage is measured by monitoring longitudinal strain. When tensile stresses due to restrained volume contraction exceed the tensile strength of concrete, the shrinkage leads to cracking, which is called shrinkage cracking. Shrinkage is classified based on the causes of volume change and the state of concrete.

Plastic shrinkage is the shrinkage that occurs due to loss of moisture from fresh concrete. This loss may in be in form of surface evaporation or moisture loss to the subgrade, for slabs on the ground. The loss of moisture leads to the formation of menisci. These menisci generate negative capillary pressures, which cause a volume reduction in the cement paste (Mindess, Young, and Darwin 2003). Because the loss of moisture is concentrated at the exposed surfaces, the volume contraction is uneven. Differential volume changes produce tensile stresses in concrete, which may result in the formation of cracks in the plastic concrete. This type of cracking generally appears in random patterns and is shallow.

Autogenous Shrinkage (also known as chemical shrinkage) is a volume change that occurs without moisture loss to the surrounding environment. It occurs when water in cement paste is consumed by the hydration reactions, and results due to self desiccation of the concrete. This type of shrinkage mainly occurs in the mixes with low water-cement (*w/c*) ratios and may be increased by the use of reactive pozzolans. For the concretes with *w/c* ratios of 0.42 and greater, autogenous shrinkage is normally small and can be considered as a part of drying shrinkage.

Drying shrinkage occurs due to the loss of moisture from hardened concrete. Among the different types of shrinkage, drying shrinkage usually results in the largest volume change. Moisture loss causes volume changes based on three mechanisms that result in changes in capillary stress, disjoining pressure, and surface free energy. Capillary stress occurs between relative humidities of 45 and 95 percent, when a meniscus forms in the pore water within pores in cement paste. The meniscus is under hydrostatic tension, and adopts a curved surface. The water exerts the corresponding compression on the solid skeleton, reducing the size of the pores. Capillary stress (P_{cap}) is a function of the pore radius (r), the surface tension of the water (γ), and the relative humidity (RH), and is given by the equation

$$\begin{aligned} P_{\text{cap}} &= \frac{2\gamma}{r} \\ &= \frac{\ln(\text{RH})}{K} \end{aligned} \tag{1.1}$$

where K is a constant.

Disjoining pressure is the pressure caused by adsorbed water confined within the small spaces of capillary pores. In this narrow space, water exerts pressure on the adjacent cement surfaces. When the adsorbed water is lost, the disjoining pressure is reduced and the cement particles are drawn closer together, which results in shrinkage. As with capillary stress, disjoining pressure is significant down to about 45 percent relative humidity. Below 45 percent RH, shrinkage is explained by changes in surface energy. As the most strongly adsorbed water surrounding the cement particles is removed, the free surface energy of the solid increases significantly. This water has high surface tension and exerts a compressive pressure on cement particle, causing a reduction in volume (Mindess, Young, and Darwin, 2003).

Carbonation shrinkage occurs as the result of chemical reactions between hardened cement paste and carbon dioxide. It is believed that CO_2 reacts with calcium silicate hydrate (C-S-H) inducing a decrease in its calcium-silica (C/S) ratio with a concomitant water loss. Carbonation shrinkage is a function of relative humidity and is greatest around 50 percent relative humidity. Carbonation shrinkage, although not very significant itself, can add to the effect of drying shrinkage and thereby lead to cracking.

1.3 FREE SHRINKAGE: MEANING AND SIGNIFICANCE

If allowed to shrink freely, concrete will usually not crack. Concrete in the bridge decks, however, is not allowed to shrink freely, due to various bridge components, such as reinforcing bars, fixed supports, and girders, that tend to restrain volume change in the deck and eventually lead to cracking. In some cases, differential movement can occur between the top and the bottom of the deck due to temperature or drying conditions.

"Free shrinkage" is the term associated with the method of test used to evaluate the shrinkage of concrete. In this method, unrestrained concrete specimens are allowed to shrink in a controlled environment. The shrinkage strain, normally the longitudinal strain, is measured at regular intervals. To evaluate the cracking tendency of concrete, another test method, in which shrinkage is restrained, is employed. The most common restrained shrinkage test involves a concrete ring that is cast on the outside of a restraining steel ring. The stresses due to shrinkage and the age of specimen when the first crack appears are monitored. In a number of studies, free and restrained shrinkage tests are performed simultaneously.

The free shrinkage test does not, by itself, evaluate the cracking tendency of concrete. There is, however, a correlation between free shrinkage and the cracking tendency of concrete. Mokarem, Weyers, and Lane (2004) reported that the potential for cracking could be minimized by limiting the unrestrained shrinkage of concrete. They stated that, length change should be limited to 0.0400 percent (400 $\mu\varepsilon$) at 28 days and 0.0500 percent (500 $\mu\varepsilon$) at 90 days to reduce the probability of cracking due to drying shrinkage. Thus, although the free shrinkage test does not directly evaluate cracking tendency, it has the potential to be used in a performance-based specification for restrained concrete systems like bridge decks.

1.4 FREE SHRINKAGE TEST

There are different ways in which the free shrinkage of concrete can be measured, and several test configurations, with different types of specimens, have been employed to evaluate the unrestrained shrinkage of concrete. Mang et al. (2005) compared four different methods to evaluate free shrinkage, including the standard test (ASTM C 157) for shrinkage measurement, a test using an embedded strain gage, a test using a Whittemore gage for the same type of specimen used with the embedded strain gage, and a test using a Whittemore gage on cylindrical specimens. The standard test followed ASTM C 157, except instead of a mechanical dial gage length comparator, the test used LVDTs (Linear Variable Differential Transformers) to measure length change. The second method used a dog-bone shaped specimen with an overall length of 694 mm (27.30 in.). The change in length was recorded over a length of 120 mm (4.68 in.) using an electrical strain gage embedded in the specimen. The third method used specimens similar to those used in the second method and a Whittemore gage to measure the change in length over a gage length of 254 mm (10 in.). The last method used 152 × 304 mm (6 × 12 in.) cylindrical specimens and a Whittemore gage to measure the change in length. Upon comparison of the standard deviation of the different test methods, the study concluded that strain measurements using the embedded strain gage had the best repeatability with the lowest standard deviation of 16.2 $\mu\varepsilon$, followed by the ASTM C 157 method using LVDT, which had a standard deviation of 25.7 $\mu\varepsilon$.

This study will employ ASTM C 157, “Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete” to measure free shrinkage of concrete. This method uses rectangular concrete prisms with gage studs at each end. A mechanical dial gage length comparator is used to measure length change over time.

1.5 PREVIOUS WORK

Several studies have evaluated the shrinkage and cracking behavior of concrete, using restrained and free shrinkage tests. Many of the conclusions from these studies are, however, contradictory, demanding more work in this area.

A number of factors affect the drying shrinkage of concrete, including the materials, construction procedures, and environmental conditions. This study will focus on the effects of concrete materials and curing period on the drying shrinkage. Tests related to cracking tendency of concrete from previous work will also be reviewed.

Effect of water-cementitious material ratio and paste content:

Shrinkage is normally controlled by the cement paste (cementitious materials and water) constituent of concrete. The cement content and water content of a concrete mix, along with the water-cementitious material (*w/cm*) ratio have a great influence on shrinkage of concrete. Hindy et al. (1994) conducted a study of the drying shrinkage of high performance concrete (HPC). They considered the effects of the *w/cm* ratio, curing time, and silica fume content on concrete shrinkage. Laboratory tests on small specimens and field tests on HPC columns were performed. Concretes were made with low *w/cm* ratios, 0.22 and 0.28. The lower *w/cm* ratio was achieved by reducing the water content (from 220 lb/yd^3 to 200 lb/yd^3) and increasing the cementitious material content including silica fume (from 800 lb/yd^3 to 940 lb/yd^3), thereby increasing the volume of paste from 28.1 percent to 29.7 percent. A blended cement containing 7 to 8 percent of silica fume was used in the lower *w/cm* ratio mixture, whereas the cement used in the other concrete mix contained no silica fume. A naphthalene-based superplasticizer was used to obtain a slump of 200 mm (8 in.). Laboratory tests conformed to ASTM C 157. Shrinkage measurements of actual columns in the field were taken using IRAD® vibrating wire extensometers. Laboratory specimens included 100 × 375 mm (3.9 × 14.8 in.) cylinders and 100 × 100 × 375 mm (3.9 × 3.9 × 14.8 in.) prisms. The curing conditions included storage in lime-saturated water at 20° C (68° F), and storage in the air at a relative humidity (RH) of 50 percent and an ambient temperature of 20° C (68° F). Some of the specimens stored in air were sealed with plastic sheet and aluminum foil to prevent moisture loss. The duration of curing varied from four days to one year. Two prisms and two cylinders from each mix were placed in lime saturated water for one year, two prisms and two cylinders were kept in air for one year, and two prisms and two cylinders were sealed for one year. Two cylinders each were sealed for four, seven, and 28 days, and then air cured for the rest of the year. Compressive strength and modulus of elasticity were also tested. The results indicated a reduction in shrinkage of concrete with lower *w/cm* ratio. The shrinkage of the concrete with the lower *w/cm* ratio was lower than the concrete with higher *w/cm* ratio under each of the different curing conditions. Hindy et al. attributed the reduction in shrinkage to both the reduced *w/cm* ratio and the silica fume. According to the authors, an increase in the *w/cm* ratio increases the total drying shrinkage and the rate of shrinkage of the cement paste by providing more space for free water diffusion and reducing the rigidity of the solid matrix to resist deformation. Silica fume densifies the hydrated cementitious paste, thereby slowing down the rate of water evaporation and, hence, drying shrinkage. In the study, the curing conditions significantly affected shrinkage. The air-cured specimens experienced the highest shrinkage, followed by the sealed specimens. The specimens that were cured in water for one year experienced slight swelling. The concrete with the low *w/cm* ratio was less susceptible to expansion. The specimens that were sealed for some time and then air cured showed that the prolonged sealed curing helped to reduce the shrinkage significantly. It was also observed that the reduction in shrinkage was more pronounced for specimens that were sealed longer as the *w/cm* ratio increased.

Not all researchers have obtained the same results as Hindy et al. (1994) in regard to the effect of the *w/c* ratio on shrinkage. Bissonnette, Pierre, and Pigeon (1999) found that the influence of *w/c* ratio on the shrinkage of cementitious materials was relatively small. An average reduction in shrinkage for 0.35 *w/c* ratio (over 0.5 *w/c* ratio) pastes, mortars, and concretes was 7 to 10 percent. Bissonnette et al. used smaller prismatic specimens than Hindy et al. (1994), 4 × 8 × 32 mm (0.16 × 0.32 ×

1.28 in.) for pastes and mortars, and 50 × 50 × 400 mm (1.97 × 1.97 × 15.75 in.) for concrete. The purpose of using smaller specimens was to obtain approximately gradient-free shrinkage. ASTM Type I cement was used along with a granitic sand and crushed limestone with a maximum nominal size of 10 mm (0.39 in.). For mortar, two different sand to binder ratios, 1 and 2, were used with each *w/c* ratio (0.35 and 0.5). For concrete, the two different *w/c* ratios were used with two paste volume fractions each, 0.30 and 0.35. The specimens were cured in lime-saturated water for the first 28 days, and thereafter, in a room with a relative humidity (RH) of 48 percent at 23° C (73° F). Overall, while the influence of *w/c* ratio on shrinkage, for a given paste content, was observed to be in the 7 to 10 percent range. The effect of paste volume on shrinkage was significant, with drying shrinkage directly proportional to the paste volume content.

The effects of *w/c* ratio, silica fume and superplasticizer content on free and restrained shrinkage of normal and high-strength concretes were studied by Bloom and Bentur (1995). Concrete mixtures containing ASTM Type I cement, crushed dolomite, and siliceous sand were used to cast 40 × 40 × 1000 mm (1.57 × 1.57 × 39.37 in.) long bar specimens. The same specimens were used for free and restrained shrinkage tests. A total of five mixes were cast, one mix with *w/cm* ratio of 0.5, three mixes with *w/cm* ratio of 0.4, and two mixes with *w/cm* ratio of 0.33. Two of the 0.4 *w/cm* mixes and one of the 0.33 *w/cm* mix used 15 percent silica fume by mass of cement. The paste content of 0.5 *w/cm* mix was 38.4 percent, while the paste contents of 0.4 and 0.33 *w/cm* mixes (without silica fume) were 35.8 percent and 33.0 percent, respectively. Because silica fume was used as an admixture (not a cement replacement), mixes using silica fume had paste contents of 39.3 percent (for 0.4 *w/cm*) and 37.1 percent (for 0.33 *w/cm*). Concretes were either exposed to hot dry conditions, 40° C (104° F) and 45 percent relative humidity, or sealed to prevent the evaporation. One end of the specimens was fixed, while the movement of the free end was monitored using a dial gage. For restrained shrinkage, the movable end (attached to the specimen) was brought back to original position using a screw assembly, and the load (and calculated stress) developed under the fully restrained condition was monitored. For concretes with *w/cm* ratios of 0.33, 0.4 and 0.5, results indicated no drastic changes in shrinkage for the different mixes. No clear trend of *w/cm* was found, with the 0.5 *w/cm* concrete showing highest shrinkage, the 0.4 *w/cm* concrete the lowest, and the 0.33 *w/cm* concrete in between. For all specimens, the concretes exposed to the hot dry environment (45 percent relative humidity at 45 °C) exhibited greater shrinkage than the sealed concretes. The shrinkage of concrete containing silica fume was significantly higher than that of concrete without silica fume at a constant *w/cm* ratio of 0.33, the difference being about 300 $\mu\varepsilon$ at 4 days of exposed curing. This could have been the effect of higher paste content of concrete containing silica fume. The two 0.4 *w/cm* mixes using silica fume used exactly identical proportions, except for the superplasticizer content. The concrete with the higher dosage of superplasticizer (3 percent of cement by weight superplasticizer content vs. 1.8 percent) experienced higher shrinkage. For the restrained shrinkage tests, none of the sealed concretes cracked, while all of the low *w/cm* exposed concretes exhibited cracking, regardless of silica fume content. According to the authors, silica fume accelerated the setting rate, and resulted in earlier cracking.

Effect of fineness of cement:

The fineness of the cement also affects the shrinkage of concrete. The rate of hydration of portland cement depends on the surface area of the clinker particles; finer cements develop strength more rapidly. The finer pore structure of finer cements leads to higher early age shrinkage in concrete.

Bennett and Loat (1970) studied the influence of cement fineness on shrinkage and creep of concrete. They used unrestrained and restrained ring tests to evaluate shrinkage and a constant stress pneumatic loading test to evaluate creep. Concretes were made with cement with three different grades of fineness, but similar compositions. Aggregates consisted of pit sand and 19 mm (¾ in.) irregular crushed quartzite. Four different *w/c* ratios in the range of 0.300 to 0.525 and aggregate to cement ratios of 3.0, 4.0 and 5.0 were used for the test mixes. Although the batch weights of different materials were not provided by the authors, it is understood that when the *w/c* ratio was increased for a constant aggregate-cement ratio, the paste content of the mix also increased. Free shrinkage specimens consisted of 483 × 102 × 102 mm (19 × 4 × 4 in.) prisms with mild-steel studs at the ends. Restrained shrinkage tests included 102 mm (4 in.) high ring specimens with a 328 mm (12.9 in.) outside diameter and 76 mm (3 in.) thickness. A 32 mm (1¼ in.) thick steel ring on the inside of concrete ring was used to provide restraint. Silicon semiconductor strain gages were used to measure strains in the steel ring. Creep tests used prismatic specimens of 508 × 102 × 102 mm (20 × 4 × 4 in.). A pneumatic loading system was used to maintain the creep specimens at a constant stress. Tests were run at relative humidities of 55 percent and 100 percent. The results indicated that, for given *w/c* and aggregate-cement ratios, finer cement results in an increase in free shrinkage but that, owing to the higher strength, there is no tendency of rapid shrinkage cracking. Only in a limited number of restrained shrinkage tests did the use of finer cement result in somewhat earlier cracking. They also observed that, based on equal workability, the higher water demand of finer cements resulted in increased shrinkage. Shrinkage versus Vebe time (workability) curves were plotted for mixes with different *w/c* ratios for the coarsest and the finest cements. At a Vebe time of 7 s, the difference in shrinkage was 200 με, which further increased for high workability mixes with high water contents. For a constant aggregate-cement ratio, an increase in *w/c* ratio caused an increase in shrinkage for all the mixes, possibly due to the increased paste contents of the higher *w/c* ratio mixes. In the restrained shrinkage ring tests, concretes made with finer cements tended to crack earlier, though not excessively so, the age at cracking being greater than 40 days, except with the finest cement at the highest *w/c* ratio. The concrete with the finest portland cement developed a high early age (3 to 5 days) shrinkage stress, but was sufficiently strong to withstand it without cracking (cracking occurred at an age of 40 days). The results of the creep tests indicated an increase in creep with the use of finer cements.

Effect of Aggregate:

The volume and type of aggregates in the concrete mix is another factor that affects the shrinkage of concrete. Aggregates restrain the shrinkage of cement paste. Hence an increase in aggregate volume and the commensurate reduction in the volume of cement paste will lead to a reduction in shrinkage. In a progress report on a long-term research program on drying shrinkage of concrete, Carlson (1938) described the effect of type of aggregate on shrinkage. The shrinkage of concretes containing different types of coarse aggregate, including quartzite, limestone, dolomite, granite, and feldspar along with several types of natural sands and gravels, was evaluated. At an age of six months, large differences were observed in the shrinkage of concretes containing different aggregates. The highest shrinkage (870 $\mu\varepsilon$) was observed with the concrete containing crushed mixed gravel and the lowest (450 $\mu\varepsilon$) was observed with the concrete containing quartzite. Some differences resulted from the fact that some aggregates required more mixing water than others to obtain a constant slump of 76 mm (3 in.), but the greater difference was due to the physical properties of aggregate itself. The water cement ratios used for the mixes were very high, varying from 0.62 to 0.87, and the paste content was 27 to 35 percent. After correction for the *w/c* ratio (shrinkage was corrected to a *w/c* ratio of 0.65 using factor of 1.75 percent change in shrinkage for each 1 percent difference in water content, the cement content being constant for all mixes), it was noted that the compressibility of the aggregates was a major factor influencing the shrinkage of concrete. Natural sands and gravel, including sandstone and dolomite pebbles, showed higher shrinkage than crushed aggregates, including granite, limestone, and quartz. Among the crushed aggregates, the shrinkage was higher for concretes containing aggregates with higher absorptions. For example, the concrete made with quartz (specific gravity 2.65 and absorption 0.1 percent) had the lowest shrinkage (450 $\mu\varepsilon$), while concrete made with crushed mixed gravel (specific gravity 2.74 and absorption 1.0 percent) had the highest shrinkage (870 $\mu\varepsilon$). It should be noted that the aggregates were in dry condition prior to mixing, and could possibly have absorbed some mix water, thereby increasing the water demand. Carlson also reported very little effect of maximum aggregate size and aggregate gradation on the shrinkage.

Alexander (1996) reported that elastic modulus, shrinkage, and creep of concrete can vary by as much as 100 percent, depending on the aggregate type. He studied the effects of 23 aggregate types including dolomites, quartz, granites, and siltstones on the properties of hardened concrete. The work consisted of two series of tests: one designed to obtain desired compressive strengths of 20, 30, 40, and 60 MPa (2.9, 4.5, 5.8, and 8.7 ksi) and the other designed to use fixed *w/c* ratios of 0.74, 0.61, 0.51, and 0.41. Free shrinkage tests used 100 × 100 × 200 mm (3.93 × 3.93 × 7.87 in.) prisms with "DEMEC" (demountable mechanical) gages on two opposite faces with a 100 mm (3.93 in.) gage length. The specimens were cured in lime-saturated water for the first 28 days and then stored at a temperature of 23° C (73° F) and 60 percent relative humidity (RH). The results indicated that aggregate influences the shrinkage in two ways: through the mixing water demand and through the stiffness of the aggregate. The mixing water demand also decided the cement and paste content of a given mix for given strength grade. The aggregates with more water demand tended to produce concretes with higher shrinkage. The basis for determining the "mixing water demand," however, was not clear in the study, and the slump for different mixes ranged from 25 to 95 mm (1 to 3.75 in.). The paste content of the mixes ranged from 26 to 30 percent. The influence of different paste contents was "eliminated" by the authors by normalizing the measured shrinkage values to a mean paste volume using Pickett's equation (Picket 1956).

$$\frac{S_{c1}}{S_{c2}} = \left[\frac{V_{p1}}{V_{p2}}\right]^{1.5} \tag{1.2}$$

where S_c is the shrinkage of concrete, and V_p is volume fraction of paste. Subscript 2 was used for a mean paste volume, and individual results were normalized to the mean paste volume. Despite normalization, aggregate type had a marked effect on shrinkage. It was observed that concretes containing aggregate with higher elastic moduli tended to restrain the shrinkage of paste, and produced concretes with lower shrinkage. Concrete made with dolomite (the aggregate with highest elastic modulus) exhibited the lowest shrinkage, whereas the concrete made with siltstone (the aggregate with lowest elastic modulus) showed the highest shrinkage. Most types of quartz and granite imparted values in between.

Effect of Mineral Admixtures:

Different mineral admixtures are often used in concrete to improve compressive strength and other mechanical properties. There are different opinions on the effect of these materials on drying shrinkage and cracking. Theoretically, one might expect an increase in drying shrinkage due to the increased proportion of C-S-H and the finer pore structure (Mindess, Young, and Darwin 2003). The findings of various studies, however, are conflicting.

Three major types of mineral admixtures are popularly used in concrete, fly ash, slag, and silica fume. A study by Khatri and Sirivivatnanon (1995) included all three materials to evaluate their effect on the mechanical properties of concrete. Seven mixes with a constant *w/cm* ratio of 0.35 and a constant cementitious material content of 430 kg/m^3 (725 lb/yd^3) were used with different percentages of mineral admixtures. The mineral admixture mixes contained 1 to 1.5 percent higher paste volume due to the difference in specific gravities. The mixes included a control mix with no mineral admixture, 10 percent silica fume with and without 10 to 25 percent fly ash, and 10 percent silica fume with two different slag cements. One of the slag cements contained 35 percent slag and the other contained 65 percent slag. A superplasticizer was used to achieve a minimum slump of 120 mm (4.7 in.). The actual slump of the mixes was in the range of 120-210 mm (4.7-8.3 in.). Drying shrinkage tests were performed using 75 × 75 × 285 mm (2.95 × 2.95 × 11.22 in.) prisms, and shrinkage was reported as the average of three specimens. The specimens were cured in lime-saturated water for the first seven days and stored thereafter in a controlled environment at 23° C (73° F) and 50 percent relative humidity. The results indicate an increase in early age shrinkage for concrete containing silica fume over the control mix. The long-term shrinkage, however, was less for the concrete using silica fume than the control concrete. Khatri et al. suggested that, although long-term shrinkage is reduced with the use of silica fume, the early age increase in shrinkage may lead to significant cracking because the tensile strength of concrete is low at early ages. The drying shrinkage of all slag mixes were found to be higher than the mixes prepared from ordinary cement. The fly ash mixes also showed higher drying shrinkage than the control concrete. The amount of fly ash, however, did not appear to affect the shrinkage characteristics. The increased shrinkage of mineral admixture mixes could have been partly contributed by the higher paste volume of these mixes.

In another study using fly ash, Atis (2003) reported a decrease in drying shrinkage with the use of fly ash. In this work, drying shrinkage and other properties of concrete containing high volumes of fly ash were tested. Fifty and 70 percent replacements by mass of the ordinary portland cement using low calcium Class F fly ash (ASTM C 618). A total of six mixtures were made, two each with 100 percent portland cement (control mixtures), 70 percent fly ash replacement and 50 percent fly ash replacement. The optimum water content required for maximum compactabilty was determined using the vibrating slump test (Cabrera and Atis 1999). The optimum water content was then used to produce concrete mixtures with zero slump. The mixtures were made workable using a carboxylic type superplasticizer. The actual *w/cm* ratios ranged from 0.28 to 0.34. The optimum water content and actual *w/cm* ratios for the fly ash mixtures were less than those for the control mixes. Due to the differences in specific gravities, however, the paste volume in fly ash mixes was higher (27.3 percent in 50 percent fly ash mix and 26.9 percent in 70 percent fly ash mix as compared to 25.9 percent in the control mix). Changes in length due to drying shrinkage of 50 × 50 × 200 mm (2 × 2 × 8 in.) concrete prisms were measured with a mechanical dial gage. The specimens were demolded one day after casting and stored at 20° C (68° F) and 65 percent relative humidity until the final measurement was taken at an age of six months. Two prisms were cast for each concrete mix, and the average concrete shrinkage was reported. It should be noted that with one day of curing, the reaction of fly ash with calcium hydroxide should be limited. Significantly lower shrinkage was observed for the high volume fly ash concrete than for the control concrete. The reduction was greater with the 70 percent fly ash replacement than with the 50 percent replacement. The shrinkage at an age of six months was lowest (294 με) with 70 percent fly ash concrete, medium (263 με) for the 50 percent fly ash concrete, and highest (385 με) for the concrete made with ordinary portland cement. It was also observed that the concrete made with superplasticizers showed about 50 percent higher shrinkage than the concrete made without superplasticizers. For the control concrete and the concrete containing 70 percent fly ash, the mixes with the higher *w/cm* ratio (0.34 versus 0.32 in the control concrete and 0.33 versus 0.30 in the concrete containing 70 percent fly ash) also contained the superplasticizer. The author attributed the higher shrinkage of higher *w/cm* concrete (554 με versus 385 με in the control concrete and 413 με versus 294 με in the concrete containing 70 percent fly ash) to the superplasticizer, rather than the *w/cm* ratio. For the concrete containing 50 percent fly ash, higher shrinkage (394 με versus 263 με) was recorded with the superplasticized concrete, although it had the lower *w/cm* ratio (0.28 versus

0.29) than non-superplasticized concrete containing 50 percent fly ash. The compressive strengths of the mixtures containing 70 percent fly ash were lower than the compressive strengths of the corresponding control mixtures at all ages. The compressive strengths of mixtures containing 50 percent fly ash, however, were comparable or higher than the strengths of the corresponding control mixtures at 7 days of age and beyond. At 28 days, the compressive strength of control concrete was 65 MPa (9430 psi), that of the concrete containing 50 percent fly ash was 67 MPa (9720 psi), while that of the concrete containing 70 percent fly ash was only 31 MPa (4500 psi). The author claimed that the low shrinkage properties and high strength of the high volume (up to 50 percent) fly ash concrete make this type of material a possible alternative to the ordinary portland cement concrete used on concrete pavements and bridge decks, where shrinkage cracking is a critical consideration.

A significant increase in shrinkage with silica fume replacement was observed in a study by Rao (1998). The work included drying shrinkage tests on mortar 25 × 25 × 250 mm (0.98 × 0.98 × 9.84 in.) prisms. The silica fume was used at replacement rates for cement ranging from 0 to 30 percent by weight. A constant *w/cm* ratio of 0.5 was used for mortars, with a cementitious material to sand ratio of 1:3 by mass. Because the specific gravity of silica fume is lower than that of cement, a constant *w/cm* ratio and cementitious material to sand ratio led to increased paste volumes in silica fume mortars. Drying shrinkage at 28 days was considered. The results indicated a significant increase in shrinkage with the use of silica fume, which further increased with the quatity of silica fume. The author concluded that the addition of silica fume increases the content of calcium silicate hydrate, which is the most important factor causing shrinkage at an age of 28 days. The increased paste volume of silica fume mortars, which could have been one of the factors contributing to the increased shrinkage of these mortars, was not considered by the author.

Whiting, Detwiler, and Lagergren (2000) studied the effects of silica fume on drying shrinkage and the cracking tendency of concrete bridge decks. Concrete mixes were developed for use in full depth and overlay placements. The overlay mixes used higher cementitious material contents and air contents and lower *w/cm* ratios than the full-depth mixes. The *w/cm* ratios ranged from 0.35 to 0.45 for full-depth mixes and from 0.30 to 0.35 for overlay mixes. The silica fume content ranged from 0 to 12 percent of the total weight of cementitious materials. For a given *w/cm* ratio, the paste volume in a mix was approximately same (within 0.3 percent) for mixtures with and without silica fume. Both unrestrained shrinkage and ring tests were performed to evaluate the cracking tendency of concrete. Unrestrained drying shrinkage tests followed AASHTO T 160 (ASTM C 157). Three prismatic 75 × 75 × 285 mm (3 × 3 × 11.25 in.) unrestrained shrinkage specimens were prepared for each mix. Overlay specimens were cured in lime-saturated water for three days and full depth specimens for seven days, after which both types of specimen were stored at 23°C (73°F) and 50 percent relative humidity. The restrained specimen was a 75 mm (3 in.) thick, and 150 mm (6 in.) high concrete ring around the outside of a 19 mm (0.75 in.) thick steel cylinder with an outside diameter of 300 mm (11.75 in.). The ring specimens were cured for one and seven days, representing the worst case scenario and good practice, respectively. Four strain gages placed on the steel ring recorded the strains once every 30 minutes using a data acquisition system. Crack formation was identified by a local decrease in the strain recorded by a strain gage. In the study, the overlay concretes exhibited more shrinkage than the full depth concretes because of their higher paste content and lower period of moist curing. For a given percentage of silica fume replacement, shrinkage was low for the mixes with low *w/cm* ratios. It should be noted, however, that the higher *w/cm* ratio mixes contained a higher paste volume for a given silica fume replacement. For example, for 1.8 percent replacement mixes, paste volume was 25.2 percent in 0.36 *w/cm* mix, while that in 0.43 *w/cm* mix was 27.5 percent. For the silica fume concretes, there was a little effect of silica fume content on the ultimate shrinkage (450 days) of concrete. At 4 days of drying, however, the shrinkage was higher for the concretes made with silica fume. Also, shrinkage increased with increased silica fume content at this age. Whiting et al. observed that concretes containing silica fume are more sensitive to the changes in *w/cm* ratio. A small change in w/cm ratio in a concrete containing silica fume can lead to significantly higher shrinkage. The cracking tendency of concrete was affected by silica fume only when concrete was not properly cured. For the specimens cured for one day, the silica fume concretes cracked sooner than the control specimens (also cured for one day) with same *w/cm* ratio. Statistical studies to obtain more definitive conclusions indicated that, for concretes cured for one day, increasing the silica fume content from zero to six percent and zero to nine percent was the only significant factor affecting cracking. The use of silica fume significantly decreased the time to first crack for mixes cured for one day. Increasing silica fume content from 6 to 9 percent, however, did not decrease the time to first crack. The authors concluded that, to achieve optimum results, the amount of silica fume used should be limited. Unless demanded by the situation, silica fume above a range of 6 to 8 percent should not be used. The authors, however, gave no clear justification for this conclusion.

ACI Committee 232 on use of fly ash in concrete reports that where the addition of fly ash increases the paste volume in a concrete mix, shrinkage may be increased slightly if the water content remains constant. If the water content is reduced, shrinkage should be about the same as concrete without fly ash. ACI Committee 233 on use of slag cement in concrete and mortars offers a similar opinion on the effect of slag on shrinkage, that is, shrinkage can be reduced when the lower paste contents are used with slag mixes The committee found that published data on the effects of slag on shrinkage indicate conflicting results, and overall, drying shrinkage is similar in portland cement concrete and concrete containing slag. ACI Committee 234 on use of silica fume in concrete reports that the drying shrinkage of concrete containing silica fume is generally comparable to that of the portland cement concrete. The committee reports that slightly higher shrinkage may be expected at early ages for mixtures with *w/cm* ratios of more than 0.60 and for concrete containing higher silica fume contents (more than 10 percent by mass of cement).

Effect of superplasticizers:

Chemical admixtures, such as superplasticizers, water reducers, air-entraining agents, and shrinkage reducing admixtures, are often used with concrete. The effect of superplasticizers on the shrinkage of concrete is of main concern because superplasticizers help to reduce the water content of concrete, which is one of the important factors affecting shrinkage. There are different ways in which mixes are proportioned when studying the effect of superplasticizers on shrinkage of concrete. Some studies design the mixes for same *w/c* ratio, but reduce the cement content (and in turn the paste content) and others design for a reduced *w/c* ratio. Phelan and Martin (1995) offered different opinions regarding the effect of superplasticizers on shrinkage. Phelan argued that a good superplasticizer can reduce the water content of concrete by 10 to 18 percent and that this reduction in water will lead to reduced shrinkage. He also contended that it is impossible to increase the shrinkage of any mix by reducing the water content of the mix and replacing its volume with aggregate. In same article, however, the other author, Martin contended that the use of many chemical admixtures will indeed reduce the mix-water content, but will not reduce the shrinkage. ACI 224R (2001) also supports this opinion. Past studies have led to conflicting opinions about the effects of superplasticizers on shrinkage.

Qi, Li, and Ma (2002) reported a reduction in free shrinkage with use of a high superplasticizer content. Ring specimens were used for both free and restrained shrinkage tests in the study. Type I portland cement was used along with a *w/cm* ratio of 0.4 and superplasticizer contents of 1.38 and 2.76 percent by weight of cementitious materials. For all of the mixtures, the mix proportion by weight of cement: sand: coarse aggregate was 1:1.84:2.67. Therefore, water content and paste content of all mixes remained constant. The ring specimen was a 35 mm (1.38 in.) thick, 140 mm (5.11 in.) high concrete ring with a 375 mm (14.76 in.) outer diameter cast around a 51 mm (2.0 in.) thick steel ring. For the free shrinkage specimen, this ring was cut into four pieces and removed during demolding. Both specimen types were cured for 4 days at 100 percent relative humidity and exposed to drying conditions of 40 percent relative humidity at 20°C (68°F) thereafter. Free shrinkage was measured using a dial-gage extensometer and DEMEC (demountable mechanical) studs fixed on the top surface of the specimen along the circumferential direction. For the restrained shrinkage specimens, the onset time of a new crack was recorded and the crack width was measured using a 30 magnification microscope. The results of these tests indicated that the shrinkage of the concrete with higher superplasticizer content (2.37 percent by weight of cement) was lower than the shrinkage of the concrete with the lower superplasticizer content (1.39 percent by weight of cement). Moreover, the major advantage of the higher dosage was a significant delay in occurrence of the first visible crack in restrained shrinkage specimens, when compared to the lower dosage. The test results showed that the higher superplasticizer content was effective in inhibiting crack opening and propagation. The authors explained these results with a theory that the action of high-range water reducers mainly derives from a better particle dispersion as admixture is adsorbed on the cement particles, and as a result, a reduction in the surface tension of water leads to lower capillary pressure. The reduced pressure can decrease the free shrinkage and shrinkage cracking width. As will be seen next, however, most other researchers have found that the use of superplasticizers in concrete leads to increased shrinkage.

Johnston, Gamble, and Malhotra (1979) studied the effects of superplasticizers on the properties of fresh and hardened concrete. The effects on shrinkage and creep were considered along with several other properties. Superplasticizers were used to reduce the cement content while maintaining the *w/c* ratio (0.5) and workability constant. Four commercially available superplasticizers were used. Three mixes were prepared for each type of superplasticizer: a mix containing no superplasticizer with 100 mm (4 in.) slump, a zero slump mix with no superplasticizer, and a 100 mm (4 in.) slump mix with a superplasticizer. The paste content of the first mix was 32.1 percent while that of the latter mixes was 23.7 percent. Shrinkage was measured using 100 × 300 mm (4 × 12 in.) cylinders with the help of DEMEC (demountable mechanical) extensometers. The specimens were moist cured for 56 days and dried at 20ºC (68ºF) and 50 percent relative humidity thereafter. The zero slump mix without a superplasticizer (with paste content of 23.7 percent) exhibited less shrinkage than the 100 mm (4 in.) slump mix without superplasticizer. The difference was 10 $\mu\varepsilon$ at 7 days and 95 $\mu\varepsilon$ at 365 days. All mixtures containing superplasticizers, except the mixture containing high-molecular-weight sulfoaryl alkylene, exhibited higher shrinkage than the mixes containing no superplasticizers. Melamine formaldehyde condensate (admixture I) and high-molecular-weight sulfoaryl alkylene (admixture II) had little effect on shrinkage. But sulfonated polymer (admixture III) and polymerized naphthalene condensate (admixture IV) increased the shrinkage. At seven days of drying, the difference between the mix containing admixture III and the mixes without superplasticizer was 35 $\mu\varepsilon$ and 45 $\mu\varepsilon$ for the 100 mm (4 in.) slump mix and the zero slump mix, respectively. At the same age, the difference between the mix containing admixture IV and the mixes without superplasticizer was 50 $\mu\varepsilon$ and 60 $\mu\varepsilon$ for the 100 mm (4 in.) slump mix and the zero slump mix, respectively. Similar results were obtained with the creep tests, admixtures I and II induced little change in total creep while admixtures III and IV increased total creep. It should be noted that the results could have been significantly affected by the difference in paste contents of the mixes, which is not considered by authors.

Brooks (1989) suggested that if measured shrinkage values are not available from specific tests for concrete containing superplasticizers, estimated long-term deformations should be increased by 20 percent. Brooks ran an analysis of the available data to develop an approximate method to estimate the shrinkage of concrete containing superplasticizers. The analysis concluded that the use of superplasticizers increases the creep and shrinkage of concrete by 3 to 132 percent. Due to limited data, no definite conclusion could be made regarding the effect of superplasticizer type on shrinkage.

ACI Committee 212 reports that superplasticizers may increase concrete drying shrinkage at a given *w/cm* ratio and cement content. If there is any simultaneous reduction in cement content and *w/cm* ratio, when the superplasticizer is used, less shrinkage may be expected than the concrete made with no superplasticizer.

Effect of curing:

One of the factors often discussed while studying the shrinkage and cracking of concrete is the curing period. The effects of curing conditions on concrete shrinkage were studied by Alsayed and Amjad (1994). Reinforced concrete slabs on grade were exposed to a hot, dry climate, and the effects of intermittent wet and dry curing were considered. During the first seven days, four methods were used to cure four different groups of specimens. Group A was sprinkled with water twice a day; Group B was covered with burlap and sprinkled with water twice a day; Group C was covered with impervious polyethylene sheet; and Group D exposed to air with no curing. In Groups A and B, no efforts were made to keep the concrete surface continuously wet. The specimens were left on the ground uncovered, and with no curing for the rest of 360 days. During the curing period, the slab specimens were stored on ground and no protection against moisture loss was provided to the sides. The specimens were provided with DEMEC gage points in both directions to measure shrinkage. Maximum shrinkage of the specimens during the test period of 360 days was 330, 343, 420, and 456 $\mu\varepsilon$ for Group A, B, C and D, respectively. The study concluded that intermittent wet curing reduces the ultimate shrinkage of concrete, and also increases the exposure time needed to develop it, but none of the methods used in the study effectively reduced the rate of shrinkage at early stages (up to 30 days) of curing. For all the curing methods used, the shrinkage rate was about 5 με per day during the first 30 days.

The effect of curing conditions on the shrinkage of normal and lightweight concrete containing pozzolanic admixtures was investigated by Nassif, Suksawang, and Mohammed (2003). Water-cementitious material ratios of 0.29 and 0.35 were used with varying percentages of silica fume, slag, and fly ash. All of the mixes contained silica fume; fly ash and slag were added to some of the mixes. 76 × 76 × 279 mm (3 × 3 × 11 in.) prisms with vibrating-wire strain gages embedded in center were used for shrinkage measurement. Stainless steel studs were also embedded on each end to measure free drying shrinkage using a length comparator. Three different curing methods, air curing, air curing after coating with a curing compound, and moist curing with wet burlap were used. The air-cured specimens were stored in a controlled environment of 25°C (77°F) and 50 percent relative humidity after demolding. In method 2, the specimens were coated with the curing compound using a brush. The moist cured specimens were wrapped with wet burlap after demolding until 28 days. The shrinkage of the air cured concrete was highest, followed by the specimens coated with the curing compound, and then the burlap-wrapped specimens. Nassif et al. concluded that effective curing reduces autogenous and drying shrinkage of concrete. To prevent autogenous shrinkage, concrete needs to be covered with wet burlap immediately after finishing, since autogenous shrinkage mainly occurs in the first 7 hours.

Powers (1959) contended that moist curing conditions are not important for controlling volume changes. Cement paste is partly restrained by unhydrated cement, and since prolonging the curing period reduces the amount of unhydrated cement, it should increase the amount of shrinkage in cement paste. The overall shrinkage of concrete, however, might be diminished by the prolonged moist curing. The reason behind this is that prolonged curing makes paste more prone to internal cracks when severely restrained, and if cracking relieves the stress around aggregate particles, the overall shrinkage might be reduced with a longer curing period. He claimed that, in general, the length of moist curing is a relatively unimportant factor in the control of shrinkage.

Darwin, Browning, and Lindquist (2004) used field observations to assess the factors that affect cracking in bridge decks. Crack surveys of steel girder bridges in Kansas were preformed over a period of 10 years by Schmitt and Darwin (1995, 1999), Miller and Darwin (2000) and Darwin, Browning, and Lindquist (2004). Crack densities on the reinforced concrete bridge decks were calculated based on crack maps prepared according to standard procedures developed by the researchers. Parameters, such as age, bridge deck type, material effects, girder end conditions, and date of construction, were found to affect cracking. It was observed that cracking in bridge decks increases over time, but most of the cracking occurs at an early age. Crack density for monolithic bridge decks was found to be lowest compared to that observed for decks with conventional high-density overlays and decks with silica fume overlays. Improved construction procedures, however, such as efforts to limit the evaporation prior to the initiation of wet curing, led to decreased cracking in more recently constructed silica fume overlay bridge decks. While considering the effects of materials, it was observed that decreases in the water content, cement content, and paste volume of concrete led to decreased cracking. This observation reconfirmed the well understood fact that the paste constituent of concrete controls shrinkage.

1.6 SUMMARY OF PREVIOUS WORK

Researchers have used different methods to investigate the shrinkage and cracking tendencies of concrete. The conclusions of these studies are contradictory in a number of cases.

It is generally agreed that an increase in the paste volume of concrete leads to an increase in drying shrinkage. Some of the studies have observed increased shrinkage with a higher *w/c* ratio, while others have found little or no clear effect of *w/c* ratio on shrinkage. Increases in water content, cement content, and paste volume leads to an increase in shrinkage and cracking. Aggregates affect shrinkage as a function of their stiffness, with stiffer aggregates providing more restraint to the shrinkage of the paste. Some aggregate types may have a higher water demand and, thereby, increase shrinkage. Use of aggregates with higher absorption values may lead to increased shrinkage, unless the aggregates are completely saturated. An increase in aggregate content of a mix will result in a decrease in shrinkage, but the gradation of aggregate does not influence shrinkage. Concretes containing fine cements tend to shrink more than those containing coarser cements. Other considerations, however, such as increased permeability and reduced compressive strength, should be given a due regard when using coarse cements. Most conflicting opinions deal with the effect of mineral admixtures on shrinkage. Most studies concluded that the use of mineral admixtures will increase shrinkage in concrete, while a few have found lower drying shrinkage with concrete containing mineral admixtures. Some of the studies concluded that concrete containing mineral admixtures will have an increased cracking tendency only if not properly cured. The use of mineral admixtures was found to increase the early age shrinkage in most cases, increasing the possibility of early age cracking. Some studies reported increased shrinkage with the use of superplasticizers. In general, however, because superplasticizers allow a reduction in the water content of concrete, their use is believed by some to result in a reduction in shrinkage. Many experts including ACI Committee 224, believe that a reduction in water content achieved by use of superplasticizer will not reduce shrinkage. Moist curing is usually required for control of early age shrinkage and cracking. Although some concrete experts claim that prolonged curing will have little effect on shrinkage, most studies have found a reduction in shrinkage with the use of an increased curing period.

1.7 OBJECTIVE AND SCOPE

The objective of this study is to assess the effects of different parameters, including paste volume, *w/c* ratio, aggregate type, cement type, curing period, and use of mineral admixtures and superplasticizers on the shrinkage of concrete for use in bridge decks. Free shrinkage tests are used to evaluate the shrinkage behavior of different concrete mixes subjected to standard drying conditions. Aggregate optimization is used for the concrete mixtures.

A series of concrete mixes is tested in total of five test programs. Program I consists of 18 mixes with three *w/c* ratios (0.40, 0.45, and 0.50), three aggregate contents (60, 70, and 80 percent), and two cement types (Type I/II and Type II coarse-ground). Program II consists of 11 mixes using three types of coarse aggregate, quartzite, limestone, and granite. A total of eight non-air-entrained and three air-entrained mixes are tested in this program. Program III contains 11 non-air-entrained concrete mixes with cement replacement by three types of mineral admixture, Class C fly ash, slag, and silica fume. In Program IV, a total of four mixes are made in two groups, non-air-entrained and air-entrained. Each group consists of two mixes, one with Type I/II cement and the other with Type II coarse ground cement. These mixes are used to evaluate the effect of differences in curing period (3, 7, 14 and 28 days). The effect of superplasticizer type, (carboxylated polyether and napthalene) is evaluated in Program V. Each set contains a control mix with no superplasticizer. In two sets, dosage levels are determined to obtain a slump of 76 mm (3 in.). In one of these sets, the control mix uses no superplasticizer and is not required to achieve the specified slump, while in the other set, the control mix uses an increased paste content to obtain the specified slump. In other sets, low, medium, and high dosage levels of the superplasticizers, based on the manufacturer's recommended dosage range, are used. This program contains a total of 32 mixes.

Three free shrinkage specimens are cast and tested for each mix. All specimens are cured in lime-saturated water for 3 days after casting, except for the specimens in Program IV, which are cured for 3, 7, 14, or 28 days. Shrinkage measurements are taken once every day for the first 30 days after casting. The interval of measurement is then increased to once every other day to an age of 90 days, once every week to an age of 180 days, and once every month, thereafter, until the final reading is taken at an age of 365 days.

CHAPTER 2: EXPERIMENTAL PROGRAM

2.1 GENERAL

The experimental work performed in the study, including the materials, equipment, and procedures, is described in this chapter. Performance in free shrinkage tests is measured as a function of water-cementitious material (*w/cm*) ratio, aggregate content, aggregate type, mineral admixture replacement of cement, use of superplasticizers, cement type, and duration of curing. All mixtures, except those used to evaluate the effects of aggregate type, contained limestone coarse aggregate, Kansas River sand, and pea gravel. Specimens were cured in lime-saturated water. All specimens, except those used to evaluate the effect of curing time on shrinkage, were cured for 3 days before drying started in a controlled environment. The study includes a total of five test programs, which are listed in Tables 2.1 through 2.5. Program I addresses the effects of water-cement (*w/c*) ratio, aggregate content, and cement type on concrete shrinkage. Program II addresses the effects of three types of coarse aggregates on shrinkage. The effects of three mineral admixtures (slag, silica fume, and Class C fly ash) on shrinkage are evaluated in Program III. The shrinkage behavior of concrete with different curing periods is studied in Program IV. Program V addresses the effects of superplasticizer type and dosage rate on shrinkage. Aggregate gradations and the mix proportions are given in Tables 2.6 through 2.17.

2.2 FREE SHRINKAGE TEST

The procedure specified in ASTM C 157 was used for casting and testing the free shrinkage specimens. Cold-rolled steel molds (Figure 2.1) from the Humboldt Manufacturing Company were used to cast the specimens. To facilitate the measurement of length change, gage studs that were knurled at one end and threaded at the other were embedded in both ends of the specimens. The specimens measured 76 × 76 × 286 mm (3 × 3 × 11¼ in.) and the gage length between the gage studs was 254 mm (10 in.). The specimens are shown in Figure 2.2. The specimens were stored in a controlled environment and measurements were taken up to 365 days. The storage conditions and frequency of measurement will be described in Sections 2.14 and 2.15, respectively. A mechanical dial gage length comparator (Figure 2.3) from the Humboldt Manufacturing Company with a least count of 0.0001 in. (0.00254 mm) and a total range of 0.4 in. (10 mm) was used to monitor the change in length of the specimens.

2.3 MATERIALS

The materials used in this study include two types of portland cement, Type I/II and Type II coarse-ground, two types of limestone, three types of quartzite, and one type of granite as coarse aggregates, and sand and pea gravel as fine aggregates. Mineral admixtures included Class C fly ash, ground granulated blast furnace slag, and silica fume. Chemical admixtures included three types of superplasticizer and an air-entraining agent.

2.3.1 CEMENT

The Type I/II cement had a specific gravity of 3.2 and a Blaine fineness of 378 m^2/kg. It was produced by Lafarge North America in Sugar Creek, MO and had a Bogue composition of 55 percent C_3S, 18 percent C_2S, 7 percent C_3A, and 10 percent C_4AF.

The coarse ground Type II cement had a specific gravity of 3.2 and a Blaine fineness of 306 m^2/kg. It was produced by Ash Grove Cement Company in Seattle, WA and had a Bogue composition of 61.5 percent C_3S, 13.44 percent C_2S, 7.69 percent C_3A, and 8.94 percent C_4AF.

2.3.2 FINE AGGREGATES

All programs used optimized aggregate gradations with combinations of sand and pea gravel as fine aggregates.

The pea gravel was KDOT classification UD-1 from Midwest Concrete Materials in Manhattan, KS. The saturated surface dry (SSD) specific gravity was 2.62, and the absorption (dry) was 0.7 percent. As listed in Table 2.6, Gradation 1 was used in all batches in Program I, Batches 85 through 88 in Program III, and Batches 94 and 95 in Program II. Gradation 2 was used in Batches 165 and 166 in Program IV, and Batches 175 through 186 in Program V. Gradation 3 was used in Batches 187 through 189 and Batches 198 through 200 in Program II, Batches 194 through 197 in Program III, Batches 201 and 207 in Program IV, and Batches 190 through 193, and Batches 208 through 211 in Program V. Gradation 4 was used in

Batches 249, 256, 259, and 260 in Program V. Gradation 5 was used in Batches 262 though 264 in Program II.

The Kansas River sand was from Victory Sand and Gravel Company in Topeka, KS. It had a saturated surface dry (SSD) specific gravity of 2.63 and 0.35 percent absorption (dry). A total of 6 gradations were used, as listed in Table 2.7. Gradation 1 was used in all batches in Program I, Batches 85 through 88 in Program III, and Batches 94 and 95 in Program II. Gradation 2 was used in Batches 167 through 174 in Program V, and Batches 165 and 166 in Program IV. Gradation 3 was used in Batches 175 through 186 in Program V. Gradation 4 was used in Batches 187 through 189, and Batches 198 through 200 in Program II, Batches 194 through 197 in Program III, Batches 201 and 207 in Program IV, and Batches 190 through 193 and Batches 208 through 211 in Program V. Gradation 5 was used in Batches 249, 256, 259, and 260 in Program V. Gradation 6 was used in Batches 262 though 264 in Program II.

2.3.3 COARSE AGGREGATES

The coarse aggregates include 19 mm (¾ in.) granite, 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, 25 mm (1 in.) quartzite, quartzite chip, and 19 mm (¾ in.) quartzite.

Granite:

The 19 mm (¾ in.) granite was obtained from Granite Mountain Quarries in Little Rock, AR. The SSD specific gravity was 2.61 and the absorption (dry) was

0.56 percent. Granite was only used in Program II. The gradations are given in Table 2.8. Gradation 1 was used in Batches 189 and 200 and Gradation 2 was used in Batch 264 in Program II.

Limestone:

The 25 mm (1 in.) limestone was a Class I limestone from the Martin Marietta Quarry in De Soto, KS. It had a SSD specific gravity of 2.57 and 2.92 percent absorption (dry). The gradations are given in Table 2.9. Gradation 1 was used in all batches in Program I, Batches 85 through 88 in Program III, and Batch 94 in Program II.

The 19 mm (¾ in.) limestone was KDOT approved Class I limestone from the Hunts Midwest Mining Sunflower Quarry in De Soto, KS. It had a SSD specific gravity of 2.58 and 3.0 percent absorption (dry). The gradations are given in Table 2.10. Gradation 1 was used in all batches in Program I, Batches 85 through 88 in Program III, and Batch 95 in Program II. Gradation 2 was used in Batches 165 and 166 in Program IV and Batches 167 through 174 in Program V. Gradation 3 was used in Batches 175 through 186 in Program V. Gradation 4 was used in Batches 188 and 199 in Program II, Batches 194 through 197 and 202 through 204 in Program III, Batch 201 in Program IV, and Batches 190 through 193 in Program V. Gradation 5 was used in Batches 208 through 211 in Program V. Gradation 6 was used in Batches 249, 256, 259, and 260 in Program V, and Batch 263 in Program II.

Quartzite:

Three types of quartzite were used in Program II, all from L. G. Everist Inc. in Dell Rapids, SD. The 25 mm (1 in.) quartzite had an SSD specific gravity of 2.63 and absorption (dry) of 0.44 percent. The quartzite chip had an SSD specific gravity of 2.63 and absorption of 0.49 percent. The 19 mm (¾ in.) quartzite had an SSD specific gravity of 2.64 and absorption (dry) of 0.44 percent. The gradations for quartzite are given in Table 2.11. Quartzite was used as coarse aggregate in Program II. Gradation 1 was used in Batches 187 and 198, Gradation 2 in Batch 262, and Gradations 3 and 4 in Batch 94.

2.3.4 MINERAL ADMIXTURES

Program III used three types of mineral admixture, fly ash, slag, and silica fume. The fly ash was a Class C fly ash and had a specific gravity of 2.83. It was obtained from Ash Grove Resources, LLC in Topeka, KS. The ground granulated blast-furnace slag had a specific gravity of 2.86 and was obtained from Holcim Inc. in Chicago, IL. The silica fume was Force 10,000 D densified microsilica from Grace Construction Products in Cambridge, MA. It had a specific gravity of 2.20. The chemical composition of all three mineral admixtures is given in Table 2.12.

2.3.5 CHEMICAL ADMIXTURES

Three types of superplasticizer were used in Program V to compare the effect of different superplasticizers on shrinkage. Superplasticizers were also used in other programs to obtain the desired workability. An air-entraining agent was used in Program IV and in some batches in Program II and V.

Superplasticizers:

Glenium 3000 NS, a carboxylated polyether based superplasticizer, is produced by BASF Admixtures, Inc. It conforms to the requirements of ASTM C 494 as a Type A and a Type F admixture. The solids content ranges from 27 to 33 percent, and the specific gravity is 1.08. The manufacturer recommends a dosage range of 260 to 780 ml/100 kg (4 to 12 fl oz/cwt) of cementitious material.

Rheobuild 1000, a naphthalene based superplasticizer, is produced by BASF Admixtures, Inc. It conforms to the requirements of ASTM C 494 as a Type A and a Type F admixture. The solids content ranges from 38.5 to 42.5 percent, and the specific gravity is 1.20. The manufacturer recommends a dosage range of 650 to 1600 ml/100 kg (10-25 fl oz/cwt) of cementitious material.

Adva 100, a carboxylated polyether based superplasticizer, is produced by Grace Construction Products. It conforms to the requirements of ASTM C 494 as a Type F admixture. The solids content ranges from 27.5 to 32.5 percent, and the specific gravity is 1.10. The manufacturer recommends a dosage range of 195 to 650 ml/100 kg (3 to 10 fl oz/cwt) of cementitious material.

Air-Entraining Agent:

The air-entraining agent was Micro Air, produced by BASF Admixtures, Inc. It conforms to the requirements of ASTM C 260. The solids content is 13 percent, and the specific gravity is 1.01. The manufacturer recommends a dosage range of 8 to 98 ml/100 kg (0.125 to 1.5 fl oz/cwt) of cementitious material.

2.4 MIX PROPORTIONING

An optimized blend of aggregates was obtained using 3 aggregates (coarse aggregates, pea gravel, and sand) for mix proportioning of all batches in this study. Aggregates were blended using a computer program (McLeod 2005) to obtain an effective gradation that was close to an ideal gradation. An ideal gradation is one in which the weights retained on each sieve are adjusted so that the Coarseness and Workability Factors (Shilstone 1990) equal preselected values. An optimized blend is the combination of aggregates resulting in a gradation that matches closely with the ideal gradation (McLeod 2005). Intermediate size aggregate particles (pea gravel) were used in all batches to reduce the voids in the matrix, thereby reducing the cement paste requirement while maintaining workability. This should help in controlling the shrinkage, as amount of cement paste in a mix is a major factor affecting shrinkage. For mix design, either the aggregate content or the cement content of mix was first selected. The computer program was used to calculate the optimum percentages of each aggregate type. Weights of respective ingredients were then determined based on the volume using the specific gravities of each material.

While designing the mixes to determine the effect of mineral admixtures on shrinkage (Program III), cement was replaced by volume and the water content was held constant. The air content was assumed to be 1.5 percent for all non air-entrained batches to account for the entrapped air in the concrete. For air-entrained concrete, the batch weights were based on the desired air content of 7 percent for air-entrained batches in Program II, 5 percent for Program IV, and 8 percent for the air-entrained batches of Program V. Deviations from these air contents will change the weights of mix ingredients slightly on a cubic meter or cubic yard basis.

2.5 MIXING EQUIPMENT

Most of non-air-entrained batches were hand mixed in mixing trays. Containers with lids were used for batches with superplasticizer that exhibited delayed set to avoid the loss of moisture. The air-entrained concrete batches and some of the superplasticized concrete batches were mixed in a counter current pan mixer. The description of respective programs in subsequent sections includes the volume of batches and types of mixing used. Mixing procedures are described in Section 2.13.

2.6 PROGRAM I (AGGREGATE CONTENT, WATER-CEMENT RATIO, CEMENT TYPE)

The variables included in Program I were aggregate content, water-cement ratio, and cement type (fineness of cement). A total of 18 batches were cast with three specimens in each batch. Batches 62 through 70 were made with Type I/II cement, and Batches 70 through 79 were made with Type II coarse ground cement. Three water cement (*w/c*) ratios, 0.40, 0.45, and 0.50, were used with aggregate contents of 60, 70, and 80 percent by volume of the concrete. No mineral or chemical admixtures were used for this program. All mixes used an optimized aggregate gradation containing 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, pea gravel, and sand. All batches were hand mixed, and the batch volume was 0.008 m^3 (0.01 yd^3). The test matrix for this program is shown in Table 2.1, and mix proportions are given in Table 2.13.

2.7 PROGRAM II (COARSE AGGREGATE TYPES)

The effect of coarse aggregate type on shrinkage was evaluated in Program II. Three types of coarse aggregate were used, including quartzite, granite, and limestone. A total of eight non-air-entrained and three air-entrained batches were made, with three specimens in each batch. The test matrix is given in Table 2.2. The non-air-entrained batches had a volume of 0.008 m^3 and were hand mixed. For air-entrained batches, concrete was machine mixed in 0.016 m^3 (0.02 yd^3) batches. Three specimens were cast for each batch.

Batches 94 and 95 were made with Type I/II cement and a *w/c* ratio of 0.45. The aggregate content was 70 percent. Batch 94 had an optimized gradation containing 25- mm (1 in.) quartzite, quartzite chip, pea gravel, and sand. Batch 95 had an optimized gradation containing 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, pea gravel, and sand. No chemical or mineral admixtures were used for these batches.

Batches 187, 188, and 189 were made with Type I/II cement and a 70 percent aggregate content. The *w/c* ratio was 0.45. No mineral or chemical admixtures were used. Batches 187, 188, and 189 contained 19 mm (1 in.) quartzite, limestone, and granite as coarse aggregates, respectively. The coarse aggregates were blended with pea gravel and sand in each batch to obtain an optimized gradation.

Batches 198, 199, and 200 were replications of batches 187, 188, and 189, respectively. A slight change in quantities of aggregates between batches 188 and 199 was due to small change in gradation of the coarse aggregates.

Batches 262, 263, and 264 were air-entrained with 7.4 percent air. 19 mm (¾ in.) quartzite, limestone, and granite were used as coarse aggregates for batches 262, 263 and 264, respectively. An optimized gradation was obtained using pea gravel and sand. The aggregate content was 68.8 percent by volume for all three batches. Type I/II cement was used with 0.45 *w/c* ratio. These batches used Adva 100 superplasticizer to obtain the desired workability. The air entraining agent was Micro Air.

The mix proportions for the Program II batches are given in Table 2.14.

2.8 PROGRAM III (MINERAL ADMIXTURES)

Three types of mineral admixture, fly ash, ground granulated blast-furnace slag, and silica fume were used in Program III to evaluate their effect on shrinkage. A total of 11 batches were made with three specimens in each batch. All batches were hand mixed, and had a volume of 0.008 m^3 (0.01 yd^3). Type I/II cement was used with a partial replacement of cement by mineral admixtures. The replacement was made by volume to maintain constant water and aggregate contents. Because the mineral admixtures have a lower specific gravity than portland cement, water-cementitious material (*w/cm*) ratio by weight, deviated from the control *w/c* ratio of 0.45. The test matrix for this program is shown in Table 2.3.

Batches 85 through 88 used an optimized blend of 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, pea gravel, and sand with an aggregate content of 70 percent. No chemical admixtures were used in these batches. The control batch (Batch 85) contained no mineral admixture and had a *w/c* ratio of 0.45. In Batch 86, 30 percent of the cement was replaced on a volume basis by slag, giving a *w/cm* ratio based on weight of 0.465. Class C fly ash was used to replace 30 percent cement on a volume basis in Batch 87, giving a *w/cm* ratio of 0.469. Batch 88 used a 10 percent replacement by volume of cement by silica fume, giving a *w/cm* ratio of 0.470.

In Batches 94 through 97, an optimized blend of 19 mm (¾ in.) limestone, pea gravel, and sand with an aggregate content of 70 percent was used. These batches used the same replacements and *w/cm* ratios as Batches 85 through 88. Batch 94 was the control batch, with no mineral admixture, and Batches 96, 97, and 98 used slag, fly ash, and silica fume, respectively. In Batches 96 and 97, the mineral admixtures were added to the dry mixed aggregates along with the cement. In Batch 98, silica fume was premixed with cement before the concrete was mixed. A low dosage of Adva 100 superplasticizer was used in Batch 98 to improve workability.

To investigate the effect on shrinkage of a better distribution of silica fume in the concrete mix than obtained in previous batches, three additional batches (Batches 202 through 204) were made. Batch 202 served as the control batch with no mineral or chemical admixture. Batch 203 was similar to Batch 202, except that it contained a low dosage of Adva 100 superplasticizer. Batch 204 used silica fume to replace 10 percent of the cement by volume and used a low dosage of Adva 100 superplasticizer to improve workability. The silica fume was premixed with the fine aggregate to obtain a better dispersion of particles in the concrete matrix.

The mix proportions for Program III are given in Table 2.15.

2.9 PROGRAM IV (CURING PERIOD)

The effects of increased curing periods on the shrinkage of concrete with two different cement types were studied in Program IV. Table 2.4 shows the test matrix for this program.

Batches 165 and 166 were non-air-entrained, machine mixed batches with a volume of 0.0325 m^3 (0.0425 yd^3). These batches used a *w/c* ratio of 0.45 and an aggregate content of 70 percent. Both batches contained an optimized blend of 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, pea gravel, and sand. No chemical or mineral admixtures were used. Batches 165 and 166 were made with Type I/II cement and Type II coarse ground cement, respectively. For both batches, specimens were cured for 3, 7, 14, and 28 days in sets of 3 specimens for each curing period.

Batch 201 was air-entrained concrete made with Type I/II cement. A total of 12 specimens were cast and cured for 3, 7, 14 and 28 days in sets of three specimens for each curing period. The mix had a *w/c* ratio of 0.45, and the aggregate content was 70 percent. An optimized aggregate blend containing 19 mm (¾ in.) limestone, pea gravel, and sand was used. The mix had an air content of 5.5 percent. Micro Air served as the air entraining agent. Batch 201 was machine mixed and had a volume of 0.0325 m^3 (0.0425 yd^3).

Batch 207 was made with Type II coarse-ground cement. It was machine mixed and air-entrained. As with Batch 201, 12 specimens were cast with three each cured for 3, 7, 14 and 28 days. The *w/c* ratio and aggregate content were 0.45 and 70 percent, respectively. The batch contained the same aggregates as Batch 201. Micro Air was used for air entrainment, and the actual air content of mix was 4.75 percent, deviating somewhat from the design value of 5 percent. The batch volume was 0.0325 m^3 (0.0425 yd^3).

Table 2.15 lists the mix proportions used for Program IV.

2.10 PROGRAM V (SUPERPLASTICIZERS)

The effect of superplasticizers on shrinkage was evaluated in Program V. The variables included the type and dosage of the superplasticizers. Test matrix is shown in Table 2.5.

Batches 167 through 174 had a *w/c* ratio of 0.45 and an aggregate content of 75 percent. The aggregates were an optimized blend of 25 mm (1 in.) limestone, 19 mm (¾ in.) limestone, pea gravel, and sand. Type I/II cement was used and the batch volume was 0.008 m^3 (0.01yd^3). All batches were hand mixed with three specimens cast for each batch. The dosage range recommended by manufacturer was used to determine dosages levels. In addition to a control batch with no superplasticizer, three batches were made for each of two superplasticizers, Glenium 3000 NS and Rheobuild 1000, with low, medium, and high dosages. The two superplasticizers represent different chemical types, namely, carboxylated polyether and naphthalene.

The concrete in Batch 167 contained no superplasticizer. This batch served as the control batch for batches 168 through 174. Batches 168, 169, and 170 used low, medium and high dosages of Glenium 3000 NS, respectively. Batch 174 was a replication of Batch 170, because Batch 170 was not cast correctly. Low, medium and high dosages of Rheobuild 1000 were used, respectively, in Batches 171, 172, and 173. Concrete set was significantly retarded in Batches 168 through 174. The retardation was significantly greater for the higher dosages. The mixes were retarded for 5 to 7 hours at high dosages, 2 to 5 hours at medium dosages, and 1 to 1.5 hours at low dosages. The fact that the admixtures were both Type A and Type F superplasticizers (and not purely Type F high-range water reducers) might have caused the retardation. Also, the dosage levels recommended by manufacturer seemed to be upper bound estimates.

Batches 175 through 182 also contained Glenium 3000 NS and Rheobuild 1000 with same dosage values as batches 168 through 174. Batch 175 was a control batch, and batches 176, 177, and 178 contained low, medium, and high dosages of

Glenium 3000 NS respectively. Batches 179 through 181 contained low, medium and high dosages of Rheobuild 1000. Batch 182 was a replication of Batch 181, because one of the specimens was damaged while demolding Batch 181. The mixes were similar to the mixes in Batches 167 through 174, except aggregates consisted of an optimized blend of 19 mm (¾ in.) limestone, pea gravel, and sand. The concrete was mixed in 0.008 m^3 (0.01 yd^3) hand batches. The concrete in these batches was also retarded, as observed for Batches 168 through 174.

Another carboxylated polyether based superplasticizer, Adva 100 was used in Batches 183 through 186 and Batches 190 through 193. Batch 183 served as a control batch with no superplasticizer. Batches 184, 185, and 186, respectively, used low, medium, and high dosages of Adva 100. The mix design was similar to Batches 175 through 182. Batches 190, 191, 192, and 193 were replications of Batches 184, 185, 186, and 183, respectively. The concrete was hand mixed in 0.008 m^3 (0.01 yd^3) batches. Although this superplasticizer is a Type F superplasticizer, retardation of concrete still occurred, probably due to the upper bound estimate of dosage levels recommended by manufacturer. Concrete set was retarded by 4 to 5 hours for high dosages, 2 to 2.5 hours for medium dosages, and 45 minutes to 1 hour for low dosages.

In batches 208 through 211, superplasticizer dosages were adjusted to obtain a slump of 76 ± 13 mm (3 ± ½ in.). Batch 208 served as the control batch without any superplasticizer. Type I/II cement was used with a *w/c* ratio of 0.45 and an aggregate content of 70 percent. The batches were non-air-entrained and machine mixed with a batch volume of 0.016 m^3 (0.02 yd^3). An optimized blend of aggregates containing 19 mm (¾ in.) limestone, pea gravel, and sand was used. In batches 209, 210, and 211, appropriate dosages of Adva 100, Glenium 3000 NS, and Rheobuild 1000 were used respectively. The measured concrete slump was 2¼, 2¾, 3, and 3¼ in., respectively, for Batches 208, 209, 210, and 211. The purpose of using mixes with equal slumps was to make realistic concrete and obtain a fairer comparison between concrete containing the different superplasticizers than obtained in the previous batches.

Air-entrained concrete was used to study the effect of superplasticizers on shrinkage in Batches 249, 256, 259, and 260. The mixes were designed for an air content of 8 ± ½ percent. For batches 249, 256, and 259 (Glenium 3000 NS, Rheobuild 1000, and Adva 100, respectively), an aggregate content of 67.8 percent was used, with a *w/c* ratio of 0.45. Appropriate dosages of superplasticizers were used to obtain a slump of 76 ± 13 mm (3 ± ½ in.). The air entraining agent was Micro Air. In Batch 260, no superplasticizer was used, but the percentage of paste was increased to obtain a slump in the same range as the superplasticizer mixes. The aggregate content for Batch 260 was 63.5 percent, and the water cement ratio was 0.45. The increase in paste volume to obtain the same slump was used to compare the shrinkage of concrete of similar workability, with and without a superplasticizer. The concrete was machine mixed with a batch volume of 0.016 m^3 (0.02 yd^3).

Mix proportions for all batches in Program V are shown in Table 2.17.

2.11 MIXING

Hand mixing was used for the concrete in Program I, all batches in Program II, except 262 through 264, Program III, and Batches 175 through 186 and 190 through 193 of Program V. The volume for all hand mixed batches was 0.008 m^3 (0.01 yd^3). The free surface moisture of fine aggregates, measured in accordance with ASTM C 70, was used to calculate batch weights. Coarse aggregates were soaked in water for 24 hours before mixing and prepared to a saturated surface dry (SSD) condition in accordance with ASTM C 127. A 533 × 787 × 76 mm (21 × 31 × 3 in.) steel pan was used for hand mixing. The surface of the pan was dampened and coarse and fine aggregates were combined and mixed in the pan without adding water. The cementitious materials were then added to the mixed aggregates and thoroughly mixed until a uniform mixture was obtained. A ring was formed with the dry mix in the pan, and the water was added in the middle of the ring. As the water soaked in, the rest of the dry material was moved to the center from the sides. After all water was added, the batch was thoroughly mixed using two trowels for three minutes. After a rest period of three minutes, the concrete was mixed thoroughly for another two minutes.

For the hand mixed batches in Program V, the mixing pan was an 864 × 406 × 140 mm (34 × 16 × 5.5 in.) Rubbermaid® plastic container with a lid. This change was made to avoid moisture loss after mixing since the concrete was significantly retarded due to use of superplasticizers. Prior to mixing, the superplasticizer was mixed with ten percent of the mix water. After combining aggregates and mixing with cement, as described earlier, the other 90 percent of the mix water was added to the dry mixture and mixed thoroughly for one minute. The water with the superplasticizer was then added, and the concrete was mixed for three minutes. After resting three minutes, the concrete was mixed thoroughly for another two minutes. If the mix was not stiff enough to cast, the concrete was kept in the containers covered with the lid. While in the containers, the concrete was mixed for one minute every 30 to 45 minutes until it was ready to cast.

For Batches 262 to 264 in Program II, the concrete was mixed in the pan mixer using a batch volume of 0.016 m^3 (0.02 yd^3). The weights of the fine aggregates and water were corrected for the free surface moisture on fine aggregates. To obtain an optimized aggregate gradation, the coarse aggregates were sieved through a 9.1 mm (⅜ in.) sieve, and the fraction retained on that sieve and fraction passing through it were treated as two different size aggregates while proportioning the mix. The superplasticizer was combined with 10 percent of the mix water and the air entraining agent was combined with another 10 percent. The coarse aggregate and 80 percent of the mix water were first added to the dampened mixer. The mixer was started and the fine aggregate and cement were added to the revolving pan. The concrete was mixed for one minute followed by the addition of the water with the superplasticizer. The concrete was again mixed for one minute, and finally, the water containing the air-entraining agent was added. Mixing was continued for three minutes. The mixer was stopped, and the concrete was allowed to rest in the mixer for three minutes. The pan was covered with a plastic sheet during the rest period to avoid the moisture loss. The mixer was restarted, and mixing continued for another two minutes. During the three minute rest period, a preliminary reading of temperature was recorded. After the mixing was completed, the plastic concrete was tested for slump (ASTM C 143), air content by the volumetric method (ASTM C 173), and temperature (ASTM C 1064). If the requirements for air content and slump were met, the concrete was then transported to the casting room in a 533 × 787 × 76 mm (21 × 31 × 3 in.) steel pan. The pan was covered with a plastic sheet until casting was complete, to avoid the moisture loss.

The concrete in Program IV was machine mixed in 0.035 m^3 (0.0425 yd^3) batches as just described. The only differences were that the concrete contained no superplasticizer, 90 percent of mix water was mixed with the coarse aggregates, and the remaining 10 percent water was added with the air entraining agent. Concrete was tested for both slump and air content, but there was no specific requirement for slump.

The non-air-entrained machine mixed batches in Program V (Batches 208 through 211) were mixed using a procedure similar to the one described for Program IV. Superplasticizers were added to the mixture using a procedure similar to that used for the air entraining agent. Air-entrained machine mixed batches (Batches 249, 256, 259, and 260) were mixed as described for the machine mixed batches of Program II.

2.12 CASTING

A vibrating table was used to cast the specimens. The steel molds were coated with mineral oil before placing the concrete. Concrete was briefly hand-mixed in the pan and placed in the molds in two layers of approximately equal depth. After placing the first layer, the concrete was packed underneath the gage studs by hand. The first layer was then vibrated using the vibrating table. The vibration time and frequency varied depending on the stiffness of the mix. Typically the first layer was vibrated for 15 to 20 seconds. The second layer of concrete was then placed, and the concrete was packed in the corners of the molds by hand. The second layer was also vibrated. Excess concrete was then removed with a 51 × 133 mm (2 × 5½ in.) handmade steel strike-off screed. The outside and top edges of the molds were then cleaned to remove excess concrete using a moist sponge, and specimens were moved from vibrating table to the casting room floor for initial curing.

2.13 CURING

Immediately after casting, 152 μm (6 mil) Marlex® plastic strips were used to cover the exposed concrete surface of the specimens. Then the entire mold (top and sides) was covered with 89 μm (3.5 mil) plastic sheets. The plastic sheets were secured to the molds using rubber bands. The specimens were grouped in sets of three (for each batch) and a 12.7 mm (½ in.) thick square piece of Plexiglas® was placed on the top of each set of three specimens. Four 152 × 305 mm (6 × 12 in.) concrete cylinders were then placed on the Plexiglas® to hold it firmly in place. The goal was to avoid any moisture loss from the top surface of concrete specimens before demolding. In accordance with ASTM C 157, the specimens were demolded 23½ ± ½ hours after casting. The initial reading was taken on the specimens using the length comparator at this time. The specimens were then placed in lime-saturated water in a curing tank for additional two days at 23 ± 0.5 °C (73 ± 1 °F), giving a total curing period of three days for each specimen. Curing periods of 3, 7, 14, and 28 days were used for the specimens in Program IV. After curing in lime-saturated water, the specimens were allowed to dry in standard conditions described in next section, and the length measurements were recorded, as described in Section 2.14.

2.14 DRYING

An environmental room fabricated with structural lumber and 89 μm (3.5 mil) plastic sheeting was used to store the specimens during drying and data collection. The room was located in a temperature and humidity controlled laboratory. The dimensions of the room were 3.7 × 3.7 × 2.1 m (12 × 12 × 6.8 ft), and the specimens were stored on wooden racks with a minimum clearance of 25 mm (1 in.). The specimens were allowed to dry from all sides in accordance with ASTM C 157. The relative humidity inside the drying room was maintained at 50 ± 4 percent using a humidifier during winter and a dehumidifier during summer. The temperature was maintained at 23 ± 2°C (73 ± 3°F). The length comparator was located in the drying room, and the readings were taken in the drying room.

2.15 DATA COLLECTION

The lengths of the specimens were determined using a length comparator in accordance with ASTM C 157. A reference bar was used to establish a reference reading before the specimens in each batch were read. The dial gage was read with the reference bar in the comparator for each batch of specimens and then the comparator dial was read with the specimens in the comparator. Care was taken to position the specimen in such a way that the same side of the specimen was at top during the measurement every time.. The initial CRD (Comparator Reading Difference, difference between the comparator reading of a specimen and that of the bar) was recorded immediately after demolding. The length change at a given age was calculated as the difference between the CRD at that age and the initial CRD. The strain was calculated as the length change divided by the gage length of 254 mm (10 in.). The shrinkage, in microstrain, for any batch is reported as the average strain of three specimens at a given age.

According to ASTM C 157, measurements should be taken at ages of 4, 7, 14 and 28 days and 8, 16, 32 and 64 weeks for the specimens stored in air. More frequent measurements were made in this study to obtain a better comparison between the shrinkage behaviors of the batches. After removing the specimens from the curing tank, readings were recorded every day for a period of 30 days. The reading interval then increased to every other day between 30 and 90 days. Readings were taken once a week from 91 to 180 days and once a month from 181 to 365 days. The final reading was recorded at 365 days.

In Program IV, for the specimens that were stored in curing tank for more than three days, comparator readings were also taken 3, 7, 14, and 28 days after casting. For example, for the specimens that were cured for 28 days, readings were recorded at 3 days, 7 days and 14 days, and the specimens were then returned to the curing tank. For these readings, the specimens were temporarily kept in a bucket of water to avoid drying. In this case, after taking the 28-day reading, drying and data collection proceeded as described for other specimens.

CHAPTER 3: RESULTS AND EVALUATION

3.1 GENERAL

This chapter presents the results of the free shrinkage tests. The effects of aggregate content, water-cement ratio, aggregate type, mineral admixtures, curing times, cement type, and the use of superplasticizers are evaluated. Comparisons are made over the full test period and at specific ages ranging from 30 days to one year.

The values of free shrinkage reported in the chapter represent the average of the three specimens for each batch. The individual specimen free shrinkage curves are presented in Figures A3.1 through A3.88 in Appendix A. Figures 3.1 through 3.89 compare the batches in each program. As explained in Chapter 2, the specimens were cured for three days for all batches, except for selected batches in Program IV, which is used to evaluate the effects on shrinkage for curing periods of 3, 7, 14, and 28 days. The specimens were stored in a controlled environment at 23 ± 2°C (73 ± 3°F) and 50 ± 4 percent relative humidity. Free shrinkage was recorded as the change in length over a gage length (distance between tips of gage studs) of 254 mm (10in.) up to a period of one year.

The specimens were cast and protected against moisture loss during the first 24 hours. The specimens were demolded 23½ ± ½ hours after casting, and the initial length reading was recorded as the day 1 reading. The specimens were then cured in lime saturated water for 2 additional days. Drying started on day three, except as noted for Program IV. The reading on day three was taken before the specimens were subjected to drying. For Program IV, drying started upon completion of the curing period. The comparisons based on the drying period for Program IV are shown in figures identified as “drying only”, where the reading on day 1 indicates the reading recorded one day after drying began.

3.2 STATISTICAL ANALYSIS

Because the sample size for each variable is small (three specimens per batch), the Student’s t-test is used to determine if the observed differences are statistically significant. This test is used when the population variance is not known and the sample size is small. The test determines if the difference in the sample means (X_1 and X_2) represents an actual difference in the population means (μ_1 and μ_2) at a particular level of confidence (α). At a 95 percent confidence level (that is at a level of significance α = 0.05), there is a five percent probability that the test will (incorrectly) indicate a statistically significant difference in sample means when, actually, there is no difference (or a 95 percent probability that it will correctly indicate a difference in sample means when there is a difference). A two-sided t-test is used in the analyses performed in this study. This means that there is a probability of $\alpha/2$ that $\mu_1 < \mu_2$ and $\alpha/2$ that $\mu_1 > \mu_2$ when, in fact, μ_1 and μ_2 are equal. A “Y” in the tables indicates that there is a statistical difference between two samples at a confidence level of 95 percent (α = 0.05), and an “N” indicates that there is no statistical difference between samples at the lowest confidence level, 80 percent

(α=0.20). Statistical differences at confidence levels of, but not exceeding 90 and 80 percent confidence levels are indicated by "90" and "80," respectively.

3.3 PROGRAM I (AGGREGATE CONTENT, WATER-CEMENT RATIO, CEMENT TYPE)

The effect of aggregate content (60, 70, and 80 percent), and water-cement ratio (0.40, 0.45 and 0.50) on concrete shrinkage was evaluated in Program I using two cements, Type I/II and Type II coarse-ground. The test matrix and mix proportions for the corresponding batches are presented in Tables 2.1 and 2.13 respectively. Free shrinkage for individual specimens is presented in Figures A3.1 through A3.18 in Appendix A.

3.3.1 COMPARISON BETWEEN BATCHES

The average free shrinkage curves for Program I are presented in Figures 3.1 through 3.12. The legend to the right of the plots in Figures 3.1 through 3.6 indicates the aggregate content, as a percent of concrete volume, and the water-cement ratio, also expressed in percent. For example, 70-45 in the legend indicates that the concrete had an aggregate content volume of 70 percent and a water-cement ratio of 0.45 by weight. For Figures 3.7 through 3.12, the legend indicates the cement type and aggregate content.

Figure 3.1 shows the average free shrinkage strain versus time during the first 30 days after casting for batches containing Type I/II cement with varying water-cement ratios and aggregate contents. The greatest shrinkage is observed for the concrete with lowest aggregate content (60 percent) and a water-cement ratio of 0.40. For a given water-cement ratio, the shrinkage decreases with an increase in aggregate content. Shrinkage is lowest with the highest aggregate content (80 percent) and a water-cement ratio of 0.5. No clear trend of change in shrinkage is observed as a function of water-cement ratio. Figures 3.2 and 3.3 present the same data up to ages of 180 and 365 days, respectively. The effect of aggregate content on shrinkage becomes more prominent and the trend can be easily observed in these figures. It is also observed that for a given aggregate content, there is no significant effect of water-cement ratio on shrinkage. The data in Figures 3.1 through 3.3 is summarized in Table 3.1 and the average free shrinkage values are provided at 3, 7, 30, 90, 180 and 365 days after casting.

The free shrinkage of batches with Type II coarse-ground cement is compared in Figures 3.4 through 3.6. The trend is similar to that observed for Type I/II cement in regard to aggregate content, that is, shrinkage decreased as the aggregate content increased. The data from these batches is also summarized in Table 3.1.

Results of Student's t-test for various water-cement ratios are presented in Tables 3.8 through 3.13. The differences between shrinkage of various batches are, in fact, statistically significant in many cases. Due to the lack of a clear trend between shrinkage and water-cement ratio, however, these differences do not lead to any significant conclusions. Tables 3.14 through 3.19 present the Student's t-test results for different aggregate contents. Results of the Student's t-test confirm the observation that shrinkage decreases as the aggregate content increases. With few exceptions, the differences observed between the free shrinkage at various aggregate contents are statistically significant.

Figures 3.7 through 3.12 compare the shrinkage of concretes containing Type I/II and Type II coarse-ground cement. It is easily observed that for a given aggregate content and water-cement ratio, concrete containing Type II coarse-ground cement exhibits significantly lower shrinkage than concrete containing Type I/II cement. This trend is consistent at all aggregate contents and water-cement ratios. The difference as a function of cement type is highest for aggregate content of 60 percent and water-cement ratio of 0.40 (206 $\mu\varepsilon$) and lowest for 80 percent aggregate content and 0.50 water-cement ratio (50 $\mu\varepsilon$). A summary of shrinkage data presented in Figures 3.7 through 3.12 is given in Table 3.2.

3.3.2 SUMMARY OF PROGRAM I

It is observed that concrete shrinkage decreases as the aggregate content is increased. This is attributed, not only to the restraint provided by aggregates to shrinkage, but also to the reduction in cement paste with the increase in aggregate content. The trend is consistent with different water-cement ratios and cement types. Shrinkage is reduced significantly with use of Type II coarse-ground cement when compared with Type I/II cement. This can be explained by the fact that the unhydrated portion of larger cement particles in Type II coarse-ground cement act as aggregates, which provides restraint to shrinkage, and the coarser pore structure, which results in decreased surface tension when a meniscus is formed and, thus, lower shrinkage forces exerted on the surrounding cement paste.

3.4 PROGRAM II (COARSE AGGREGATE TYPES)

Three different types of coarse aggregate, quartzite, limestone and granite, were evaluated in Program II. Both non-air-entrained and air-entrained concrete were tested using batches cast in four sets. The test matrix and mix proportions are given in Tables 2.2 and 2.14, respectively. The aggregate gradations used are given in Tables 2.6 through 2.11. Individual specimen free shrinkage curves are presented in Figures A3.19 through A3.29.

3.4.1 COMPARISON BETWEEN BATCHES

Two coarse aggregates were used in the first set, quartzite and limestone. As shown in Figures 3.13-3.15, the shrinkage of concrete made with quartzite is significantly lower than that of concrete made with limestone. Free shrinkage measurements for Program II are summarized in Table 3.3. The difference in shrinkage is 54 με at 30 days, 80 με at 180 days and 74 με at 365 days. The results of Student’s t-test (Table 3.20a) indicate that these differences are statistically significant at all ages.

The second set of specimens included limestone, quartzite, and a third coarse aggregate, granite. As shown in Figures 3.16 through 3.18, the differences in shrinkage for concrete made with the different coarse aggregates are small. The average shrinkage values are within 37 με at all ages, and the differences in shrinkage are not statistically significant (Table 3.20b), except at 180 days, where the shrinkage of the limestone batch (387 με) exhibits a small, but statistically significant higher shrinkage than the quartzite (350 με) and granite (350 με) batches.

Because the results of the second set differ considerably from the results of the first set, a third set was cast with the three coarse aggregates. The average free shrinkage curves for this set are shown in Figures 3.19-3.21. Through an age of 30 days (Fig. 3.19), concrete containing granite (283 με) is observed to have less shrinkage than that containing limestone (320 με) or quartzite (340 με). The results of the statistical analysis (Table 3.20c) show that, at 30 days, the difference in shrinkage of concrete containing quartzite and that containing granite is statistically significant at a confidence level of 80 percent, while the difference in shrinkage between the concrete containing limestone and that containing granite is not statistically significant. At an age of 365 days, the relative order of average shrinkage remains the same, the difference between the shrinkage of concrete containing granite and that containing quartzite is statistically significant at the highest confidence level of 95 percent, and the difference between the shrinkage of concrete containing granite and that containing limestone is significant at the lowest confidence level of 80 percent.

Again, the results of the third set are not consistent with the previous results; the difference in shrinkage between the limestone and quartzite batches observed in the first set is not present in the third set. Also, the difference in shrinkage observed between the quartzite and granite batches was not observed in the second set.

Therefore, a fourth set was cast to evaluate the effects of types of coarse aggregate on shrinkage in batches 262-264, using air entrained concrete. Figures 3.22 -3.24 compare the average free shrinkage of different batches. The free shrinkage measurements at different ages are summarized in Table 3.3b. At an age of 30 days, the limestone batch experienced the highest shrinkage (377 με), followed by the quartzite (347 με) and granite (313 με) batches. The difference in shrinkage for the limestone and quartzite batches is 30 με and is statistically significant at the confidence level of 90 percent (Table 3.20d). The difference between quartzite and granite batches is 34 με and is significant at the confidence level of 80 percent. The difference of 64 με between limestone and granite batches is statistically significant at 95 percent confidence level. Differences similar to those observed at 30 days are observed at 180 and 365 days. At 365 days, the differences between quartzite and granite, and limestone and granite are statistically significant at 95 percent confidence level. The difference between granite and quartzite is significant at 80 percent confidence level.

3.4.2 SUMMARY OF PROGRAM II

As the aggregates in concrete offer restraint to the shrinkage, it is expected of aggregates with a higher modulus of elasticity should help in reducing the shrinkage. The limestone aggregates used in this program are more porous and have a lower modulus of elasticity than the quartzite and granite aggregates. Hence, it is expected that concrete made from limestone would shrink more than concrete made from the other two aggregates. The results of first non-air-entrained set are according to these expectations, and the limestone batch in this set experienced significantly more shrinkage than the quartzite batch at all ages. In the air-entrained (fourth) set, it is observed that the concrete containing limestone shrinks more than either of the other two concretes, but the difference between limestone and quartzite batches decreased with age and is statistically significant at confidence level of 80 percent at 180 and 365 days. The results for sets one and four are not consistent with the second and third non-air-entrained sets. In the second set, the differences observed between different batches were not significant, and in the third set, the granite batch exhibited significantly lower shrinkage than either of the other two batches, but the quartzite batch shrank more than the limestone batch. Hence, while it appears that concrete containing denser aggregates exhibits less shrinkage than concrete containing more porous aggregates, the results for individual batches are not always consistent with this observation.

3.5 PROGRAM III (MINERAL ADMIXTURES)

The effect of mineral admixtures on shrinkage was evaluated in Program III. The mineral admixtures used included Class C fly ash, ground granulated blast-furnace slag, and silica fume. Type I/II cement was partially replaced by 30 percent Class C fly ash (Batches 87 and 196), 30 percent slag (Batches 86 and 195) or 10 percent silica fume (Batches 88, 197 and 204). The replacements were based on volume, and as a result, the *w/cm* ratio by weight increased for the concretes containing mineral admixtures from 0.45 for the control batches to 0.465 for the slag batches, 0.469 for the Class C fly ash batches, and 0.470 for the silica fume batches. Four control batches (Batches 85, 194, 202 and 203) were made. Control batches 85, 194, and 202 did not contain a superplasticizer, while Control batch 203 did for better comparison with Batch 204, which contained a 10 percent silica fume volume replacement of cement and was also superplasticized to obtain better workability. The test matrix is given in Table 2.3 and mix proportions are listed in Table 2.15. Free shrinkage measurements at different ages are summarized in Table 3.4. Individual specimen shrinkage curves are presented in Figures A3.30-A3.40.

3.5.1 COMPARISON BETWEEN BATCHES

A total of three sets of specimens were cast. The average free shrinkage curves comparing batches in first set are presented in Figures 3.25-3.27. As shown in Figure 3.25, during the first 30 days, the slag and fly ash mixes shrank more than the control and silica fume mixes. The difference in shrinkage between the slag and control mix was 30 με and was statistically significant at the confidence level of 90 percent (Table 3.21a). The shrinkage of the fly ash mix was higher than that of the control mix by 34 με, and this difference was statistically significant at a confidence level of 95 percent. The silica fume mix shrank significantly less than slag mix (by 40 με) and fly ash mix (by 44 με). The silica fume mix also shrank less than the control mix (by 10 με), but the difference was not statistically significant. Figure 3.26 compares the shrinkage of same batches up to an age of 180 days. The results of

Student's t-test are presented in Table 3.21a. At 180 days, the shrinkage values of the control, slag and silica fume mixes are within 12 $\mu\varepsilon$ of each other. The shrinkage of the fly ash mix is higher than the other three mixes, with differences between 31 to 43 $\mu\varepsilon$. At 365 days, however, the silica fume and slag mixes shrink more than the control mix (Figure 3.27), while the fly ash mix continued to exhibit the greatest shrinkage; the differences between the shrinkage of the fly ash mix and that of other mixes are statistically significant at confidence levels of 95, 90, and 80 percent for the control, slag and silica fume mixes, respectively (Table 3.21a). There is no significant difference in shrinkage between the slag and silica fume mixes. At 365 days, the control mix shrinks less than the silica fume mix by 39 $\mu\varepsilon$ and the slag mix by 33 $\mu\varepsilon$; the differences are significant at a confidence level of 80 percent in both cases.

A second set of specimens using same mineral admixtures and similar mix proportions was cast (Batches 194-197). As compared to the silica fume batch in the previous set (Batch 88), silica fume was premixed with cement in this set and a low dosage of the superplasticizer Adva 100 was used to obtain better workability (for Batch 197). Superplasticizer was not used for the control batch or the concrete containing other mineral admixtures. Figures 3.28-3.30 compare the average values of free shrinkage for the batches in the second set. As shown in Figure 3.28, the shrinkage of the fly ash and slag batches is higher than that of the control batch. This observation is similar to that for the first set (Batches 85-88). At 30 days, the difference between the slag mix and control mix is just 20 $\mu\varepsilon$, however, the difference between the fly ash and control mixes is 54 $\mu\varepsilon$. The silica fume mix, however, exhibits 36 με less shrinkage than the control mix at 30 days. The results of Student's t-test for these batches are presented in Table 3.21b and indicate that none of the differences observed between control batch and other three batches is statistically significant. The differences between the slag and silica fume mixes and the fly ash and silica fume mixes are statistically significant at a confidence level of 80 percent. Figure 3.29 shows the corresponding plots up to an age of 180 days. It is easily seen that the fly ash mix shrinks more than the control mix throughout this period. The slag mix exhibits higher shrinkage up to an age of 90 days and, thereafter, exhibits a value that is similar to the control mix. The silica fume mix consistently shrinks less than the control mix, but the difference appears to decrease after of 60 days. None of the differences observed at an age of 180 days is statistically significant. The shrinkage plots for these batches up to an age of 365 days are shown in Figure 3.30. Similar observations are made, in that the fly ash mix shrinks more than the control mix, the slag mix shrinks about the same as the control mix, and the silica fume mix shrinks less than the control mix. The difference between the shrinkage of the control mix and those of the corresponding mixes is 50 με for the fly ash mix, 6 με for the slag mix (slag mix shrinks slightly less than control mix), and 43 με for silica fume mix. However, none of these differences is statistically significant. This could be due to the large scatter of data points in individual batches, as shown in Figures A3.30 through A3.40, but trends in the data appear to be consistent, with fly ash mix exhibiting higher shrinkage than the control mix, the slag mix exhibiting shrinkage similar to the control mix, and the silica fume mix exhibiting less shrinkage than the control mix.

A third set to compare the silica fume mix with two control mixes was cast in Batches 202-204. Batch 202 was a control batch with no mineral or chemical admixtures. Batch 204 used 10 percent replacement of cement by silica fume on a volume basis. To obtain a better distribution of silica fume particles in the mix, the silica fume was mixed with the fine aggregate before the concrete was mixed. A low dosage of Adva 100 superplasticizer was used to improve the workability of the concrete. Batch 203 was similar to Batch 202, except it also contained a low dosage of Adva 100 for a better comparison with the silica fume mix. Figure 3.31 shows that the silica fume mix undergoes higher shrinkage than either control batch through 30 days. The difference between the silica fume mix (204) and the control mix (202) is 50 $\mu\varepsilon$ (statistically significant at the confidence level of 80 percent) (Table 3.21c) and 53 $\mu\varepsilon$ between the silica fume mix and the superplasticized control mix (203) (not statistically significant). From Figure 3.32, it is seen that this difference appears to decrease, with the silica fume and the control mixes exhibiting similar shrinkage after 90 days. At 180 days and 365 days (Figure 3.33) there is no noticeable difference between three mixes.

3.5.2 SUMMARY OF PROGRAM III

Based on three sets in this program, fly ash appears to consistently increase the shrinkage of concrete. Although the statistical analysis does not support this conclusion, there are reasons to believe that fly ash does not help in reducing the shrinkage. Slag does not appear to affect the ultimate shrinkage of concrete to great extent, but the early age shrinkage may be increased with the use of slag. No certain conclusions can be made about the use of silica fume, as it did not increase the shrinkage of concrete in the first two sets, but the early age shrinkage was increased with use of silica fume in the third set. It should be noted that, when the mixes were designed, cement was replaced by volume while the water content was held constant. As a result, the *w/cm* ratios of the mineral admixture mixes were slightly higher than the control mix. The results could have been affected to a certain degree due to the higher *w/cm* ratios.

In general, the results of the tests are not consistent, and future testing is needed before firm conclusions can be made. Because the mineral admixtures react more slowly than the portland cement alone, the effect of the curing period on concrete containing mineral admixtures is known to be significant. Future batches made with mineral admixtures should be cured for a longer period. A standard mixing procedure should be used when using silica fume in dry densified form to obtain a consistent distribution of particles in the mix. The effects of Class F fly ash, as well as Class C fly ash from other sources on shrinkage should be evaluated before general conclusions about use of fly ash are made.

3.6 PROGRAM IV (CURING PERIOD AND CEMENT TYPE)

Non-air-entrained and air-entrained concrete was tested for effects of curing period and cement type on shrinkage in Program IV. Type I/II and Type/II coarse-ground cements were used with curing periods of 3, 7, 14, and 28 days. The individual specimen free shrinkage curves are shown in Figures A3.41 through A3.56. The test matrix and mix proportions are given in Tables 2.4 and 2.16, respectively.

3.6.1 EFFECT OF CURING PERIOD

The effect of the length of the curing period on shrinkage of non-air-entrained concrete is presented in Figures 3.34-3.45. For concrete made with Type I/II cement, the results up to an age of 30 days are shown in Figure 3.34. Tables 3.5 and 3.6 summarize the free shrinkage measurements. Some specimens from this program exhibited swelling during the curing period. As shown in Figure 3.34, the specimens cured for three days did not experience any swelling during the curing period, but those cured longer did, and the amount of swelling increased with the length of curing period. Also, at a given age, the longer the curing period, the lower the shrinkage. Figure 3.35 shows the same batches based on the drying period. Thirty days after drying began, the concrete cured for 3, 7, 14, and 28 days exhibited average shrinkage strains of 333, 337, 320 and 227 με, respectively. The differences between the specimens cured for 3, 7, and 14 days, however, are not statistically significant at this age (Table 3.22). Differences between the specimens cured for 28 days and those cured shorter periods are statistically significant. Figures 3.36 and 3.38 show results for these batches up to ages of 180 and 365 days after casting, respectively. Figures 3.37 and 3.39 show the results based on drying period. The results are similar to those observed at 30 days. Shrinkage decreased with longer curing periods, except the concrete cured for seven days shrank consistently more than the concrete cured for three days. The statistical analysis of the results is presented in Table 3.22. The shrinkage values based on drying period are used for the statistical analysis. Three hundred days after drying began, the difference between concrete cured for seven days and that cured for 14 days is statistically significant at the 95 percent confidence level. Also, the differences between concrete cured for 28 days and concrete cured for shorter periods are statistically significant at the 95 percent confidence level. There is no significant difference between the shrinkage of concrete cured for three days and that cured for 14 days.

The average free shrinkage plots for non-air-entrained batches made with Type II coarse-ground cement are presented in Figures 3.40-3.45. Figures 3.40, 3.42, and 3.44 show the results based on age after casting, while Figures 3.41, 3.43, and 3.45 show the results based on drying period. The concrete cured for longer periods exhibited consistently less shrinkage throughout the test. When comparison is based on the drying period, however, the differences between different batches are smaller. The results of Student's t-test are presented in Table 3.23. The difference between the concrete cured for three days and that cured for seven days as well as the difference between the concrete cured for seven days and that cured for 14 days is not statistically significant at 30 days. After 180 days of drying, the differences between the concrete cured for 28 days and that cured for shorter periods are statistically significant. The difference between the concrete cured for 14 days and that cured for seven days is also statistically significant at the 80 percent confidence level. The difference between the concrete cured for three days and that cured for seven days, however, is not statistically significant. Statistical analysis of results at after 300 days of drying indicates similar differences as those after 180 days.

For air-entrained batches made with Type I/II cement, a more pronounced effect of curing on shrinkage is observed. The shrinkage is reduced by a considerable amount when the curing period is increased from 3 to 7, from 7 to 14, and from 14 to 28 days. Figures 3.46, 3.48, and 3.50 show the results for these batches based on age after casting and Figures 3.47, 3.49, and 3.51 show the results based on age after initiation of drying. The results of statistical analysis are presented in Table 3.24. At all ages, the differences in shrinkage are statistically significant at the 95 percent confidence level, with the exception that the difference between the concrete cured for seven days and that cured for 14 days after 30 days of drying being significant at confidence level of 90 percent (Table 3.24). At 365 days, the difference between the concrete cured for three days and that cured for seven days is highest (177 $\mu\varepsilon$), followed by the difference between the concrete cured for 14 days and that cured for 28 days (57 $\mu\varepsilon$). The difference between the concrete cured for seven days and that cured for 14 days is relatively small (23 $\mu\varepsilon$).

The effect of increased curing on the air-entrained concrete made with Type II coarse-ground cement is similar to that observed for concrete made with Type I/II cement. Figures 3.52 and 3.53 show the results for these batches up to age of 30 days. Shrinkage decreases with increased curing period at this age. The difference between the shrinkage of concrete cured for three days and that of concrete cured for seven days, as well as that between concrete cured for 14 days and 28 days, is not statistically significant, while all of the other differences in shrinkage are statistically significant at the 95 percent confidence level (Table 3.25). From Figures 3.55 and 3.57, it is seen that concrete cured for seven days experiences less shrinkage than concrete cured for 3 days up to age of 70 to 75 days. After this age, however, there is no noticeable difference between the shrinkage of these batches. Similar behavior is observed with concrete cured for 14 days and 28 days. The shrinkage of concrete cured for 28 days is less than that of concrete cured for 14 days up to an age of 136 days. After this age the difference between the shrinkage of these two batches is not noticeable. The results of statistical analysis (Table 3.25) support the observation that there is no significant difference between the shrinkage of concrete cured for 14 days and that cured for 28 days. The other differences in shrinkage, however, are statistically significant.

3.6.2 EFFECT OF CEMENT TYPE

In addition to the evaluation described in Program I, the effect of type of cement on shrinkage was also evaluated in Program IV. Figures 3.58 through 3.65

show comparisons between the shrinkage of concrete made with Type I/II and Type II coarse ground cements cured for different periods. For the non-air-entrained concrete (Figures 3.58 through 3.61), there is no apparent effect of cement type on shrinkage of the concrete cured for three days. For the longer curing periods, however, the concrete made with Type II coarse-ground cement exhibits less shrinkage than the concrete made with Type I/II cement. The statistical analysis (Table 3.26) also indicates that there is no significant difference between the shrinkage of concrete made with two types of cement for concrete cured for three days. The difference for the concrete cured for seven days is significant at confidence levels of 90, 80, and 90 percent, respectively, at 30, 180, and 300 days of drying. For the concrete cured for 14 days, the difference is significant at a confidence level of 95 percent at all ages. For the concrete cured for 28 days, the difference is significant at a confidence level of 90 percent at 30 days, and at a confidence level of 95 percent at 180 and 300 days of drying, respectively. For air-entrained concrete (Figures 3.62 through 3.65), cement type affects shrinkage more significantly. The difference in shrinkage for concrete made with the two types of cement is statistically significant (Table 3.27) at the confidence level of 95 percent for most of the batches and at all ages. The exceptions are concrete cured for 28 days at 180 and 300 days, with the difference being significant at confidence level of 80 percent. Interestingly, the Type I/II cement concrete cured for 14 days shrinks significantly (80 percent confidence level) more than the Type II coarse-ground cement concrete cured for seven days.

Hence, the higher shrinkage experienced due to the limited curing period could be compensated by using Type II coarse-ground cement in place of Type I/II cement.

3.6.3 SUMMARY OF PROGRAM IV

With a few exceptions, increased curing reduces shrinkage. The effect is more clearly noticeable for concrete made with Type I/II cement, although a similar trend is observed for concrete made with Type II coarse-ground cement. The difference between shrinkage of concrete cured for seven days and that cured for 14 days, as well as concrete cured for 14 days and that cured for 28 days is significant for most of the batches made. The difference between the concrete cured for three days and seven days, however, is not significant in many cases. Hence, increasing the duration of moist curing from seven to 14 days can be a major step in controlling the shrinkage. Also, the use of Type II coarse-ground cement can significantly help in reducing the shrinkage. The shrinkage of air-entrained concrete made with Type II coarse ground cement cured for seven days was less than that of air-entrained concrete made with Type I/II cement cured for 14 days. Use of coarse ground cement in concrete can effectively help in crack control on bridge decks. It should be confirmed, however, that the use of coarse ground cement does not reduce the compressive strength or increase the permeability beyond the acceptable limits.

3.7 PROGRAM V (SUPERPLASTICIZERS)

Three superplasticizers were tested for their effect on shrinkage in Program V. A total of four sets of non-air-entrained concrete and one set of air-entrained concrete were cast. The individual specimen free shrinkage curves are presented in Figures A3.57 through A3.89. The test matrix and mix proportions are given in Table 2.5 and 2.17, respectively. Free shrinkage measurements are summarized in Table 3.7.

3.7.1 EFFECT OF SUPERPLASTICIZER TYPE AND DOSAGE

In the first set (Batches 167 through 174), two superplasticizers, Glenium 3000 NS and Rheobuild 1000 were used. The range recommended by the manufacturer was used to determine the three dosage levels, low, medium and high. The low and high dosages were the lower and upper limits of the range, respectively, and the medium dosage was the average of the two. Concrete set was significantly retarded in concrete containing superplasticizer for Batches 167 through 174. Retardation was significantly greater for the higher dosages. The mixes were retarded for 5 to 7 hours at high dosages, 2 to 5 hours at medium dosages, and 1 to 1.5 hours at low dosages. The fact that the admixtures were classified as both Type A and Type F admixtures (and not purely Type F high-range water reducers) might have caused the retardation. Figures 3.66 through 3.71 present the results for this set. As shown in Figures 3.66-3.68 for Glenium 3000 NS, shrinkage was not affected by the dosage rate of superplasticizer up to 180 days. The statistical analysis supports this observation (Table 3.28a). At 365 days, the results indicate that the batches with low and high dosages of superplasticizer shrank more than the control batch and the batch with medium dosage shrank less than the control batch. None of the differences is significant at the highest confidence level. Also, there is no clear trend in shrinkage behavior with the increase in superplasticizer dosage. The concrete with high dosage of Glenium 3000 NS experienced the highest shrinkage, followed by the concrete with low dosage, no superplasticizer (control), and medium dosage. Figures 3.69-3.71 present the results for different dosages of Rheobuild 1000. The batch with high dosage of superplasticizer experienced more shrinkage than the rest of the batches containing superplasticizer. The differences are significant at the 95 percent confidence level at 30 days and at the 90 percent confidence level at 180 and 365 days. The difference between the concrete containing high dosage and control concrete was not significant at 30 days, but at 180 and 365 days, the former exhibited higher shrinkage (difference significant at 95 percent confidence level) than the later (Table 3.28b). However, there is no clear trend of change in shrinkage with increase in amount of superplasticizer.

A third type of superplasticizer, Adva 100 was added to the study in the second set of Program V (Batches 175 through 186), which also included Glenium 3000 NS and Rheobuild 1000. Concrete set was retarded in a similar way, for similar periods, to that described for the first set for concrete containing Glenium 3000 NS and Rheobuild 1000. Set retardation of the concrete containing Adva 100 was less than that containing the other superplasticizers. For concrete containing Adva 100, concrete set was retarded by 2 to 3 hours for high dosages, 1 to 1.5 hours for medium dosages, and 0.5 to 0.75 hours for low dosages. For the batches cast with Glenium 3000 NS (Figures 3.72-3.74), the concrete with all dosage levels exhibited more shrinkage than the control batch. Table 3.29a presents the results of statistical analysis. The difference between control concrete and concrete containing low dosage was significant at confidence levels of 90 percent at 30 and 180 days, and 80 percent at 365 days. The difference between the control concrete and concrete containing the medium dosage was significant at confidence levels of 95 percent at 30 and 180 days, and 90 percent at 365 days. The difference between control concrete and concrete containing the high dosage was significant at confidence levels of 95 and 80 percent at 30 and 180 days, respectively, but was not significant at 365 days. There is no clear trend of change in shrinkage, however, with the dosage of superplasticizer. The concrete with the low dosage experienced the highest shrinkage, followed by the concrete with medium and then high dosage. Moreover, the results were not consistent with the results of the first set. For the batches made with Rheobuild 1000 (Figures 3.75-3.77), similar results are obtained as those in the first set, except no significant difference between the control batch and the batch using high dosage of superplasticizer is observed. Although two batches containing high dosage of Rheobuild 1000 were cast, the set retardation observed with the second batch (Batch 182) containing high dosage of Rheobuild 1000 was significantly less than that observed for the first batch (Batch 181) containing high dosage. Also, as shown in Figures 3.75-3.77, the second batch exhibited much higher shrinkage, by 80 to 143 $\mu\varepsilon$, than other batches containing Rheobuild 1000 at 30 days. Due to these reasons, the results for the first batch (which was cast at the same time as the batches containing low and medium dosages of Rheobuild 1000 were cast) are used for the comparison. The results of the Student's t-test are presented in Table 3.29b. Again, there is no clear trend of shrinkage with the change in dosage. For the batches containing Adva 100 (Figures 3.78-3.80), the effect of superplasticizer on shrinkage is not noticeable. The differences observed are within 10 $\mu\varepsilon$ and are not statistically significant (Table 3.30a), with the exception of the difference between batches with low and high dosages being statistically significant at 30 days. This difference disappears at later ages. For concrete containing Glenium 3000 NS, and Rheobuild 1000, it is generally observed that the concrete containing low dosage exhibits higher shrinkage than the control concrete as well as the concrete containing medium and high dosage. This could be a result of significant set retardation observed with concrete containing high and medium dosages of superplasticizers.

The third set consisted of additional batches with different dosages of Adva 100. Figures 3.81-3.83 present the average free shrinkage curves for this set. The results of Student's t-test are presented in Table 3.30b. The results obtained are very similar to the results of previous batches made with Adva 100. No apparent or significant difference was observed between the control batch and batches with three dosages of superplasticizer.

Batches with different types of superplasticizer at the same dosage level are compared using Student's t-test. Tables 3.31a, 3.31b, and 3.31c present the results of Student's t-test for low, medium, and high dosages, respectively. At low and medium dosages, there is no significant difference between the shrinkage of concrete made with the different superplasticizers. At the high dosage, the difference is not significant at 30 days. At 180 days, concrete containing Rheobuild 1000 exhibited the least shrinkage, followed by Glenium 3000 NS, and Adva 100. All of these differences were significant at the confidence level of 95 percent. Similar differences are observed at 365 days at confidence level of 90 percent for the difference between Rheobuild 1000 and Glenium 3000 NS, and that between Glenium 3000 NS and Adva 100 and at confidence level of 95 percent for the difference between Rheobuild 1000 and Adva 100.

In the fourth set, all three superplasticizer were used, and the dosages were based on the quantity of superplasticizer required to obtain a slump of 76 ± 12 mm (3 ± ½ in.). Figures 3.84-3.86 present the average free shrinkage curves for this set. The batches using different superplasticizers exhibited significantly more shrinkage than the control batch at all ages. The difference is statistically significant at the highest level of confidence for all three types of superplasticizers (Table 3.32a). Figure 3.85 shows that, up to age of 180 days, there appears to be no noticeable difference among the shrinkage values exhibited by the concretes containing superplasticizers. After 180 days (Figure 3.86), the concrete containing Rheobuild 1000 experienced more shrinkage than the other batches containing a superplasticizer; the difference is statistically significant. Also, the results of Student's t-test (Table 3.32a) indicate that the concrete containing Glenium 3000 NS exhibited higher shrinkage than the batch containing Adva 100 (difference of 10 $\mu\varepsilon$, statistically significant at 80 percent confidence level) at 30 days. This difference, however, is not statistically significant at later ages.

For the air-entrained concrete in Program V, the superplasticizer dosages were adjusted to obtain the same slump for all batches. The control batch did not contain a superplasticizer; rather, an increased paste content was used to obtain the same slump as the other batches with superplasticizers. The results for this set are presented in Figures 3.87-3.89. At 30 days (Figure 3.87), there is little difference between the shrinkage of different batches. The results of Student's t-test (Table 3.32b) support this observation, indicating that the use of superplasticizers increases the shrinkage of concrete, but that, for this comparison, the shrinkage is increased to an extent that it would be experienced by increasing the paste content (from 24.5 percent to 28.7 percent) to obtain a similar slump. From 30 to 180 days, the batch containing Rheobuild 1000 exhibited less shrinkage than rest of the batches (Figure 3.88). At 180 and 365 days, the concrete containing Rheobuild exhibited less shrinkage than rest of the batches, while the highest shrinkage was exhibited by control concrete. The differences are relatively small (40 to 54 με) and are not statistically significant. The lack of a significant difference could be due to the large scatter of data observed in the individual specimens of this set.

3.7.2 SUMMARY OF PROGRAM V

Although the results of different sets in the superplasticizer program are inconsistent, there are reasons to believe that the superplasticizers increased the shrinkage of concrete. For most of non-air-entrained batches, the concrete containing a superplasticizer experienced higher shrinkage than the control concrete. However, no clear trend could be obtained for change in shrinkage with change in dosage of superplasticizers. The lack of a trend could be due to the increased set retardation for the mixes with the higher dosages, as discussed earlier. For the batches in which the superplasticizer dosages were based on the quantity required to obtain a slump of 76 ± 12 mm (3 ± ½ in.), an increase in shrinkage was observed for superplasticized batches compared to the control batch for non-air-entrained concrete. For the air-entrained batches, because the control batch contained significantly more paste to obtain similar slump to the superplasticized batches, it was expected that the superplasticized batches would experience less shrinkage than the control batches, but no difference was observed. This indicates that the superplasticizers increased the shrinkage of concrete. Additional batches designed in a similar manner are needed, however, to fully justify such a conclusion.

3.8 COMPARISON OF RESULTS WITH PREVIOUS WORK

Most researchers agree that an increase in the volume of cement paste in concrete will lead to higher drying shrinkage. The effect of *w/c* ratio on shrinkage is not clearly understood, and different studies have led to conflicting conclusions. Hindy et al. (1994) observed increased shrinkage with a higher *w/c* ratio. A relatively small reduction in shrinkage was observed with a lower *w/c* ratio by Bissonnette, Pierre, and Pigeon (1999). No clear trend of shrinkage with *w/c* ratio was found by

Bloom and Bentur (1995). Bennett and Loat (1970) reported an increase in shrinkage with higher *w/c* ratios and paste contents. The current results indicate no clear trend of shrinkage with *w/c* ratio. The effect of increased aggregate content (and, in turn, reduced cement paste), however, is clearly observed. An increased aggregate content resulted in lower shrinkage in all concrete mixes. It is worth noting that in many of the previous studies, a change in the *w/c* ratio was associated with a change in paste content. As a result, no firm conclusions can be made in regard to the effect of *w/c* ratio based on past work, but it appears to have, at most, a minor effect for mixes with equal paste content.

An increase in shrinkage with finer cements was reported by Bennett and Loat (1970). They also observed that the finer cements, however, did not lead to significant increase in cracking tendency. This study compared the shrinkage of concrete containing coarse ground Type II cement (Blaine fineness = 306 m^2/kg) with that occurring for concrete containing Type I/II cement (Blaine Fineness = 378 m^2/kg) in Programs I and IV. In both programs, shrinkage was lower when Type II coarse ground cement was used.

Most of the previous researchers reported that shrinkage decreases with use of stiffer and less porous aggregates. Carlson (1938) reported that the compressibility of aggregates was a major factor influencing the shrinkage of concrete. In that study, some aggregates affected the shrinkage through increased water demand for constant workability, but many of the aggregates affected the shrinkage through the physical properties of aggregate itself. Alexander (1996) reported lower shrinkage for concrete made with aggregates that had higher moduli of elasticity. Overall in this study, concrete containing denser aggregates (quartzite and granite) exhibited less shrinkage than concrete containing a more porous aggregate (limestone). The results for individual batches, however, were not always consistent with this observation.

Conflicting conclusions have been made by various researchers regarding the effect of mineral admixtures on concrete shrinkage. Khatri and Sirivivatnanon (1995) reported higher shrinkage with the use of slag or fly ash. The use of silica fume led to higher early age shrinkage, but the long-term shrinkage decrease when silica fume was used. They suggested that, although long-term shrinkage is decreased, the higher early age shrinkage could lead to significant cracking because of low tensile strength of concrete at early age. Atis (2003), however, reported a decrease in drying shrinkage with the use of fly ash. The reduction was greater with higher percentages of fly ash replacement. A significant increase in shrinkage with silica fume replacement was observed in a study by Rao (1998). Whiting, Detwiler, and Lagergren (2000) also reported high early age shrinkage with the use of silica fume. They observed that the cracking tendency was affected only when silica fume concrete were not properly cured. In this study, fly ash appears to consistently increase the shrinkage of concrete. Slag, however, does not appear to affect the ultimate shrinkage of concrete to a great extent, but early age shrinkage may be increased with the use of slag. No certain conclusions can be made about the use of silica fume. In most previous studies, the effect of differences in specific gravities of mineral admixtures and cement, and in turn, the effect on the change in the paste content of the mixes were not considered by researchers when reaching their conclusions, and in many cases, the concrete containing mineral admixtures was cured for only a short period. In future studies, the paste content of mixes should be held constant when studying the effect of mineral admixtures on shrinkage. Specimens should also be cured for longer times in studies evaluating the effect of mineral admixtures on shrinkage.

Alsayed and Amjad (1994) observed reduced shrinkage with intermittent wet curing as compared to dry curing. They reported that none of the curing methods, however, effectively reduced the early age shrinkage of concrete. Nassif, Suksawang, and Mohammed (2003) reported that moist curing with wet burlap led to lower shrinkage as compared to air curing or curing using a curing compound. They also reported that concrete needs to be covered immediately with wet burlap after finishing to effectively limit shrinkage. T. C. Powers (1959), however, claimed that moist curing has no significant effect on shrinkage. A significant effect of curing period on both air-entrained and non-air-entrained concrete containing either Type I/II or Type II coarse ground cement was observed in this study. Longer curing periods allow concrete to swell, delay the initiation of drying and result in increased hydration, which limits the quantity of water that can be lost due to evaporation. With few exceptions, concrete cured for longer periods exhibited lower shrinkage than that cured for shorter periods.

Qi, Li, and Ma (2002) reported a reduction in free shrinkage with the use of a high superplasticizer content. Johnston, Gamble, and Malhotra (1979), however, observed increased shrinkage with some admixture types and little effect on shrinkage with other admixture types. An analysis of available data by Brooks (1989) indicated that the use of superplasticizers increases the creep and shrinkage of concrete by 3 to 132 percent. The results of this study indicate that superplasticizers increase the shrinkage of concrete, although the results from different sets in the superplasticizer program are inconsistent. There is no clear trend of change in shrinkage, however, with the dosage of superplasticizer.

Overall, most of the studies, including this study, indicate that an increase in aggregate content (and reduction in paste content) leads to decreased shrinkage. Most researchers also agree that moist curing, and longer curing periods, as well as coarser cements help to limit shrinkage. More work is needed to clearly understand the effect of aggregate type, mineral admixtures, and superplasticizers on shrinkage.

CHAPTER 4: SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The effects of paste volume, water-cement (*w/c*) ratio, aggregate type, cement type, curing period, mineral admixtures, and superplasticizers on the free shrinkage of concrete are evaluated with the goal of establishing guidelines to reduce cracking in reinforced concrete bridge decks. The work is organized in five test programs. Three 76 × 76 × 286 mm (3 × 3 × 11¼ in.) concrete prisms were cast and tested in accordance with ASTM C 157 for each mixture up to an age of 365 days under controlled conditions of 23 ± 2°C (73 ± 3°F) and 50 ± 4 percent relative humidity. The specimens were cured in lime-saturated water until drying began. Drying in the controlled environment began on day 3 after casting, except as noted below for Program IV.

Program I evaluated the effect of aggregate content (and, in turn, paste content) and water-cement ratio on shrinkage using two types of cement. A total of 18 batches were made with aggregate contents of 60, 70, and 80 percent, water-cement ratios of 0.40, 0.45, and 0.50, and two either Type I/II or Type II coarse-ground cement.

Program II was used to evaluate the effect of coarse aggregate type on shrinkage. Four sets of specimens, three non-air-entrained and one air-entrained, were cast. In the first set, two types of coarse aggregate, limestone and quartzite, were used. Granite was added as a third coarse aggregate for the balance of Program II.

Type I/II cement was used with a *w/c* ratio of 0.45 and an aggregate content of 70 percent in all batches in this program.

Program III evaluated the effects of mineral admixtures on concrete shrinkage. A total of three sets were cast, and all of the batches used non-air-entrained concrete. The first two sets contained concrete with one of three mineral admixtures, Class C fly ash, blast furnace slag, or silica fume, as a partial replacement by volume for cement. Volume replacements of 30 percent were used for Class C fly ash and slag and 10 percent for silica fume. Free shrinkage was compared with that of a control batch containing no mineral admixture. An aggregate content of 70 percent was used with a *w/c* ratio of 0.45 by mass for the control batch. For concrete containing mineral admixtures, the aggregate content was same, but the *w/cm* ratio (by weight) varied slightly, because of the difference in specific gravities between cement and the mineral admixtures. For concrete containing slag, fly ash, and silica fume, the *w/cm* ratios were 0.465, 0.469, and 0.470, respectively. In the third set, two control batches were made, one without any admixtures and one with a low dosage of Adva 100 superplasticizer. These batches were compared with a batch containing a 10 percent volume replacement of cement by silica fume. The purpose of this additional set was to evaluate the effect of better distribution of silica fume in the mix, and to compare the silica fume concrete (containing superplasticizer) with a control concrete containing superplasticizer, as well as a control concrete containing no superplasticizer. Silica fume was premixed with fine aggregates before mixing the concrete to obtain a better dispersion of silica fume particles throughout the mix. This batch also used a low dosage of Adva 100 superplasticizer to improve the workability of the mix.

Program IV was used to study the effects of increased curing on shrinkage for concrete containing Type I/II cement and Type II coarse ground cement. Specimens were cured for 3, 7, 14, and 28 days in lime-saturated water. Shrinkage was compared based on both the age after casting and drying period. Both non-air-entrained and air-entrained concretes were tested. All batches used a *w/c* ratio of 0.45 and aggregate content of 70 percent.

Program V studied the effects of superplasticizers on shrinkage. The types of superplasticizers and the dosage rates were compared using five sets of test specimens. Four sets were non-air-entrained, and one set was air-entrained. In the first set, three dosage rates of Glenium 3000 NS or Rheobuild 1000 were used in non-air-entrained concrete. In the second set, a third superplasticizer, Adva 100, was used, along with the two previous superplasticizers. In the third set, the batches containing Adva 100 from second set were replicated. In the fourth set, non-air-entrained concrete was used, and the dosage rates of three superplasticizers were adjusted to obtain a slump of 76 ± 12 mm (3 ± ½ in.). The control batch used no chemical admixtures and had no specific slump requirements. In the fifth set, air-entrained concrete was used. The dosage rates of the superplasticizers were adjusted in a manner similar to that in fourth set. The control batch did not use a chemical admixture, but a slump of 76 ± 12 mm (3 ± ½ in.) was obtained by increasing the paste content of the mix. All of the batches in Program V used an aggregate content of 70 percent and a *w/c* ratio of 0.45.

4.2 CONCLUSIONS

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

1. Concrete shrinkage decreases with an increase in the aggregate content (and decrease in paste content) of the mix. For a given aggregate content, no clear effect of water-cement ratio on the shrinkage is observed.
2. In general, granite coarse aggregates result in lower shrinkage than limestone coarse aggregates. A similar conclusion cannot be made with quartzite coarse aggregate, although in some cases shrinkage of concrete containing quartzite coarse aggregate was lower than that of concrete containing limestone.
3. The use of a 30 percent volume replacement of portland cement by Class C fly ash without changing the water or aggregate content in concrete generally leads to increased shrinkage. Laboratory mixes using Class C fly ash exhibited more shrinkage than the control concrete in most cases.
4. The use of a 30 percent volume replacement of portland cement by blast furnace slag without changing the water or aggregate content in concrete can lead to increased early age shrinkage, although the ultimate shrinkage does not appear to be significantly affected.

5. An increase in the curing period helps to reduce shrinkage. Possible reasons include delayed initiation of drying, initial expansion of the concrete, and increased hydration that limits the quantity of water that can be lost due to evaporation. In the current study, a significant reduction in shrinkage was observed when the curing period is increased from 7 to 14 or 28 days. The difference in shrinkage for concrete cured for three days and concrete cured for seven days was not large in many cases.
6. The use of Type II coarse ground cement results in significantly less shrinkage than Type I/II cement. The reduction in shrinkage was observed for all mixtures and all curing periods.
7. The use of superplasticizers in concrete appears to increase shrinkage to a degree. The results, however, do not present a clear picture of the effect of superplasticizer dosage on shrinkage.

4.3 RECOMMENDATIONS

1. To minimize the shrinkage and, in turn, cracking in bridge decks, mixes with lower paste contents and higher aggregate contents should be used.
2. Granite should be used as coarse aggregate instead of limestone wherever possible.
3. The use of mineral admixtures in bridge deck concrete should be avoided until sufficient data indicating a reduction in shrinkage with use of these materials is available.

4. In future testing, Class F fly ash should be tested for its effect on the shrinkage. The duration of moist curing should be increased if mineral admixtures are used.
5. The duration of curing should be increased for the tests, with recommended minimums of 7 and 14 days.
6. Type II coarse-ground cement (Blaine fineness less than approximately 310 m^2/kg) should be used wherever available, once test results are available to demonstrate that the permeability and compressive strength of the concrete are not adversely affected.

REFERENCES

Alexander (1996). "Aggregates and the Deformation Properties of Concrete," *ACI Materials Journal*, Nov.-Dec., Vol. 93, No. 6, pp. 569-577.

Alsayed, S. and Amjad, M. (1994). "Effect of Curing Conditions on Strength, Porosity, Absorptivity and Shrinkage of Concrete in Hot and Dry Climate," *Cement and Concrete Research*, Vol. 24, Jul., No. 7, pp. 1390-1398.

American Society of Civil Engineers (2005). "Report Card for America's Infrastructure," ASCE website: www.asce.org/reportcard/2005

ASTM C 157-04 (2004). "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," *2005 Annual Book of ASTM Standards*, Vol. 4.02, American Society of Testing and materials, West Conshohocken, PA.

Bennett, E. and Loat, D. (1970). "Shrinkage and Creep of Concrete as Affected by the Fineness of Portland Cement," *Magazine of Concrete Research*, Jun., Vol. 22, No. 71, pp. 69-78.

Bissonnette, B., Pierre, P., and Pigeon, M. (1999). "Influence of Key Parameters on Drying Shrinkage of Cementitious Materials," *Cement and Concrete Research*, Oct., Vol. 29, No. 10, pp. 1655-1662.

Bloom, R. and Bentur, A. (1995). "Free and Restrained Shrinkage of Normal and High-Strength Concretes," *ACI Materials Journal*, Mar-Apr., Vol. 92, No. 2, pp. 211-217.

Brooks, J. (1989) "Influence of Mix Proportions, Plasticizers, and Superplasticizers on Creep and Drying Shrinkage of Concrete," *Magazine of Concrete Research*, Sep., Vol. 41, No. 148, pp. 145-153.

Cabrera, J. G., and Atis, C. D. (1999). "Design and Properties of High Volume Fly Ash High-Performance Concrete," *Proc., ACI Int. Conf. On High Performance Concrete and Performance and Quality Control Structures*, ACI SP-186, pp. 21-37.

Carlson, R. (1938). "Drying Shrinkage of Concrete as Affected by Many Factors," *ASTM Proceedings*, Vol. 38, Part II, pp. 419-440.

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

Federal Highway Administration (FHWA) (2005). "FHWA Bridge Programs NBI Data," FHWA website: www.fhwa.dot.gov/bridge/defbr05.htm

Florida Department of Transportation (FDOT), (2005), "Evaluation of Shrinkage Cracking Potential of Concrete Used in Bridge Decks in Florida," Report No. 4910-4504-797-12, Sep., pp. 87-94.

Hindy, E., Miao, B., Chaallal, O., and Aïtcin, P. (1994). "Drying Shrinkage of Ready-Mixed High-Performance Concrete," *ACI Structural Journal*, May-Jun., Vol. 91, No. 3, pp. 300-305.

Johnston, C., Gamble, B., and Malhotra, V. (1979) "Effects of Superplasticizers on Properties of Fresh and Hardened Concrete," *Transportation Research Record*, No. 720, pp. 1-7.

Khatri, R. and Sirivivatnanon, V. (1995). "Effect of Different Supplementary Cementitious Materials on Mechanical Properties of High Performance Concrete," *Cement and Concrete Research*, Jan., Vol. 25, No. 1, pp. 209-220.

Mang, T., Subramanian, R., Brown, D., and Broward, C. (2005). "Evaluation of Shrinkage Cracking Potential of Concretes Used in Bridge Decks in Florida," University of Florida, Report No. 4910-4504-797-12, pp.39-49, 80-81.

McLeod, H. (2005). "Guide for Developing Optimized Concrete Mixtures," M.S. Thesis, University of Kansas, Lawrence, Kansas, 33 pp.

Mindess, S., Young, F., and Darwin, D (2003). *Concrete*, 2nd ed., Prentice-Hall, Inc., Englewood Cliffs, New Jersey, pp. 417-432.

Mokarem, D., Weyers, R., and Lane, D. (2005). "Development of a Shrinkage Performance Specifications and Prediction Model Analysis for supplemental cementitious material concrete mixtures," *Cement and Concrete Research*, May, Vol. 35, No. 5, pp. 918-925.

Nassif, H., Suksawang, N., and Mohammed, M. (2003). "Effect of Curing Methods on Early-Age and Drying Shrinkage of High-Performance Concrete," *Transportation Research Record*, Vol. 1834, Paper No. 03-4120, pp. 48-58.

Phelan, W. and Martin, R. (1995). "How Do Admixtures Influence Shrinkage?," *Concrete Construction*, Jul., Vol. 40, No. 7, pp. 611-617.

Pickett, G. (1956). "Effect of Aggregate on Shrinkage of Concrete and a Hypothesis Concerning Shrinkage," *ACI Journal, Proceedings*, Jan.,Vol. 52 No. 1, pp. 581-590.

Powers, T. C. (1959). “Causes and Control of Volume Change,” *Journal of Portland Cement Association Research and Development Laboratories*, Jan., Vol. 1, pp. 29-39.

Qi, M., Li, Z., and Ma, B. (2002). “Shrinkage and Cracking Behavior of High Performance Concrete Containing Chemical Admixtures,” *Journal of Zhejiang University SCIENCE*, Jun., Vol. 3, No. 2, pp. 188-193.

Rao, G. (1998). “Influence of Silica Fume Replacement of Cement on Expansion and Drying Shrinkage,” *Cement and Concrete Research*, Oct., Vol. 28, No. 10, pp. 1505-1509.

Shilstone, J. M., Sr. (1990). “Concrete Mixture Optimization,” *Concrete International*, Jun., Vol. 12, No. 6, pp. 33-39.

Whiting, A., Detwiler, R., and Lagergren, E. (2000). “Cracking Tendency and Drying Shrinkage of Silica Fume Concrete for Bridge Deck Applications,” *ACI Materials Journal*, Jan.-Feb., Vol. 97, No. 1, pp. 71-76.

TABLES

Table 2.1 – Program I (Aggregate Content, Water-Cement Ratio, Cement Type) test matrix

w/c Ratio		Aggregate content by volume		
		60%	**70%**	**80%**
	Type I/II cement			
	0.40	Batch 68	Batch 66	Batch 62
	0.45	Batch 69	Batch 64	Batch 63
	0.50	Batch 70	Batch 65	Batch 67
	Type II coarse-ground cement			
	0.40	Batch 77	Batch 74	Batch 71
	0.45	Batch 78	Batch 75	Batch 72
	0.50	Batch 79	Batch 76	Batch 73

0.008 m^3 (0.01 yd^3) hand batches
Mix proportions in Table 2.13

Table 2.2 – Program II (Coarse Aggregate Types) test matrix

Limestone	Batch 94	Type I/II cement, 0.0478 m^3 (0.0625 yd^3) hand batches, Mix proportions in Table 2.14
Quartzite	Batch 95	
Quartzite	Batch 187	Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches, Mix proportions in Table 2.14
Limestone	Batch 188	
Granite	Batch 189	
Quartzite	Batch 198	Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches, Mix proportions in Table 2.14
Limestone	Batch 199	
Granite	Batch 200	
Quartzite	Batch 262	Type I/II cement, 0.016 m^3 (0.02 yd^3) hand batches, Mix proportions in Table 2.14
Limestone	Batch 263	
Granite	Batch 264	

Table 2.3 – Program III (Mineral Admixtures) test matrix

Control	Batch 85	Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Mix proportions in Table 2.15
30% Slag replacement	Batch 86	
30% Class C Fly Ash replacement	Batch 87	
10% Silica Fume replacement	Batch 88	
Control	Batch 194	Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Mix proportions in Table 2.15
30% Slag replacement	Batch 195	
30% Class C Fly Ash replacement	Batch 196	
10% Silica Fume replacement	Batch 197	
Control	Batch 202	Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Mix proportions in Table 2.15
Control with superplasticizer	Batch 203	
10 % Silica Fume replacement	Batch 204	

Table 2.4 – Program IV (Curing Period) test matrix

3 Day Cure	Batch 165	Type I/II cement 0.0325 m^3 (0.0425 yd^3) mixer batches Mix proportions in Table 2.16
7 Day Cure	Batch 165	
14 Day Cure	Batch 165	
28 Day Cure	Batch 165	
3 Day Cure	Batch 166	Type II coarse-ground cement 0.0325 m^3 (0.0425 yd^3) mixer batches Mix proportions in Table 2.16
7 Day Cure	Batch 166	
14 Day Cure	Batch 166	
28 Day Cure	Batch 166	
3 Day Cure	Batch 201	Type I/II cement 0.0325 m^3 (0.0425 yd^3) mixer batches (air-entrained) Mix proportions in Table 2.16
7 Day Cure	Batch 201	
14 Day Cure	Batch 201	
28 Day Cure	Batch 201	
3 Day Cure	Batch 207	Type II coarse-ground cement 0.0325 m^3 (0.0425 yd^3) mixer batches Mix proportions in Table 2.16
7 Day Cure	Batch 207	
14 Day Cure	Batch 207	
28 Day Cure	Batch 207	

Table 2.5 – Program V (Superplasticizers) test matrix

Control	Batch 167	Batch 174 was a repeat batch of Batch 170 Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Glenium 3000NS base chemical: Polycarboxalate Rheobuild 1000 base chemical: Naphthalene Mix proportions in Table 2.17
Low dosage Glenium 3000NS	Batch 168	
Medium dosage Glenium 3000NS	Batch 169	
High dosage Glenium 3000NS	Batch 170, Batch 174	
Low dosage Rheobuild 1000	Batch 171	
Medium dosage Rheobuild 1000	Batch 172	
High dosage Rheobuild 1000	Batch 173	
Control	Batch 175	Batch 182 was a repeat batch of Batch 181 Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Glenium 3000NS base chemical: Polycarboxalate Rheobuild 1000 base chemical: Naphthalene Mix proportions in Table 2.17
Low dosage Glenium 3000NS	Batch 176	
Medium dosage Glenium 3000NS	Batch 177	
High dosage Glenium 3000NS	Batch 178	
Low dosage Rheobuild 1000	Batch 179	
Medium dosage Rheobuild 1000	Batch 180	
High dosage Rheobuild 1000	Batch 181, Batch 182	
Control	Batch 183, Batch 193	Batches 193, 190, 191 and 192 are repeats of batches 183, 184, 185 and 186, respectively. Type I/II cement, 0.008 m^3 (0.01 yd^3) hand batches Adva 100 base chemical: Polyoxyalkylene Mix proportions in Table 2.17
Low dosage Adva 100	Batch 184, Batch 190	
Medium dosage Adva 100	Batch 185, Batch 191	
High dosage Adva 100	Batch 186, Batch 192	
Control	Batch 208	Superplasticizer dosages for 3±½ in.slump for batches 209, 210, 211 Type I/II cement, 0.016 m^3 (0.02 yd^3) mixer batches Mix proportions in Table 2.17
Adva 100	Batch 209	
Glenium 3000NS	Batch 210	
Rheobuild 1000	Batch 211	
Control	Batch 260	Superplasticizer dosages for 3±½ in.slump for batches 249, 256, 259 Type I/II cement, 0.016 m^3 (0.02 yd^3) mixer batches (air-entrained) Mix proportions in Table 2.17
Adva 100	Batch 259	
Glenium 3000NS	Batch 249	
Rheobuild 1000	Batch 256	

Table 2.6– Pea gravel gradations

Sieve size	*% Retained*				
	Gradation 1	**Gradation 2**	**Gradation 3**	**Gradation 4**	**Gradation 5**
9.51 mm (3/8 in.)	0	0	0	0	0
4750 μm (No. 4)	10.3	12.5	9.6	9.5	8.4
2360 μm (No. 8)	41.0	40.5	33.6	40.9	35.3
1180 μm (No. 16)	32.9	30.2	33.7	35.2	34.4
600 μm (No. 30)	8.6	9.0	12.2	8.8	11.0
300 μm (No. 50)	4.9	5.6	7.4	3.4	6.6
150 μm (No. 100)	1.8	1.7	3.0	1.3	3.3
75 μm (No. 200)	0.4	0.4	0.4	0.3	0.6
Pan	0.1	0.2	0.1	0.6	0.3

Gradation 1: Program I, Program III: 85 through 88, Program II: 94 and 95
Gradation 2: Program V: 175 through 186, Program IV: 165 and 166,
Gradation 3: Program II 187 through 189 and 198 through 200, Program III 94 through 197, Program IV: 201 and 207,
Program V: 190 through 193, 208 through 211
Gradation 4: Program V: 249, 256, 259 and 260
Gradation 5: Program II: 262 through 264

Table 2.7 – Sand gradations

Sieve size	*% Retained*					
	Gradation 1	**Gradation 2**	**Gradation 3**	**Gradation 4**	**Gradation 5**	**Gradation 6**
9.51 mm (3/8 in.)	0	0	0	0	0	0
4750 μm (No. 4)	1.4	1.6	1.4	2.0	0.9	0.9
2360 μm (No. 8)	13.1	12.7	12.8	11.8	10.0	8.5
1180 μm (No. 16)	21.3	20.9	23.8	20.1	18.9	17.2
600 μm (No. 30)	24.2	25.4	27.6	25.1	25.7	26.1
300 μm (No. 50)	28.6	29.5	25.7	28.0	27.5	30.9
150 μm (No. 100)	10.3	8.6	7.6	11.5	13.3	14.2
75 μm (No. 200)	1.0	1.0	0.9	1.3	3.1	1.7
Pan	0.1	0.2	0.2	0.2	0.6	0.4

Gradation 1: Program I, Program III: 85 through 88, Program II: 94 and 95
Gradation 2: Program IV: 165 and 166, Program V: 167 through 174
Gradation 3: Program V: 175 through 186
Gradation 4: Program II 187 through 189 and 198 through 200, Program III 194 through 197, Program IV: 201 and 207,
Program V: 190 through 193, 208 through 211
Gradation 5: Program V: 249, 256, 259, and 260
Gradation 6: Program II: 262 through 264

Table 2.8 – 19-mm (3/4-in.) Granite gradations

Sieve size	***% Retained***	
	Gradation 1	**Gradation 2**
38.1 mm (1 ½ in.)	0	0
25.4 mm (1 in.)	0	0
19.0 mm (¾ in.)	1.3	1.3
12.7 mm (½ in.)	20.4	35.8
9.51 mm (3/8 in.)	30.0	32.6
4750 μm (No. 4)	45.5	27.8
2360 μm (No. 8)	1.7	1.1
1180 μm (No. 16)	1.1	1.5

Gradation 1: Program II: 189 and 200
Gradation 2: Program II: 264

Table 2.9 – 25-mm (1-in.) Limestone gradations

Sieve size	***% Retained***	
	Gradation 1	**Gradation 2**
38.1 mm (1 ½ in.)	0	0
25.4 mm (1 in.)	0	0
19.0 mm (¾ in.)	25.9	25.9
12.7 mm (½ in.)	71.7	71.7
9.51 mm (3/8 in.)	1.5	1.5
4750 μm (No. 4)	0.2	0.2
2360 μm (No. 8)	0.0	0.0
1180 μm (No. 16)	0.6	0.6

Gradation 1: Program I, Program III: 85 through 88, Program II: 94
Gradation 2: Program IV: 165 and 166

Table 2.10 – 19-mm (3/4-in.) Limestone gradations

Sieve size	*% Retained*					
	Gradation 1	**Gradation 2**	**Gradation 3**	**Gradation 4**	**Gradation 5**	**Gradation 6**
38.1 mm (1 ½ in.)	0	0	0	0	0	0
25.4 mm (1 in.)	0	0.1	0	0	0	0
19.0 mm (¾ in.)	0	0.1	0	0	0	0
12.7 mm (½ in.)	23.0	11.3	17.5	18.9	22.6	17.1
9.51 mm (3/8 in.)	26.5	18.7	25.8	25.5	26.1	29.0
4750 µm (No. 4)	42.1	48.7	45.6	46.4	41.7	47.7
2360 µm (No. 8)	6.1	15.1	6.1	7.7	7.4	3.8
1180 µm (No. 16)	2.3	6.1	2.8	1.5	2.2	2.3

Gradation 1: Program I, Program III: 85 through 88, Program II: 95
Gradation 2: Program IV: 165 and 166, Program V: 167 through 174
Gradation 3: Program V: 175 through 186
Gradation 4: Program II: 188 and 199, Program V: 190 through 193, Program III: 194 through 197, 202 through 204, Program IV: 201
Gradation 5: Program V: 208 through 211
Gradation 6: Program V: 249, 256, 259 and 260, Program II: 263

Table 2.11 – Quartzite gradations

Sieve size	***% Retained***			
	Gradation 1 19 mm (3/4-in.)	**Gradation 2 19 mm (3/4-in.)**	**Gradation 3 25 mm (1-in.)**	**Gradation 4 (Chip)**
38.1 mm (1 ½ in.)	0	0	0	0
25.4 mm (1 in.)	0	0	0	0
19.0 mm (¾ in.)	2.0	3.9	8.3	0
12.7 mm (½ in.)	31.1	42.8	46.9	0.3
9.51 mm (3/8 in.)	34.4	24.6	23.0	17.5
4750 µm (No. 4)	31.4	25.7	17.6	76.0
2360 µm (No. 8)	0.8	1.4	2.3	5.5
1180 µm (No. 16)	0.3	1.6	1.9	0.7

Gradation 1: Program II: 187 and 198
Gradation 2: Program II: 262
Gradation 3: Program II: 94
Gradation 4: Program II: 94

Table 2.12 Chemical Composition of mineral admixtures

Component	Percentage		
	Fly Ash	**Slag**	**Silica Fume**
SiO_2	26.70	32.70	90.87
Al_2O_3	17.57	8.58	0.48
Fe_2O_3	6.19	1.70	1.62
CaO	32.01	44.82	0.42
MgO	7.30	9.33	0.98
Na_2O	2.35	0.30	0.43
K_2O	0.31	0.41	1.29
SO_3	4.17	1.16	0.28

Table 2.13 – Mix Proportions-Program I-Aggregate Content, Water-Cement Ratio, Cement Type

Batch	**62**	**63**	**64**	**65**	**66**
w/c	0.40	0.45	0.45	0.5	0.40
Aggregate content %	80	80	70	70	70
Cement, kg/m^3 (lb/yd^3):					
Type I/II	281 (473)	262 (442)	393 (663)	369 (622)	421 (709)
Coarse-ground Type II	-	-	-	-	-
Water, kg/m^3 (lb/yd^3)	112 (189)	118 (199)	177 (298)	185 (311)	169 (284)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	416 (701)	416 (701)	364 (613)	364 (613)	364 (613)
19-mm (3/4-in.) Limestone	688 (1159)	688 (1159)	602 (1014)	602 (1014)	602 (1014)
Fine Aggregate, kg/m^3 (lb/yd^3)	623 (1049)	623 (1049)	545 (918)	545 (918)	545 (918)
Pea Gravel, kg/m^3 (lb/yd^3)	353 (595)	353 (595)	309 (521)	309 (521)	309 (521)

Batch	**67**	**68**	**69**	**70**
w/c	0.50	0.40	0.45	0.5
Aggregate content %	80	60	60	60
Cement, kg/m^3 (lb/yd^3):				
Type I/II	246 (415)	561 (946)	525 (884)	492 (829)
Coarse-ground Type II	-	-	-	-
Water, kg/m^3 (lb/yd^3)	123 (207)	224 (378)	236 (398)	246 (415)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	416 (701)	312 (526)	312 (526)	312 (526)
19-mm (3/4-in.) Limestone	688 (1159)	516 (869)	516 (869)	516 (869)
Fine Aggregate, kg/m^3 (lb/yd^3)	623 (1049)	467 (787)	467 (787)	467 (787)
Pea Gravel, kg/m^3 (lb/yd^3)	353 (595)	265 (446)	265 (446)	265 (446)

Quantities of cement, water and aggregate based on 2% air

Table 2.13 – Mix Proportions-Program I-continued

Batch	**71**	**72**	**73**	**74**	**75**
w/c	0.40	0.45	0.50	0.40	0.45
Aggregate content %	80	80	80	70	70
Cement, kg/m^3 (lb/yd^3):					
Type I/II	-	-	-	-	-
Coarse-ground Type II	281 (473)	262 (442)	246 (415)	421 (709)	393 (663)
Water, kg/m^3 (lb/yd^3)	112 (189)	118 (199)	123 (207)	169 (284)	177 (298)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	416 (701)	416 (701)	416 (701)	364 (613)	364 (613)
19-mm (3/4-in.) Limestone	688 (1159)	688 (1159)	688 (1159)	602 (1014)	602 (1014)
Fine Aggregate, kg/m^3 (lb/yd^3)	623 (1049)	623 (1049)	623 (1049)	545 (918)	545 (918)
Pea Gravel, kg/m^3 (lb/yd^3)	353 (595)	353 (595)	353 (595)	309 (521)	309 (521)

Batch	**76**	**77**	**78**	**79**
w/c	0.50	0.40	0.45	0.50
Aggregate content %	70	60	60	60
Cement, kg/m^3 (lb/yd^3):				
Type I/II	-	-	-	-
Coarse-ground Type II	369 (622)	561 (946)	525 (884)	492 (829)
Water, kg/m^3 (lb/yd^3)	185 (311)	224 (378)	236 (398)	246 (415)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	364 (613)	312 (526)	312 (526)	312 (526)
19-mm (3/4-in.) Limestone	602 (1014)	516 (869)	516 (869)	516 (869)
Fine Aggregate, kg/m^3 (lb/yd^3)	545 (918)	467 (787)	467 (787)	467 (787)
Pea Gravel, kg/m^3 (lb/yd^3)	309 (521)	265 (446)	265 (446)	265 (446)

Quantities of cement, water, and aggregates based on 2% air

Table 2.14 – Mix Proportions-Program II-Aggregate Types

Batch	**94**	**95**	**187**	**188**	**189**
w/c	0.45	0.45	0.45	0.45	0.45
Aggregate content %	70	70	70	70	70
Cement, kg/m^3 (lb/yd^3):					
Type I/II	374 (630)	374 (630)	374 (630)	374 (630)	374 (630)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	-	364 (613)	-	-	-
19-mm (3/4-in.) Limestone	-	635 (1070)	-	882 (1485)	-
25-mm (1-in.) Quartzite	883 (1488)	-	-	-	-
Quartzite Chip	130 (219)	-	-	-	-
19-mm (3/4-in.) Quartzite	-	-	899 (1514)	-	-
19-mm (3/4-in.) Granite	-	-	-	-	895 (1508)
Fine Aggregate, kg/m^3 (lb/yd^3)	582 (981)	639 (1076)	521 (877)	511 (860)	518 (873)
Pea Gravel, kg/m^3 (lb/yd^3)	245 (412)	182 (307)	420 (708)	413 (695)	419 (706)

Quantities of cement, water, and aggregates based on 2% air for batches 94 and 95
Quantities of cement, water, and aggregates based on 1.5% air for batches 187 to 189

Table 2.14 – Mix Proportions-Program II- continued

Batch	**198**	**199**	**200**
w/c	0.45	0.45	0.45
Aggregate content %	70	70	70
Cement, kg/m^3 (lb/yd^3):			
Type I/II	374 (630)	374 (630)	374 (630)
Coarse-ground Type II			
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
19-mm (3/4-in.) Limestone	-	891 (1500)	-
19-mm (3/4-in.) Quartzite	899 (1514)	-	-
19-mm (3/4-in.) Granite	-	-	895 (1508)
Fine Aggregate, kg/m^3 (lb/yd^3)	521 (877)	515 (868)	518 (873)
Pea Gravel, kg/m^3 (lb/yd^3)	420 (708)	417 (702)	419 (706)

Quantities of cement, water, and aggregates based on 1.5% air

Table 2.14 – Mix Proportions-Program II- continued

Batch	262	263	264
w/c	0.45	0.45	0.45
Aggregate content %	68.8	68.8	68.8
Cement, kg/m^3 (lb/yd^3):			
Type I/II	317 (535)	317 (535)	317 (535)
Water, kg/m^3 (lb/yd^3)	143 (241)	143 (241)	143 (241)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
19-mm (3/4-in.) Limestone: retained on 9.1 mm (3/8-in.) sieve	-	536 (902)	-
19-mm (3/4-in.) Limestone: passing through 9.1 mm (3/8-in.) sieve	-	319 (537)	-
19-mm (3/4-in.) Quartzite: retained on 9.1 mm (3/8-in.) sieve	539 (907)	-	-
19-mm (3/4-in.) Quartzite: passing through 9.1 mm (3/8-in.) sieve	321 (540)	-	-
19-mm (3/4-in.) Granite: retained on 9.1 mm (3/8-in.) sieve	-	-	539 (907)
19-mm (3/4-in.) Granite: passing through 9.1 mm (3/8-in.) sieve	-	-	321 (540)
Fine Aggregate, kg/m^3 (lb/yd^3)	315 (530)	314 (528)	315 (530)
Pea Gravel, kg/m^3 (lb/yd^3)	626 (1055)	624 (1050)	626 (1055)
Superplasticizer, mL/m^3 (oz/yd^3)	786 (20.3) [a]	786 (20.3) [a]	786 (20.3) [a]
Air-entraining Agent, mL/m^3 (oz/yd^3)	210 (5.4) [b]	210 (5.4) [b]	210 (5.4) [b]
Slump, mm (in.)	70 (2.75)	76 (3)	70 (2.75)
Air Content, %	7.40	7.40	7.40
Temperature, ˚C (˚F)	18 (64)	18 (65)	18 (65)

Quantities of cement, water, and aggregates based on 7 % air

[a] – Adva 100 (Grace Construction Products)

[b] – Daravair 1000 (Grace Construction Products)

Table 2.15 – Mix Proportions-Program III-Mineral admixtures

Batch	**85**	**86**	**87**	**88**
w/cm	0.45	0.465	0.469	0.470
Aggregate content %	70	70	70	70
Cementitious material, kg/m^3 (lb/yd^3):				
Type I/II	374 (630)	253 (426)	251 (423)	322 (542)
30% Slag	-	108 (182)	-	-
30% Fly Ash	-	-	107 (181)	-
10% Silica Fume	-	-	-	36 (60)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	364 (613)	364 (613)	364 (613)	364 (613)
19-mm (3/4-in.) Limestone	635 (1070)	635 (1070)	635 (1070)	635 (1070)
Fine Aggregate, kg/m^3 (lb/yd^3)	639 (1076)	639 (1076)	639 (1076)	639 (1076)
Pea Gravel, kg/m^3 (lb/yd^3)	182 (307)	182 (307)	182 (307)	182 (307)

Quantities of cement, water, and aggregates based on 2% air

Table 2.15 – Mix Proportions-Program III-continued

Batch	**194**	**195**	**196**	**197**
w/c	0.45	0.465	0.469	0.470
Aggregate content %	70	70	70	70
Cementitious material, kg/m^3 (lb/yd^3):				
Type I/II	374 (630)	253 (426)	251 (423)	322 (542)
30% Slag	-	108 (182)	-	-
30% Fly Ash	-	-	107 (181)	-
10% Silica Fume	-	-	-	36 (60)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
19-mm (3/4-in.) Limestone	872 (1469)	872 (1469)	872 (1469)	872 (1469)
Fine Aggregate, kg/m^3 (lb/yd^3)	702 (1183)	702 (1183)	702 (1183)	702 (1183)
Pea Gravel, kg/m^3 (lb/yd^3)	249 (420)	249 (420)	249 (420)	249 (420)
Superplasticizer, mL/m^3 (oz/yd^3)	-	-	-	699 (18) [a]

Quantities of cement, water, and aggregates based on 1.5% air
[a] – Adva 100 (Grace Construction Products)
Silica fume premixed with cement

Table 2.15 – Mix Proportions-Program III-continued

Batch	**202**	**203**	**204**
w/c	0.45	0.45	0.470
Aggregate content %	70	70	70
Cementitious material, kg/m^3 (lb/yd^3):			
Type I/II	374 (630)	374 (630)	322 (542)
30% Slag	-	-	-
30% Fly Ash	-	-	-
10% Silica Fume	-	-	36 (60)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):			
19-mm (3/4-in.) Limestone	872 (1469)	872 (1469)	872 (1469)
Fine Aggregate, kg/m^3 (lb/yd^3)	702 (1183)	702 (1183)	702 (1183)
Pea Gravel, kg/m^3 (lb/yd^3)	249 (420)	249 (420)	249 (420)
Superplasticizer, mL/m^3 (oz/yd^3)	-	699 (18) [a]	699 (18) [a]

Quantities of cement, water, and aggregates based on 1.5% air

[a] – Adva 100 (Grace Construction Products)

Silica fume premixed with fine aggregate

Table 2.16 – Mix Proportions-Program IV-Curing Period

Batch	165	166	201	207
w/c	0.45	0.45	0.45	0.45
Aggregate content %	70	70	70	70
Cement, kg/m^3 (lb/yd^3):				
Type I/II	374 (630)	-	328 (552)	-
Coarse-ground Type II	-	374 (630)	-	328 (552)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	148 (249)	148 (249)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	364 (613)	364 (613)	-	-
25-mm (3/4-in.) Limestone	635 (1070)	635 (1070)	872 (1469)	872 (1469)
Fine Aggregate, kg/m^3 (lb/yd^3)	639 (1076)	639 (1076)	702 (1183)	702 (1183)
Pea Gravel, kg/m^3 (lb/yd^3)	182 (307)	182 (307)	249 (420)	249 (420)
Air-entraining Agent, mL/m^3 (oz/yd^3)	-	-	186 (4.8) [a]	96 (2.5) [a]
Slump, mm (in.)	-	-	32 (1.25)	32 (1.25)
Air Content, %	-	-	5.50	4.75
Temperature, ˚C (˚F)	-	-	25 (77)	22 (71)

Quantities of cement, water, and aggregates for batches 165 and 166 based on 2% air
Quantities of cement, water, and aggregates for batches 201 and 207 based on 5% air
[a] – Daravair 1000 (Grace Construction Products)

Table 2.17 – Mix Proportions-Program V-Superplasticizers

Batch	**167**	**168**	**169**	**170**	**171**
w/c	0.45	0.45	0.45	0.45	0.45
Aggregate content %	75	75	75	75	75
Cement, kg/m^3 (lb/yd^3):					
Type I/II	328 (552)	328 (552)	328 (552)	328 (552)	328 (552)
Water, kg/m^3 (lb/yd^3)	148 (249)	148 (249)	148 (249)	148 (249)	148 (249)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	497 (837)	497 (837)	497 (837)	497 (837)	497 (837)
19-mm (3/4-in.) Limestone	554 (933)	554 (933)	554 (933)	554 (933)	554 (933)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	573 (965)	573 (965)	573 (965)	573 (965)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	287 (483)	287 (483)	287 (483)	287 (483)
Superplasticizers, mL/m^3 (oz/yd^3)					
Rheobuild 1000	-	-	-	-	2135 (55.2)
Glenium 3000 NS	-	854 (22.1)	1708 (44.2)	2562 (66.2)	-
Adva 100	-	-	-	-	-

Quantities of cement, water, and aggregates based on 1.5% air

Table 2.17 – Mix Proportions-Program V-Superplasticizers continued

Batch	**172**	**173**	**174**	**175**	**176**
w/c	0.45	0.45	0.45	0.45	0.45
Aggregate content %	75	75	75	75	75
Cement, kg/m^3 (lb/yd^3):					
Type I/II	328 (552)	328 (552)	328 (552)	308 (519)	308 (519)
Water, kg/m^3 (lb/yd^3)	148 (249)	148 (249)	148 (249)	139 (234)	139 (234)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	497 (837)	497 (837)	497 (837)	-	-
19-mm (3/4-in.) Limestone	554 (933)	554 (933)	554 (933)	1015 (1710)	1015 (1710)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	573 (965)	573 (965)	683 (1151)	683 (1151)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	287 (483)	287 (483)	254 (428)	254 (428)
Superplasticizers, mL/m^3 (oz/yd^3)					
Rheobuild 1000	3737 (96.6)	5338 (138.0)	-	-	-
Glenium 3000 NS	-	-	2562 (66.2)	-	804 (20.5)
Adva 100	-	-	-	-	-

Quantities of cement, water, and aggregates based on 1.5% air
Batch 174 is repetition of batch 170

Table 2.17– Mix Proportions-Program V-Superplasticizers continued

Batch	**177**	**178**	**179**	**180**	**181**
w/c	0.45	0.45	0.45	0.45	0.45
Aggregate content %	75	75	75	75	75
Cement, kg/m^3 (lb/yd^3):					
Type I/II	308 (519)	308 (519)	308 (519)	308 (519)	308 (519)
Water, kg/m^3 (lb/yd^3)	139 (234)	139 (234)	139 (234)	139 (234)	139 (234)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	-	-	-	-	-
19-mm (3/4-in.) Limestone	1015 (1710)	1015 (1710)	1015 (1710)	1015 (1710)	1015 (1710)
Fine Aggregate, kg/m^3 (lb/yd^3)	683 (1151)	683 (1151)	683 (1151)	683 (1151)	683 (1151)
Pea Gravel, kg/m^3 (lb/yd^3)	254 (428)	254 (428)	254 (428)	254 (428)	254 (428)
Superplasticizers, mL/m^3 (oz/yd^3)					
Rheobuild 1000	-	-	2010 (51.2)	3518 (89.5)	5025 (127.9)
Glenium 3000 NS	1608 (40.9)	2412 (61.4)	-	-	-
Adva 100	-	-	-	-	-

Quantities of cement, water, and aggregates based on 1.5% air

Table 2.17 – Mix Proportions-Program V-Superplasticizers continued

Batch	182	183	184	185	186
w/c	0.45	0.45	0.45	0.45	0.45
Aggregate content %	75	75	75	75	75
Cement, kg/m^3 (lb/yd^3):					
Type I/II	328 (552)	308 (519)	308 (519)	308 (519)	308 (519)
Water, kg/m^3 (lb/yd^3)	148 (249)	139 (234)	139 (234)	139 (234)	139 (234)
Coarse Aggregate, kg/m^3 (lb/yd^3):					
25-mm (1-in.) Limestone	497 (837)	-	-	-	-
19-mm (3/4-in.) Limestone	554 (933)	1015 (1710)	1015 (1710)	1015 (1710)	1015 (1710)
Fine Aggregate, kg/m^3 (lb/yd^3)	573 (965)	683 (1151)	683 (1151)	683 (1151)	683 (1151)
Pea Gravel, kg/m^3 (lb/yd^3)	287 (483)	254 (428)	254 (428)	254 (428)	254 (428)
Superplasticizers, mL/m^3 (oz/yd^3)					
Rheobuild 1000	5025 (127.9)	-	-	-	-
Glenium 3000 NS	-	-	-	-	-
Adva 100	-	-	602 (15.3)	1307 (33.3)	2010 (51.2)

Quantities of cement, water, and aggregates based on 1.5% air
Batch 182 is repetition of batch 181

Table 2.17 – Mix Proportions-Program V-Superplasticizers continued

Batch	**190**	**191**	**192**	**193**
w/c	0.45	0.45	0.45	0.45
Aggregate content %	75	75	75	75
Cement, kg/m^3 (lb/yd^3):				
Type I/II	308 (519)	308 (519)	308 (519)	308 (519)
Water, kg/m^3 (lb/yd^3)	139 (234)	139 (234)	139 (234)	139 (234)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	-	-	-	-
19-mm (3/4-in.) Limestone	1015 (1710)	1015 (1710)	1015 (1710)	1015 (1710)
Fine Aggregate, kg/m^3 (lb/yd^3)	683 (1151)	683 (1151)	683 (1151)	683 (1151)
Pea Gravel, kg/m^3 (lb/yd^3)	254 (428)	254 (428)	254 (428)	254 (428)
Superplasticizers, mL/m^3 (oz/yd^3)				
Rheobuild 1000	-	-	-	-
Glenium 3000 NS	-	-	-	-
Adva 100	-	602 (15.3)	1307 (33.3)	2010 (51.2)

Quantities of cement, water, and aggregates based on 1.5% air
Batches 190, 191, 192, and 193 are repetitions of batches 184, 185,186 and 183 respectively

Table 2.17 – Mix Proportions-Program V-Superplasticizers continued

Batch	**208**	**209**	**210**	**211**
w/c	0.45	0.45	0.45	0.45
Aggregate content %	70	70	70	70
Cement, kg/m^3 (lb/yd^3):				
Type I/II	374 (630)	374 (630)	374 (630)	374 (630)
Water, kg/m^3 (lb/yd^3)	168 (283)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
25-mm (1-in.) Limestone	-	-	-	-
19-mm (3/4-in.) Limestone	921 (1551)	921 (1551)	921 (1551)	921 (1551)
Fine Aggregate, kg/m^3 (lb/yd^3)	666 (1122)	666 (1122)	666 (1122)	666 (1122)
Pea Gravel, kg/m^3 (lb/yd^3)	236 (397)	236 (397)	236 (397)	236 (397)
Superplasticizers, mL/m^3 (oz/yd^3)				
Rheobuild 1000	-	-	-	360 (9.2)
Glenium 3000 NS	-	-	360 (9.2)	-
Adva 100	-	360 (9.2)	-	-
Slump, mm (in.)	57 (2.25)	70 (2.75)	76 (3.00)	83 (3.25)
Temperature, ˚C (˚F)	20.6 (69)	20 (68)	20 (68)	20 (68)

Quantities of cement, water, and aggregates based on 1.5% air
Superplasticizer dosages for 3.0 ± 0.5 in. slump

Table 2.17 – Mix Proportions-Program V-Superplasticizers continued

Batch	**249**	**256**	**259**	**260**
w/c	0.45	0.45	0.45	0.45
Aggregate content %	67.8	67.8	67.8	63.5
Cement, kg/m^3 (lb/yd^3):				
Type I/II	318 (535)	374 (630)	374 (630)	374 (630)
Water, kg/m^3 (lb/yd^3)	143 (241)	168 (283)	168 (283)	168 (283)
Coarse Aggregate, kg/m^3 (lb/yd^3):				
19-mm (3/4-in.) Limestone: retained on 9.1 mm (3/8-in.). sieve	439 (740)	921 (1551)	921 (1551)	412 (693)
19-mm (3/4-in.) Limestone: passing through 9.1 mm (3/8-in.) sieve	325 (548)			305 (514)
Fine Aggregate, kg/m^3 (lb/yd^3)	438 (737)	666 (1122)	666 (1122)	410 (691)
Pea Gravel, kg/m^3 (lb/yd^3)	578 (974)	236 (397)	236 (397)	542 (912)
Superplasticizers, mL/m^3 (oz/yd^3)				
Rheobuild 1000	-	1572 (40)	-	-
Glenium 3000 NS	1048 (26.7)	-	-	-
Adva 100	-	-	851 (28.4)	-
Air-entraining Agent, mL/m^3 (oz/yd^3)	164 (4.2)	393 (10)	262 (6.7)	308 (7.8)
Air Content, %	8.15	7.65	8.40	7.65
Slump, mm (in.)	89 (3.50)	64 (2.50)	70 (2.75)	76 (3.00)
Temperature, ˚C (˚F)	22.8 (73)	21.1 (70)	21.1 (70)	23.8 (75)

Quantities of cement, water, and aggregates based on 8% air
Superplasticizer dosages for 3.0 ± 0.5 in. slump for batches 249, 256 and 259
Aggregate content for 3.0 ± 0.5 in. slump for batch 260

Table 3.1 - Summary of free shrinkage measurements for Program I

Batch	**68**	**66**	**62**	**69**	**64**	**63**
Cement type	I/II	I/II	I/II	I/II	I/II	I/II
w/c ratio	0.40	0.40	0.40	0.45	0.45	0.45
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	173	130	97	163	113	97
30	427	330	290	387	330	283
90	593	460	356	539	487	343
180	673	534	387	600	535	377
365	733	550	397	630	557	377

[a]Denotes days after casting

Batch	**70**	**65**	**67**	**77**	**74**	**71**
Cement type	I/II	I/II	I/II	II CG	II CG	II CG
w/c ratio	0.50	0.50	0.50	0.40	0.40	0.40
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	147	83	93	117	90	100
30	393	313	237	297	260	217
90	540	457	310	439	347	272
180	610	503	344	510	370	278
365	627	497	343	527	313	263

[a]Denotes days after casting

Batch	**78**	**75**	**72**	**79**	**76**	**73**
Cement type	II CG	II CG	II CG	II CG	II CG	II CG
w/c ratio	0.45	0.45	0.45	0.50	0.50	0.50
% aggregate	60	70	80	60	70	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	93	63	83	97	87	83
30	260	260	217	297	287	200
90	404	337	279	427	341	273
180	448	382	292	481	368	305
365	460	370	287	493	317	293

[a]Denotes days after casting

Table 3.2 - Comparison of free shrinkage measurements for various water cement ratios for Program I

Water-cement ratio = 0.40

Batch	**68**	**77**	**66**	**74**	**62**	**71**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	173	117	130	90	97	100
30	427	297	330	260	290	217
90	593	439	460	347	356	272
180	673	510	534	370	387	278
365	733	527	550	313	397	263

[a]Denotes days after casting

Water-cement ratio = 0.45

Batch	**69**	**78**	**64**	**75**	**63**	**72**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	163	93	113	63	97	83
30	387	260	330	260	283	217
90	539	404	487	337	343	279
180	600	448	535	382	377	292
365	630	460	557	370	377	287

[a]Denotes days after casting

Water-cement ratio = 0.50

Batch	**70**	**79**	**65**	**76**	**67**	**73**
Cement type	I/II	II CG	I/II	II CG	I/II	II CG
% aggregate	60	60	70	70	80	80
Day[a]	**Average Shrinkage (microstrain)**					
3	0	0	0	0	0	0
7	147	97	83	87	93	83
30	393	297	313	287	237	200
90	540	427	457	341	310	273
180	610	481	503	368	344	305
365	627	493	497	317	343	293

[a]Denotes days after casting

Table 3.3a - Summary of free shrinkage measurements for Program II (Non-air-entrained Batches)

Batch	**94**	**95**
Aggregate Type	Quartzite	Limestone
Day[a]	**Average Shrinkage (microstrain)**	
3	0	0
7	80	80
30	173	227
90	314	378
180	307	387
365	333	407

[a]Denotes days after casting

Batch	**187**	**188**	**189**
Aggregate Type	Quartzite	Limestone	Granite
Day[a]	**Average Shrinkage (microstrain)**		
3	-83	-63	-53
7	0	20	27
30	217	237	237
90	310	323	320
180	350	387	350
365	413	427	400

[a]Denotes days after casting

Batch	**198**	**199**	**200**
Aggregate Type	Quartzite	Limestone	Granite
Day[a]	**Average Shrinkage (microstrain)**		
3	-10	-7	-33
7	130	107	107
30	340	320	283
90	470	447	403
180	473	460	423
365	553	540	493

[a]Denotes days after casting

Table 3.3b - Summary of free shrinkage measurements for Program II (Air-Entrained Batches)

Batch	262	263	264
Aggregate Type	Quartzite	Limestone	Granite
Day[a]	**Average Shrinkage (microstrain)**		
3	-10	7	-37
7	77	160	87
30	347	377	313
90	497	520	447

[a]Denotes days after casting

Table 3.4 - Summary of free shrinkage measurements for Program III

Batch	**85**	**86**	**87**	**88**
Aggregate Type	Control	Slag	Class C Fly Ash	Silica Fume
Day[a]	**Average Shrinkage (microstrain)**			
3	0	0	0	0
7	110	107	113	107
30	303	333	337	293
90	418	420	443	423
180	431	426	462	419
365	402	435	478	441

[a]Denotes days after casting

Batch	**194**	**195**	**196**	**197**
Aggregate Type	Control	Slag	Class C Fly Ash	Silica Fume
Day[a]	**Average Shrinkage (microstrain)**			
3	-40	-50	-30	-67
7	90	67	77	37
30	293	313	347	257
90	400	427	487	390
180	443	427	477	393
365	503	497	553	460

[a]Denotes days after casting

Batch	**202**	**203**	**204**
Aggregate Type	Control	Superplasticized Control	Silica Fume
Day[a]	**Average Shrinkage (microstrain)**		
3	-20	-17	13
7	107	110	140
30	330	327	377
90	453	457	470
180	480	490	487
365	540	547	543

[a]Denotes days after casting

Table 3.5 - Summary of free shrinkage measurements for Program IV

Batch	**165-3d**	**165-7d**	**165-14d**	**165-28d**	**166-3d**	**166-7d**	**166-14d**	**166-28d**
Cement type	I/II				II CG			
Cure (days)	3	7	14	28	3	7	14	28
Day[a]	**Average Shrinkage (microstrain)**							
3	0	0	0	0	0	0	0	0
7	83	-3	-30	-43	57	-7	-13	-37
14	217	180	0	-17	173	93	-13	-60
28	287	270	143	-33	267	243	180	-33
30	293	270	157	0	313	250	193	60
90	473	492	463	370	473	423	363	323
180	547	586	533	471	557	513	457	417
365	527	560	510	467	517	510	440	400

[a]Denotes days after casting

Batch	**201-3d**	**201-7d**	**201-14d**	**201-28d**	**207-3d**	**207-7d**	**207-14d**	**207-28d**
Cement type	I/II				II CG			
Cure (days)	3	7	14	28	3	7	14	28
Day[a]	**Average Shrinkage (microstrain)**							
3	23	10	13	20	-7	-10	-13	-20
7	183	-7	-10	-10	83	-17	-23	-37
14	323	167	-10	-10	150	70	-27	-37
28	483	363	227	-20	257	207	100	-37
30	483	337	243	-10	257	213	117	-3
90	607	452	423	330	363	367	323	333
180	630	473	437	380	397	400	360	350
365	697	520	497	440	440	457	417	400

[a]Denotes days after casting

Table 3.6 - Summary of free shrinkage measurements for based on drying period for Program IV

Batch	165-3d	165-7d	165-14d	165-28d	166-3d	166-7d	166-14d	166-28d
Cement type	I/II				II CG			
Cure (days)	3	7	14	28	3	7	14	28
Day[a]	Average Shrinkage (microstrain)							
3	53	70	63	87	57	40	-17	17
7	140	180	63	110	103	93	67	60
30	333	337	320	227	302	270	237	193
90	480	487	480	423	472	437	404	388
180	543	583	529	465	556	513	457	411
300	540	573	532	466	537	505	458	415

[a]Denotes days after drying began

Batch	201-3d	201-7d	201-14d	201-28d	207-3d	207-7d	207-14d	207-28d
Cement type	I/II				II CG			
Cure (days)	3	7	14	28	3	7	14	28
Day[a]	Average Shrinkage (microstrain)							
3	143	80	57	20	57	47	7	0
7	250	167	103	70	127	70	63	27
30	500[b]	367	340	275	279[b]	280	220	193
90	632[b]	456[b]	437	370	376[b]	383	340	333
180	634[b]	478[b]	445[b]	386[b]	400[b]	407[b]	377[b]	378[b]
300	695[b]	519[b]	493[b]	440[b]	450[b]	460[b]	423[b]	407[b]

[a]Denotes days after drying began
[b]Denotes interpolated value

Table 3.7a - Summary of free shrinkage measurement for Program V (Non-air-entrained concrete)

Batch	**167**	**168**	**169**	**170**	**174**[b]
Superplasticizer (Dosage)	Control (None)	Glenium 3000NS (Low)	Glenium 3000NS (Medium)	Glenium 3000NS (High)	Glenium 3000NS (High)
Day[a]	**Average Shrinkage (microstrain)**				
3	0	0	0	0	0
7	53	60	30	23	117
30	237	267	280	193	233
90	387	393	333	310	437
180	457	460	434	357	480
365	413	430	387	293	447

[a]Denotes days after casting
[b]Batch 174 was a replication of Batch 170

Batch	**171**	**172**	**173**
Superplasticizer (Dosage)	Rheobuild 1000 (Low)	Rheobuild 1000 (Medium)	Rheobuild 1000 (High)
Day[a]	**Average Shrinkage (microstrain)**		
3	0	0	0
7	97	100	127
30	210	217	260
90	397	407	457
180	467	457	513
365	430	423	467

[a]Denotes days after casting

Batch	**175**	**176**	**177**	**178**
Superplasticizer (Dosage)	Control (None)	Glenium 3000NS (Low)	Glenium 3000NS (Medium)	Glenium 3000NS (High)
Day[a]	**Average Shrinkage (microstrain)**			
3	-17	-33	-20	10
7	0	87	3	33
30	200	300	257	260
90	343	447	393	383
180	333	447	403	370
365	363	463	413	386

[a]Denotes days after casting

Table 3.7a - Summary of free shrinkage measurements for Program V (Non-air-entrained concrete), cont.

Batch	**179**	**180**	**181**	**182** [b]
Superplasticizer (Dosage)	Rheobuild 1000 (Low)	Rheobuild 1000 (Medium)	Rheobuild 1000 (High)	Rheobuild 1000 (High)
Day [a]	**Average Shrinkage (microstrain)**			
3	-47	-13	-60	-3
7	107	13	-35	133
30	283	263	220	363
90	443	417	360	537
180	460	427	325	540
365	460	427	340	547

[a]Denotes days after casting
[b]Batch 182 was a replication of Batch 181

Batch	**183**	**184**	**185**	**186**
Superplasticizer (Dosage)	Control (None)	Adva 100 (Low)	Adva 100 (Medium)	Adva 100 (High)
Day [a]	**Average Shrinkage (microstrain)**			
3	10	10	-7	-17
7	80	67	67	60
30	257	257	260	250
90	417	413	403	407
180	440	423	437	433
365	443	433	440	437

[a]Denotes days after casting

Batch	**193**	**190**	**191**	**192**
Superplasticizer (Dosage)	Control (None)	Adva 100 (Low)	Adva 100 (Medium)	Adva 100 (High)
Day [a]	**Average Shrinkage (microstrain)**			
3	-33	-33	-33	-30
7	30	40	20	33
30	213	237	230	237
90	310	333	330	337
180	317	350	327	337
365	360	397	373	387

[a]Denotes days after casting

Table 3.7a - Summary of free shrinkage measurements for Program V (Non-air-entrained concrete), cont.

Batch	208	209	210	211
Superplasticizer	Control	Adva 100	Glenium 3000NS	Rheobuild 1000
Day[a]	**Average Shrinkage (microstrain)**			
3	-17	-13	-10	-10
7	83	93	87	107
30	330	357	367	357
90	467	500	507	520
180	507	550	560	573
365	547	590	593	630

[a]Denotes days after casting

Table 3.7b - Summary of Free Shrinkage Measurement from Program V for air-entrained batches

Batch	260	249	256	259
Superplasticizer	Control	Glenium 3000NS	Rheobuild 1000	Adva 100
Day[a]	**Average Shrinkage (microstrain)**			
3	0	30	-33	3
7	187	207	150	187
30	487	523	473	497
90	657	673	600	653
180	700	693	660	697
365	757	737	703	737

[a]Denotes days after casting

Table 3.8-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 60% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
427	0.40	90	80
387	0.45		N
393	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
673	0.40	95	90
600	0.45		N
610	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
733	0.40	Y	95
630	0.45		N
627	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.9-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 70% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
330	0.40	N	N
330	0.45		N
313	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
534	0.40	N	N
535	0.45		80
503	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
550	0.40	N	80
557	0.45		80
497	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.10-Program I Student's t-test results for concretes with different water-cement ratios containing Type I/II cement and 80% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
290	0.40	N	95
283	0.45		95
237	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
387	0.40	N	90
377	0.45		80
344	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
397	0.40	N	90
377	0.45		N
343	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)

"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)

Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.11-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 60% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
297	0.40	Y	N
260	0.45		95
297	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
510	0.40	Y	80
448	0.45		80
481	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
527	0.40	Y	90
460	0.45		95
493	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.12-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 70% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
260	0.40	95	95
330	0.45		N
313	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
370	0.40	Y	Y
535	0.45		80
503	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
313	0.40	Y	Y
557	0.45		80
497	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.13-Program I Student's t-test results for concretes with different water-cement ratios containing Type II coarse-ground cement and 80% aggregate content, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		0.45	0.50
217	0.40	N	90
217	0.45		80
200	0.50		

180 days

Average Shrinkage (με)		0.45	0.50
278	0.40	N	80
292	0.45		N
305	0.50		

365 days

Average Shrinkage (με)		0.45	0.50
263	0.40	N	N
287	0.45		N
293	0.50		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.14-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type I/II cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
427	60%	95	Y
330	70%		N
290	80%		

180 days

Average Shrinkage (με)		70%	80%
673	60%	Y	Y
534	70%		Y
387	80%		

365 days

Average Shrinkage (με)		70%	80%
733	60%	Y	Y
550	70%		Y
397	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.15-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type I/II cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
387	60%	95	Y
330	70%		90
283	80%		

180 days

Average Shrinkage (με)		70%	80%
600	60%	95	Y
535	70%		Y
377	80%		

365 days

Average Shrinkage (με)		70%	80%
630	60%	90	Y
557	70%		Y
377	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.16-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type I/II cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
393	60%	Y	Y
313	70%		Y
237	80%		

180 days

Average Shrinkage (με)		70%	80%
610	60%	Y	Y
503	70%		Y
344	80%		

365 days

Average Shrinkage (με)		70%	80%
627	60%	Y	Y
497	70%		Y
343	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.17-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.40 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
297	60%	90	Y
260	70%		90
217	80%		

180 days

Average Shrinkage (με)		70%	80%
510	60%	Y	Y
370	70%		95
278	80%		

365 days

Average Shrinkage (με)		70%	80%
527	60%	Y	Y
313	70%		N
263	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.18-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.45 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
260	60%	N	Y
260	70%		95
217	80%		

180 days

Average Shrinkage (με)		70%	80%
448	60%	95	Y
382	70%		95
292	80%		

365 days

Average Shrinkage (με)		70%	80%
460	60%	90	Y
370	70%		80
287	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.19-Program I Student's t-test results for concretes with different aggregate contents at a constant water-cement ratio of 0.50 and containing Type II coarse-ground cement, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		70%	80%
297	60%	N	Y
287	70%		Y
200	80%		

180 days

Average Shrinkage (με)		70%	80%
481	60%	Y	Y
368	70%		95
305	80%		

365 days

Average Shrinkage (με)		70%	80%
493	60%	Y	Y
317	70%		80
293	80%		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.20a-Program II Student's t-test results for non-air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Quartzite (94)
227	Limestone (95)	Y
173	Quartzite (94)	

180 days

Average Shrinkage (με)		Quartzite (94)
387	Limestone (95)	Y
307	Quartzite (94)	

365 days

Average Shrinkage (με)		Quartzite (94)
407	Limestone (95)	Y
333	Quartzite (94)	

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.20b-Program II Student's t-test results for non-air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Limestone (188)	Granite (189)
217	Quartzite (187)	N	N
237	Limestone (188)		N
237	Granite (189)		

180 days

Average Shrinkage (με)		Limestone (188)	Granite (189)
350	Quartzite (187)	80	N
387	Limestone (188)		Y
350	Granite (189)		

365 days

Average Shrinkage (με)		Limestone (188)	Granite (189)
413	Quartzite (187)	N	N
427	Limestone (188)		N
400	Granite (189)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.20c-Program II Student's t-test results for non-air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Limestone (199)	Granite (200)
340	Quartzite (198)	N	80
320	Limestone (199)		N
283	Granite (200)		

180 days

Average Shrinkage (με)		Limestone (199)	Granite (200)
473	Quartzite (198)	N	80
460	Limestone (199)		N
423	Granite (200)		

365 days

Average Shrinkage (με)		Limestone (199)	Granite (200)
553	Quartzite (198)	N	Y
540	Limestone (199)		80
493	Granite (200)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.20d-Program II Student's t-test results for air-entrained concrete containing different aggregate types 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Limestone (263)	Granite (264)
347	Quartzite (262)	90	80
377	Limestone (263)		Y
313	Granite (264)		

180 days

Average Shrinkage (με)		Limestone (263)	Granite (264)
520	Quartzite (262)	80	80
550	Limestone (263)		Y
487	Granite (264)		

365 days

Average Shrinkage (με)		Limestone (263)	Granite (264)
567	Quartzite (262)	80	Y
590	Limestone (263)		Y
523	Granite (264)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.21a-Program III Student's t-test results for concrete containing Type I/II cement with mineral admixtures by volume replacement at 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Slag (86)	Fly Ash (87)	Silica Fume (88)
303	Control(85)	90	Y	N
333	Slag(86)		N	Y
337	Fly Ash(87)			Y
293	Silica Fume(88)			

180 days

Average Shrinkage (με)		Slag (86)	Fly Ash (87)	Silica Fume (88)
431	Control(85)	N	Y	N
426	Slag(86)		Y	N
462	Fly Ash(87)			Y
419	Silica Fume(88)			

365 days

Average Shrinkage (με)		Slag (86)	Fly Ash (87)	Silica Fume (88)
402	Control(85)	80	Y	80
435	Slag(86)		90	N
478	Fly Ash(87)			80
441	Silica Fume(88)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.21b-Program III Student's t-test results for concrete containing Type I/II cement with mineral admixtures by volume replacement at 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Slag (195)	Fly Ash (196)	Silica Fume (197)
293	Control(194)	N	N	N
313	Slag(195)		N	80
347	Fly Ash(196)			80
257	Silica Fume(197)			

180 days

Average Shrinkage (με)		Slag (195)	Fly Ash (196)	Silica Fume (197)
443	Control(194)	N	N	N
427	Slag(195)		N	N
477	Fly Ash(196)			N
393	Silica Fume(197)			

365 days

Average Shrinkage (με)		Slag (195)	Fly Ash (196)	Silica Fume (197)
503	Control(194)	N	N	N
497	Slag(195)		N	N
553	Fly Ash(196)			80
460	Silica Fume(197)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.21c-Program III Student's t-test results for concrete containing Type I/II cement with mineral admixtures by volume replacement at 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Superplasticized Control (203)	Silica Fume (204)
330	Control (202)	N	80
327	Superplasticized Control (203)		N
377	Silica Fume (204)		

180 days

Average Shrinkage (με)		Superplasticized Control (203)	Silica Fume (204)
480	Control (202)	N	N
490	Superplasticized Control (203)		N
487	Silica Fume (204)		

365 days

Average Shrinkage (με)		Superplasticized Control (203)	Silica Fume (204)
540	Control (202)	N	N
547	Superplasticized Control (203)		N
543	Silica Fume (204)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.22-Program IV Student's t-test results (Batch 165) for different curing periods, for non-air-entrained concrete containing Type I/II cement

30 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
333	3 days	N	N	Y
337	7 days		N	Y
320	14 days			Y
227	28 days			

180 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
543	3 days	80	N	95
583	7 days		90	Y
529	14 days			90
465	28 days			

300 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
515	3 days	90	N	Y
564	7 days		Y	Y
506	14 days			Y
443	28 days			

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.23-Program IV Student's t-test (Batch 166) results for different curing periods, for non-air-entrained concrete containing Type II coarse-ground cement

30 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
302	3 days	N	90	Y
270	7 days		N	90
237	14 days			Y
193	28 days			

180 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
556	3 days	N	Y	Y
513	7 days		80	Y
457	14 days			Y
411	28 days			

300 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
520	3 days	N	90	Y
487	7 days		80	Y
433	14 days			Y
376	28 days			

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.24 Program IV Student's t-test results (Batch 201) for different curing periods, for air-entrained concrete containing Type I/II cement

30 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
500	3 days	Y	Y	Y
367	7 days		90	Y
3430	14 days			Y
275	28 days			

180 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
634	3 days	Y	Y	Y
478	7 days		Y	Y
445	14 days			Y
386	28 days			

300 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
695	3 days	Y	Y	Y
519	7 days		Y	Y
493	14 days			Y
440	28 days			

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.25-Program IV Student's t-test (Batch 207) results for different curing periods, for air-entrained concrete containing Type II coarse-ground cement

30 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
279	3 days	N	Y	Y
280	7 days		Y	Y
220	14 days			N
193	28 days			

180 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
400	3 days	N	Y	Y
407	7 days		90	Y
377	14 days			N
378	28 days			

300 days[a]

Average Shrinkage (με)		7 days	14 days	28 days
	3 days	N	Y	Y
	7 days		90	Y
	14 days			N
	28 days			

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.26-Program IV Student's t-test results (Batch 165 and 166) comparing cement type with curing periods, for different drying periods of non-air-entrained concrete

30 days[a]

			Type I/II cement (Batch 165)			
	Average shrinkage (με)		Average shrinkage (με) 333	337	320	227
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 166)	302	3 days	N			
	270	7 days		90		
	237	14 days			Y	
	193	28 days				90

180 days[a]

			Type I/II cement (Batch 165)			
	Average shrinkage (με)		Average shrinkage (με) 543	583	529	465
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 166)	556	3 days	N			
	513	7 days		80		
	457	14 days			Y	
	411	28 days				Y

300 days[a]

			Type I/II cement (Batch 165)			
	Average shrinkage (με)		Average shrinkage (με) 515	564	506	443
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 166)	520	3 days	N			
	487	7 days		90		
	433	14 days			Y	
	376	28 days				Y

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.27-Program IV Student's t-test results (Batch 201 and 207) comparing cement type with curing periods, for different drying periods of air-entrained concrete

30 days[a]

			Type I/II cement (Batch 201)			
	Average shrinkage (με)		Average shrinkage (με) 500	367	340	275
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 207)	279	3 days	Y	Y		
	280	7 days		Y	Y	
	220	14 days			Y	
	193	28 days				Y

180 days[a]

			Type I/II cement (Batch 201)			
	Average shrinkage (με)		Average shrinkage (με) 634	478	445	386
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 207)	400	3 days	Y	Y		
	407	7 days		Y	80	
	377	14 days			Y	
	378	28 days				80

300 days[a]

			Type I/II cement (Batch 201)			
	Average shrinkage (με)		Average shrinkage (με) 695	519	493	440
			3 days	7 days	14 days	28 days
Type II CG cement (Batch 207)	450	3 days	Y	Y		
	460	7 days		Y	80	
	422	14 days			Y	
	412	28 days				80

[a]Denotes the age after drying began

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.28a-Program V Student's t-test results for concrete containing Glenium 3000NS for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Low (168)	Medium (169)	High (170)
237	Control (167)	N	N	N
267	Low (168)		N	N
280	Medium (169)			N
233	High (170)			

180 days

Average Shrinkage (με)		Low (168)	Medium (169)	High (170)
457	Control (167)	N	N	N
460	Low (168)		N	N
434	Medium (169)			N
480	High (170)			

365 days

Average Shrinkage (με)		Low (168)	Medium (169)	High (170)
434	Control (167)	90	N	90
453	Low (168)		80	N
397	Medium (169)			80
473	High (170)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.28b-Program V Student's t-test results for concrete containing Rheobuild 1000 for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Low (171)	Medium (172)	High (173)
237	Control (167)	80	N	N
210	Low (171)		N	Y
217	Medium (172)			Y
260	High (173)			

180 days

Average Shrinkage (με)		Low (171)	Medium (172)	High (173)
457	Control (167)	N	N	Y
467	Low (171)		N	90
457	Medium (172)			90
513	High (173)			

365 days

Average Shrinkage (με)		Low (171)	Medium (172)	High (173)
434	Control (167)	80	N	Y
453	Low (171)		N	90
457	Medium (172)			90
503	High (173)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.29a-Program V Student's t-test results for concrete containing Glenium 3000NS for different dosage rates, 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Low (176)	Medium (177)	High (178)
200	Control (175)	90	Y	Y
300	Low (176)		N	N
257	Medium (177)			N
260	High (178)			

180 days

Average Shrinkage (με)		Low (176)	Medium (177)	High (178)
333	Control (175)	90	Y	80
447	Low (176)		N	80
403	Medium (177)			80
370	High (178)			

365 days

Average Shrinkage (με)		Low (176)	Medium (177)	High (178)
363	Control (175)	80	90	N
463	Low (176)		N	N
413	Medium (177)			80
386	High (178)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.29b-Program V Student's t-test results for concrete containing Rheobuild 1000 for different dosage rates, 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Low (179)	Medium (180)	High (181)
200	Control (175)	Y	Y	N
283	Low (179)		N	Y
263	Medium (180)			80
220	High (181)			

180 days

Average Shrinkage (με)		Low (179)	Medium (180)	High (181)
333	Control (175)	Y	Y	N
460	Low (179)		N	Y
427	Medium (180)			Y
325	High (181)			

365 days

Average Shrinkage (με)		Low (179)	Medium (180)	High (181)
363	Control (175)	Y	80	N
460	Low (179)		N	Y
427	Medium (180)			90
340	High (181)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.30a-Program V Student's t-test results for concrete containing Adva 100 for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Low (184)	Medium (185)	High (186)
257	Control (183)	N	N	N
257	Low (184)		N	Y
260	Medium (185)			N
250	High (186)			

180 days

Average Shrinkage (με)		Low (184)	Medium (185)	High (186)
440	Control (183)	N	N	N
423	Low (184)		N	N
437	Medium (185)			N
433	High (186)			

365 days

Average Shrinkage (με)		Low (184)	Medium (185)	High (186)
443	Control (183)	N	N	N
433	Low (184)		N	N
440	Medium (185)			N
437	High (186)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.30b-Program V Student's t-test results for concrete containing Adva 100 for different dosage rates, 30, 180, and 365 days after casting, cont.

30 days

Average Shrinkage (με)		Low (190)	Medium (191)	High (192)
213	Control (193)	N	N	N
237	Low (190)		N	Y
230	Medium (191)			N
237	High (192)			

180 days

Average Shrinkage (με)		Low (190)	Medium (191)	High (192)
317	Control (193)	N	N	N
350	Low (190)		N	N
327	Medium (191)			N
337	High (192)			

365 days

Average Shrinkage (με)		Low (190)	Medium (191)	High (192)
360	Control (193)	N	N	N
397	Low (190)		N	N
373	Medium (191)			N
387	High (192)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.31a-Program V Student's t-test results for concrete containing different superplasticizers (low dosage) for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Rheobuild (179)	Adva (184)
300	Glenium (176)	N	N
283	Rheobuild (179)		N
257	Adva (184)		

180 days

Average Shrinkage (με)		Rheobuild (179)	Adva (184)
447	Glenium (176)	N	N
460	Rheobuild (179)		80
423	Adva (184)		

365 days

Average Shrinkage (με)		Rheobuild (179)	Adva (184)
463	Glenium (176)	N	N
460	Rheobuild (179)		N
433	Adva (184)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.31b-Program V Student's t-test results for concrete containing different superplasticizers (medium dosage) for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Rheobuild (180)	Adva (185)
257	Glenium (177)	N	N
263	Rheobuild (180)		N
260	Adva (185)		

180 days

Average Shrinkage (με)		Rheobuild (180)	Adva (185)
403	Glenium (177)	N	80
427	Rheobuild (180)		N
437	Adva (185)		

365 days

Average Shrinkage (με)		Rheobuild (180)	Adva (185)
413	Glenium (177)	N	N
427	Rheobuild (180)		N
440	Adva (185)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.31c-Program V Student's t-test results for concrete containing different superplasticizers (high dosage) for different dosage rates, 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Rheobuild (181)	Adva (186)
257	Glenium (178)	80	N
263	Rheobuild (181)		N
260	Adva (186)		

180 days

Average Shrinkage (με)		Rheobuild (181)	Adva (186)
403	Glenium (178)	Y	Y
427	Rheobuild (181)		Y
437	Adva (186)		

365 days

Average Shrinkage (με)		Rheobuild (181)	Adva (186)
413	Glenium (178)	90	90
427	Rheobuild (181)		Y
440	Adva (186)		

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.32a-Program V Student's t-test results for non-air-entrained concrete containing different superplasticizers (dosage rates for same slump), 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Glenium (210)	Rheobuild (211)	Adva (209)
330	Control (208)	Y	Y	Y
367	Glenium (210)		N	80
357	Rheobuild (211)			N
357	Adva (209)			

180 days

Average Shrinkage (με)		Glenium (210)	Rheobuild (211)	Adva (209)
507	Control (208)	Y	Y	Y
560	Glenium (210)		80	N
573	Rheobuild (211)			Y
550	Adva (209)			

365 days

Average Shrinkage (με)		Glenium (210)	Rheobuild (211)	Adva (209)
	Control (208)	Y	Y	90
	Glenium (210)		90	N
	Rheobuild (211)			80
	Adva (209)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

Table 3.32b-Program V Student's t-test results for air-entrained concrete containing different superplasticizers (dosage rates for same slump), 30, 180, and 365 days after casting

30 days

Average Shrinkage (με)		Glenium (249)	Rheobuild (256)	Adva (259)
487	Control (260)	N	N	N
523	Glenium (249)		N	N
473	Rheobuild (256)			N
497	Adva (259)			

180 days

Average Shrinkage (με)		Glenium (249)	Rheobuild (256)	Adva (259)
700	Control (260)	N	N	N
693	Glenium (249)		N	N
660	Rheobuild (256)			N
697	Adva (259)			

365 days

Average Shrinkage (με)		Glenium (249)	Rheobuild (256)	Adva (259)
757	Control (260)	N	N	N
737	Glenium (249)		N	N
703	Rheobuild (256)			N
737	Adva (259)			

Note: "Y" indicates a significant statistical difference between the two samples at a confidence level of 95% (α=0.05)
"N" indicates that there is no significant statistical difference between two samples at the lowest confidence level, 80% (α=0.20)
Significant statistical differences at confidence levels at, but not exceeding 80% and 90% are indicated by "80" and "90" respectively.

FIGURES

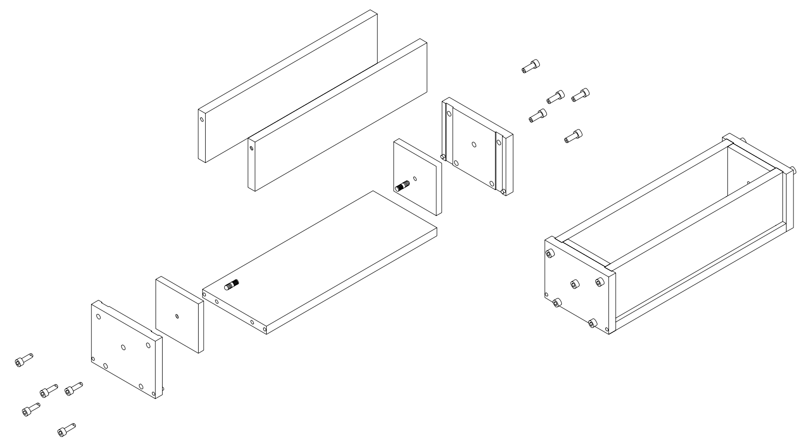

Figure 2.1 – Free Shrinkage Specimen Mold (Tritsch 2005)

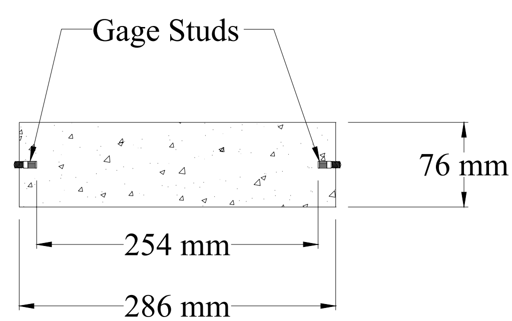

Figure 2.2 – Cross-section of Free Shrinkage Specimen (Tritsch 2005)

Figure 2.3 – **Mechanical Dial Gage Length Comparator (Sourse: Humboldt Manufacturing Company Online Catalog, http://www.humboldtmfg.com/pdf1/49.pdf)**

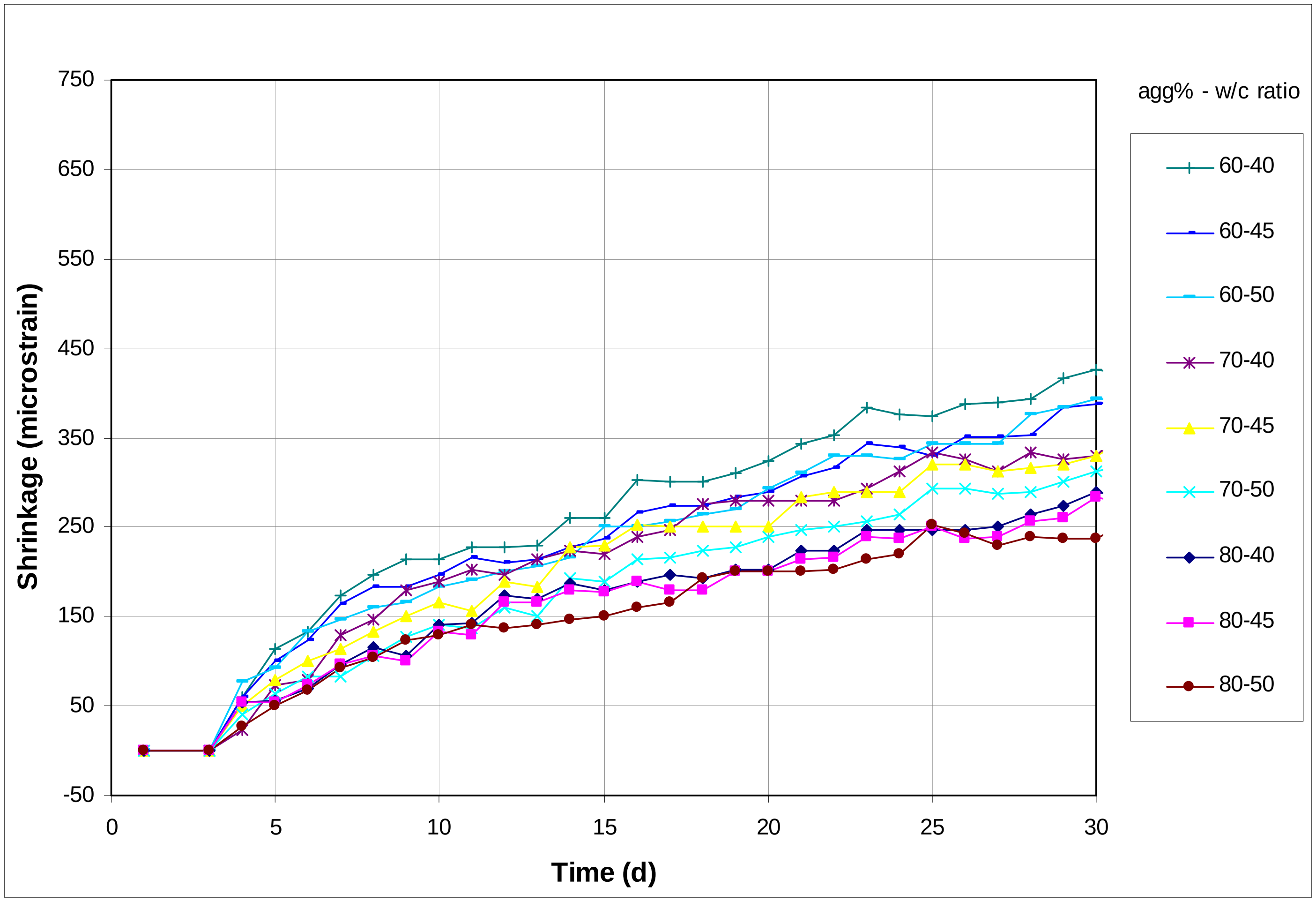

Figure 3.1 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type I/II cement.

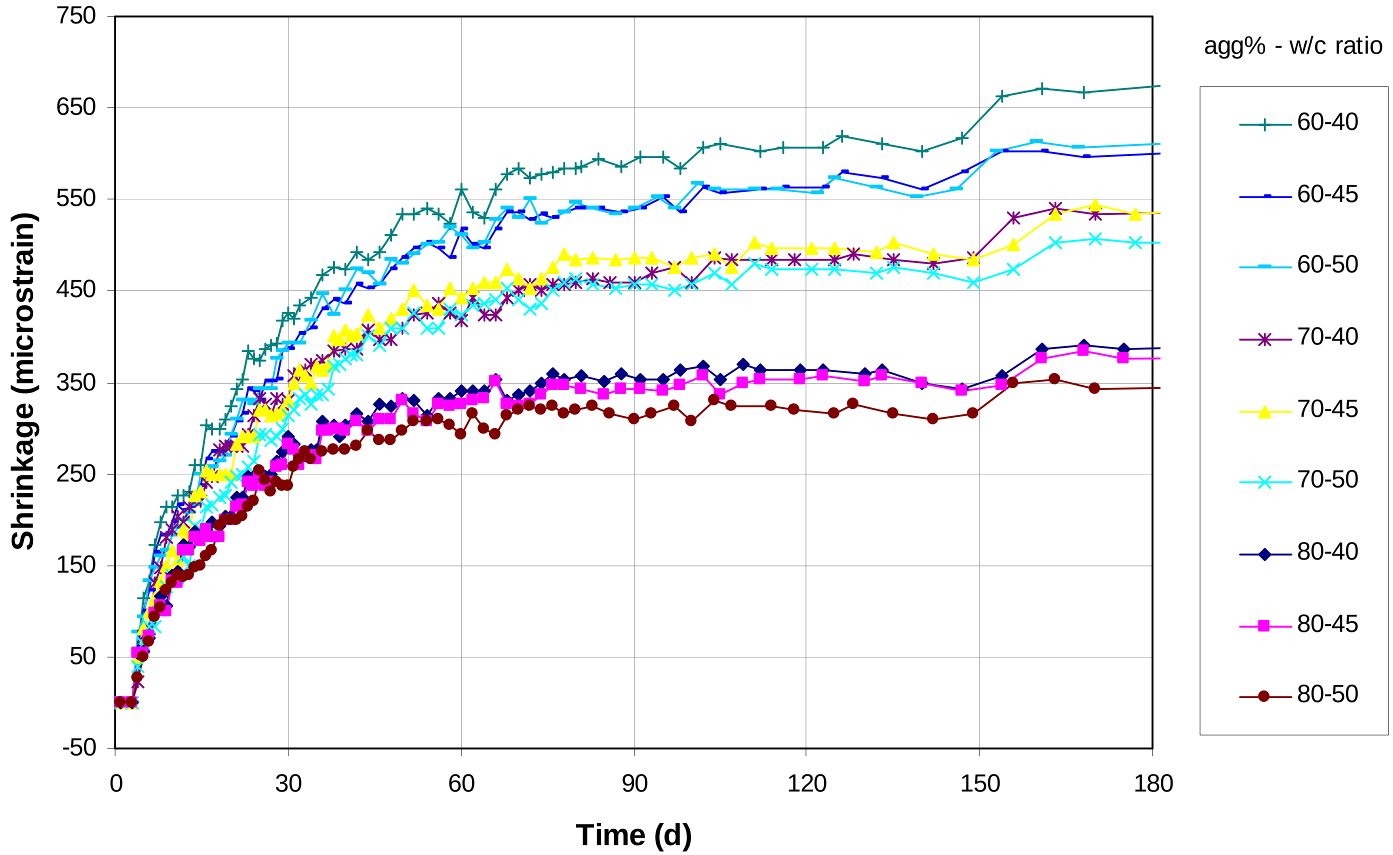

Figure 3.2 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II cement.

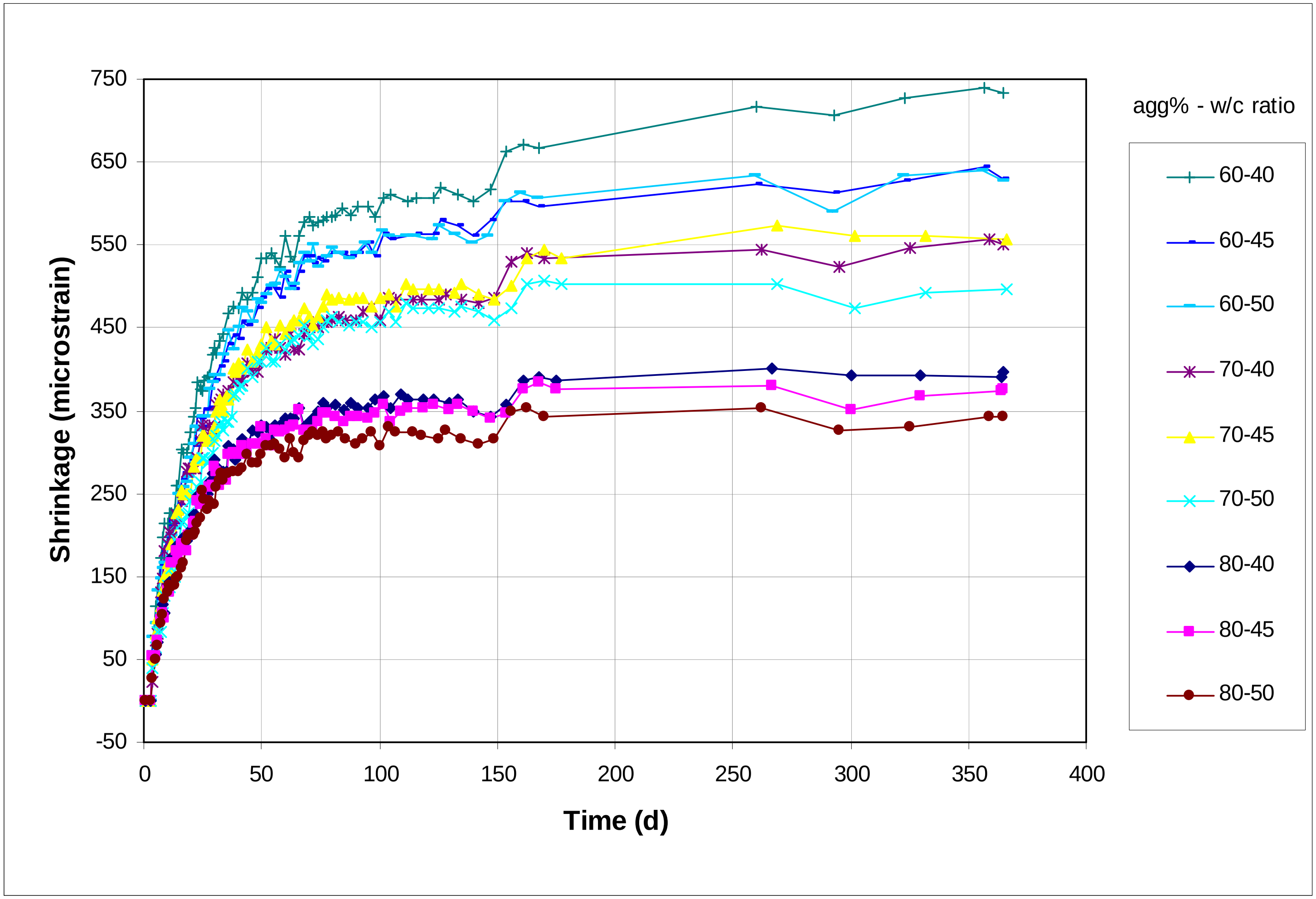

Figure 3.3 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II cement.

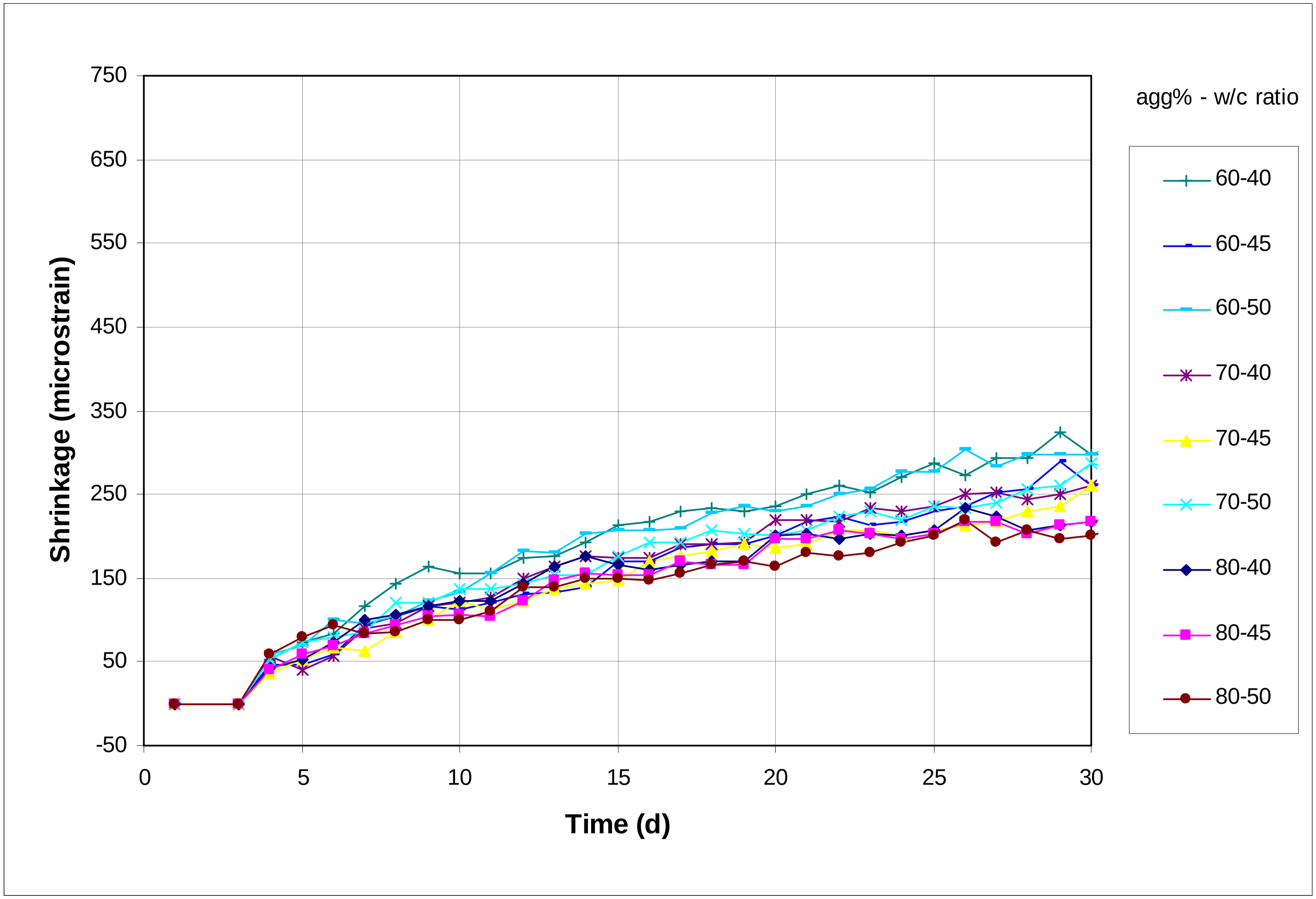

Figure 3.4 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 30 days. Type II CG cement.

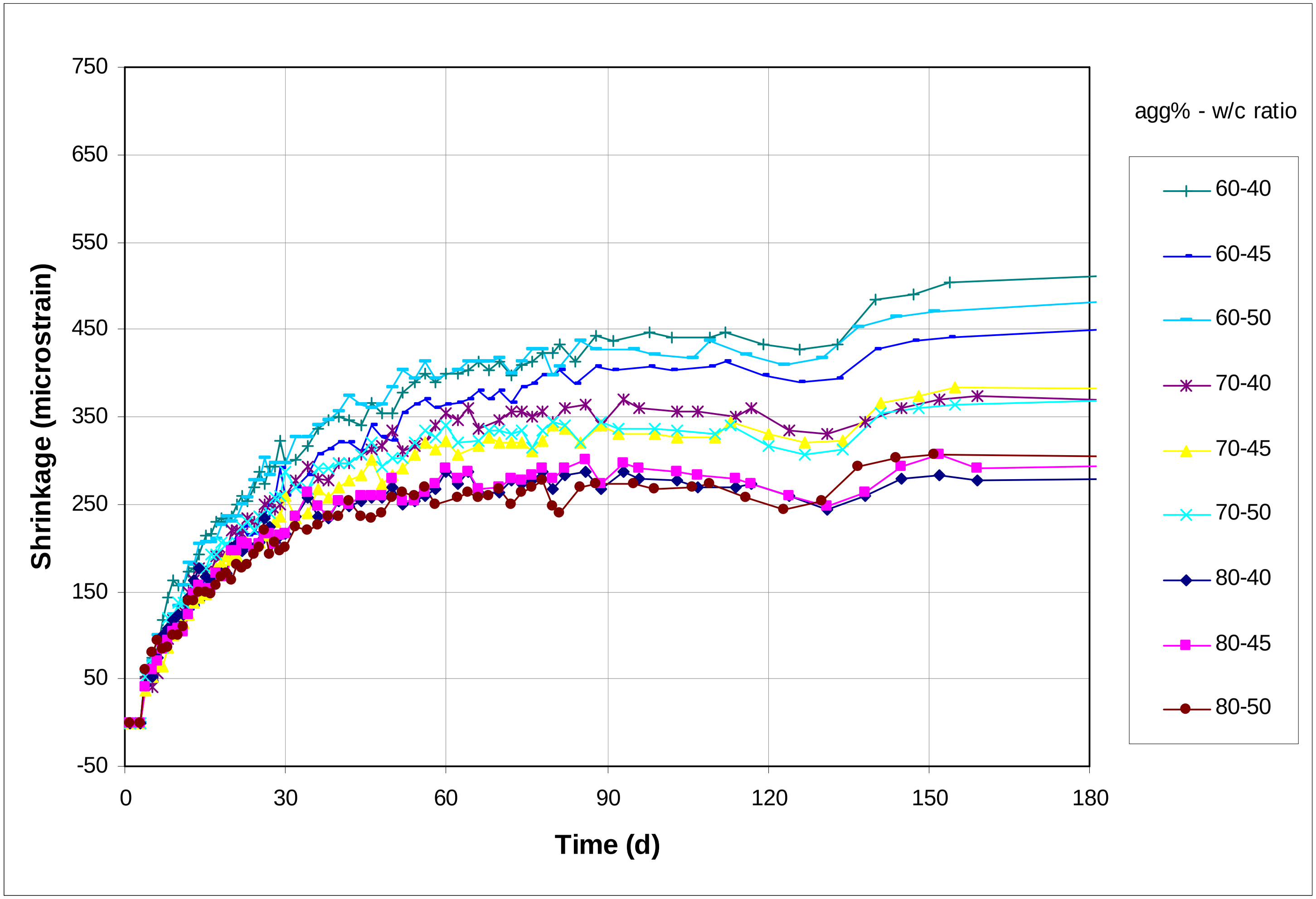

Figure 3.5 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type II coarse ground (CG) cement.

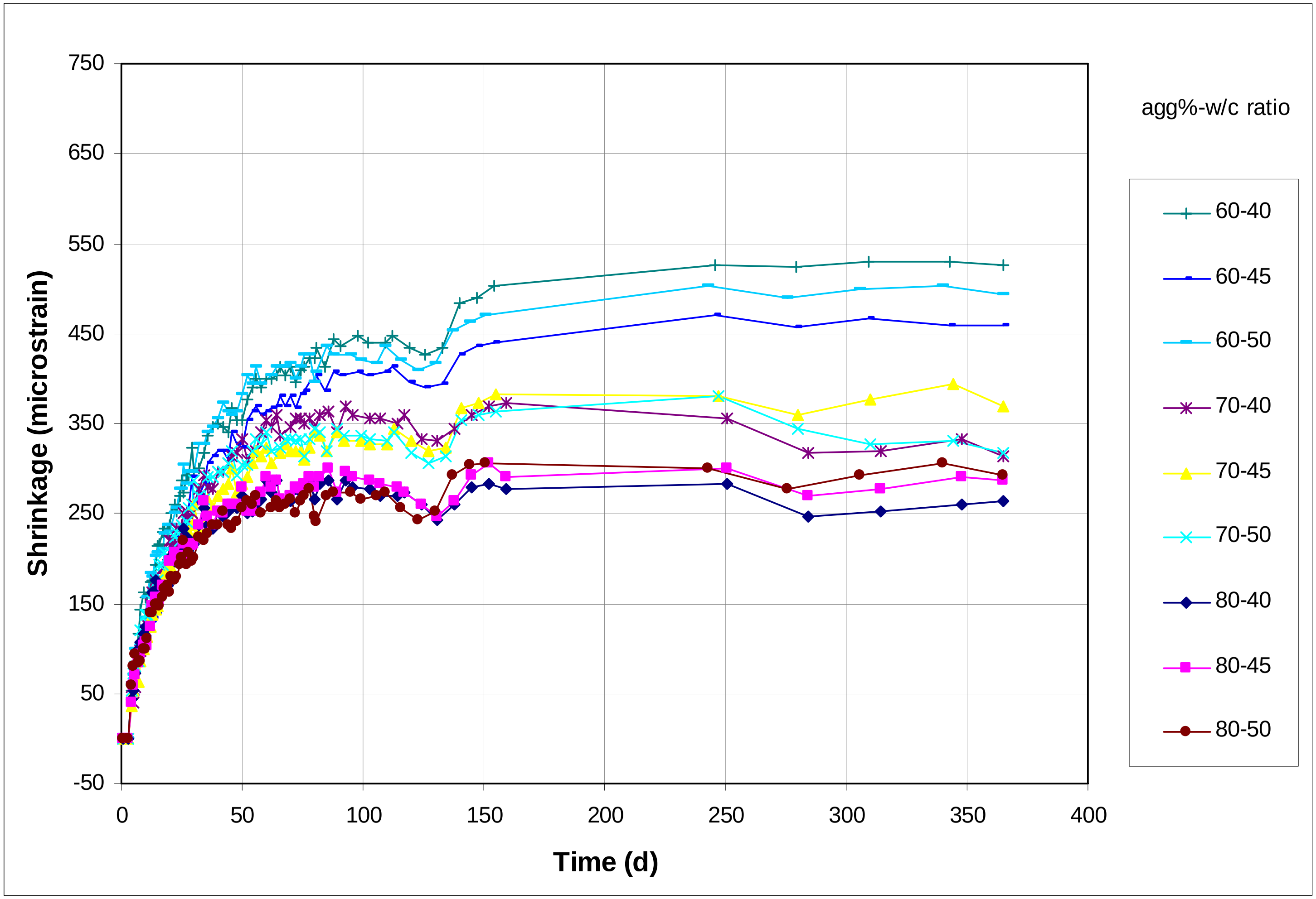

Figure 3.6 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type II coarse ground (CG) cement.

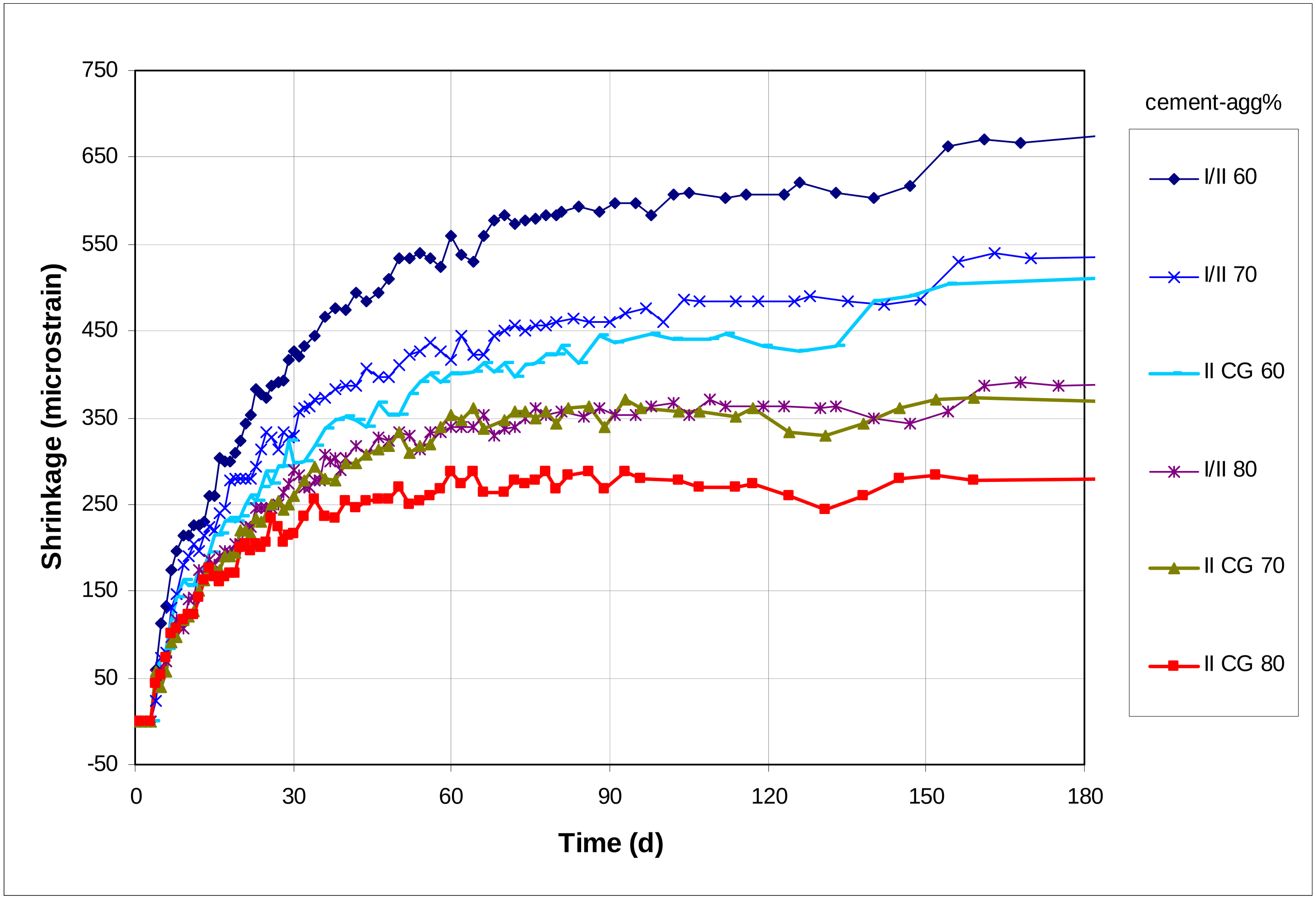

Figure 3.7 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.40.

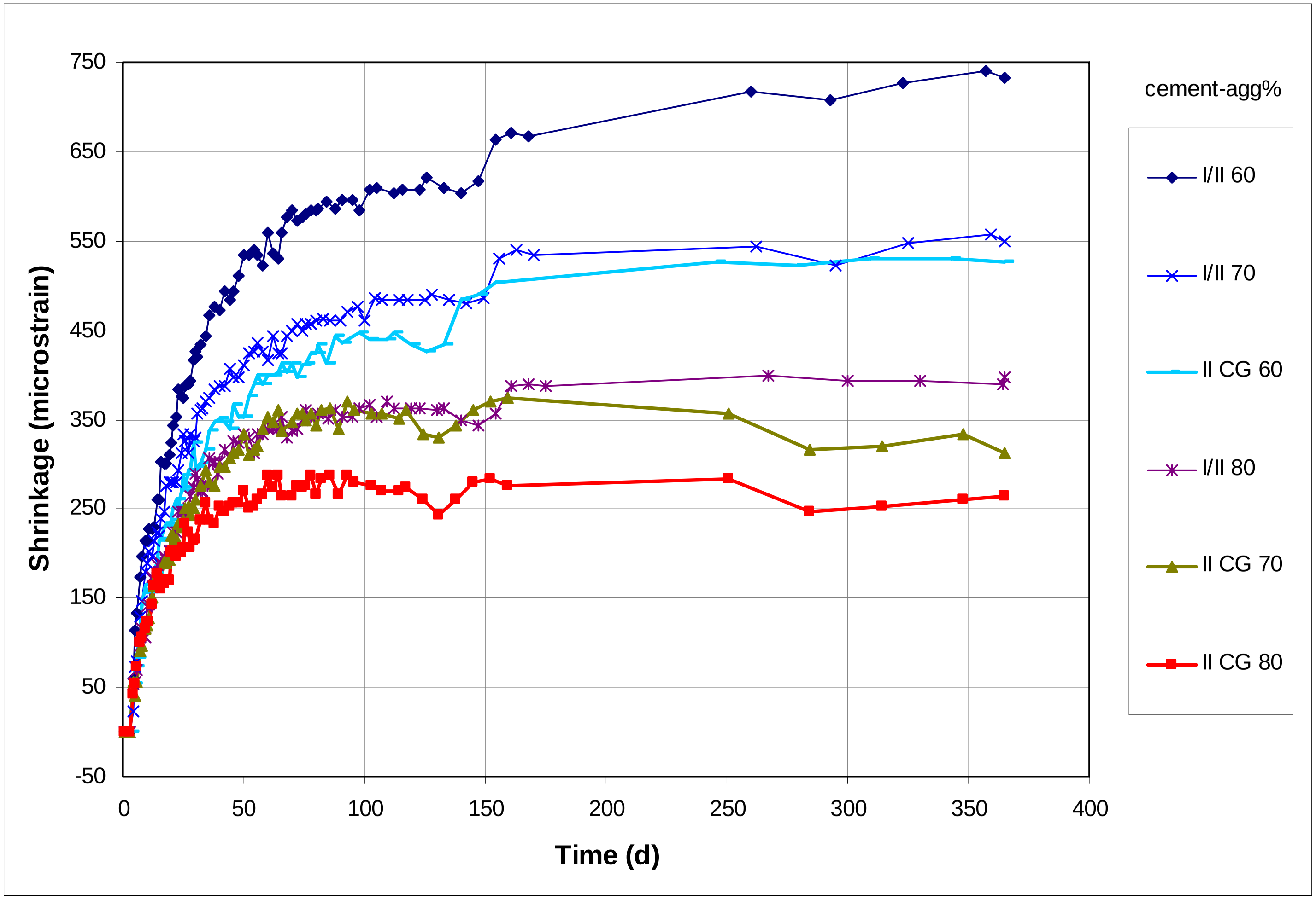

Figure 3.8 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.40.

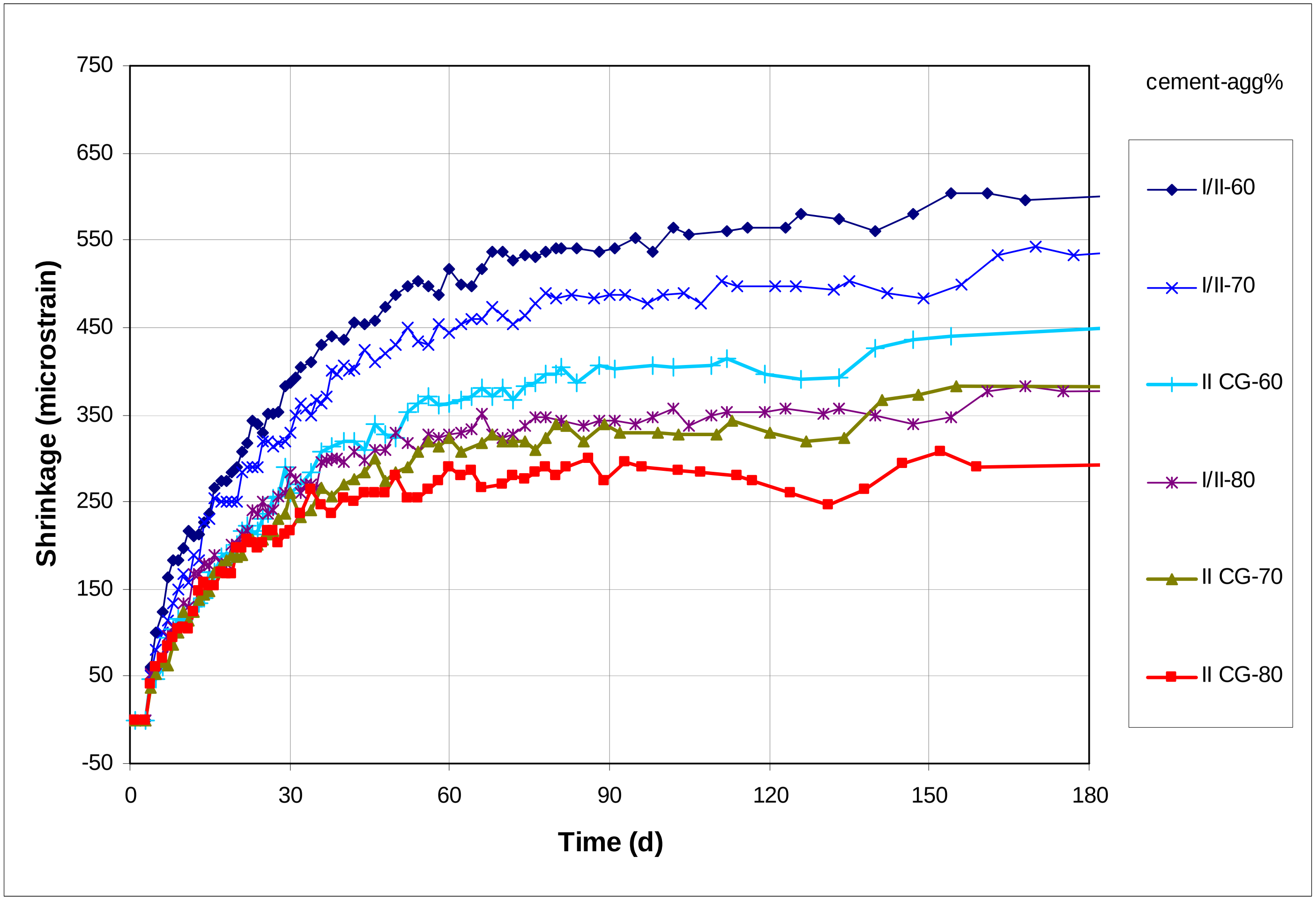

Figure 3.9 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.45.

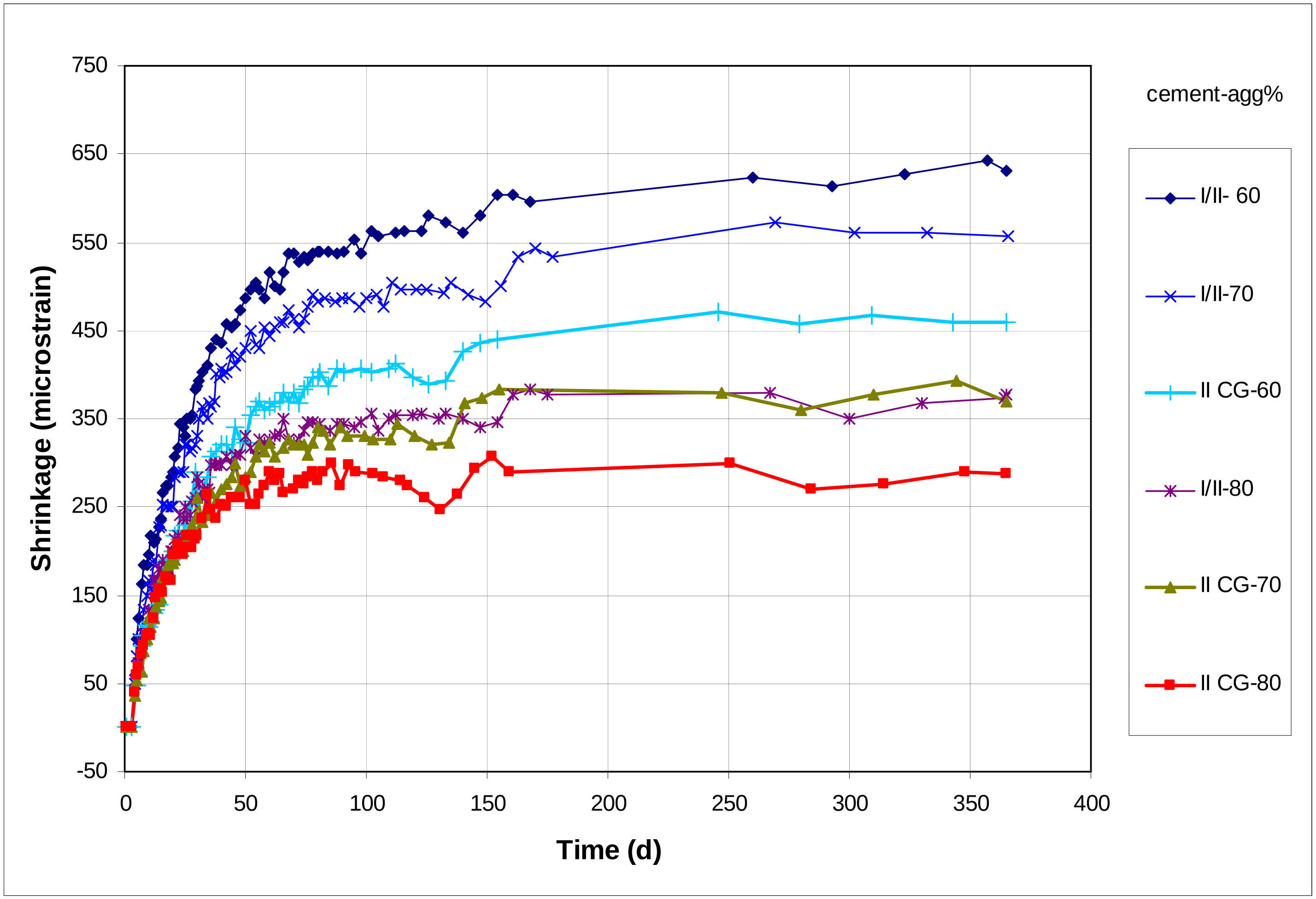

Figure 3.10 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.45.

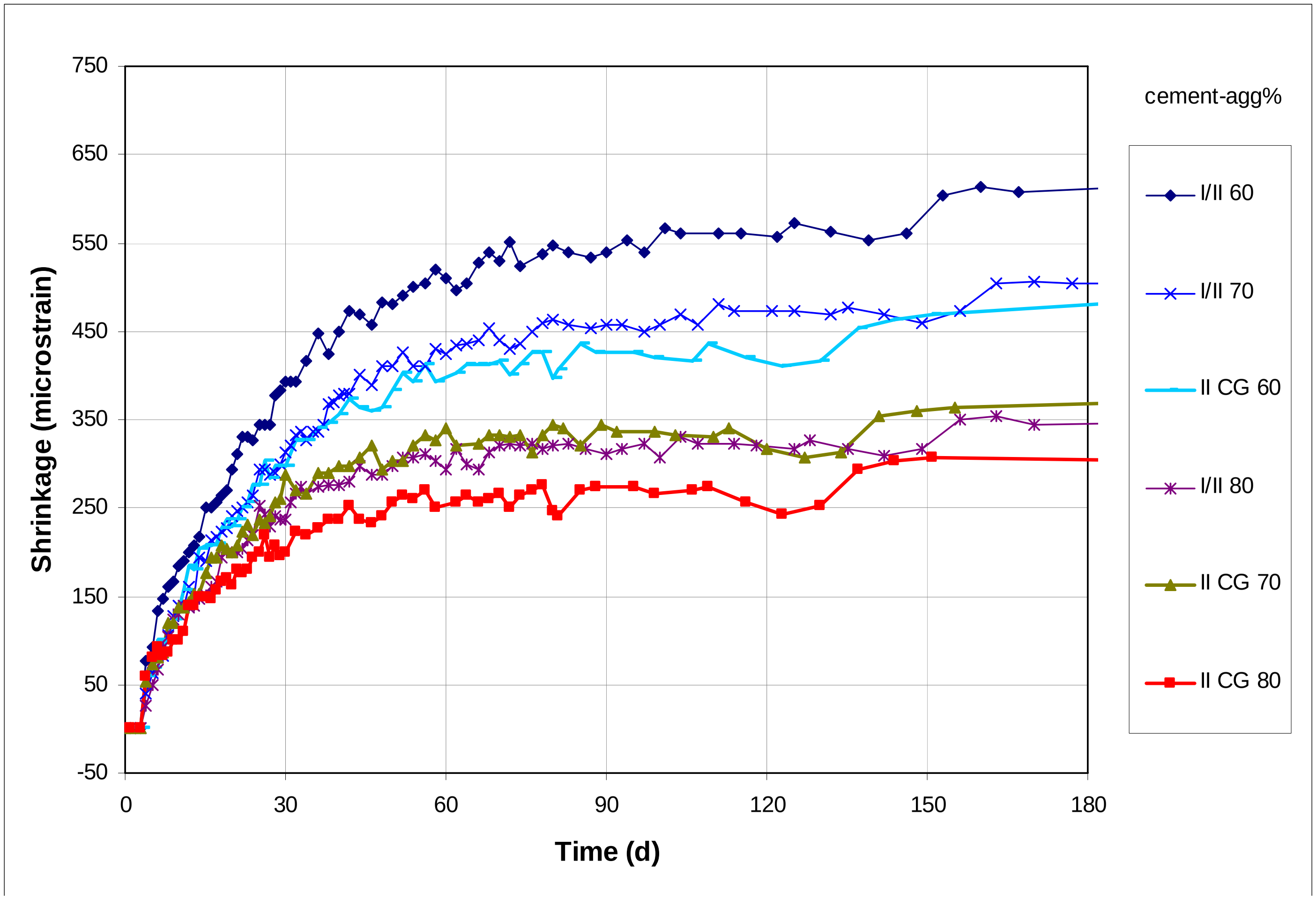

Figure 3.11 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 180 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.50.

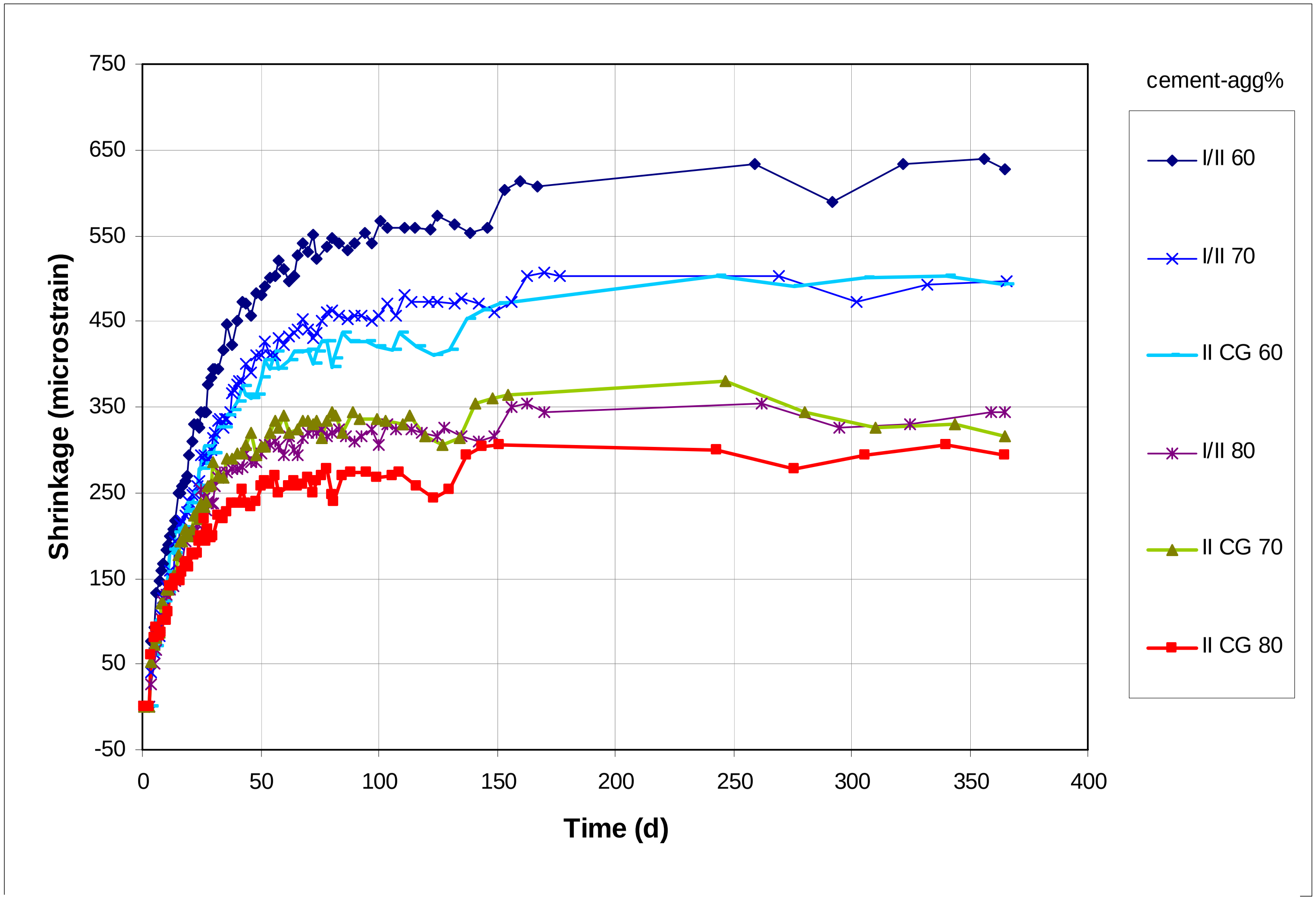

Figure 3.12 - Free Shrinkage Test, Program I. Average free shrinkage vs. time through 365 days. Type I/II and Type II coarse ground (CG) cement. w/c ratio = 0.50.

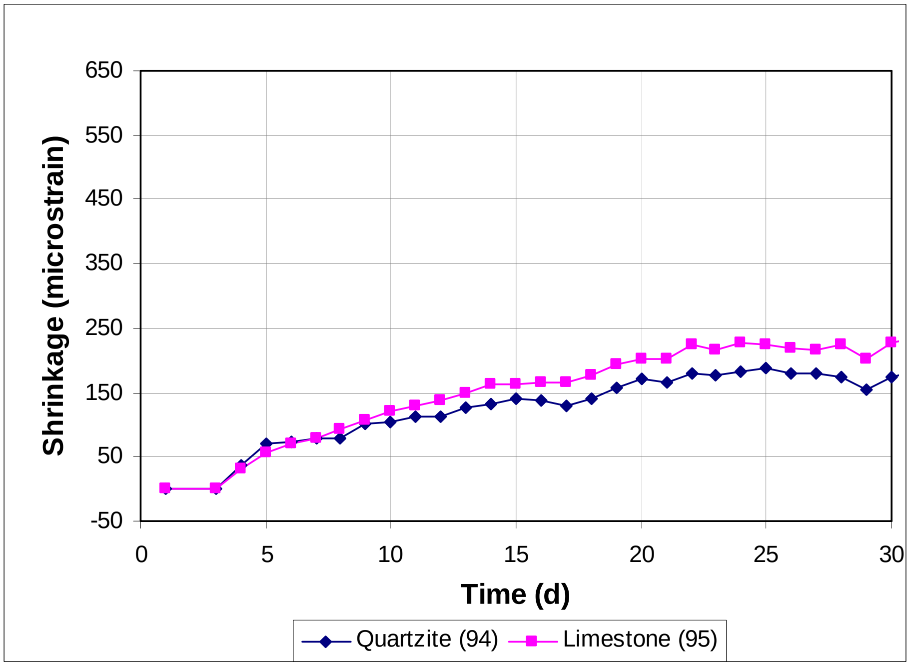

Figure 3.13 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days.

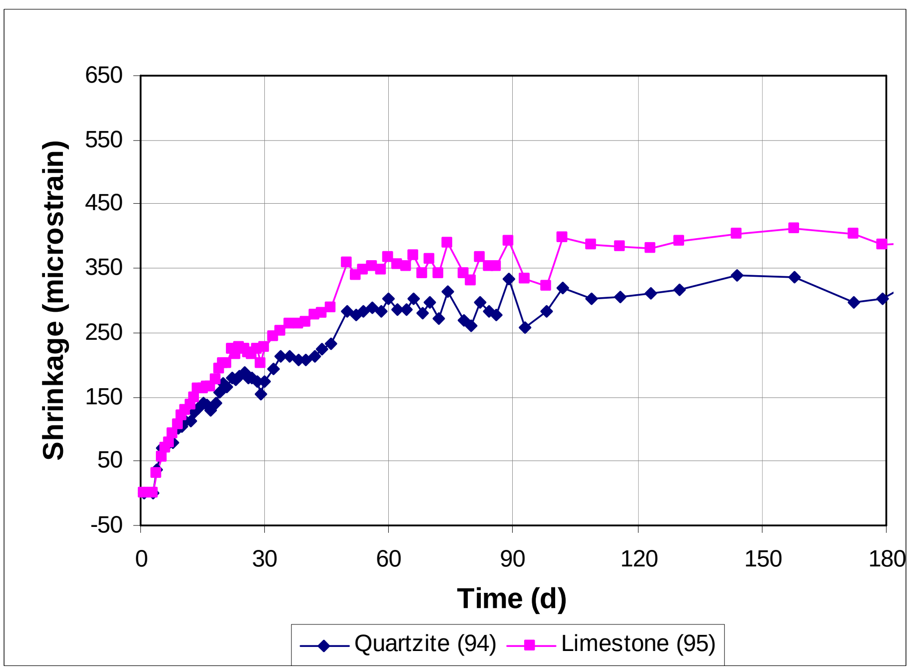

Figure 3.14 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days.

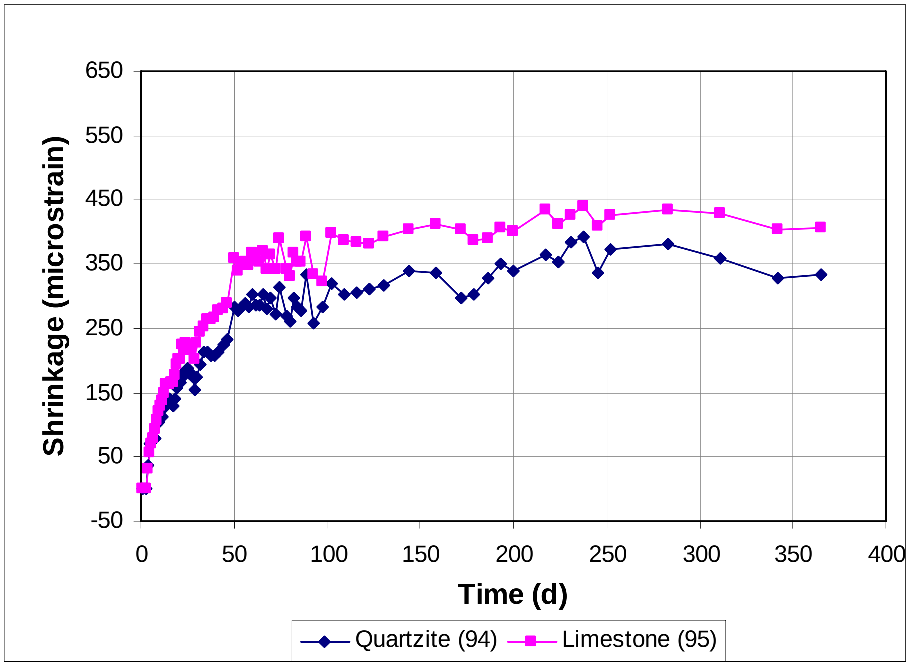

Figure 3.15 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days.

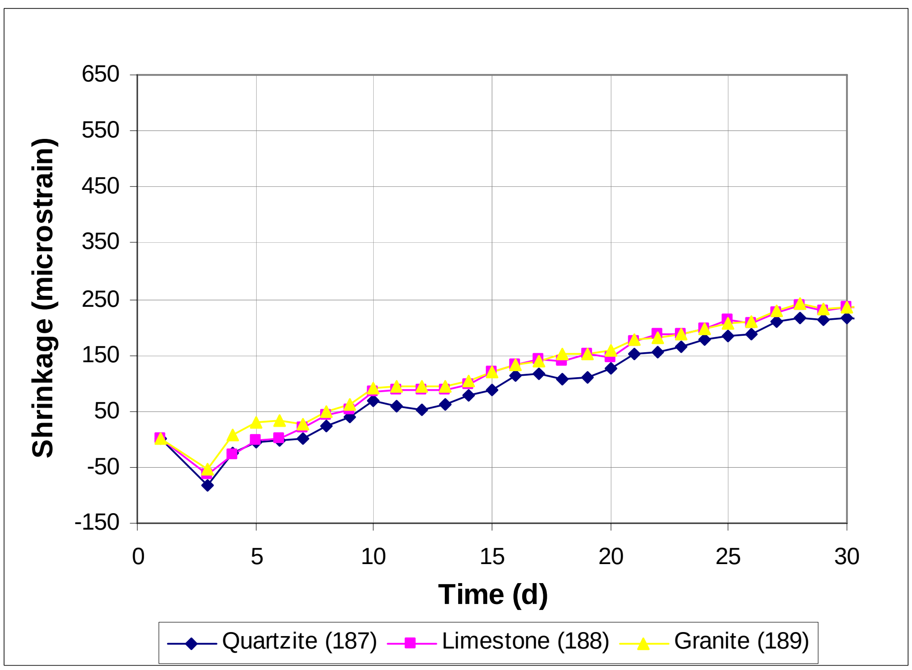

Figure 3.16 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days.

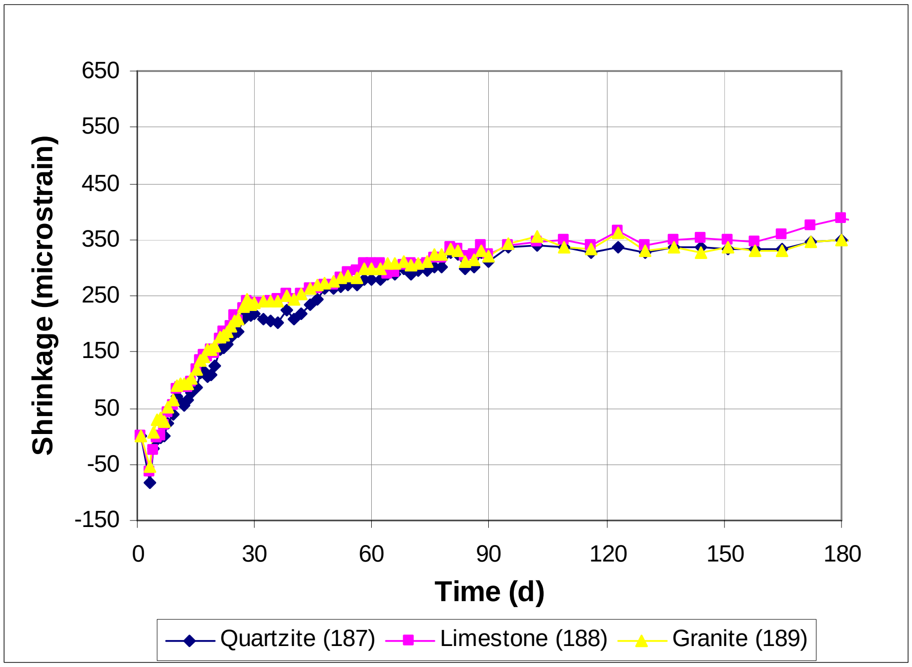

Figure 3.17 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days.

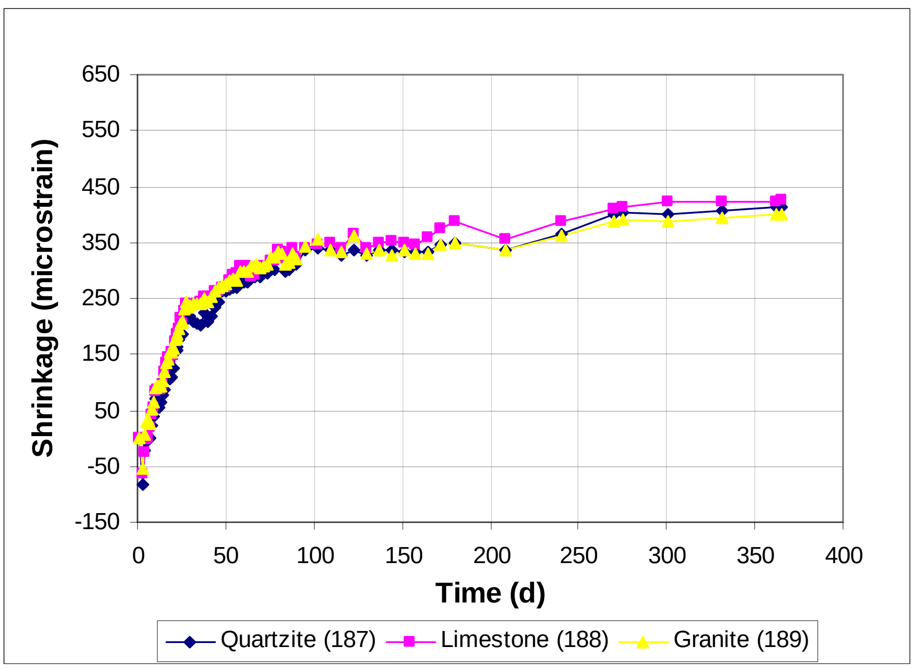

Figure 3.18 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days.

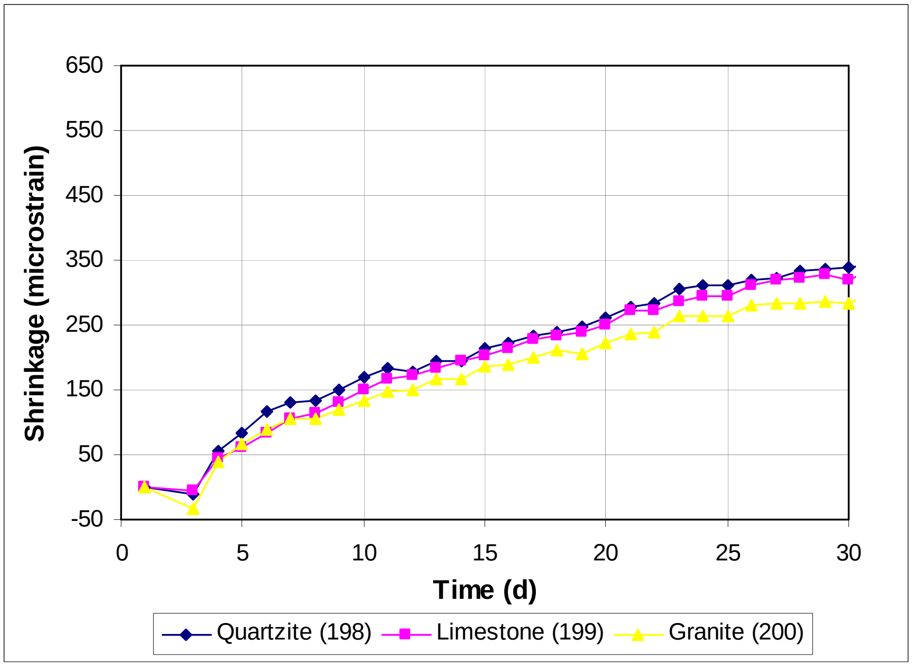

Figure 3.19 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days.

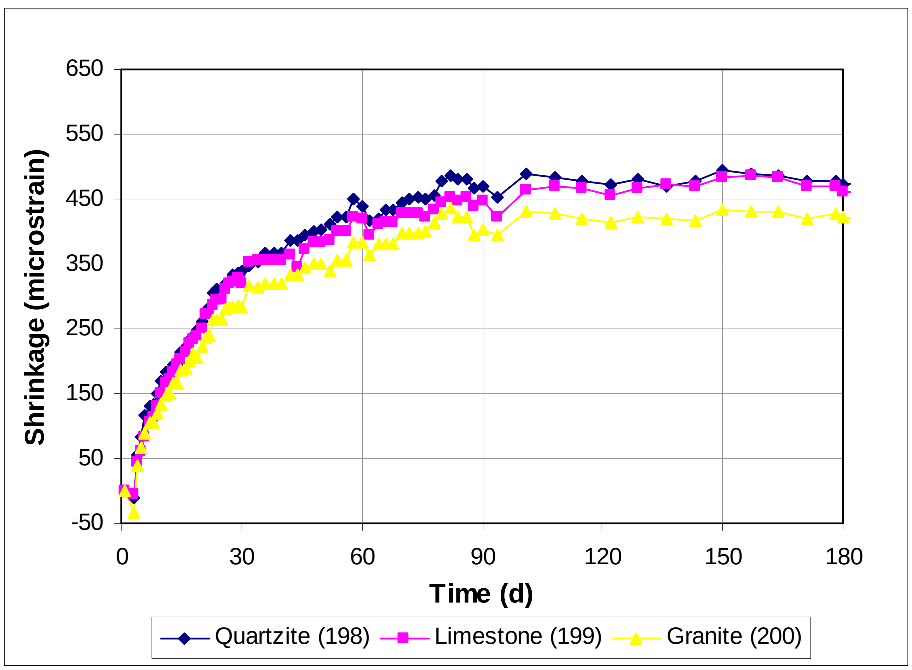

Figure 3.20 Free Shrinkage Test, Program II. Comparison of different aggregate types through 180 days.

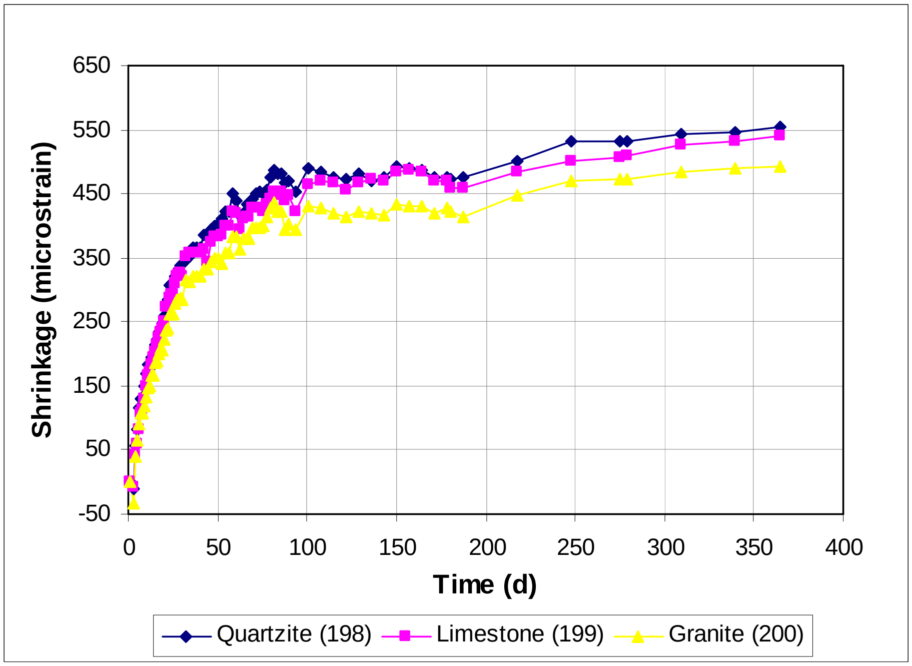

Figure 3.21 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days.

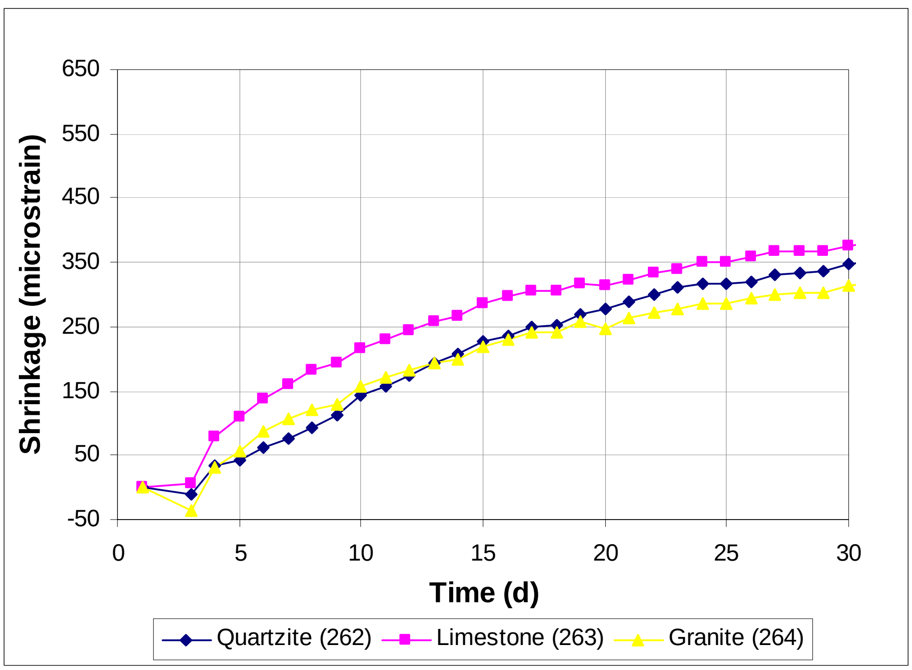

Figure 3.22 Free Shrinkage Test, Program II. Comparison of different aggregate types through 30 days.

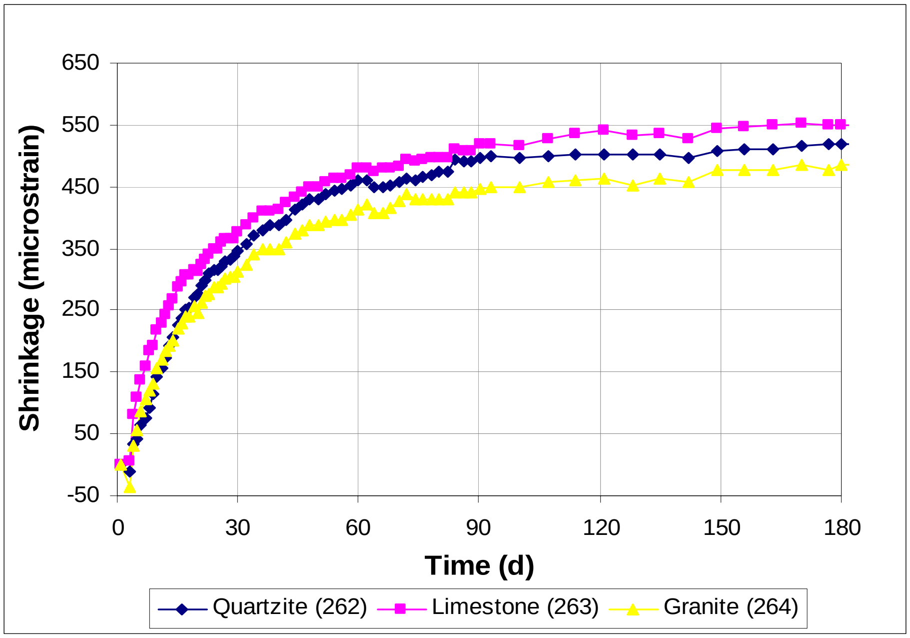

Figure 3.23 Free Shrinkage Test, Program II. Comparison of different aggregate type through 180 days.

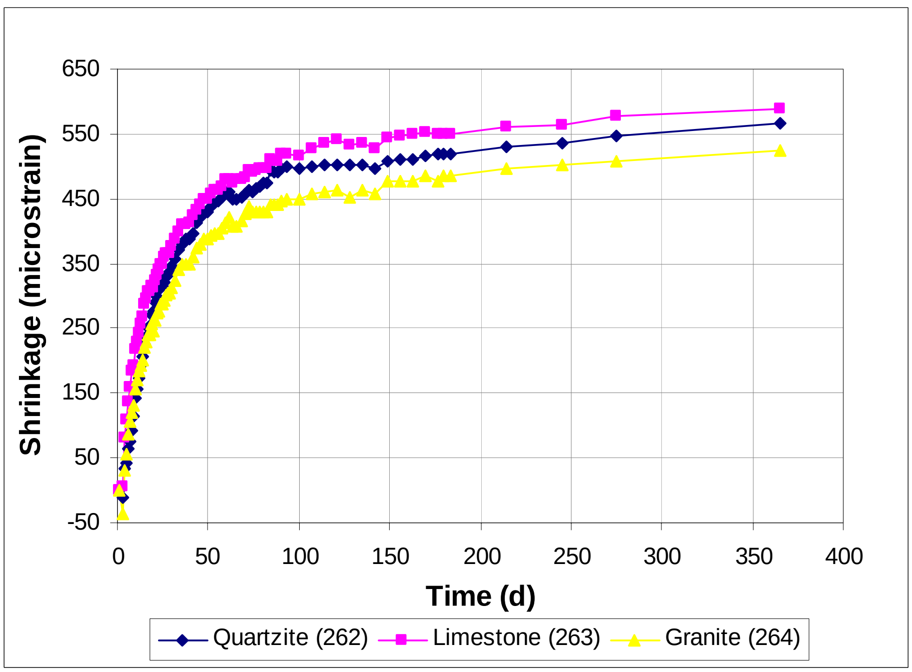

Figure 3.24 Free Shrinkage Test, Program II. Comparison of different aggregate types through 365 days.

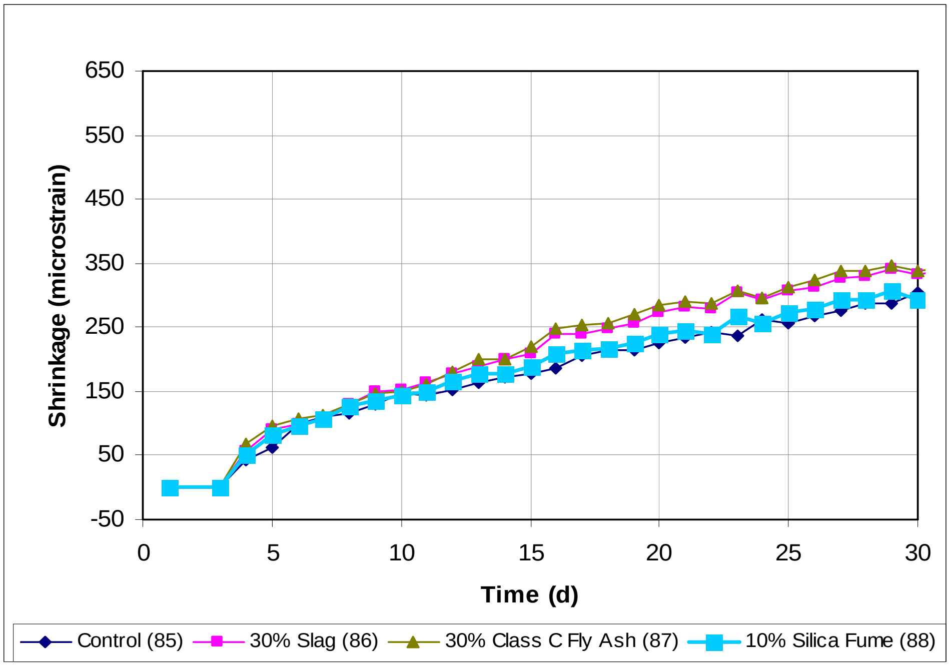

Figure 3.25 Free Shrinkage Test, Program III. Comparing mineral admixtures through 30 days.

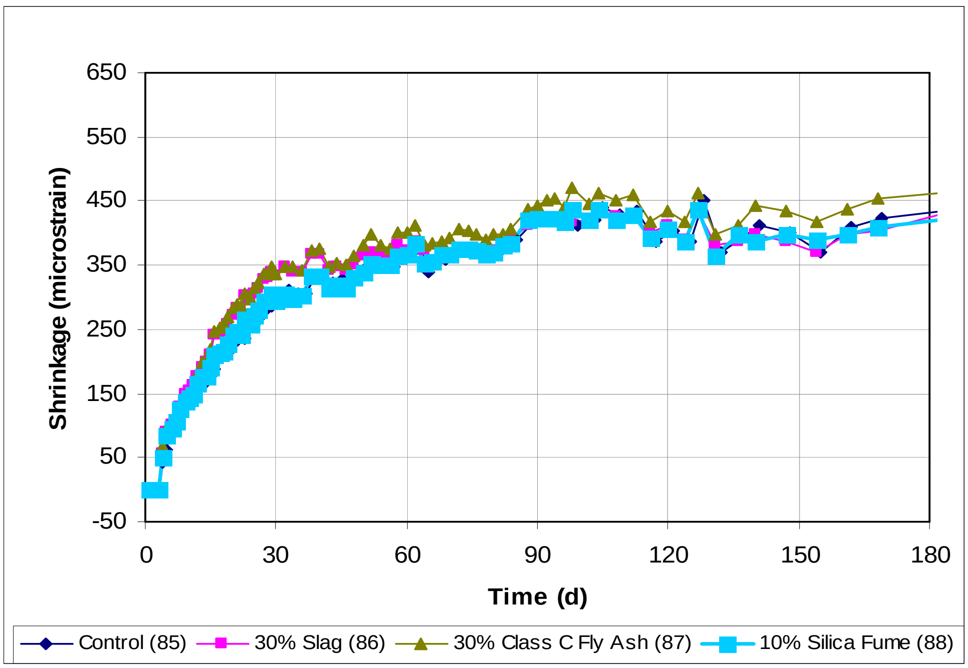

Figure 3.26 Free Shrinkage Test, Program III. Comparing mineral admixtures through 180 days.

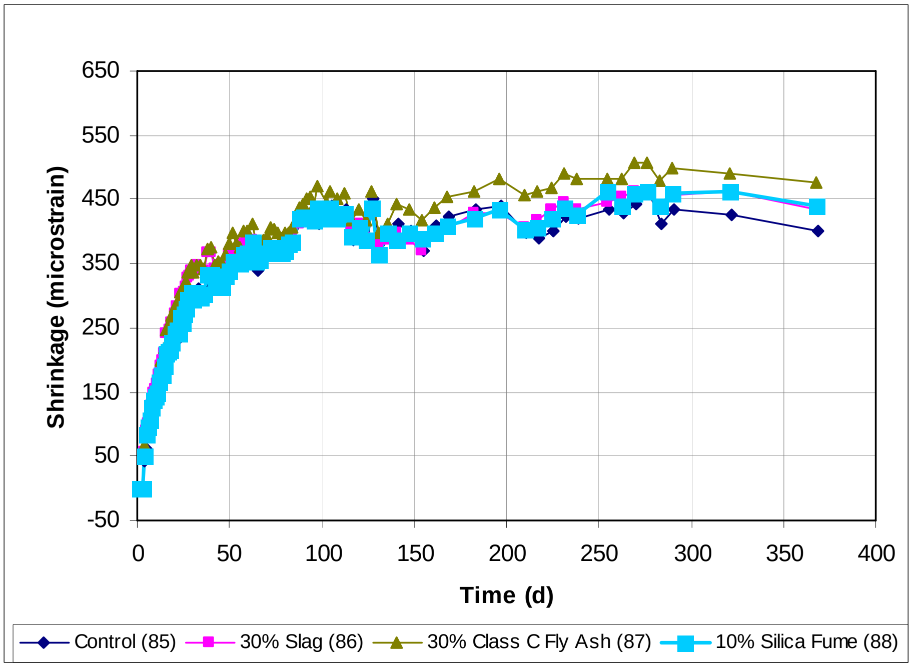

Figure 3.27 Free Shrinkage Test, Program III. Comparing mineral admixtures through 365 days.

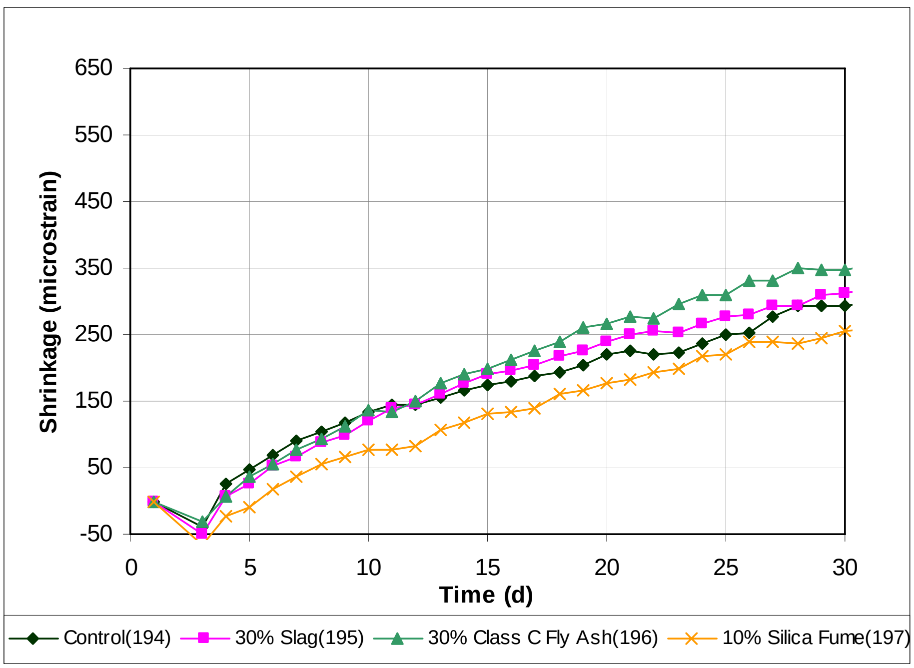

Figure 3.28 Free Shrinkage Test, Program III. Comparing mineral admixtures through 30 days.

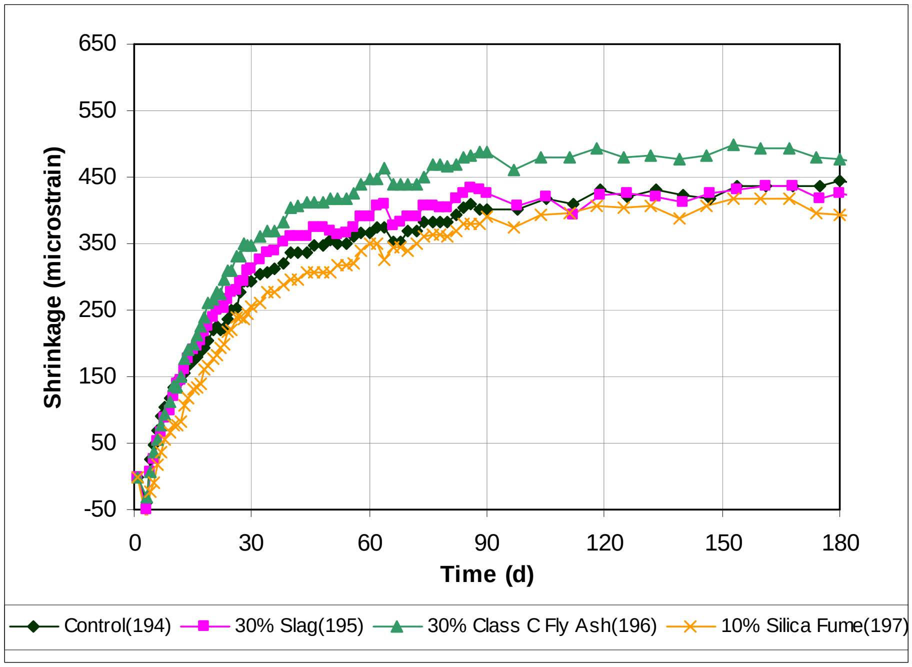

Figure 3.29 Free Shrinkage Test, Program III. Comparing mineral admixtures through 180 days.

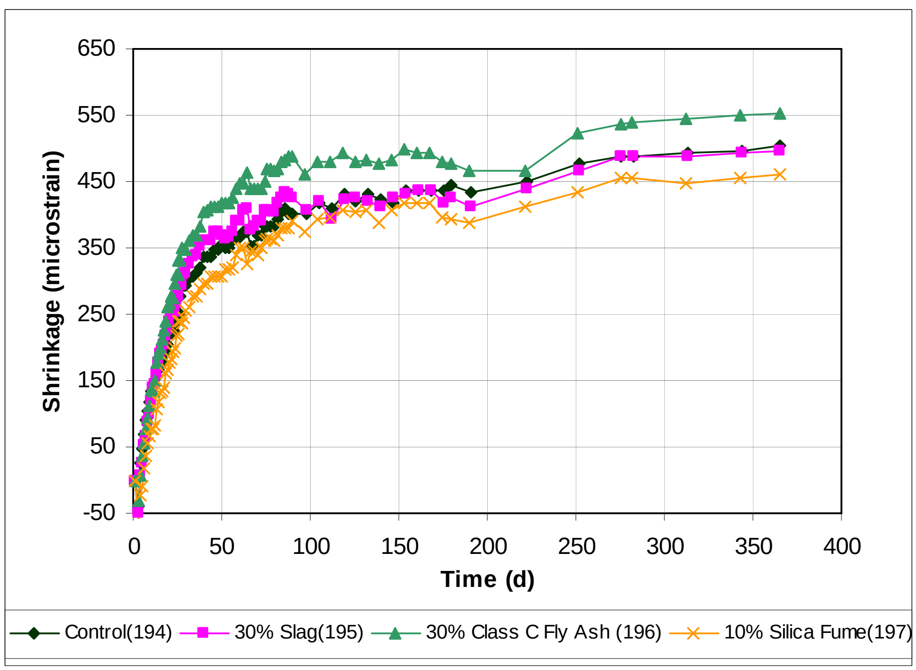

Figure 3.30 Free Shrinkage Test, Program III. Comparing mineral admixtures through 365 days.

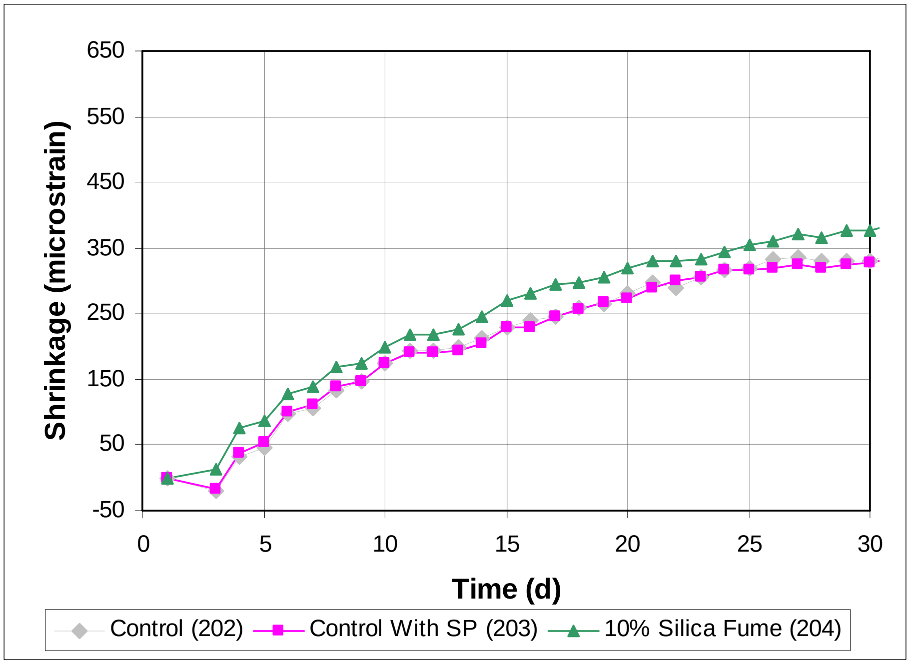

Figure 3.31 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 30 days.

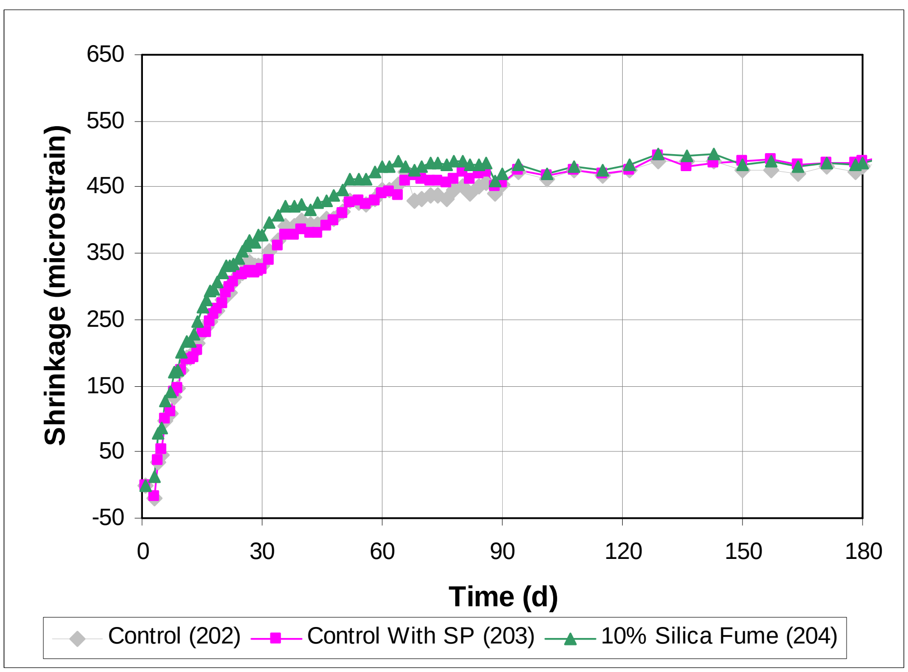

Figure 3.32 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 180 days.

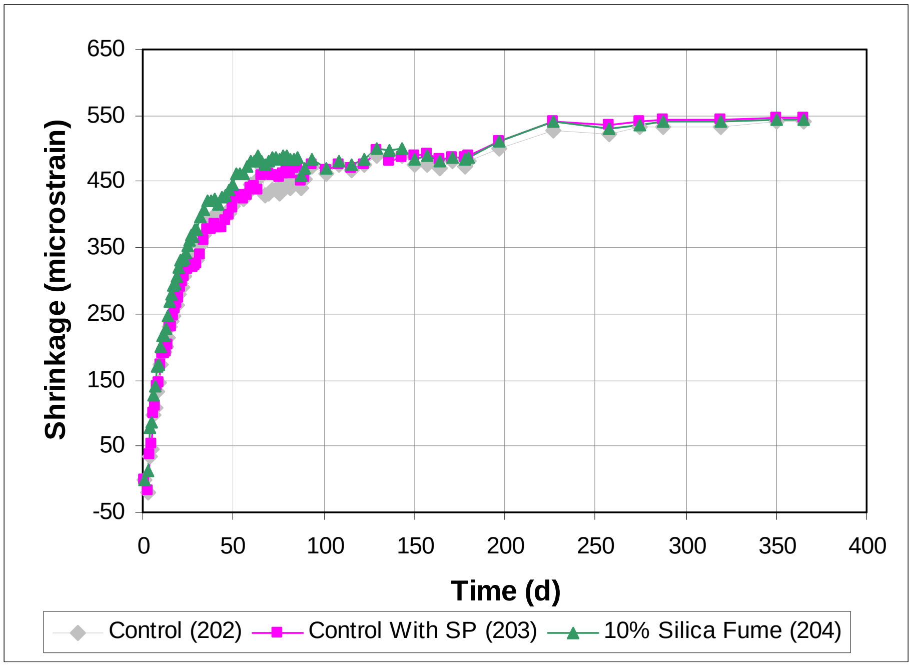

Figure 3.33 Free Shrinkage Test, Program III. Comparing Silica Fume and controls through 365 days.

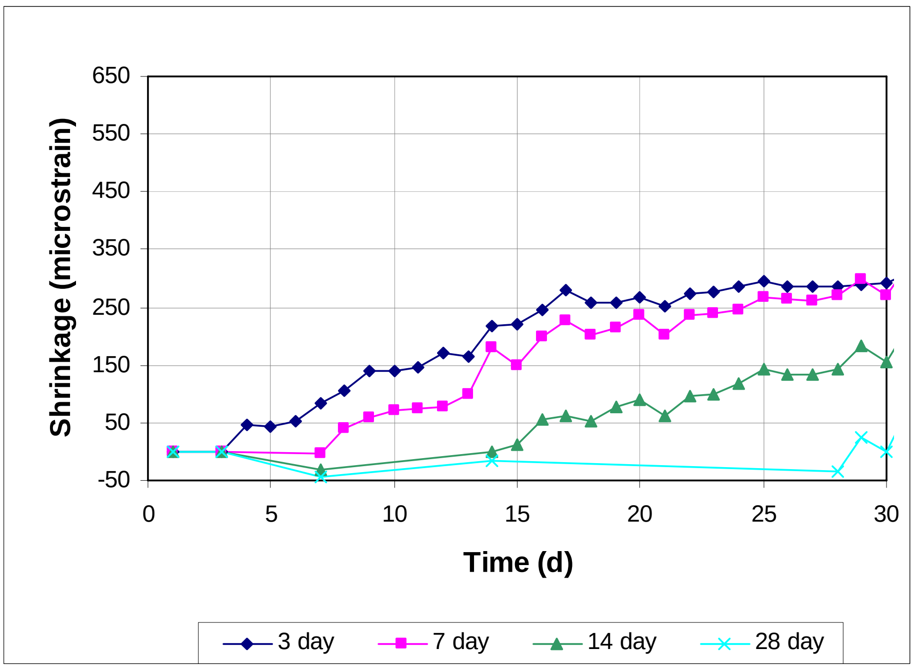

Figure 3.34 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 30 days.

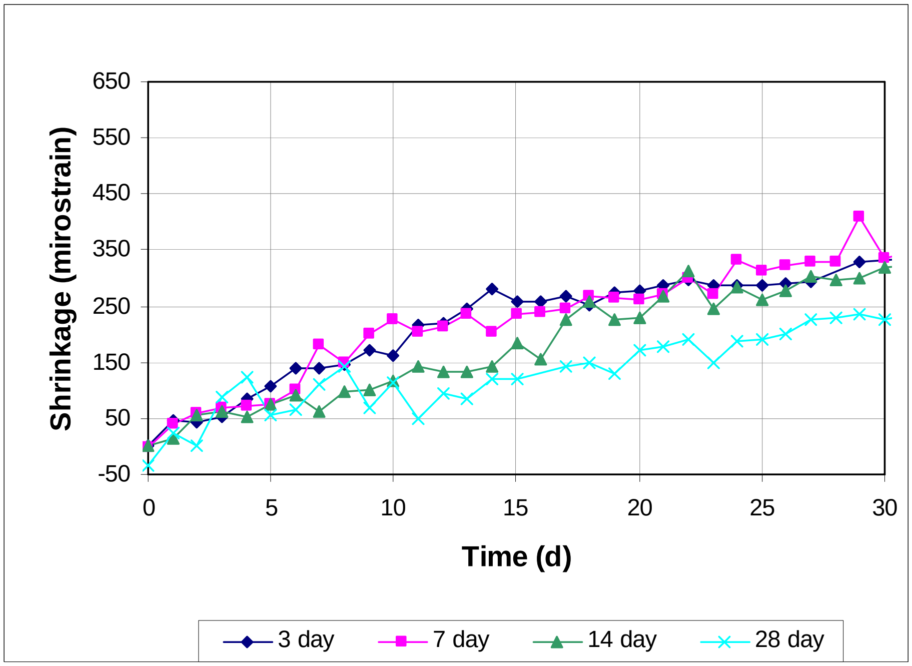

Figure 3.35 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 30 days. Drying only.

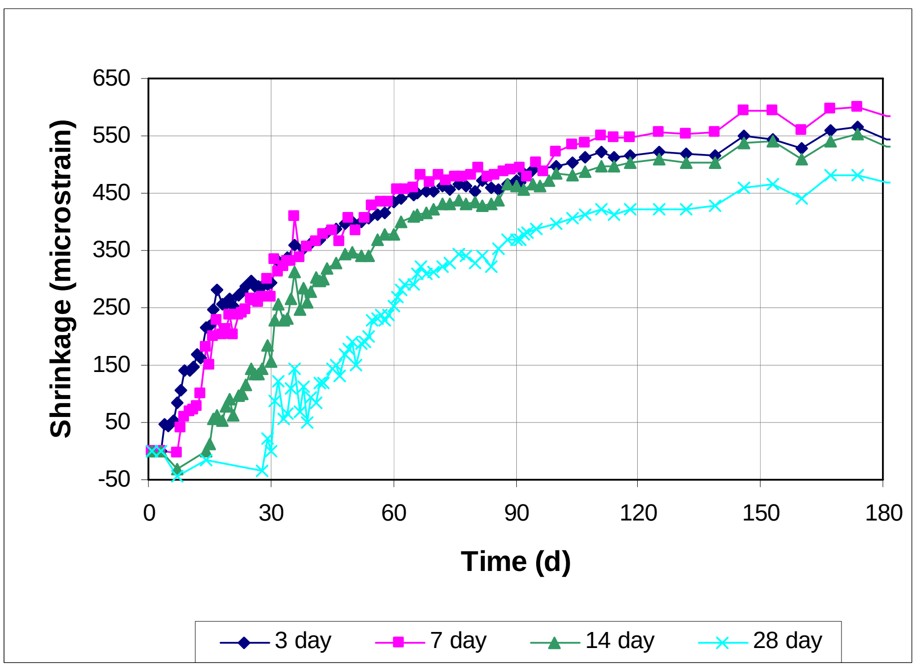

Figure 3.36 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 180 days.

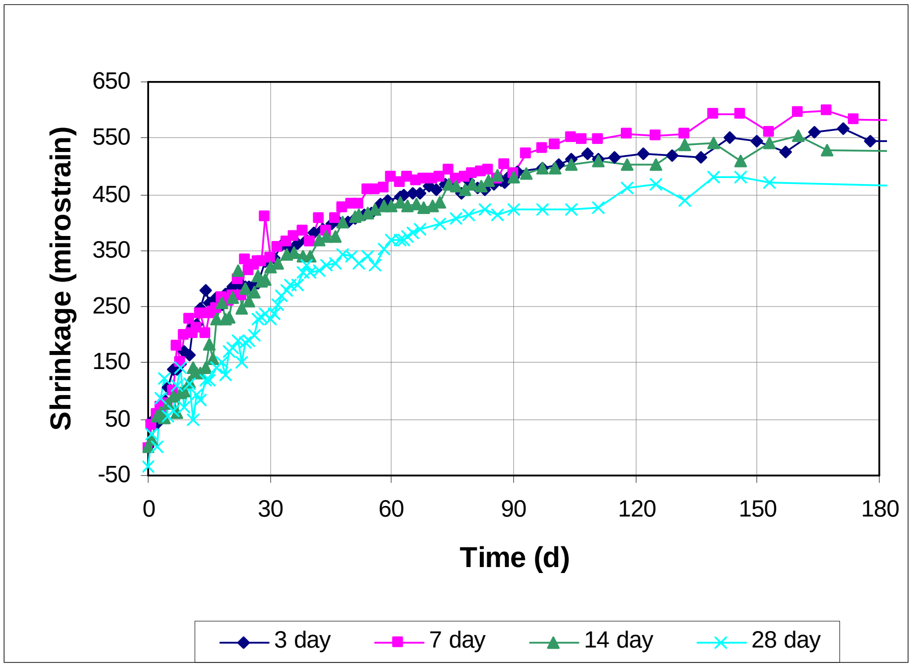

Figure 3.37 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 180 days. Drying only.

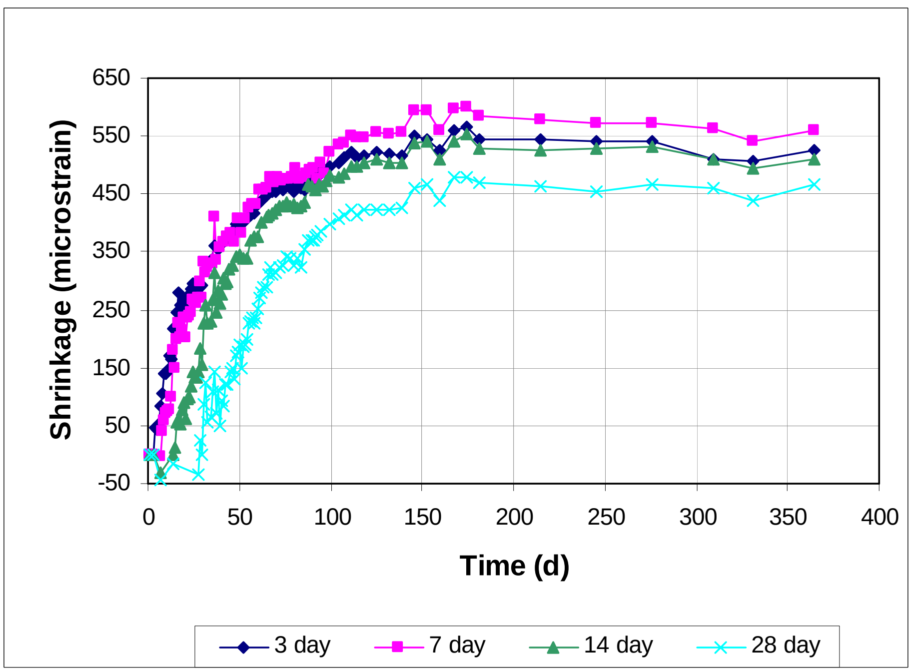

Figure 3.38 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 365 days.

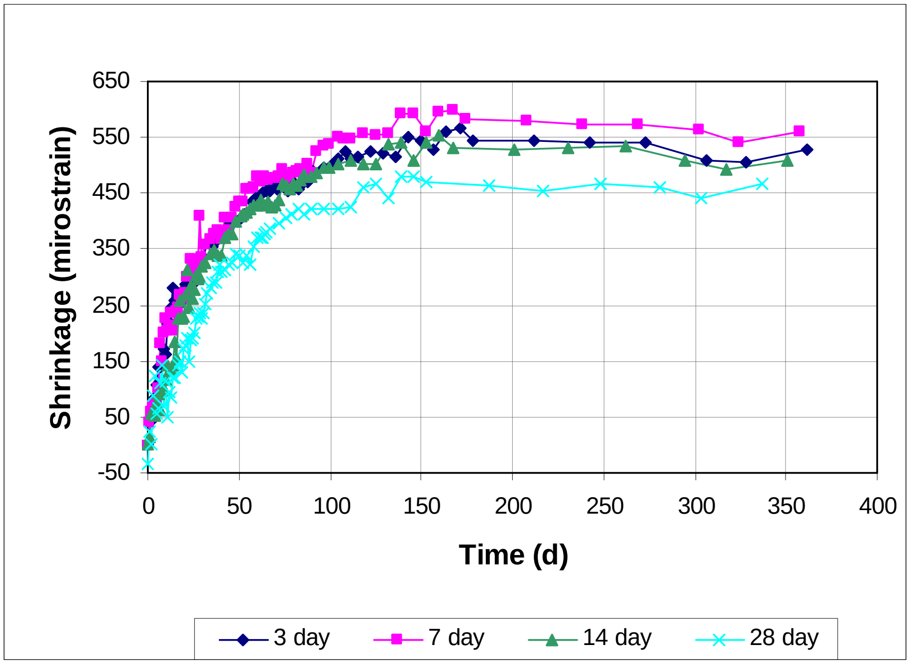

Figure 3.39 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 165. Type I/II cement through 365 days. Drying only.

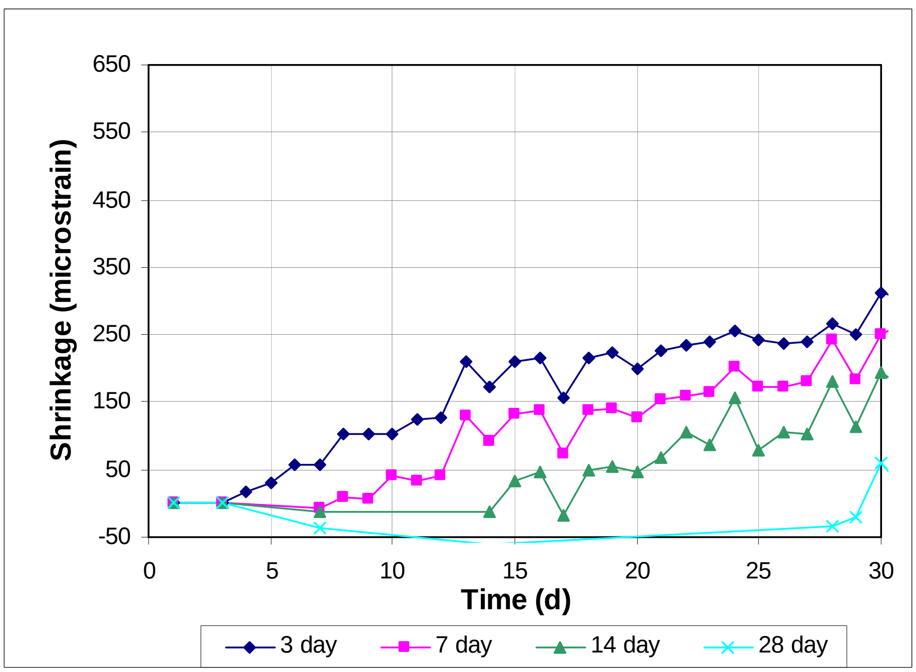

Figure 3.40 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 30 days. Type II coarse ground (CG) cement.

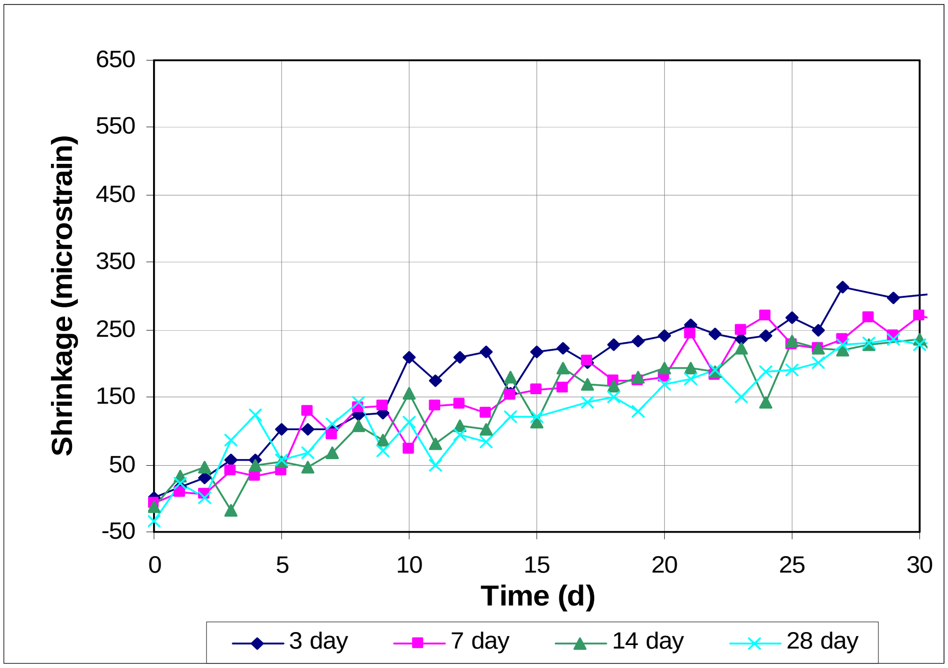

Figure 3.41 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 30 days. Drying only.

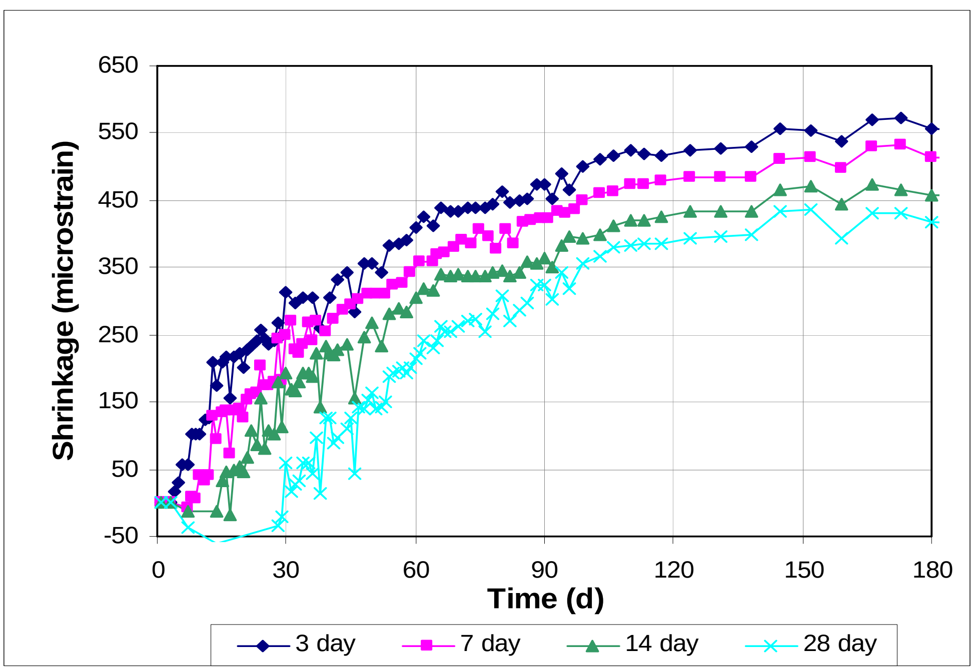

Figure 3.42 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 180 days. Type II coarse ground (CG) cement.

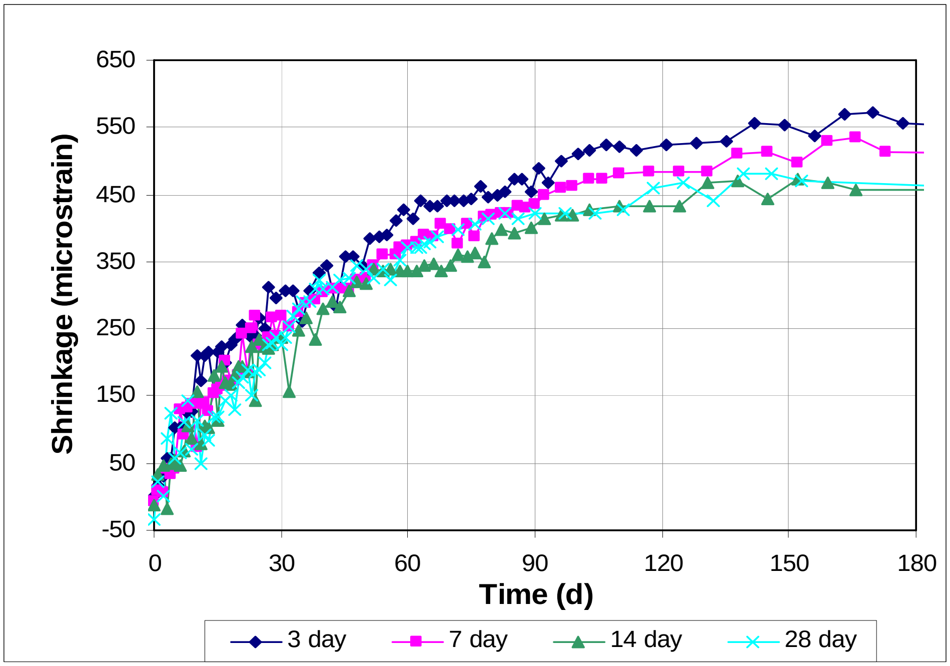

Figure 3.43 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 180 days. Drying only.

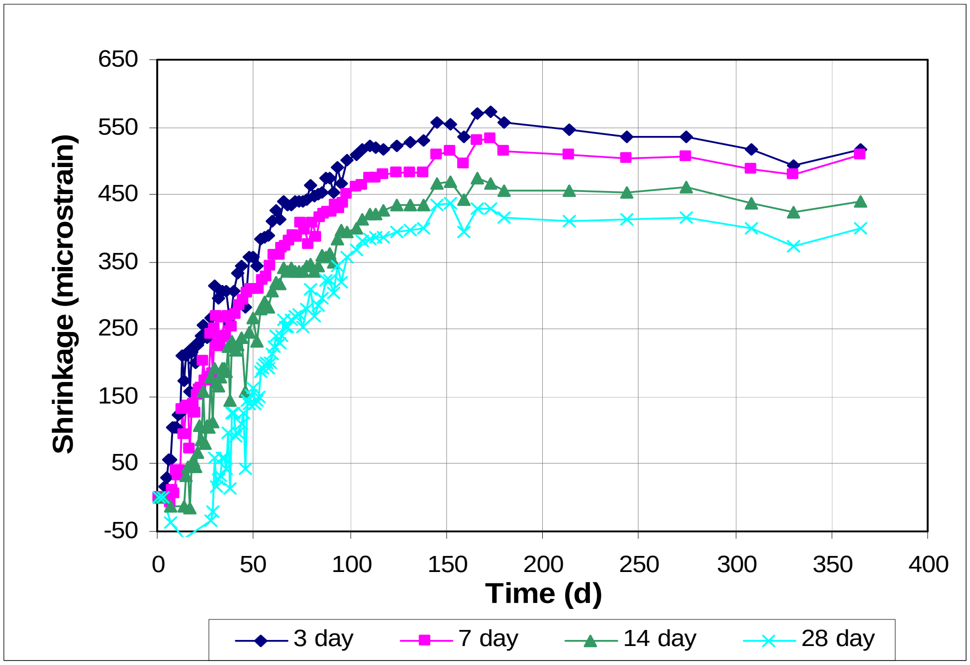

Figure 3.44 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166 through 365 days. Type II coarse ground (CG) cement.

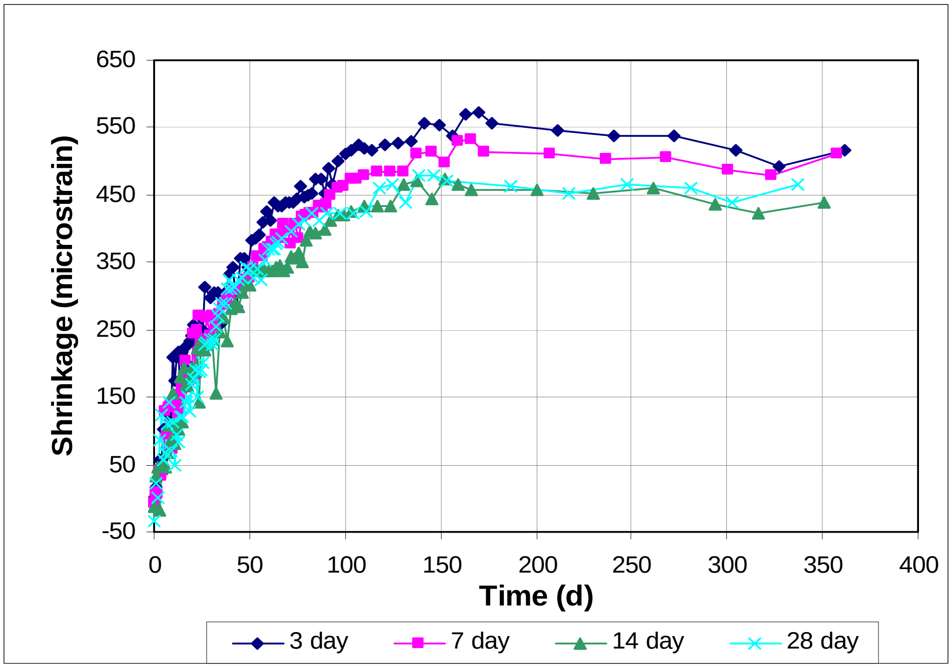

Figure 3.45 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Batch 166. Type II coarse ground (CG) cement through 365 days. Drying only.

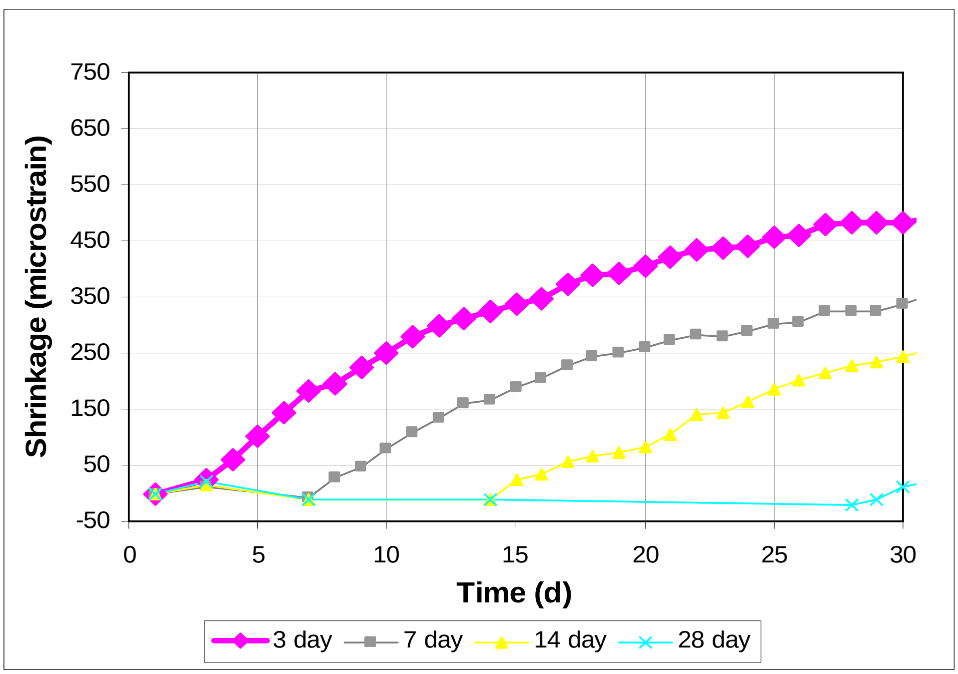

Figure 3.46 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 30 days.

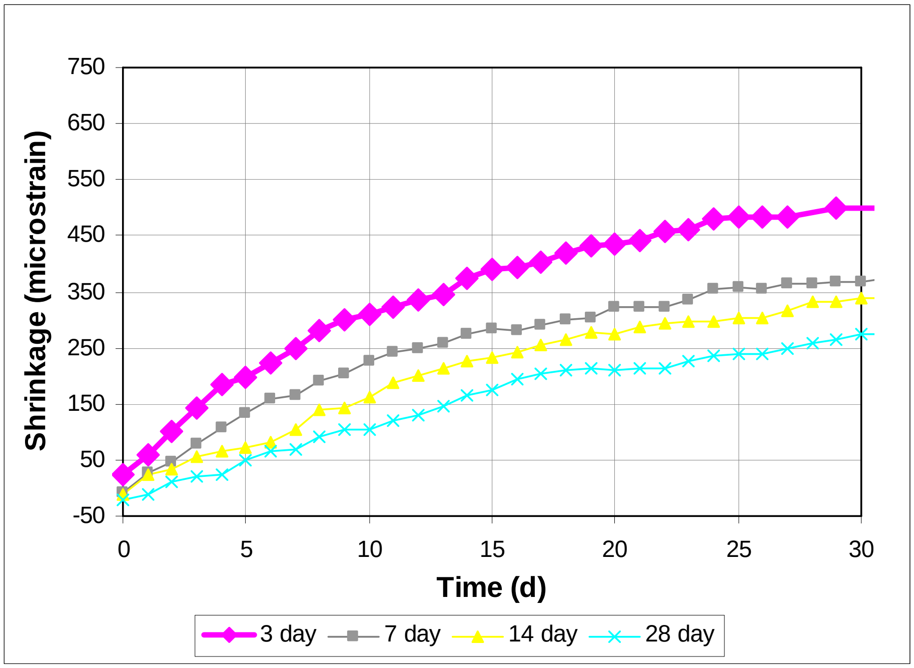

Figure 3.47 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 30 days. Drying only.

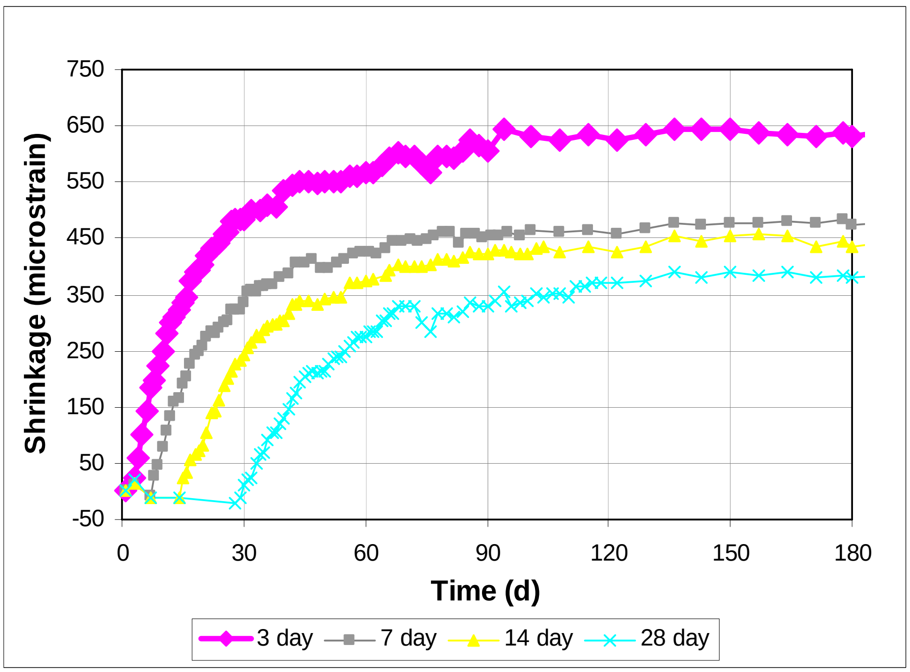

Figure 3.48 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 180 days.

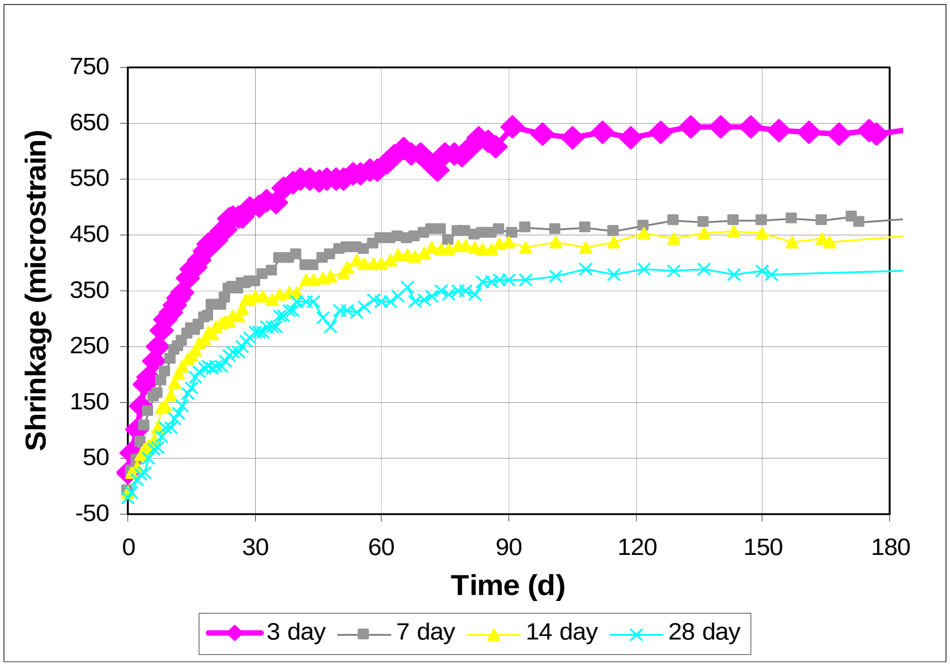

Figure 3.49 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 180 days. Drying only.

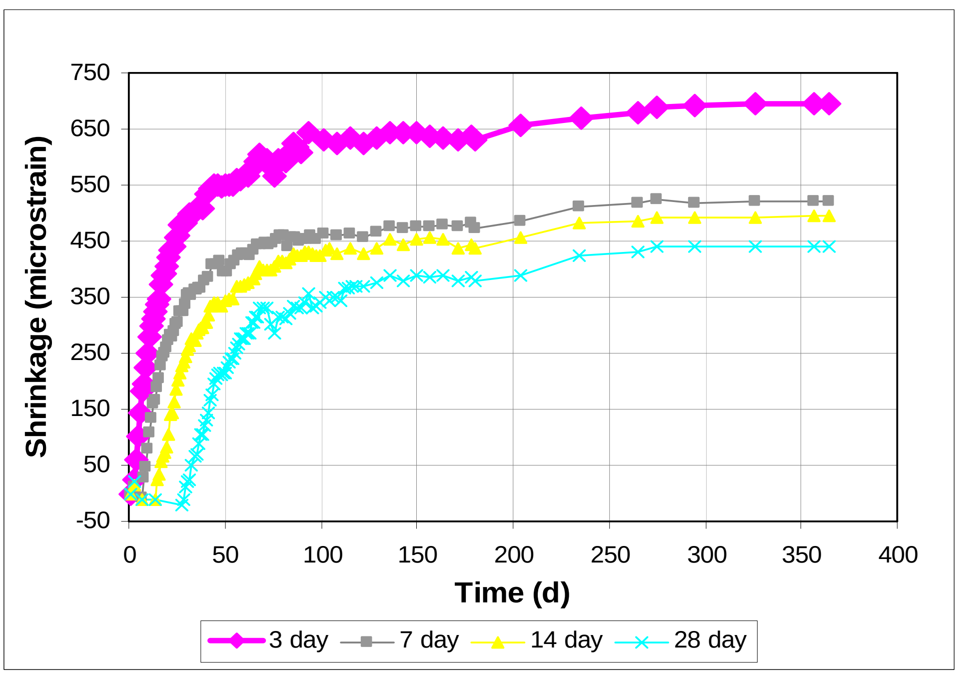

Figure 3.50 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 365 days.

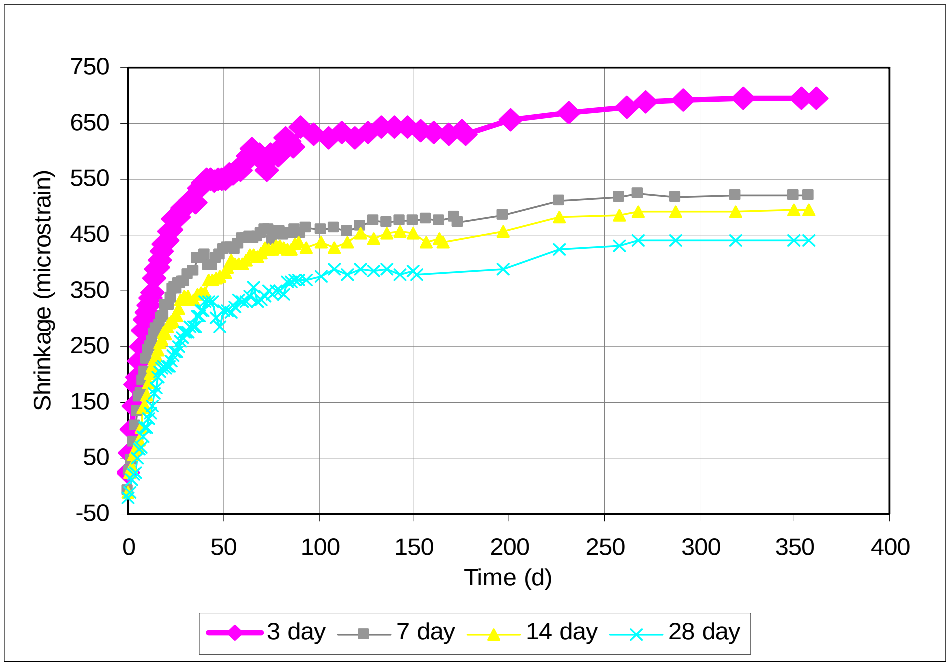

Figure 3.51 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type I/II cement. Batch 201 through 365 days. Drying only.

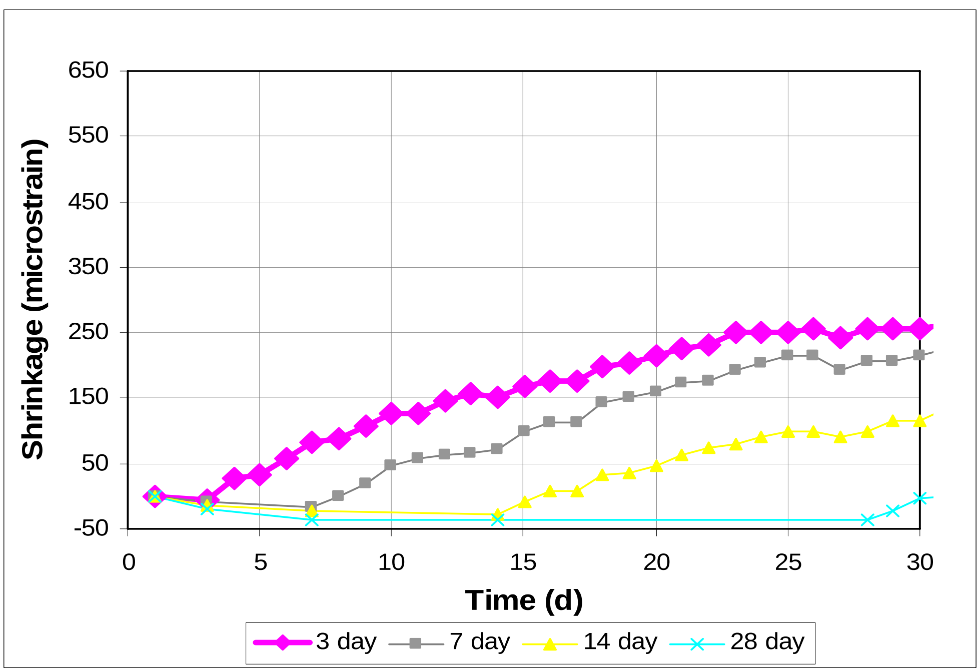

Figure 3.52 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 30 days.

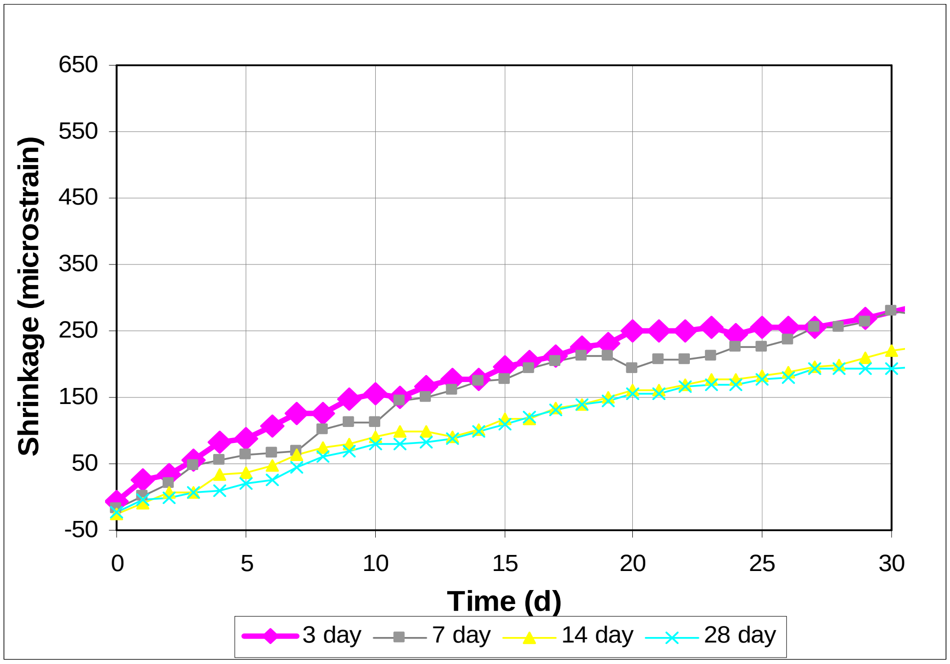

Figure 3.53 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 30 days. Drying only.

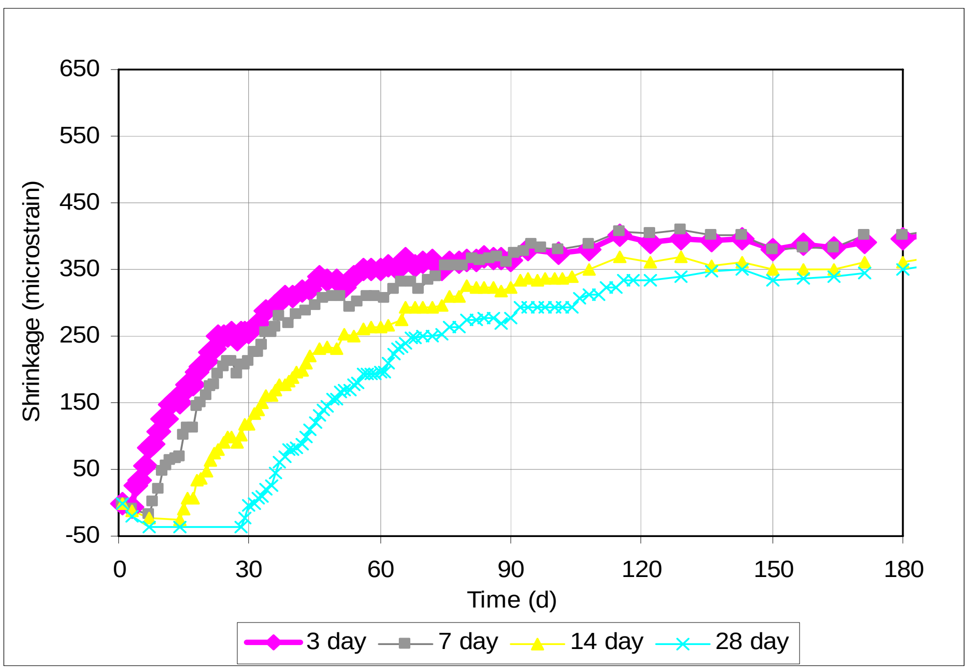

Figure 3.54 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement through 180 days. Batch 207.

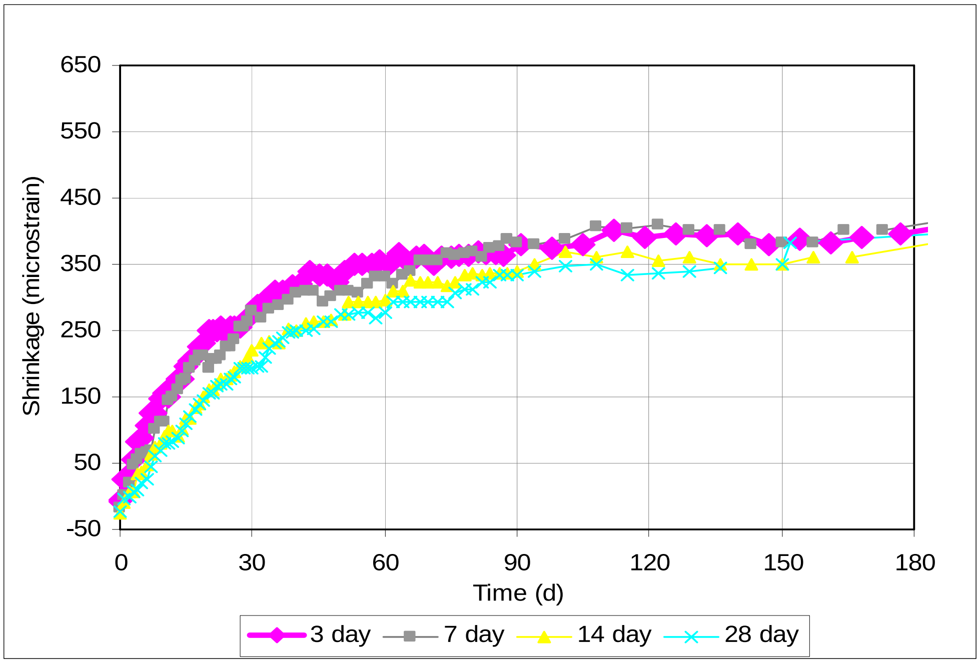

Figure 3.55 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 180 days. Drying only.

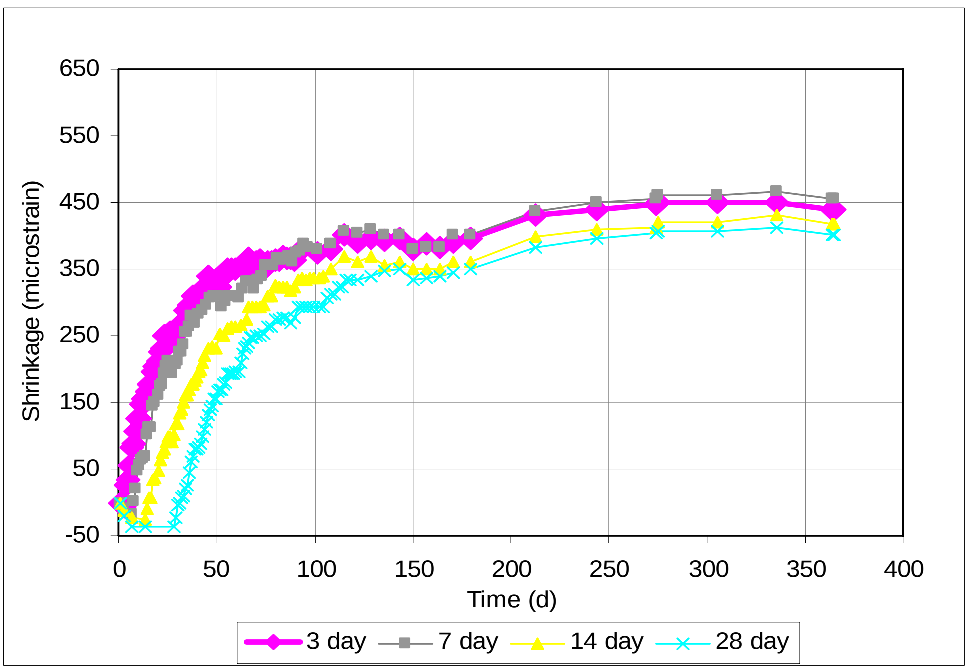

Figure 3.56 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 365 days.

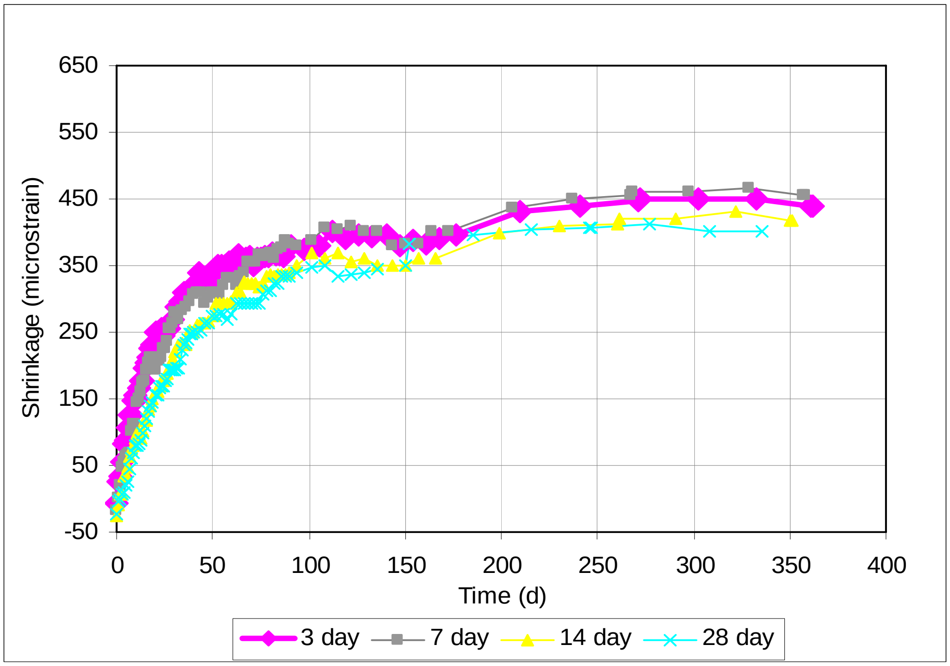

Figure 3.57 - Free Shrinkage, Program IV. Average free shrinkage vs. time for different curing times. Type II coarse ground (CG) cement. Batch 207 through 365 days. Drying only.

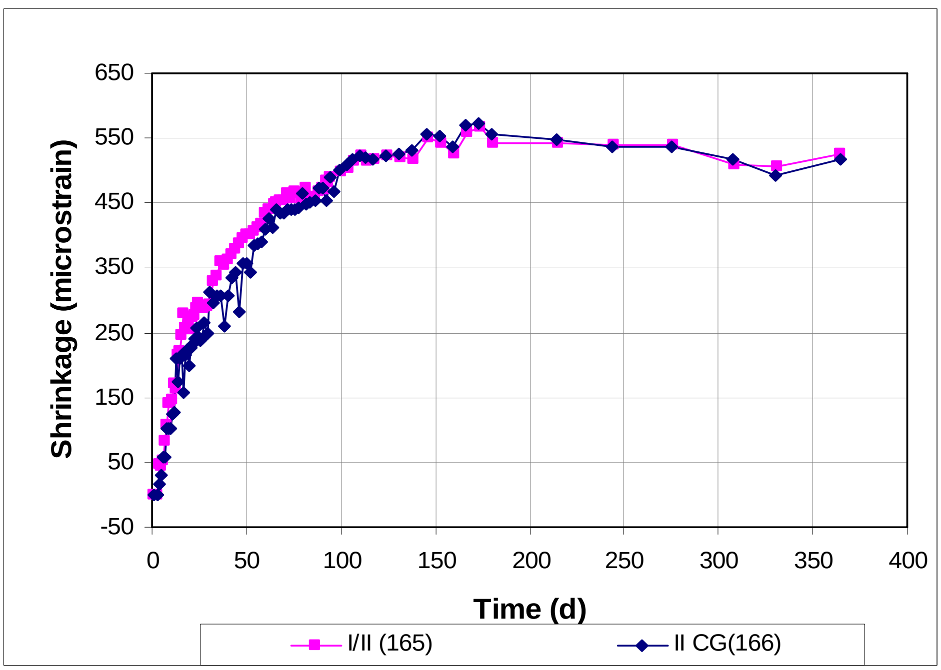

Figure 3.58 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 3-day cure specimens. Comparing cement type through 365 days.

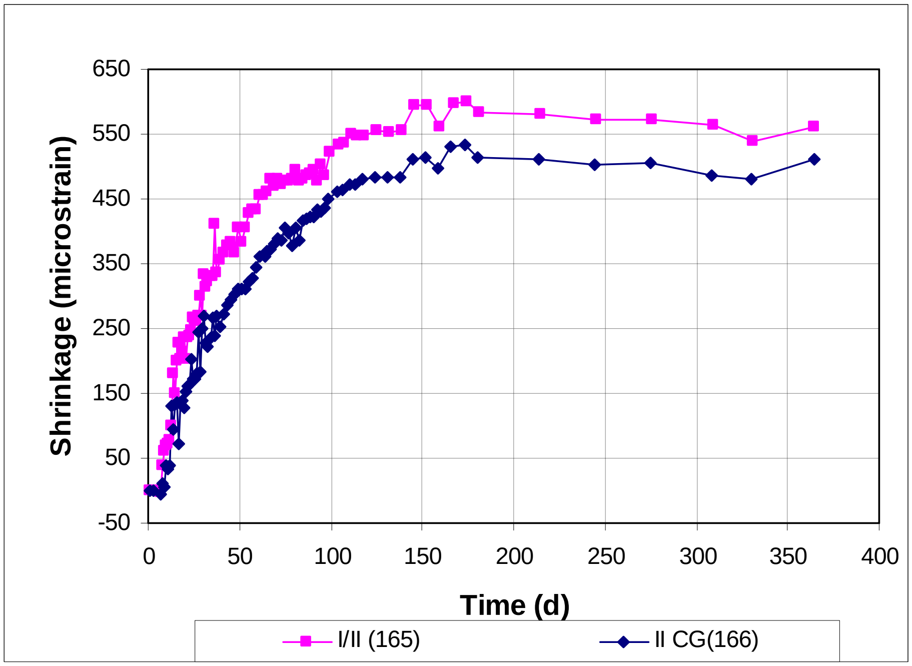

Figure 3.59 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 7-day cure specimens. Comparing cement type through 365 days.

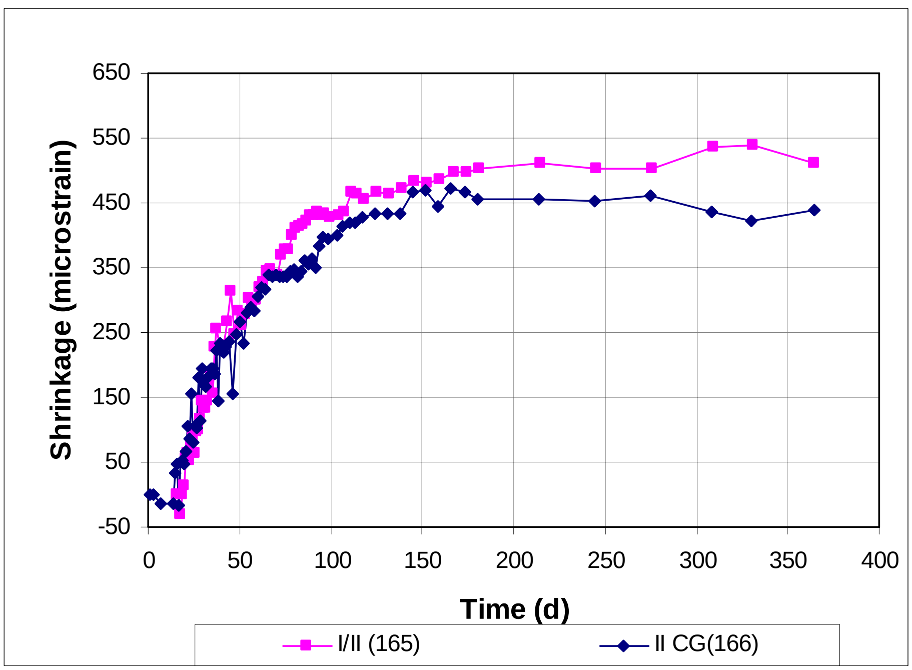

Figure 3.60 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 14-day cure specimens. Comparing cement type through 365 days.

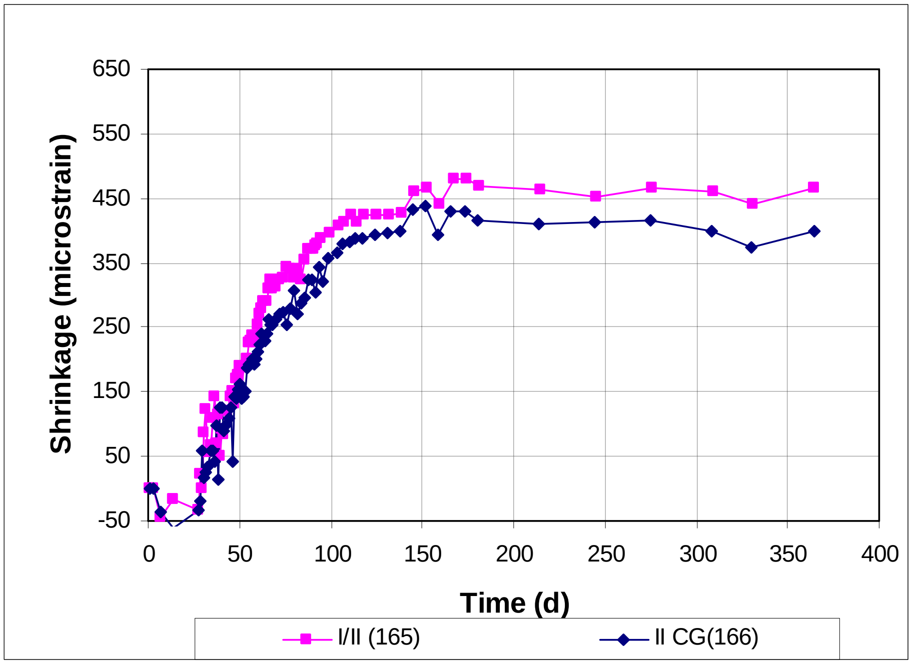

Figure 3.61 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 28-day cure specimens. Comparing cement type through 365 days.

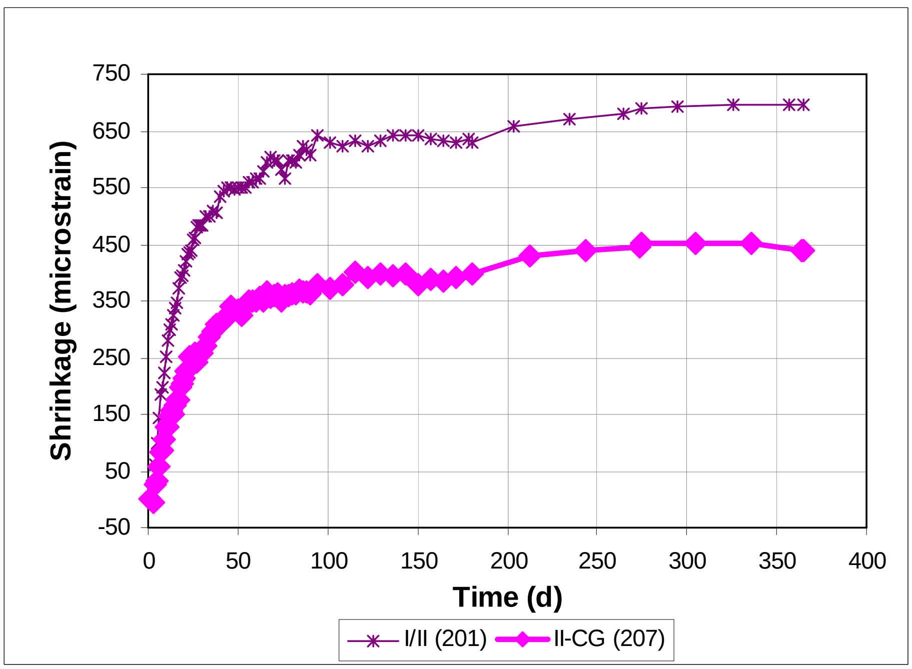

Figure 3.62 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 3-day cure specimens. Comparing cement type through 365 days.

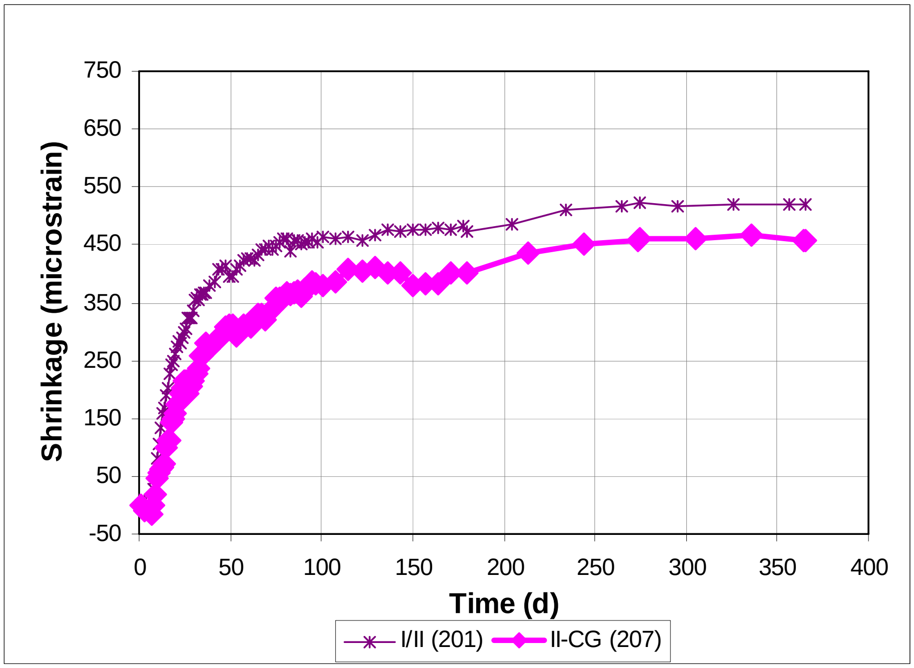

Figure 3.63 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 7-day cure specimens. Comparing cement type through 365 days.

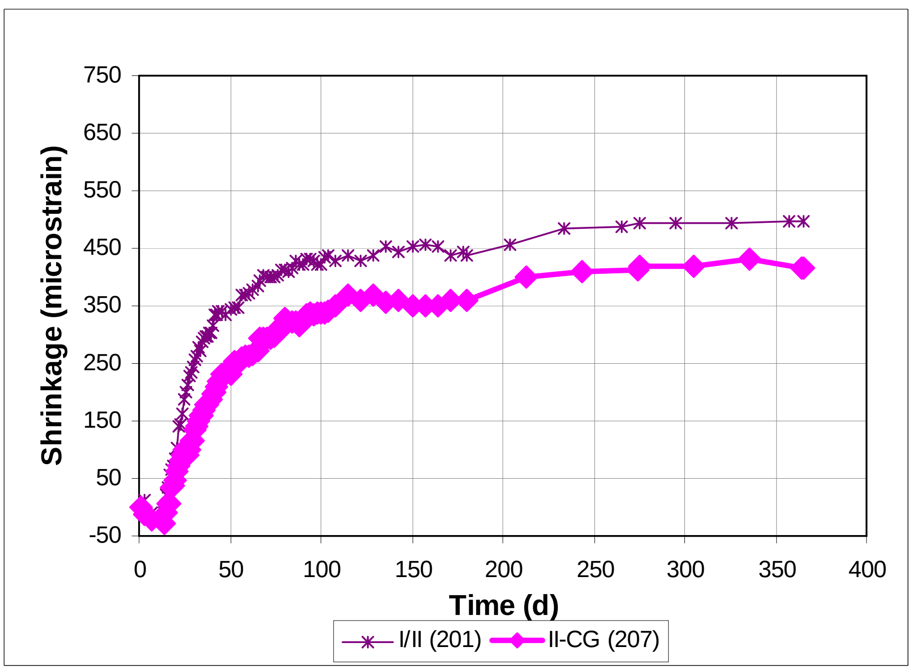

Figure 3.64 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 14-day cure specimens. Comparing cement type through 365 days.

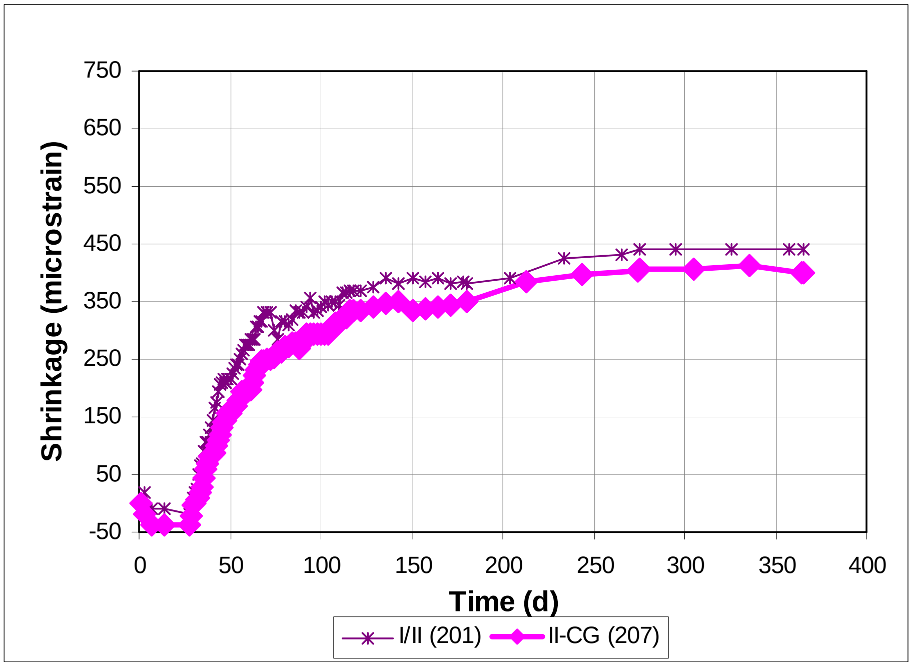

Figure 3.65 - Free Shrinkage, Program IV. Average free shrinkage vs. time for 28-day cure specimens. Comparing cement type through 365 days.

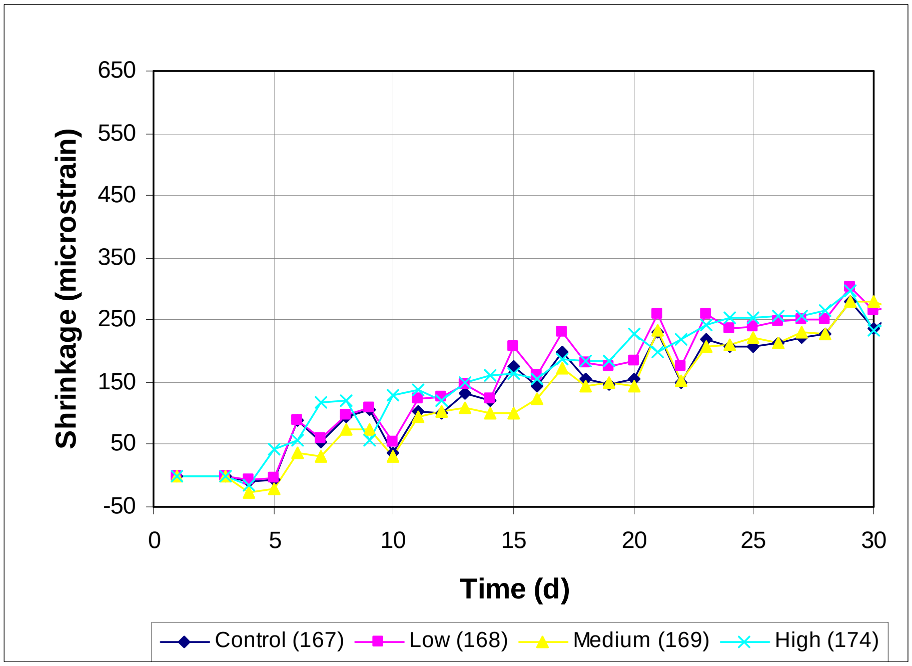

Figure 3.66 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 30 days.

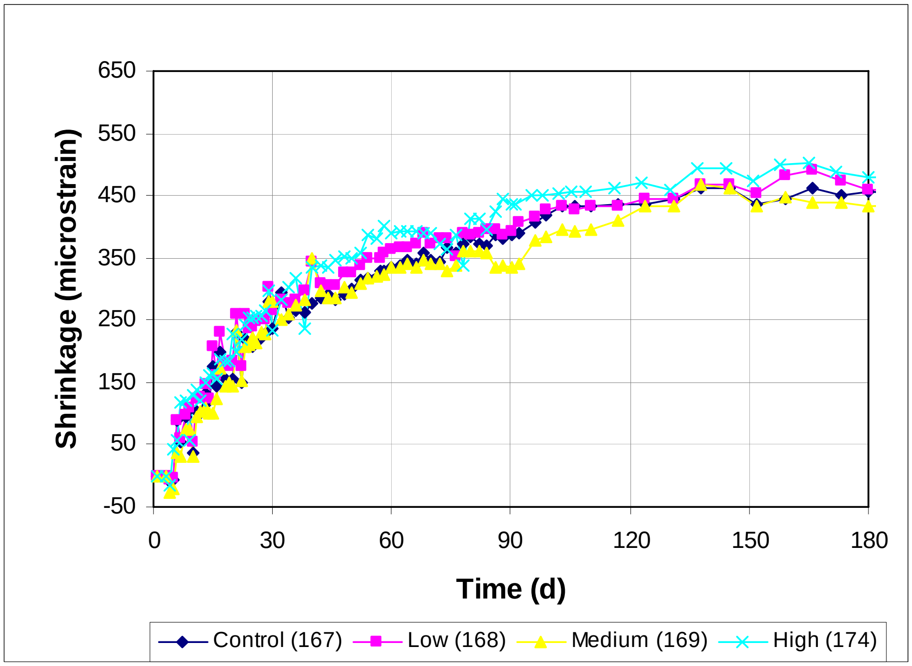

Figure 3.67 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 180 days.

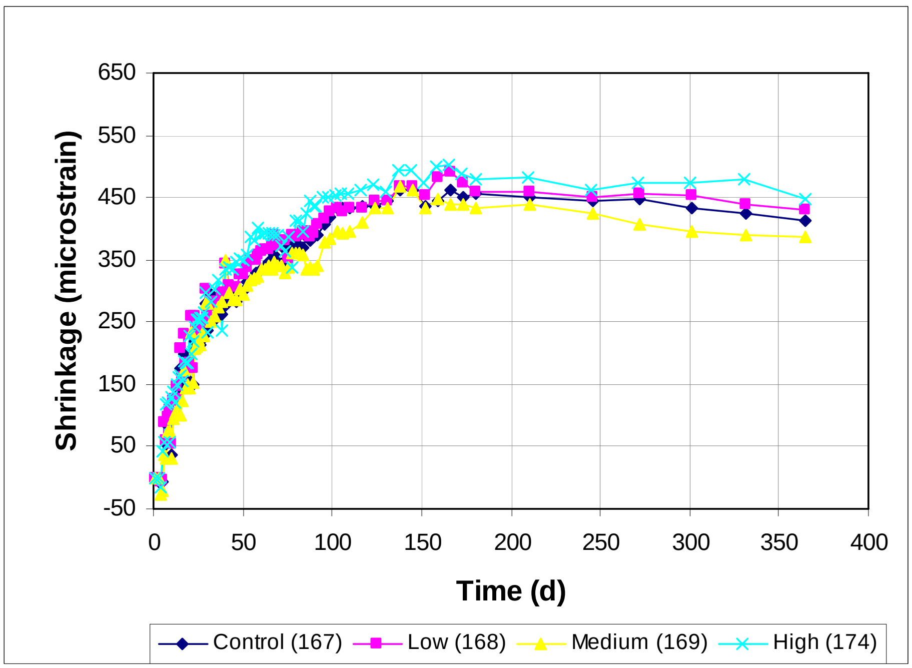

Figure 3.68 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 365 days.

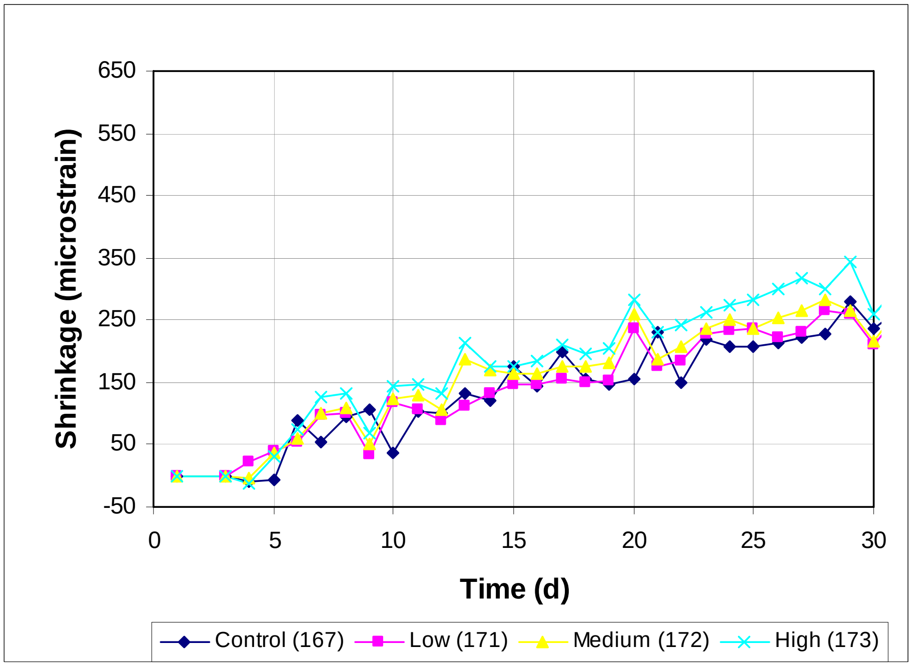

Figure 3.69 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 30 days.

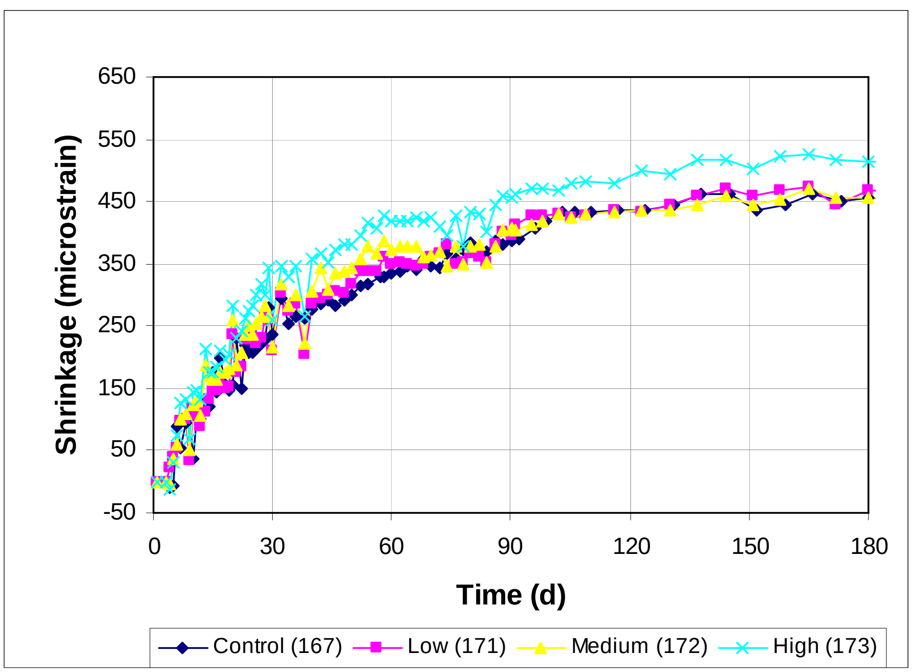

Figure 3.70 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 180 days.

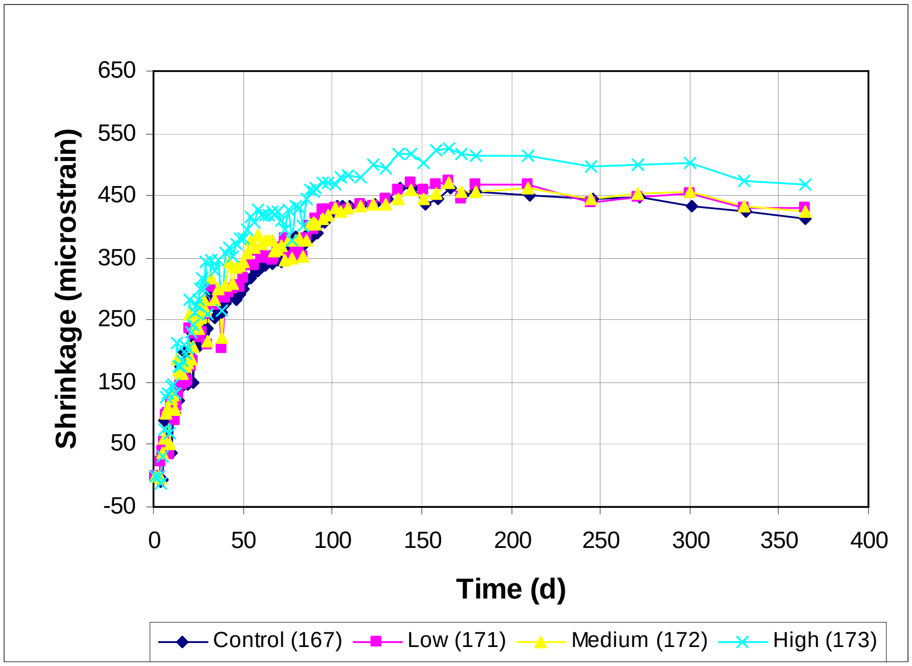

Figure 3.71 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 365 days.

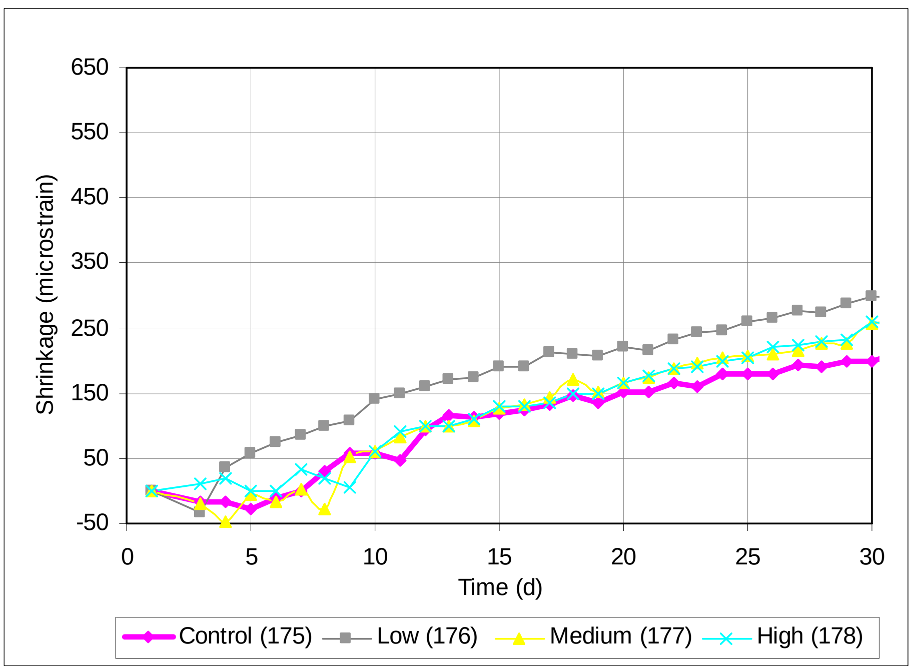

Figure 3.72 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 30 days.

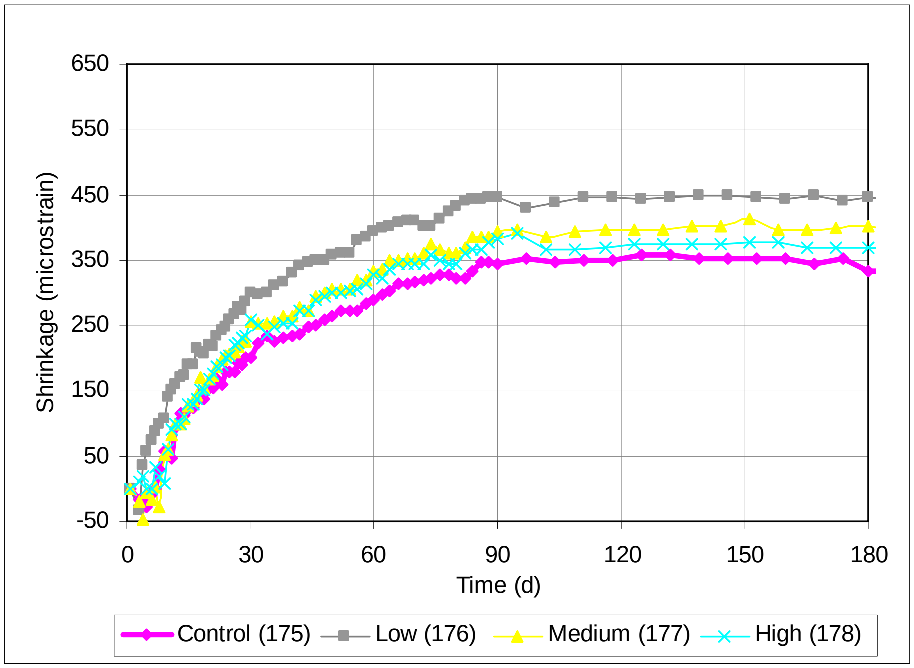

Figure 3.73 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 180 days.

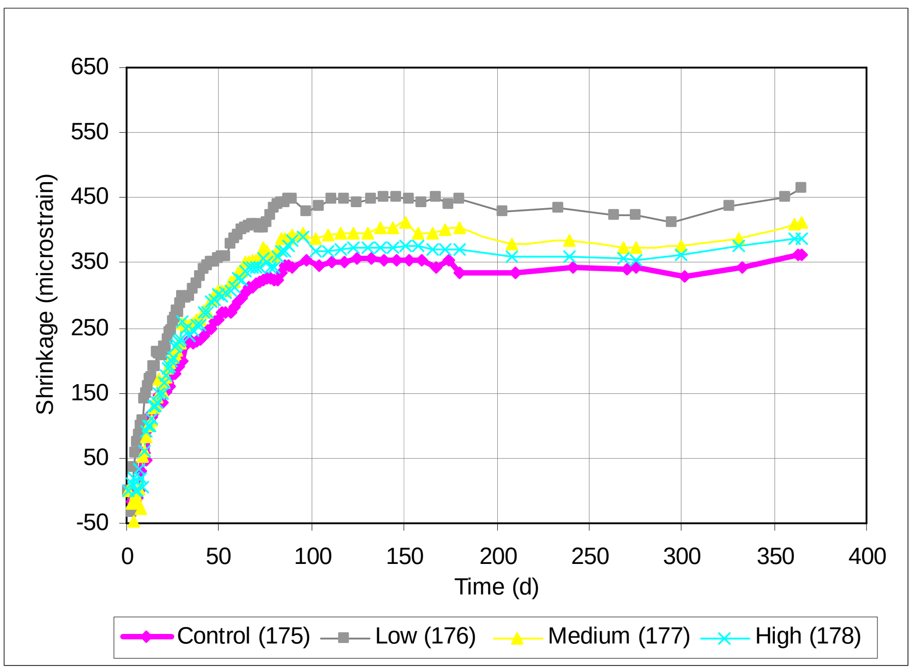

Figure 3.74 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Glenium 3000 NS through 365 days.

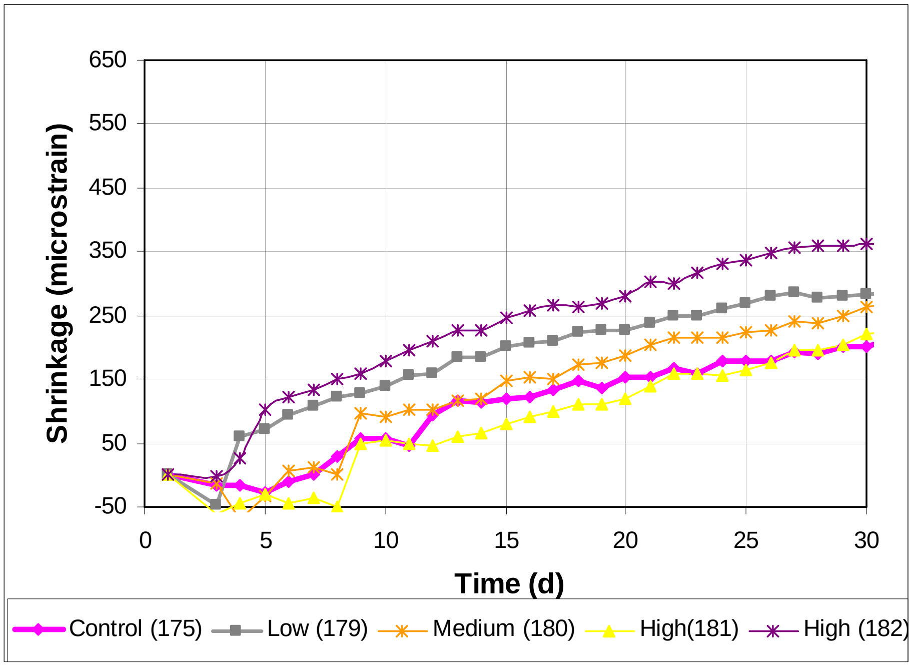

Figure 3.75 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 30 days.

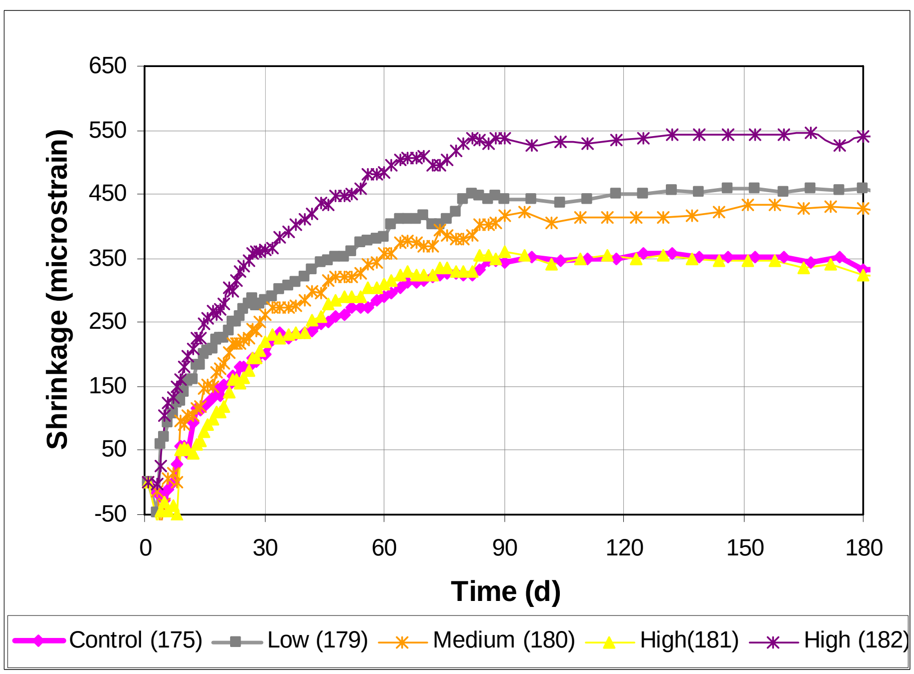

Figure 3.76 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 180 days.

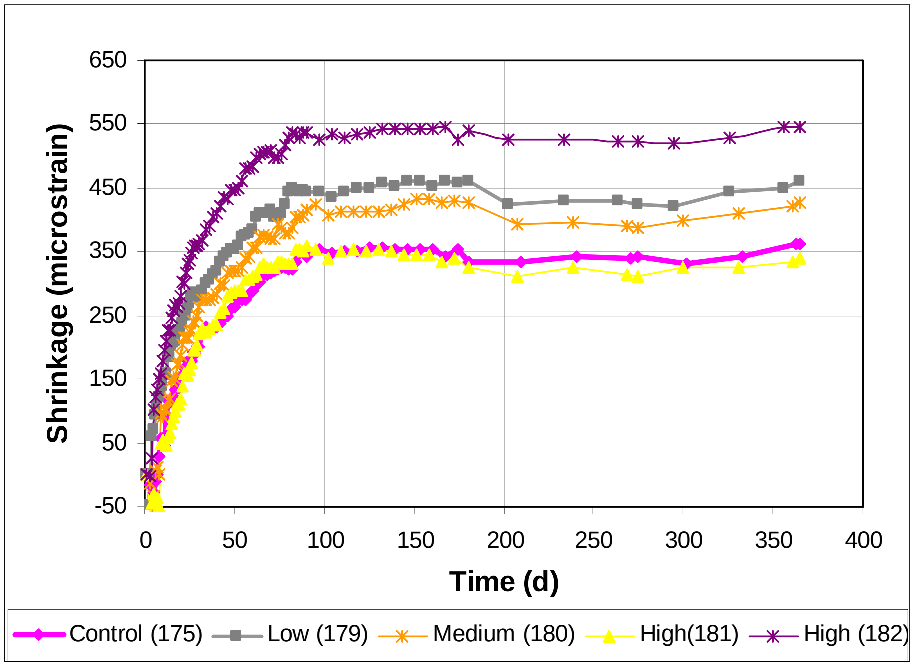

Figure 3.77 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Rheobuild 1000 through 365 days.

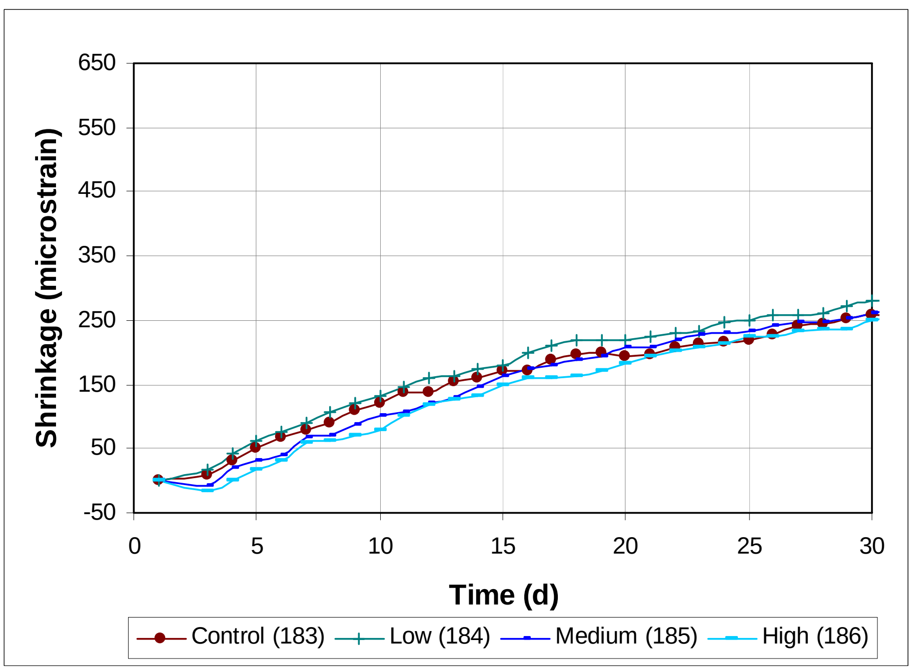

Figure 3.78 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 30 days.

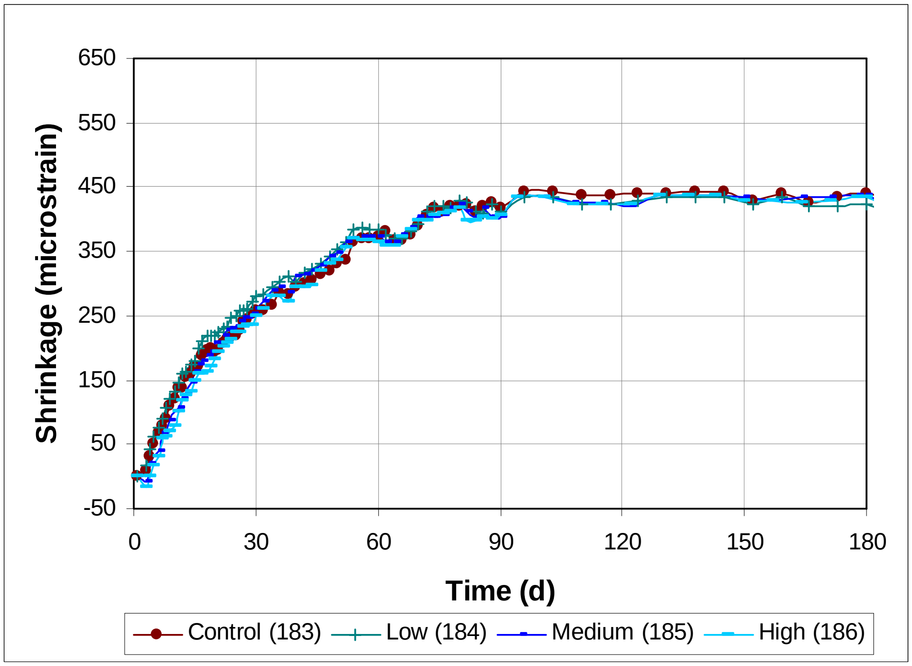

Figure 3.79 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 180 days.

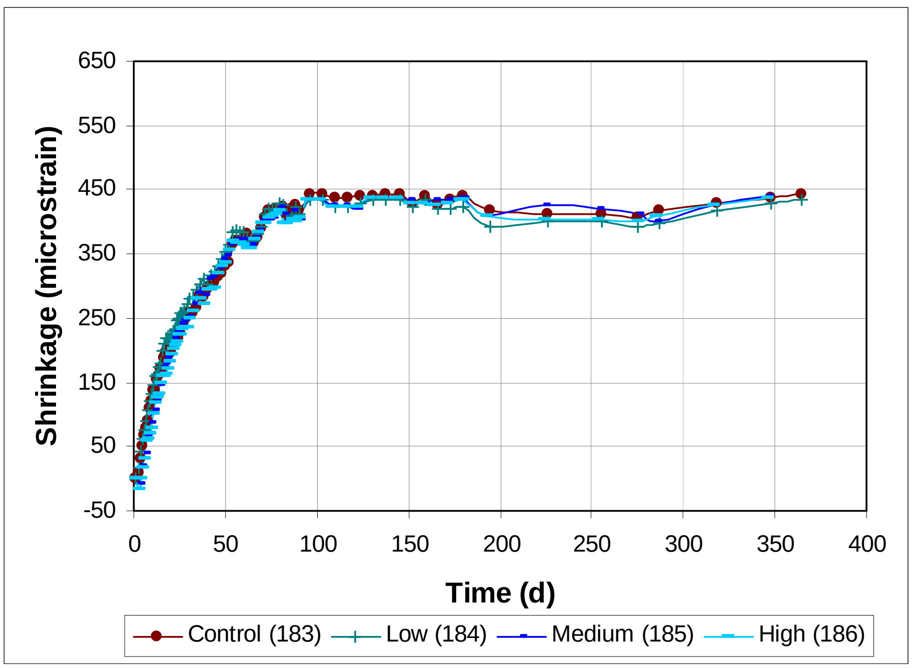

Figure 3.80 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 365 days.

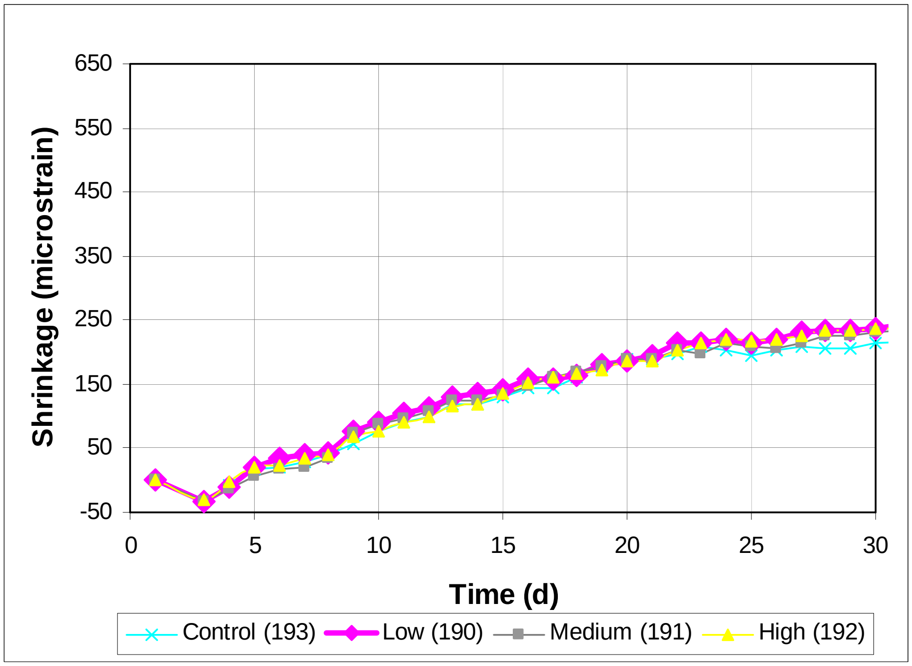

Figure 3.81 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 30 days.

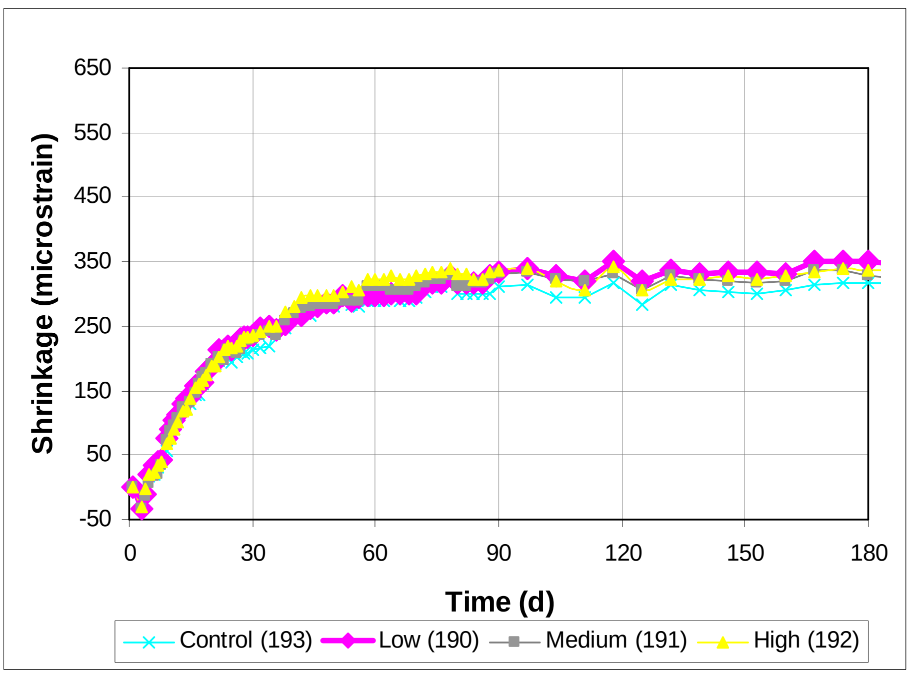

Figure 3.82 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 180 days.

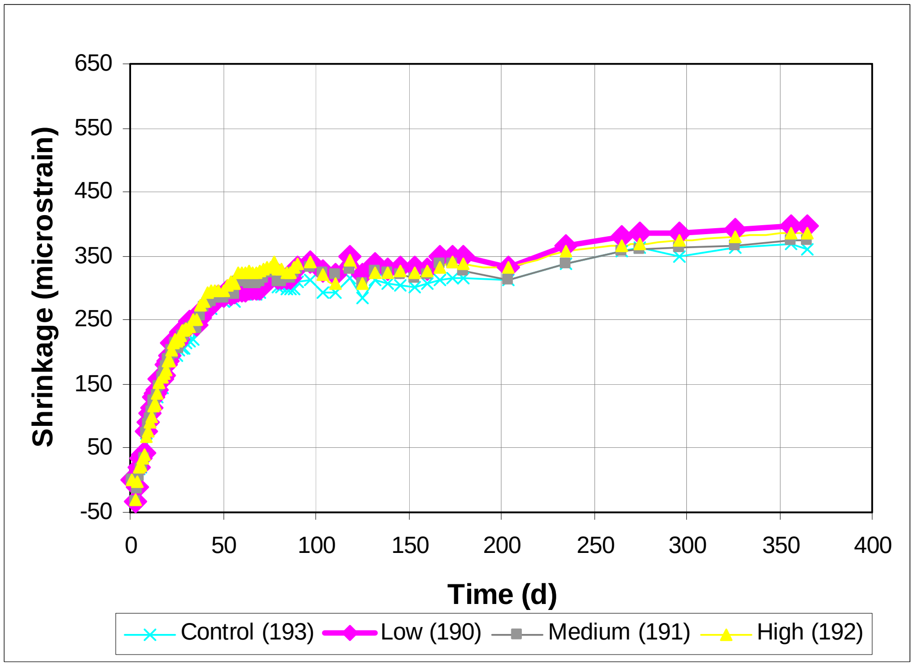

Figure 3.83 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different dosages of Adva 100 through 365 days.

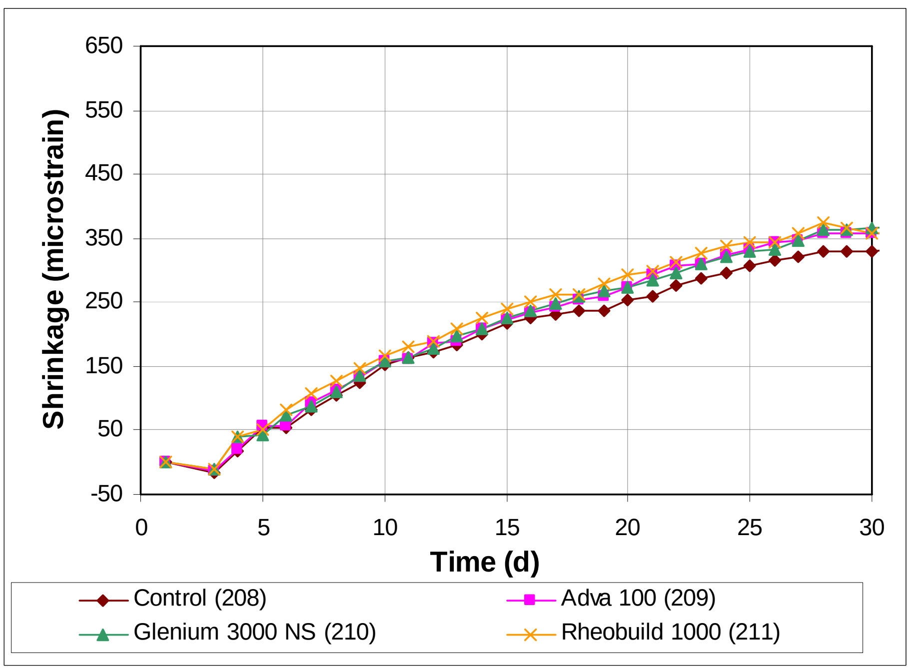

Figure 3.84 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 30 days.

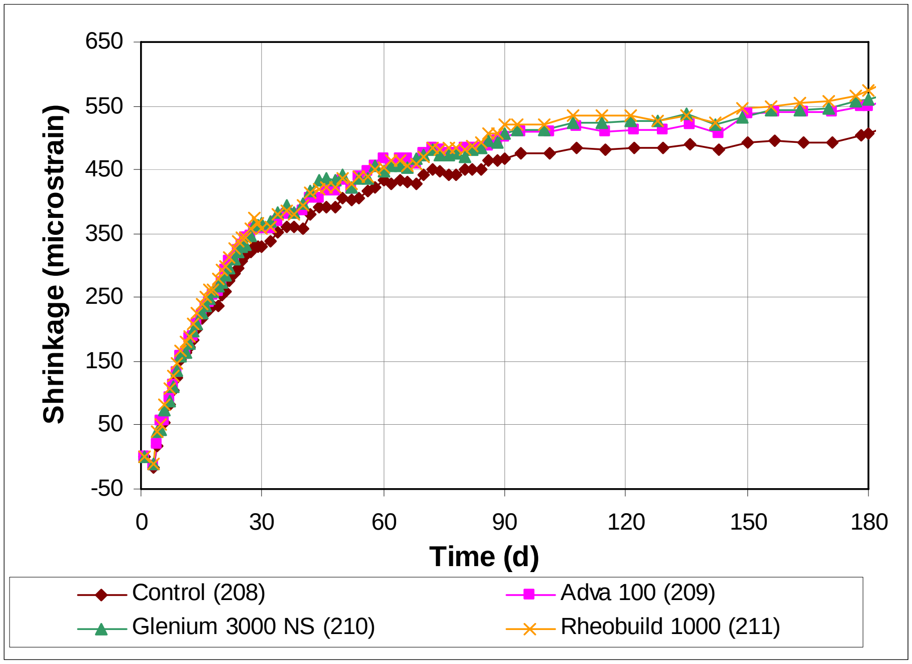

Figure 3.85 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 180 days.

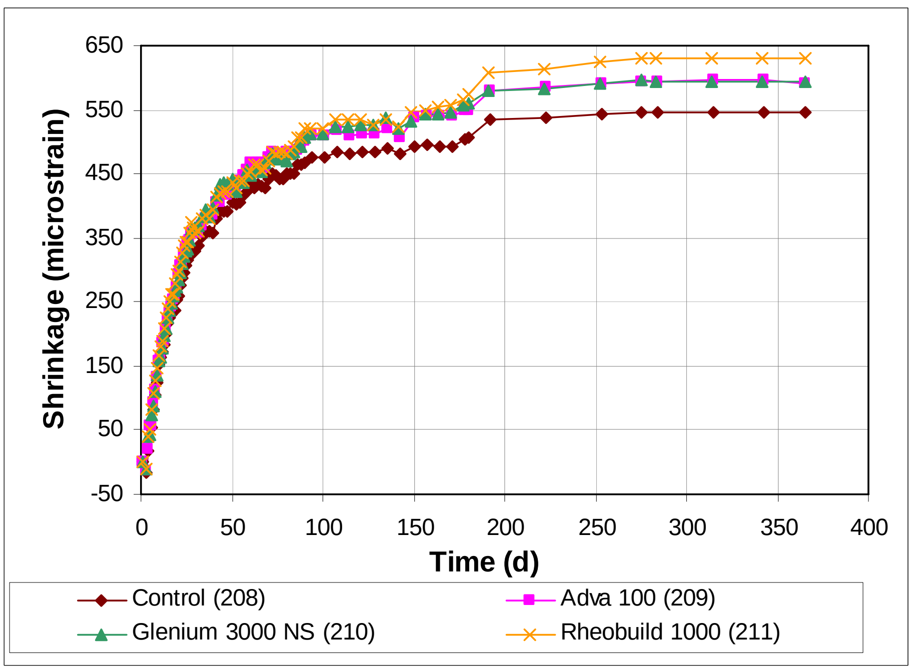

Figure 3.86 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 365 days.

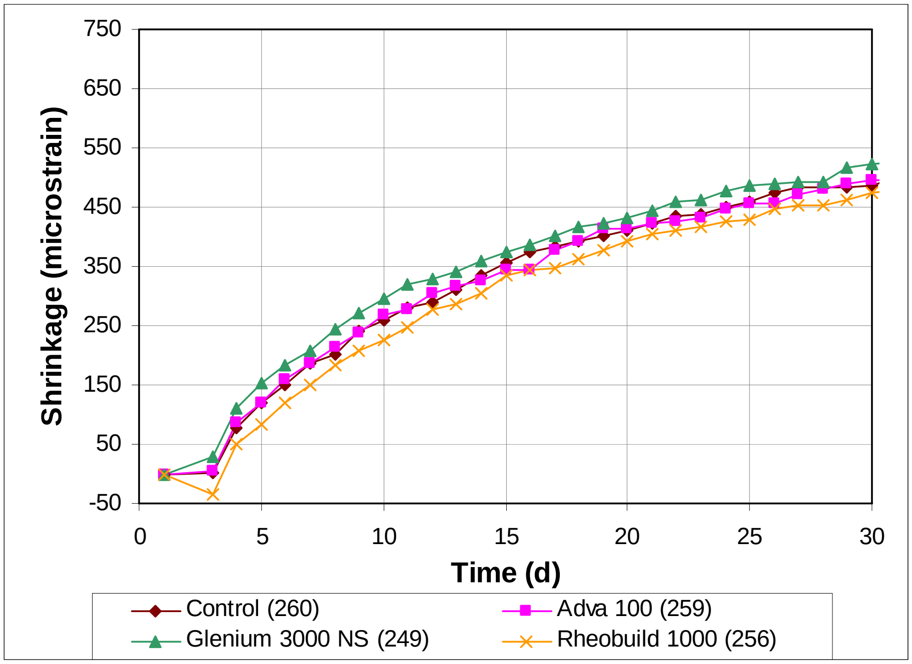

Figure 3.87 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 30 days.

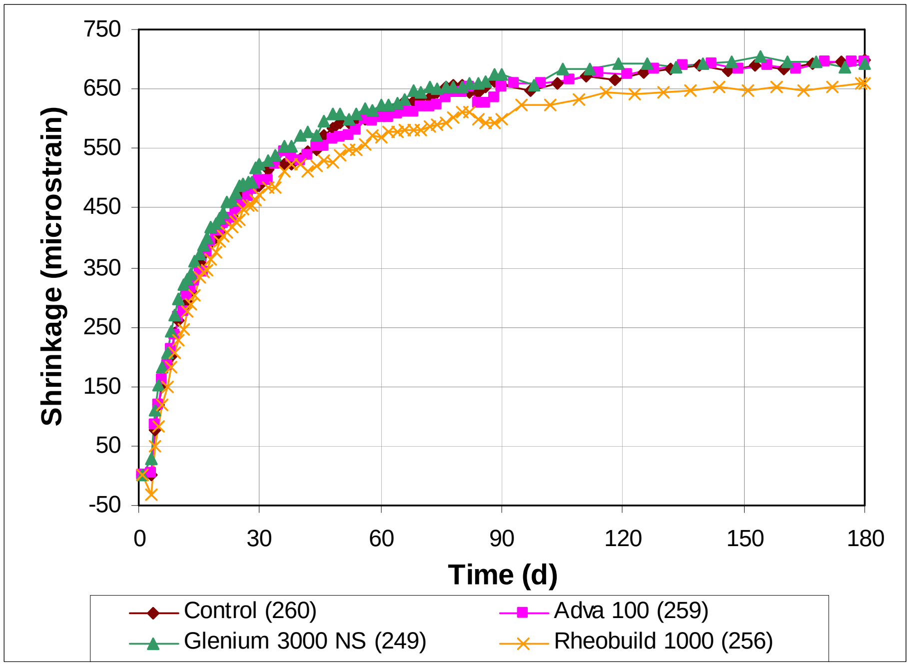

Figure 3.88 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 180 days.

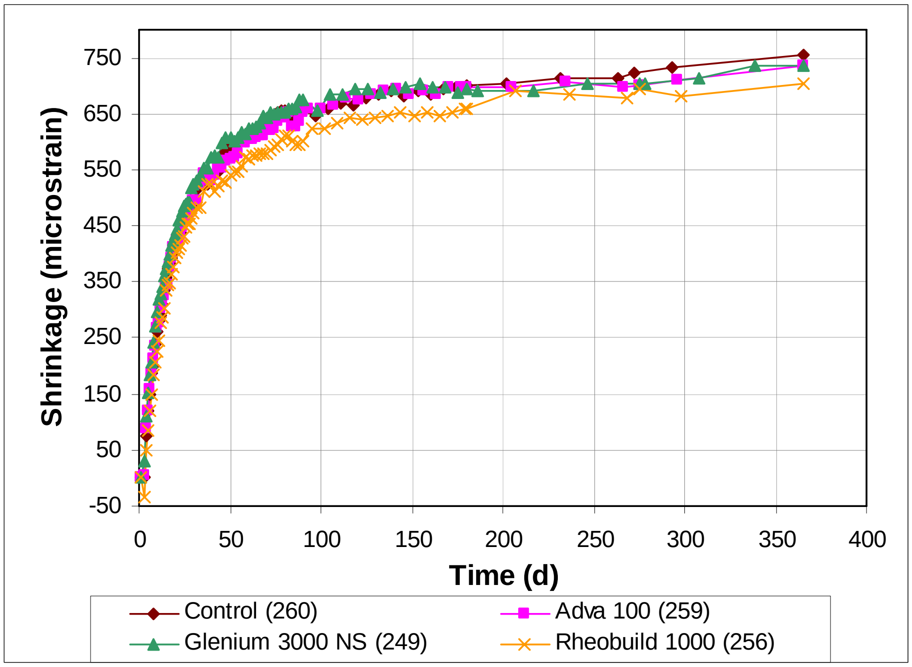

Figure 3.89 Free Shrinkage Test, Program V. Average free shrinkage vs. time. Comparing different Superplasticizers (Dosages for same slump) through 365 days.

APPENDIX A

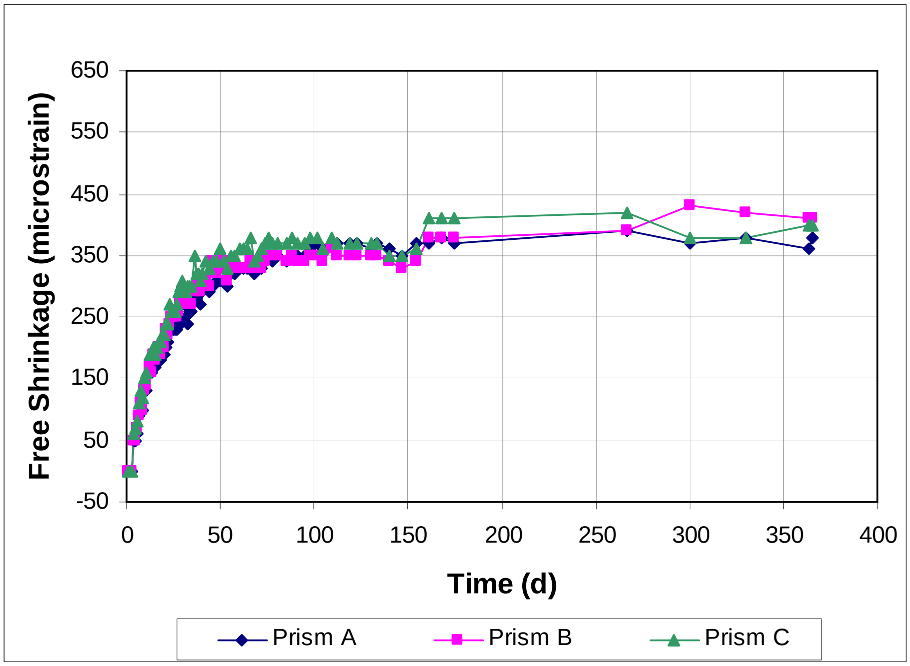

Figure A3.1 - Free Shrinkage, Batch 62. 80% Aggregate, 0.40 w/c. Type I/II cement. Drying begins at 3 days.

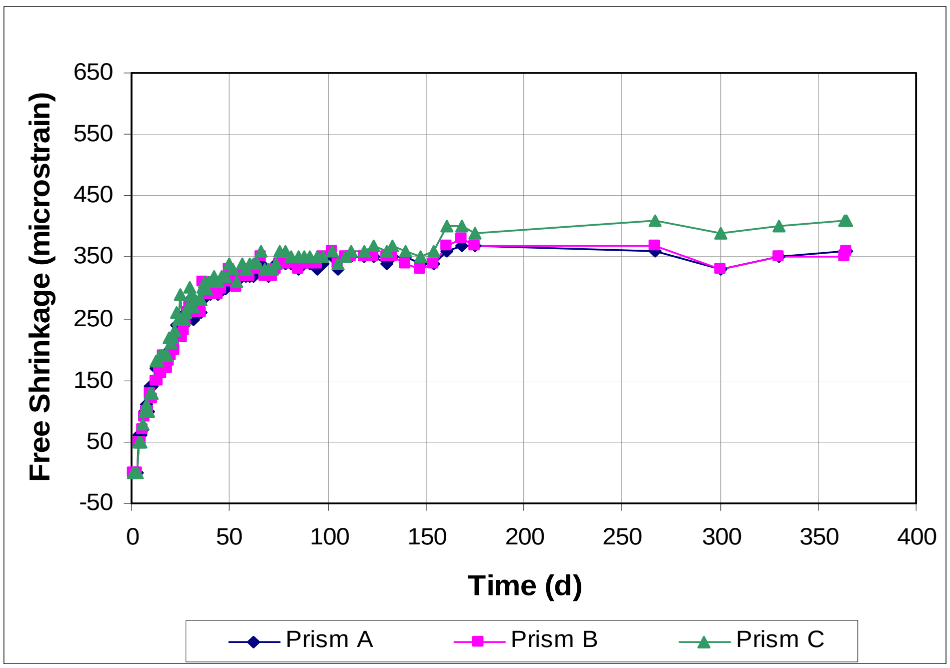

Figure A3.2 - Free Shrinkage, Batch 63. 80% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days.

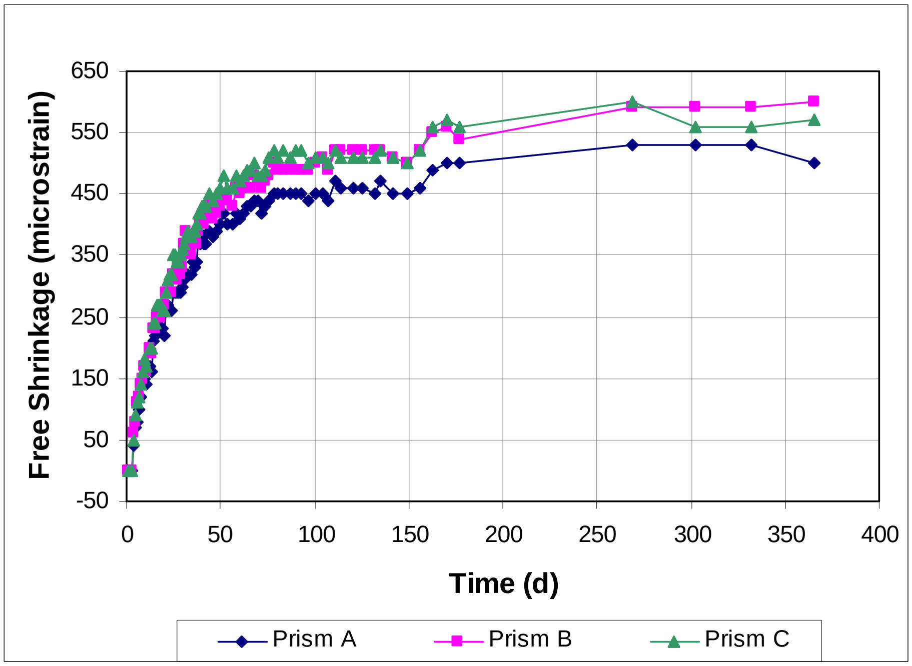

Figure A3.3 - Free Shrinkage, Batch 64. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days.

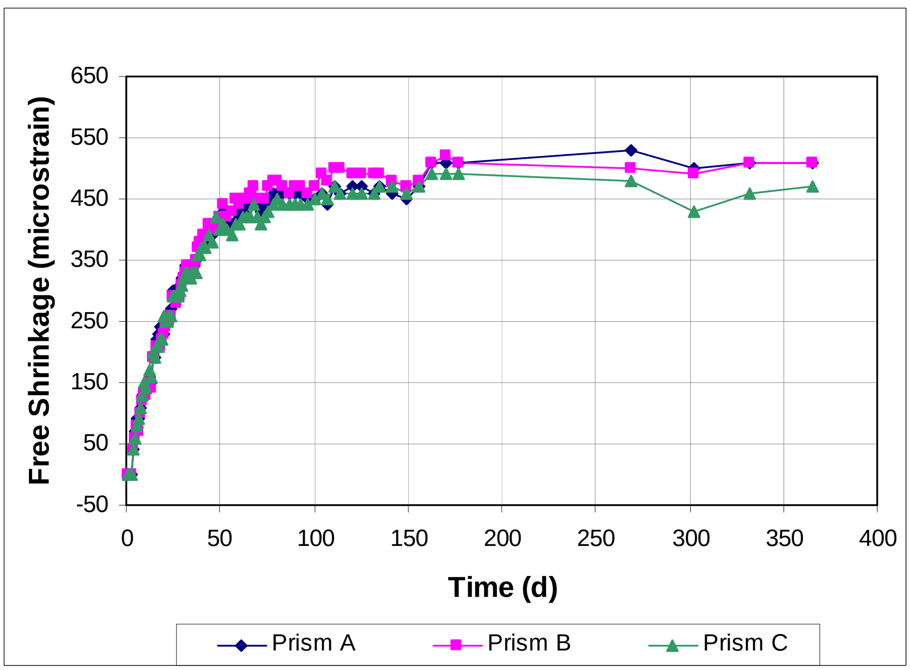

Figure A3.4 - Free Shrinkage, Batch 65. 70% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3.

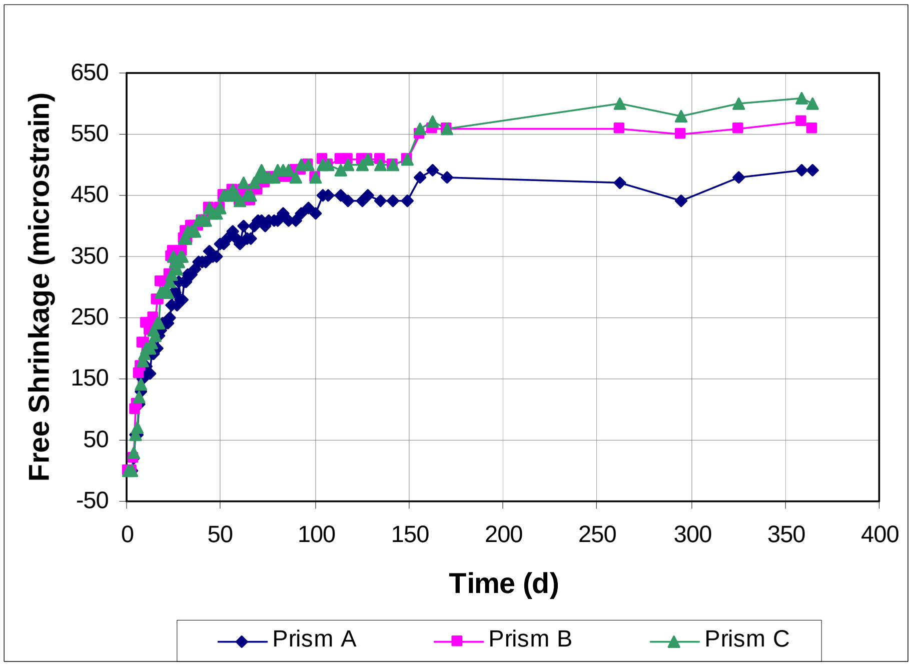

Figure A3.5 - Free Shrinkage, Batch 66. 70% Aggregate, 0.40 w/c. Type I/II cement. Drying begins on day 3.

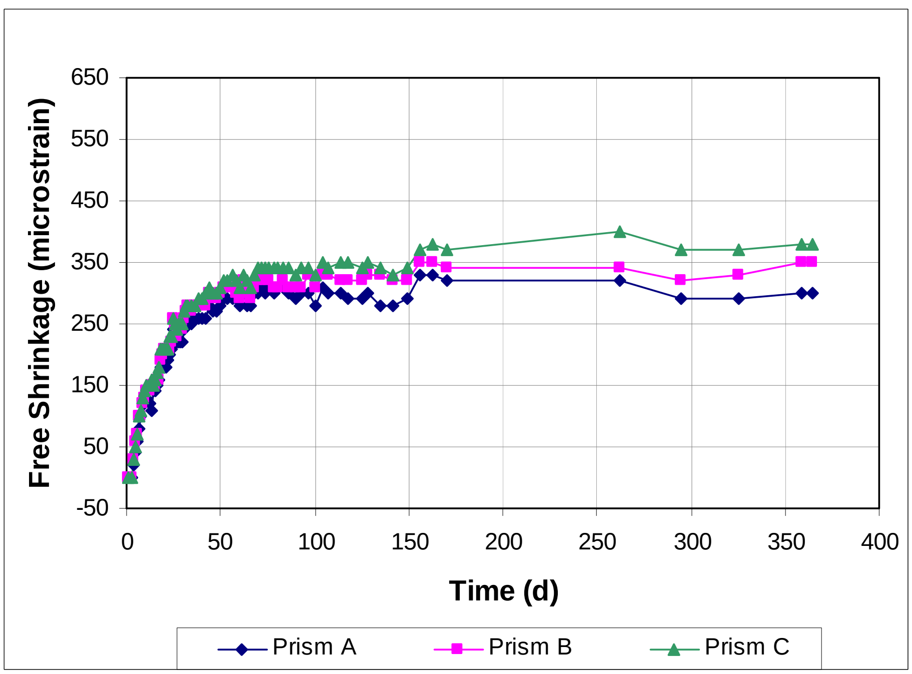

Figure A3.6 - Free Shrinkage, Batch 67. 80% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3.

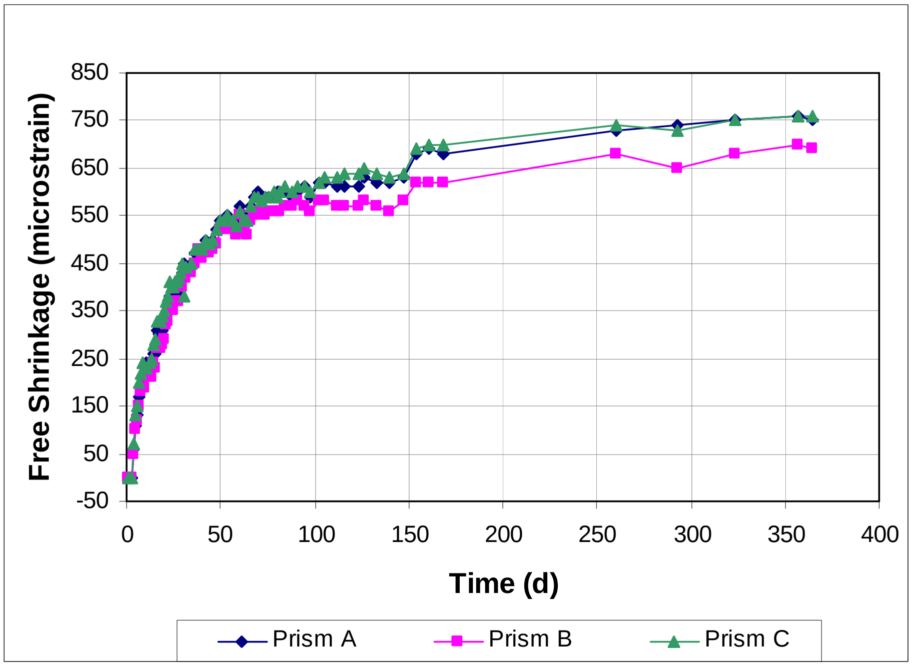

Figure A3.7 - Free Shrinkage, Batch 68. 60% Aggregate, 0.40 w/c. Type I/II cement. Drying begins on day 3.

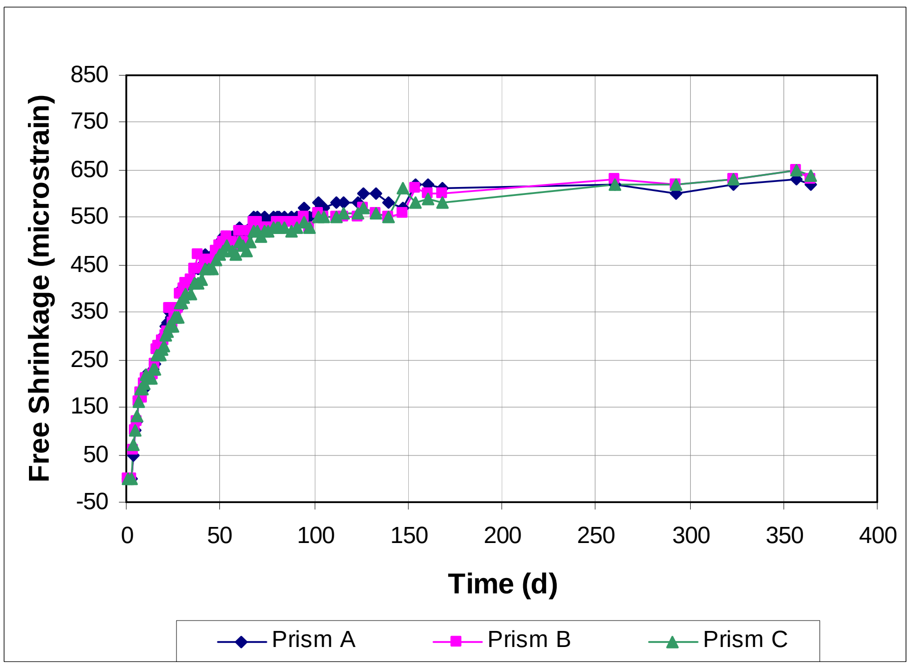

Figure A3.8 - Free Shrinkage, Batch 69. 60% Aggregate, 0.45 w/c., Type I/II cement. Drying begins on day 3.

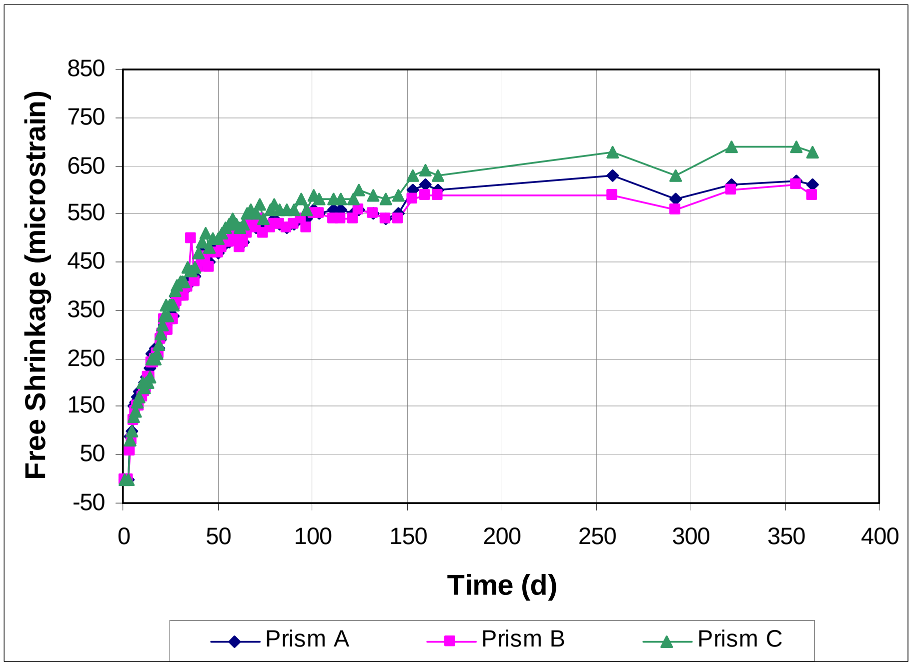

Figure A3.9- Free Shrinkage, Batch 70. 60% Aggregate, 0.50 w/c. Type I/II cement. Drying begins on day 3.

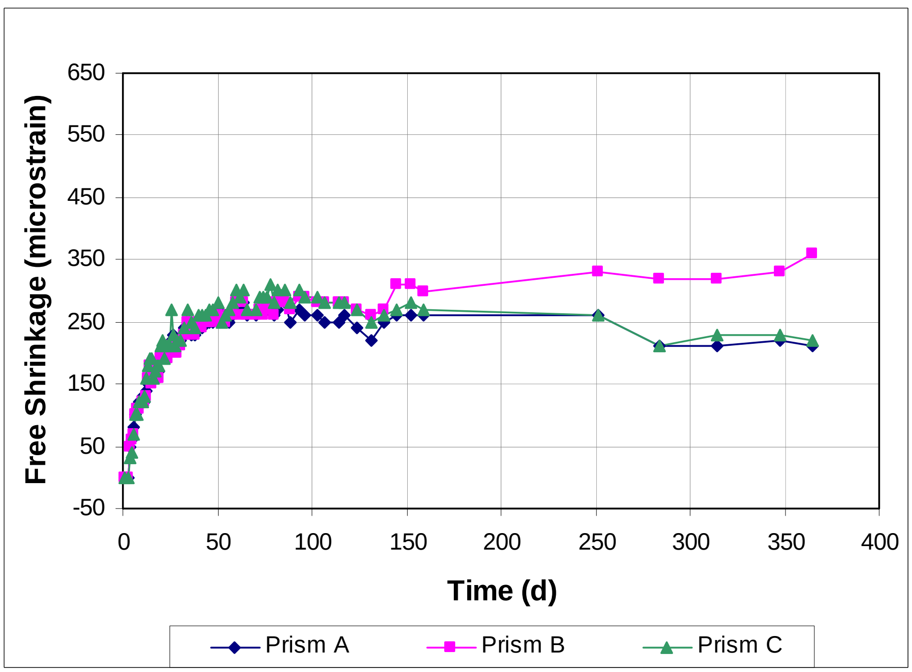

Figure A3.10 - Free Shrinkage, Batch 71. 80% Aggregate, 0.40 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

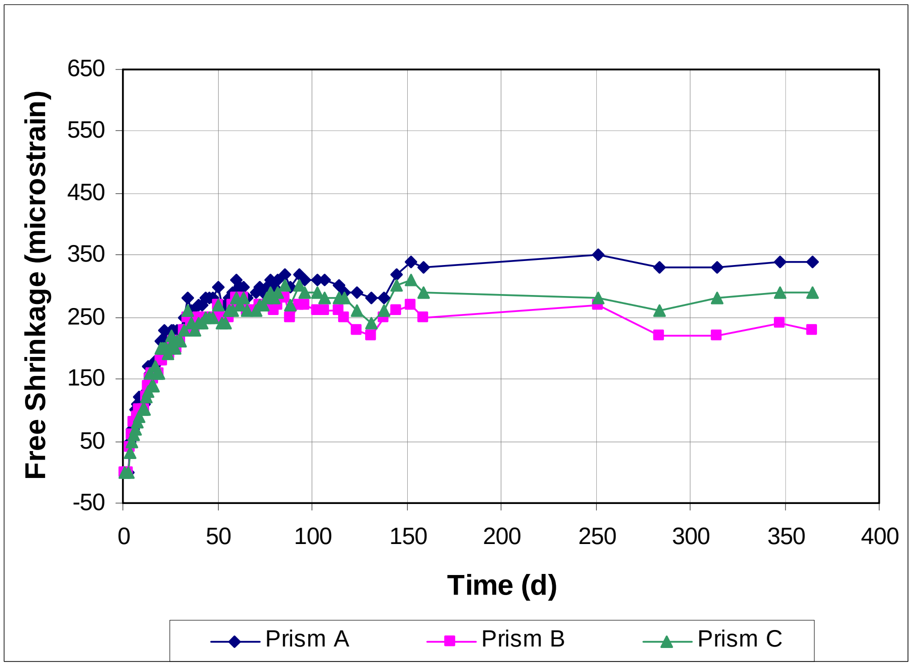

Figure A3.11 - Free Shrinkage, Batch 72. 80% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

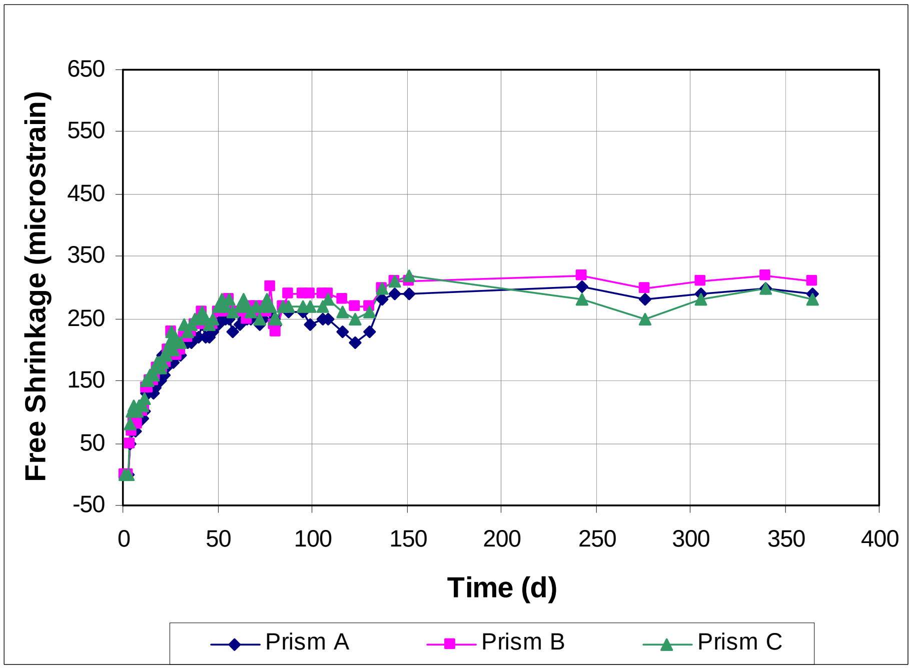

Figure A3.12 - Free Shrinkage, Batch 73. 80% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

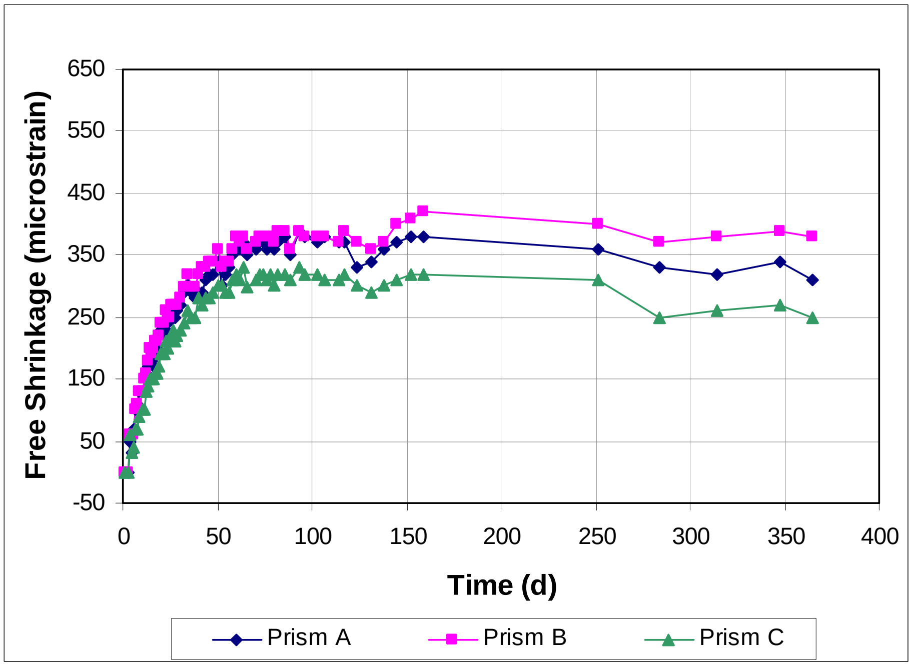

Figure A3.13 - Free Shrinkage, Batch 74. 70% Aggregate, 0.40 w/c. Type II CG cement. Drying begins on day 3.

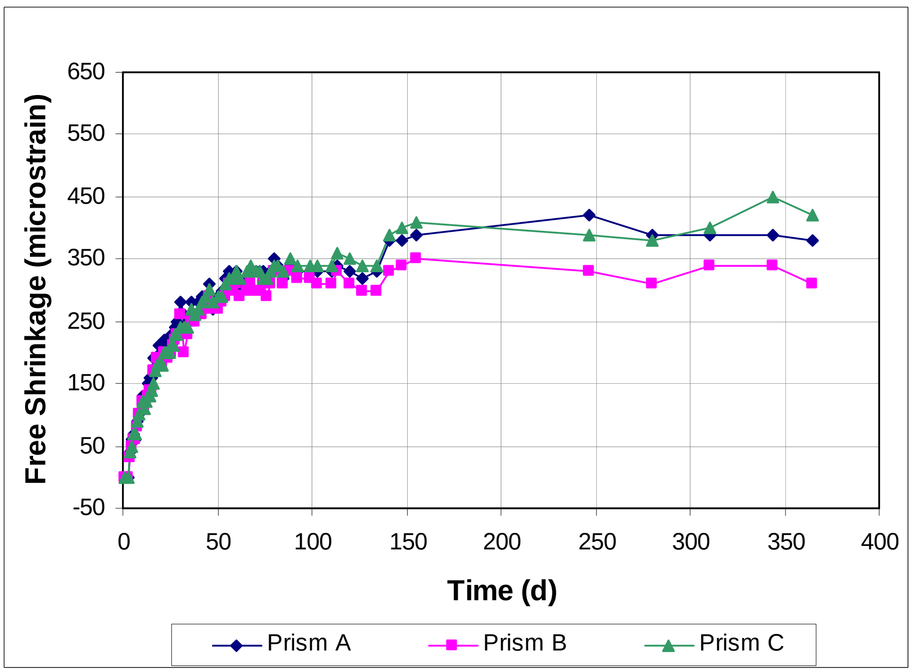

Figure A3.14 - Free Shrinkage, Batch 75. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

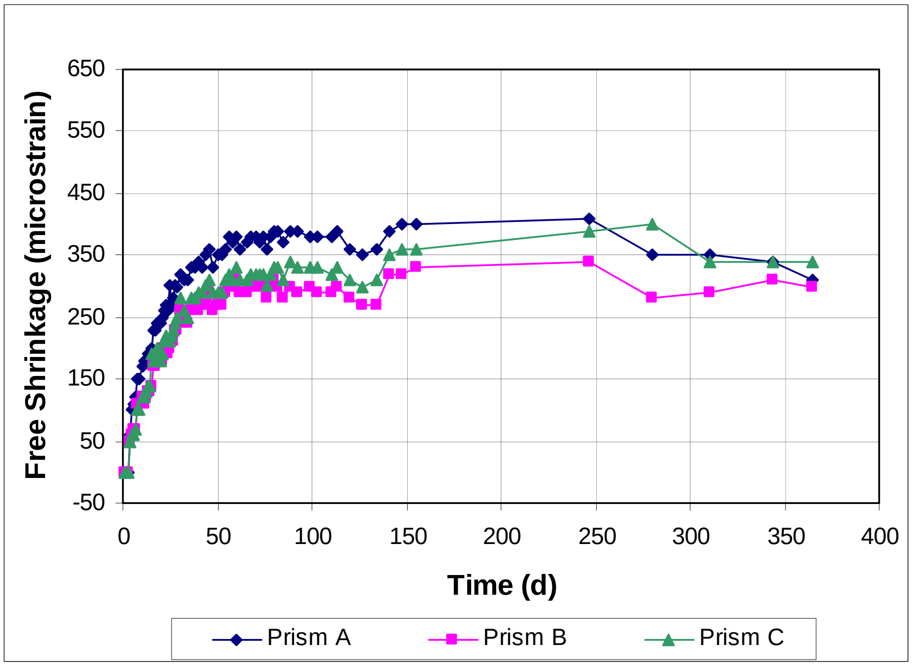

Figure A3.15 - Free Shrinkage, Batch 76. 70% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

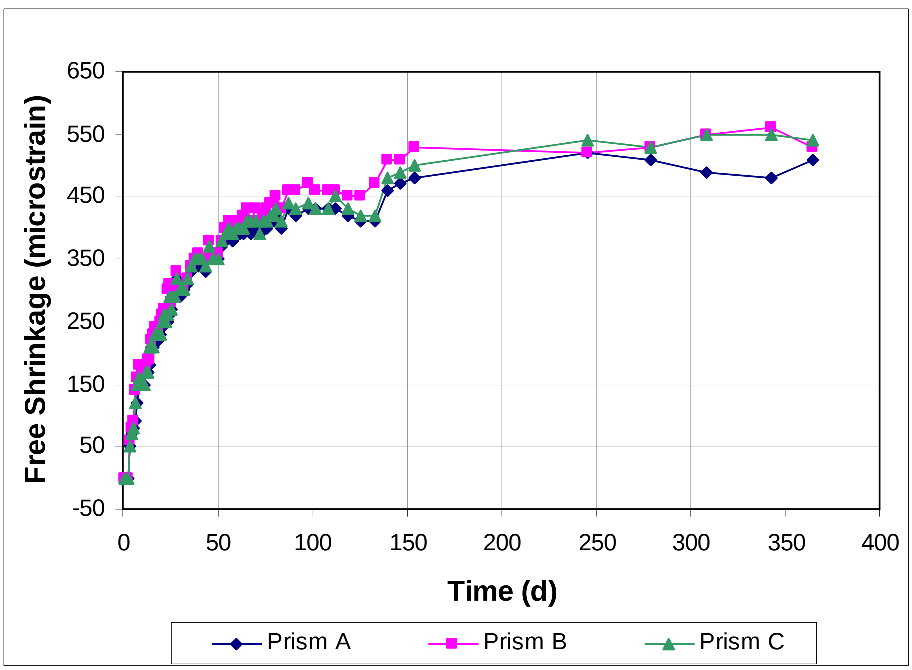

Figure A3.16 - Free Shrinkage, Batch 77. 60% Aggregate, 0.40 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

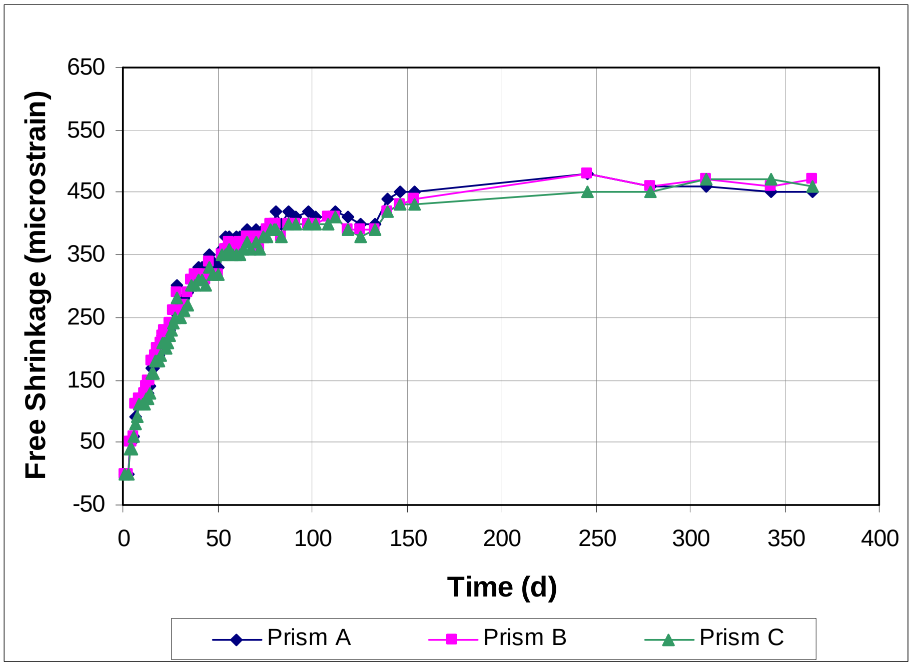

Figure A3.17 - Free Shrinkage, Batch 78. 60% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

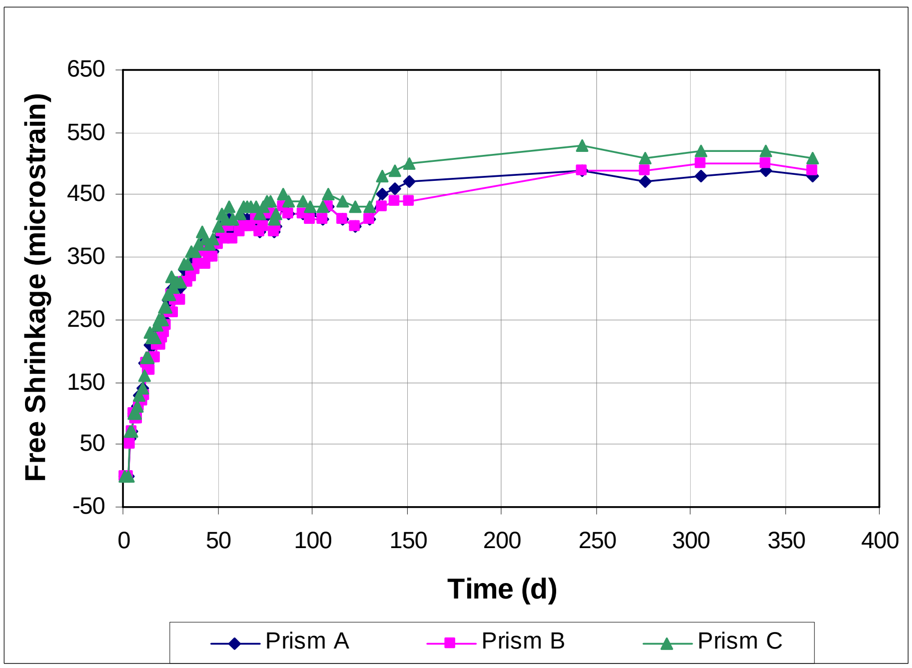

Figure A3.18 - Free Shrinkage, Batch 79. 60% Aggregate, 0.50 w/c. Type II coarse ground (CG) cement. Drying begins on day 3.

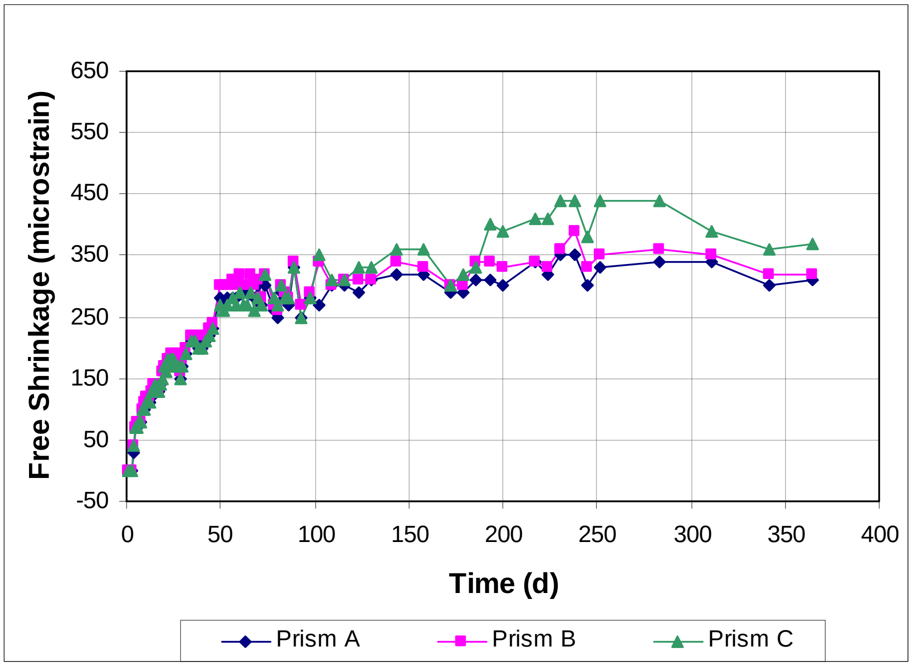

Figure A3.19 - Free Shrinkage, Batch 94. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite.

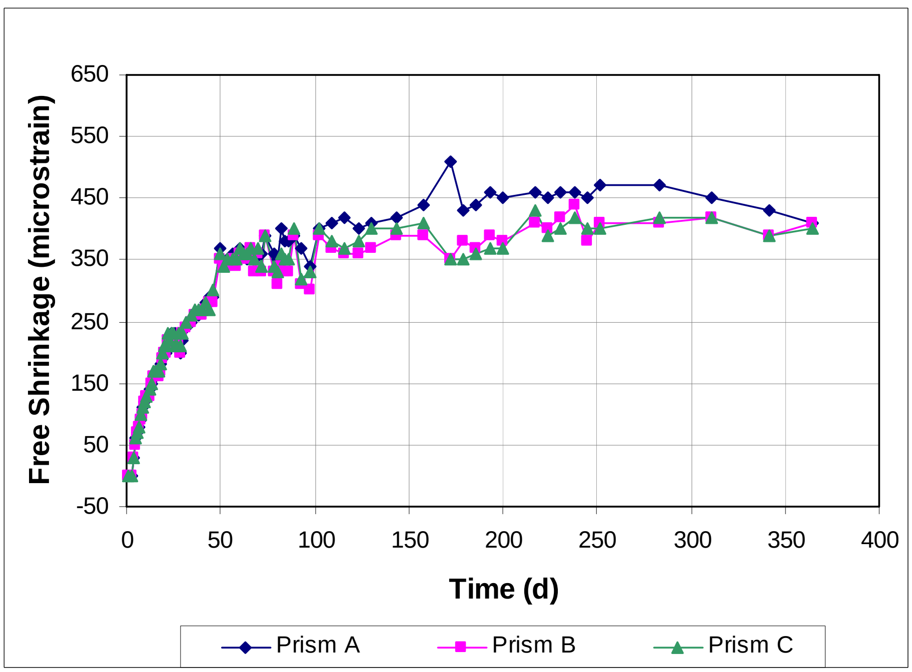

Figure A3.20 - Free Shrinkage, Batch 95. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone.

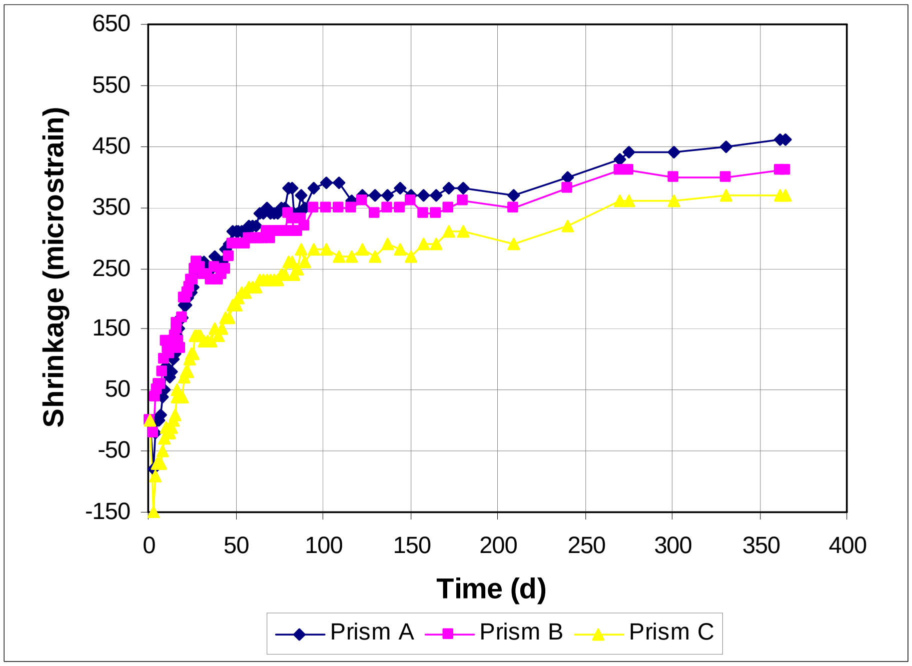

Figure A3.21 - Free Shrinkage, Batch 187. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite.

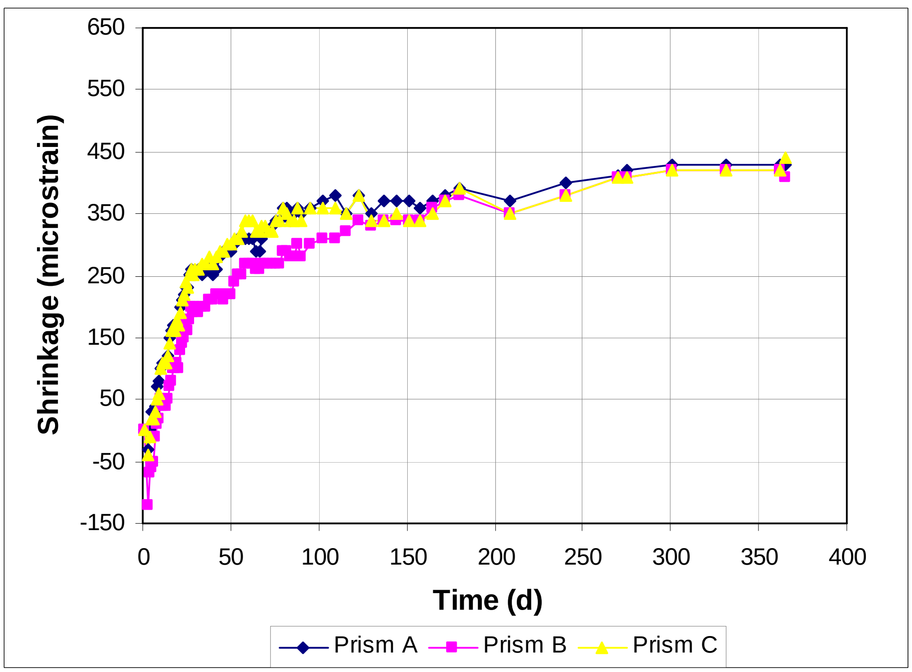

Figure A3.22 - Free Shrinkage, Batch 188. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone.

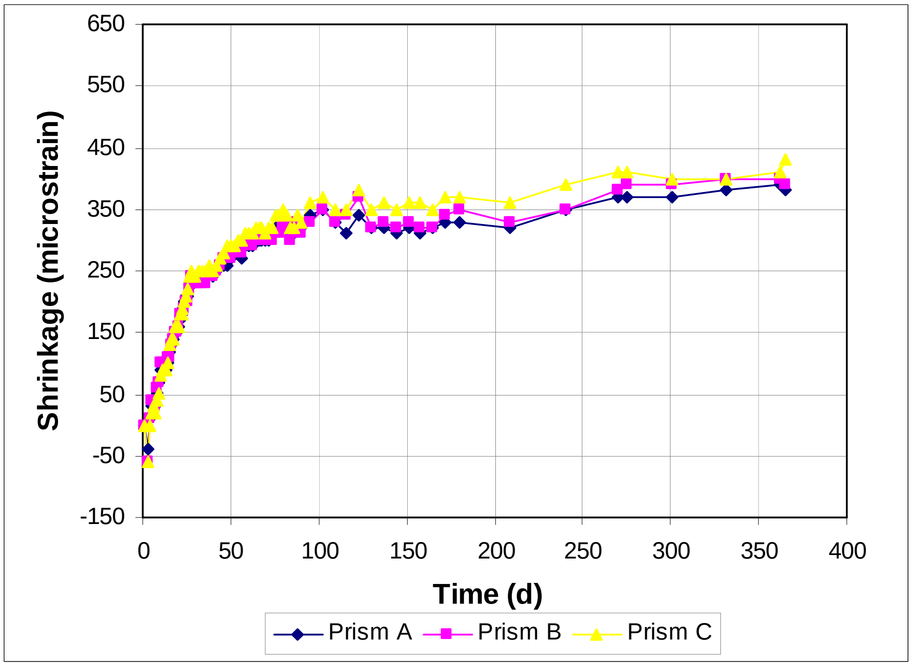

Figure A3.23 - Free Shrinkage, Batch 189. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Granite.

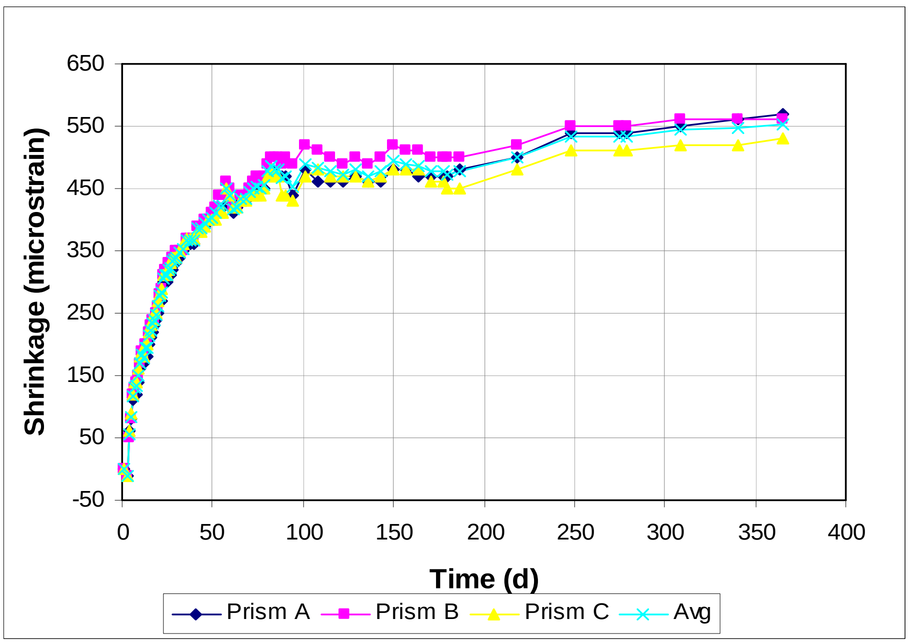

Figure A3.24 - Free Shrinkage, Batch 198. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Quartzite.

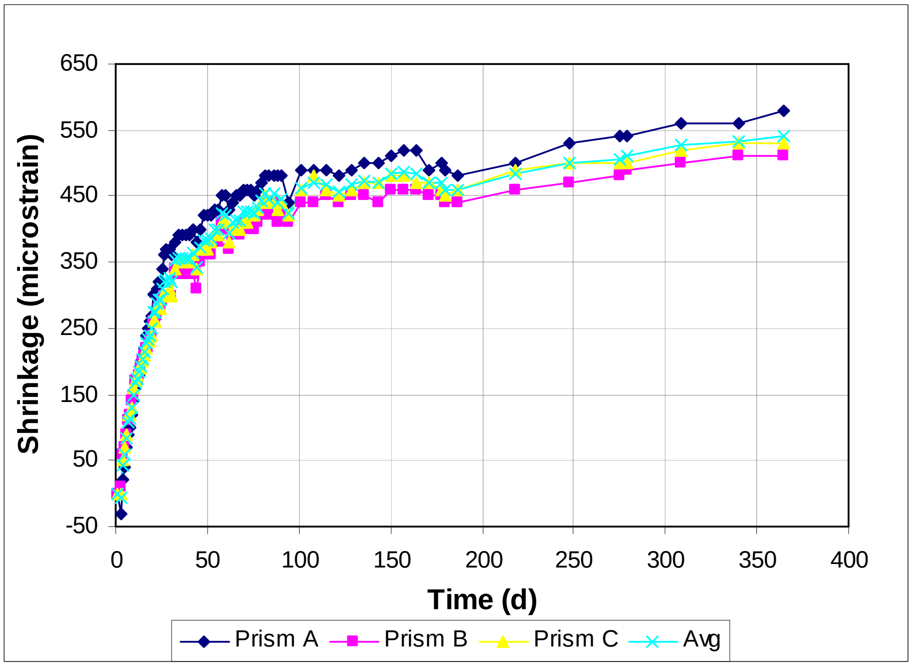

Figure A3.25 - Free Shrinkage, Batch 199. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Limestone.

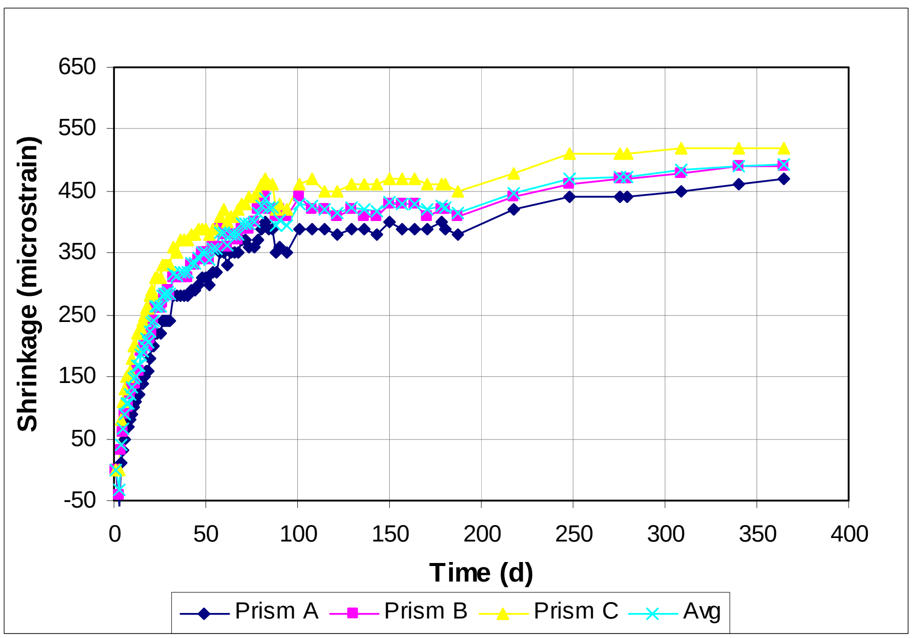

Figure A3.26 - Free Shrinkage, Batch 200. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Granite.

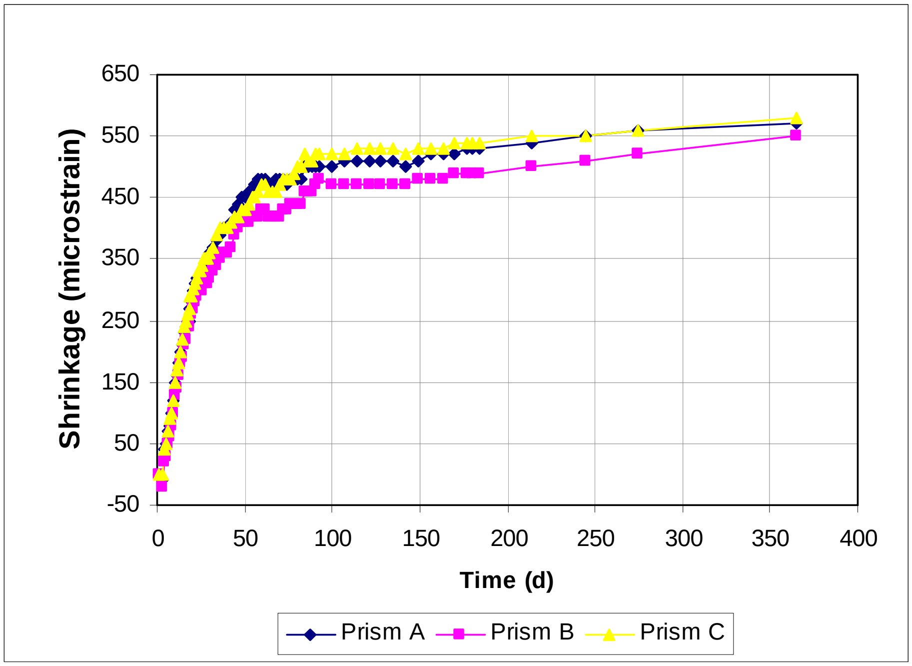

Figure A3.27 - Free Shrinkage, Batch 262. 68.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Quartzite.

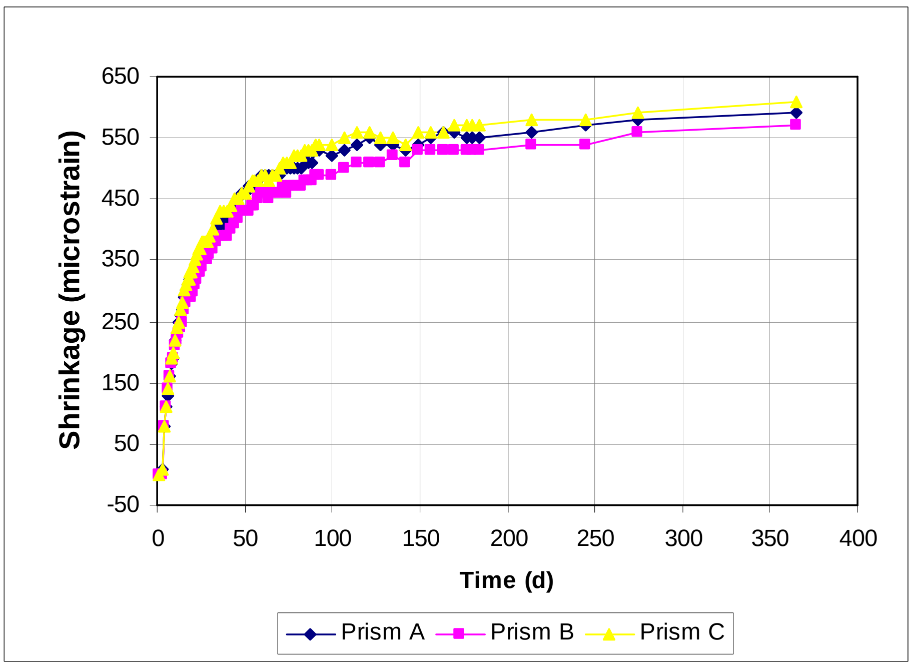

Figure A3.28 - Free Shrinkage, Batch 263. 68.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Limestone.

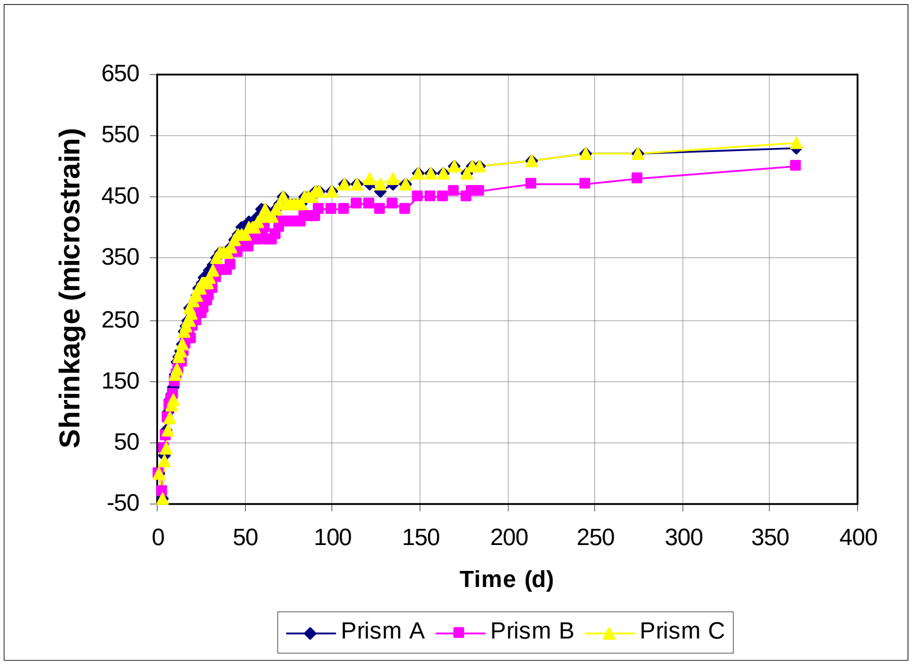

Figure A3.29 - Free Shrinkage, Batch 264. 68.8% Aggregate, 0.45 w/c., Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Granite.

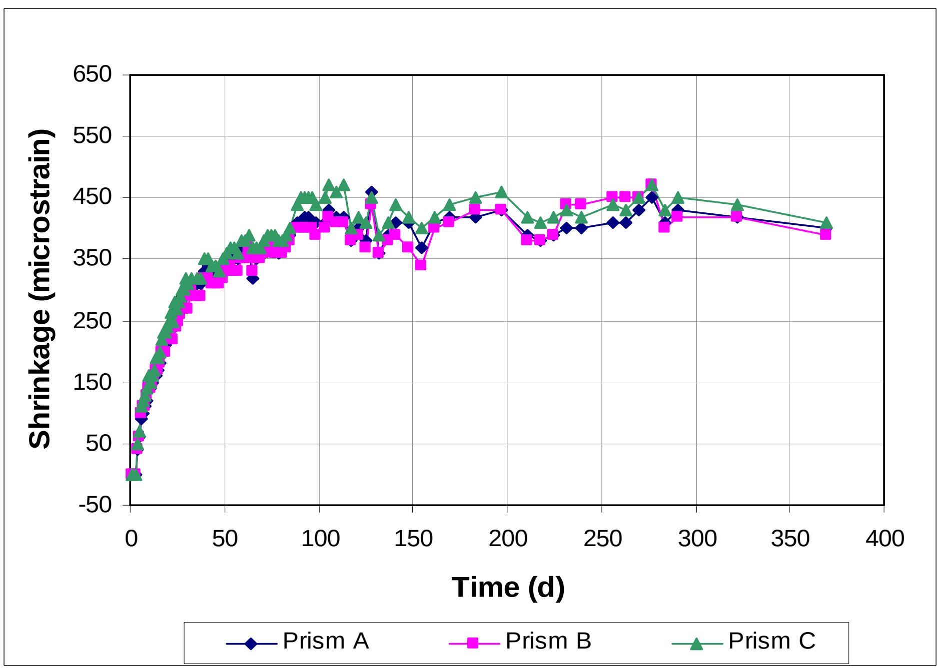

Figure A3.30 - Free Shrinkage, Batch 85. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures.

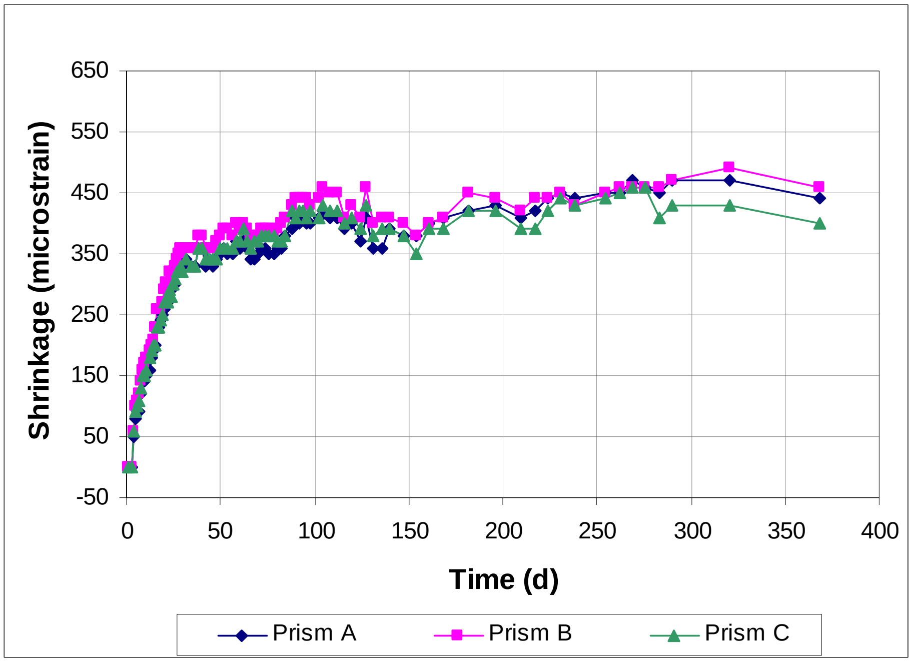

Figure A3.31 - Free Shrinkage, Batch 86. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% slag replacement.

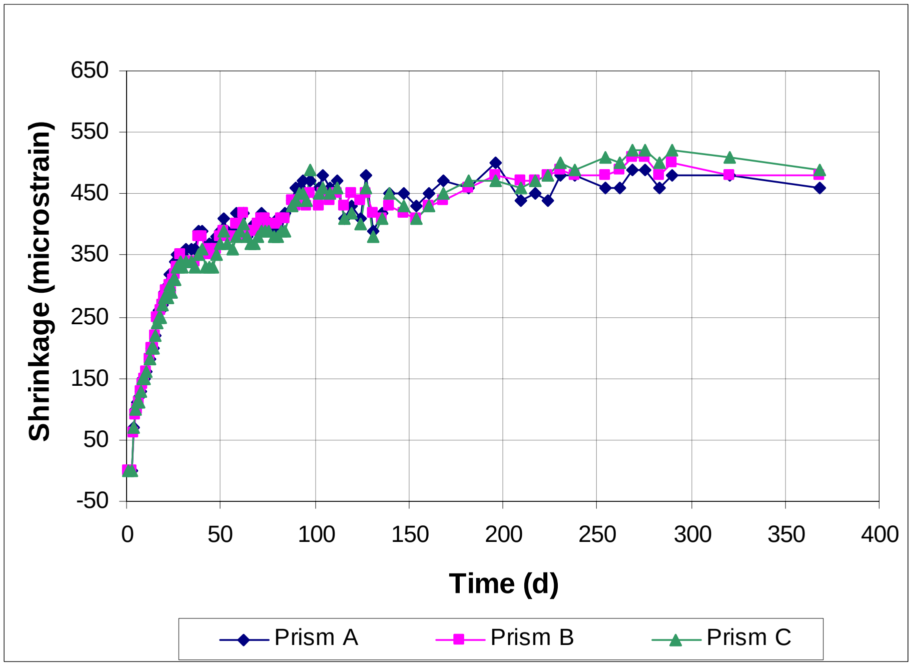

Figure A3.32 - Free Shrinkage, Batch 87. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Class C Fly Ash replacement.

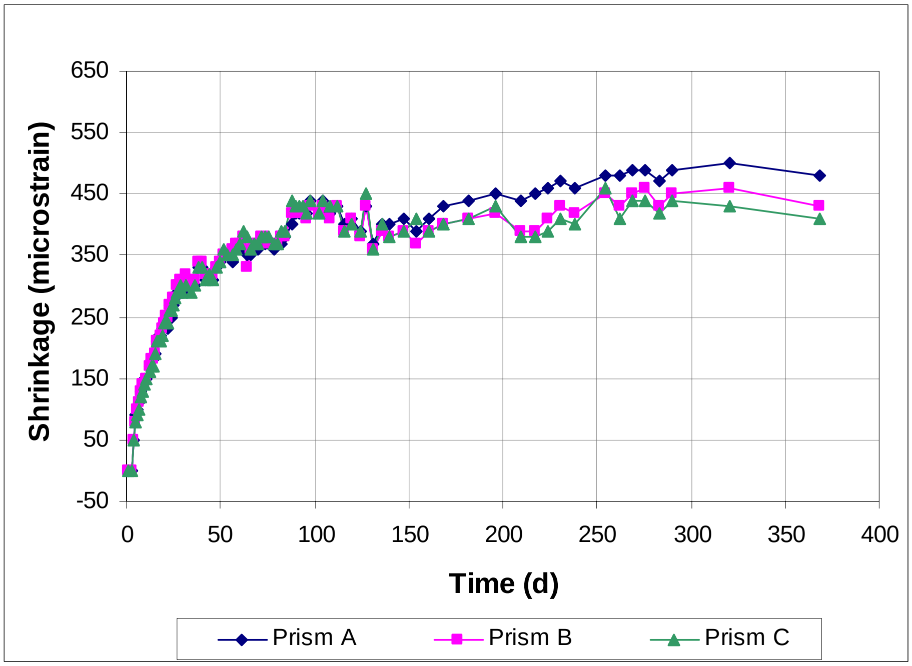

Figure A3.33 - Free Shrinkage, Batch 88. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% silica fume replacement.

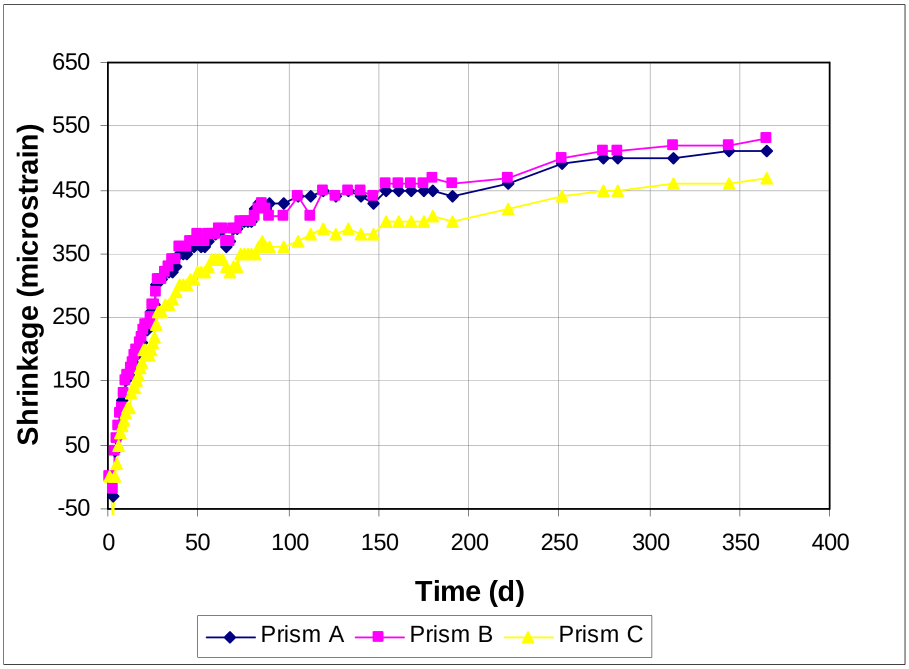

Figure A3.34 - Free Shrinkage, Batch 194. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures.

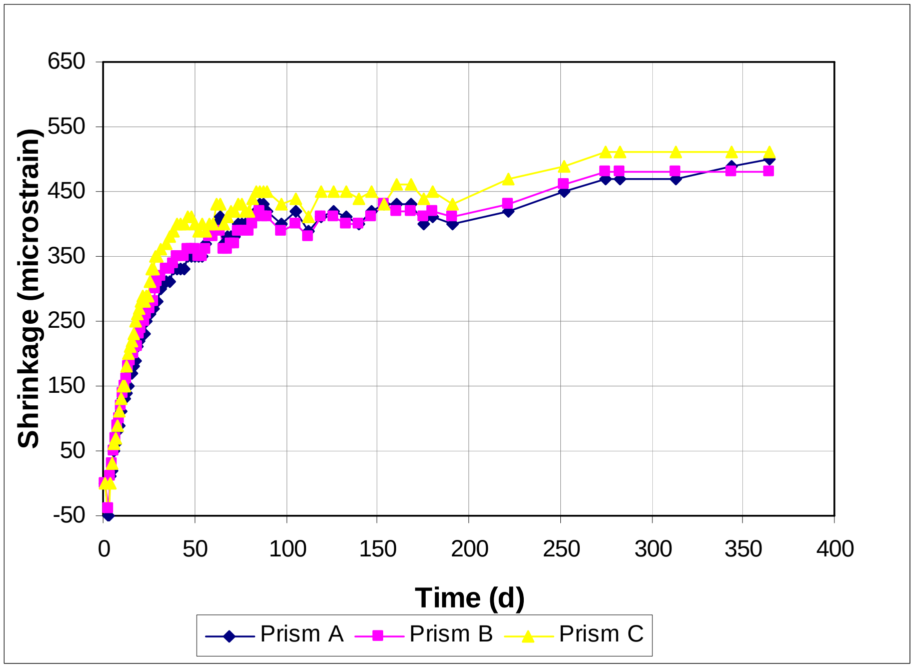

Figure A3.35 - Free Shrinkage, Batch 195. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Replacement by Slag.

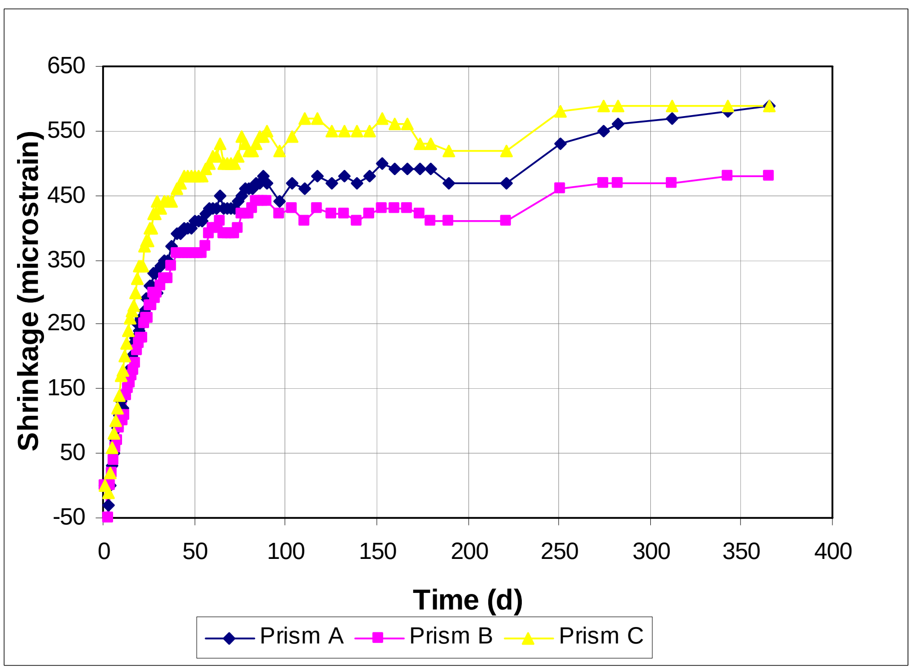

Figure A3.36 - Free Shrinkage, Batch 196. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 30% Replacement by Class C Fly Ash.

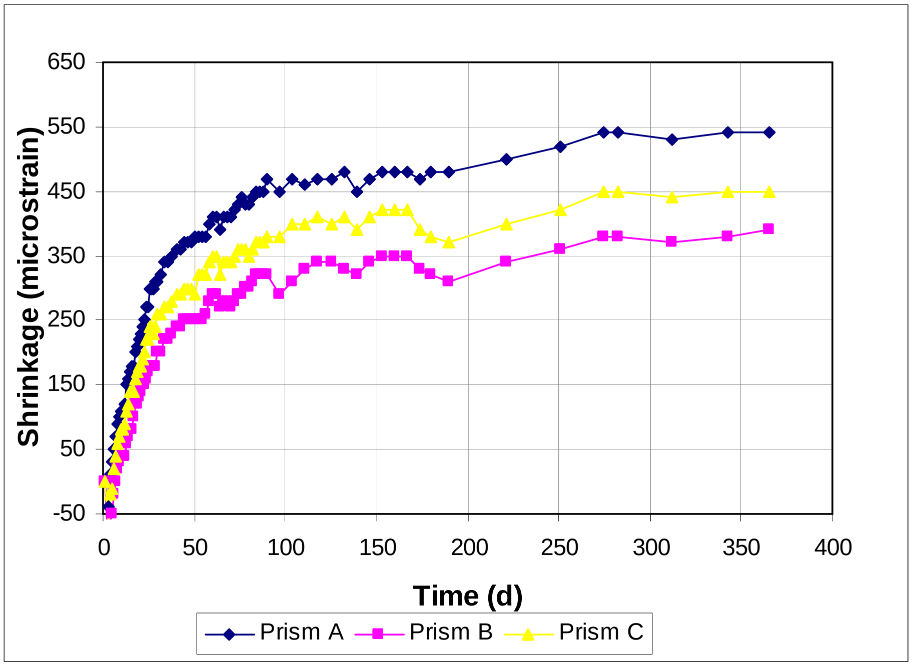

Figure A3.37 - Free Shrinkage, Batch 197. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% Replacement by Silica Fume.

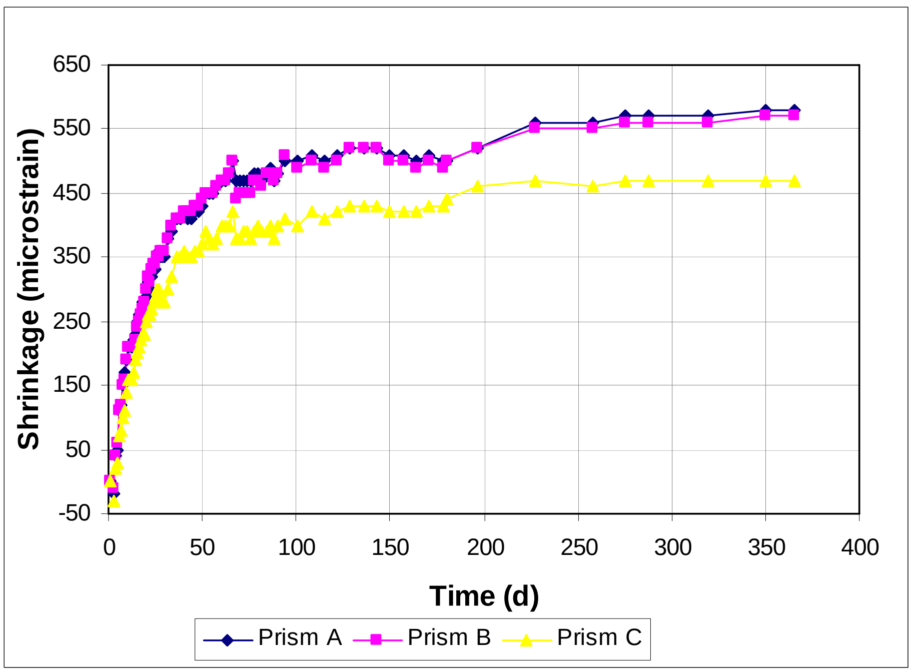

Figure A3.38 - Free Shrinkage, Batch 202. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures.

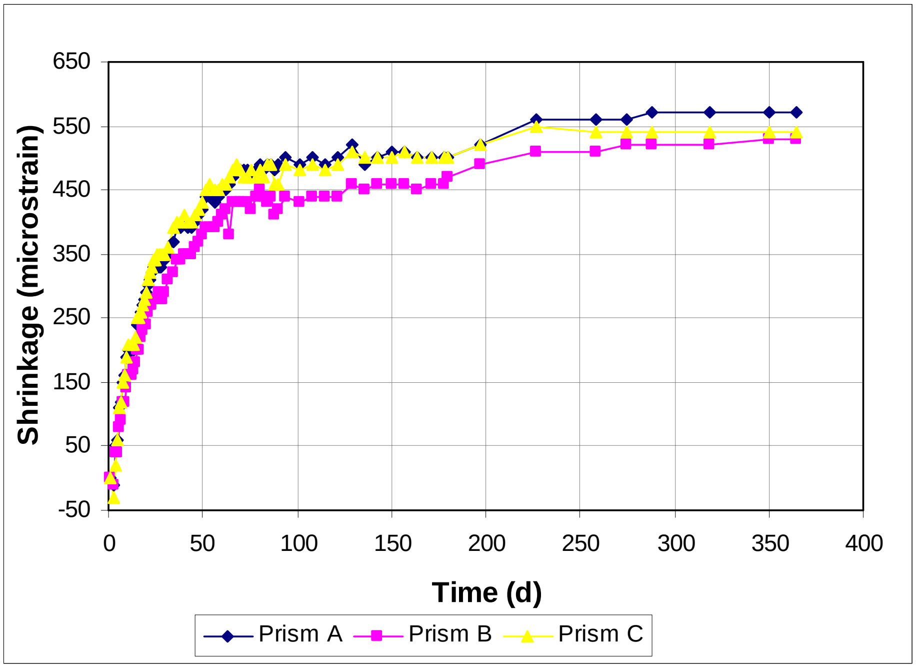

Figure A3.39 - Free Shrinkage, Batch 203. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no mineral admixtures. Adva superplasticizer.

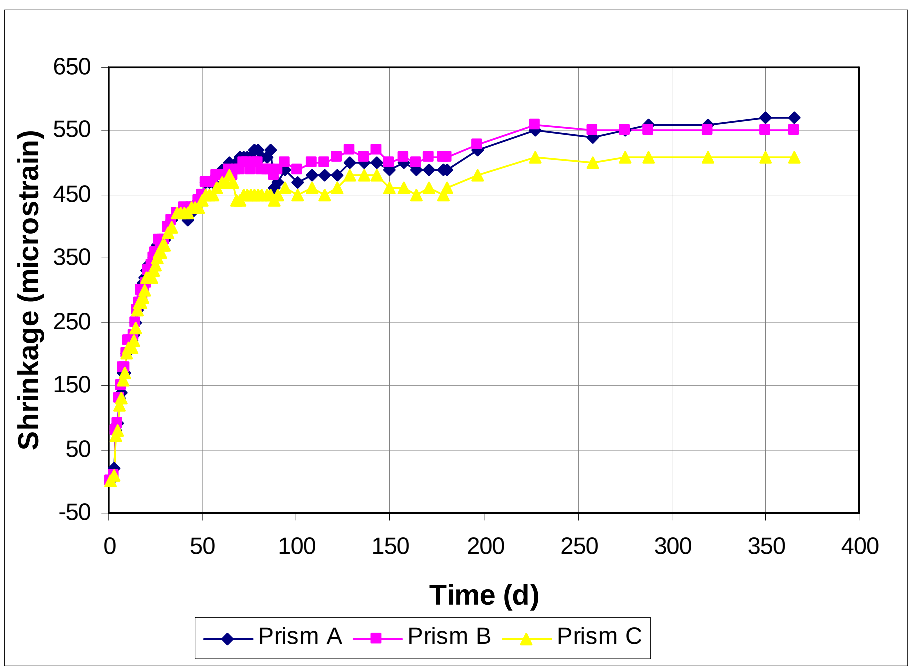

Figure A3.40 - Free Shrinkage, Batch 204. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. 10% Replacement by Silica Fume. Adva superplasticizer.

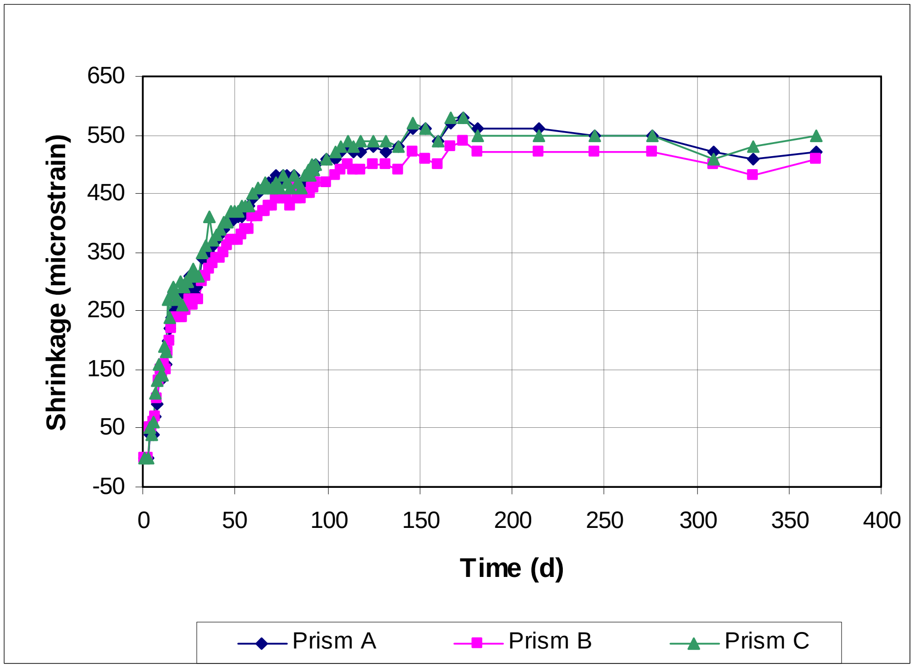

Figure A3.41 - Free Shrinkage, Batch 165, 3-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days.

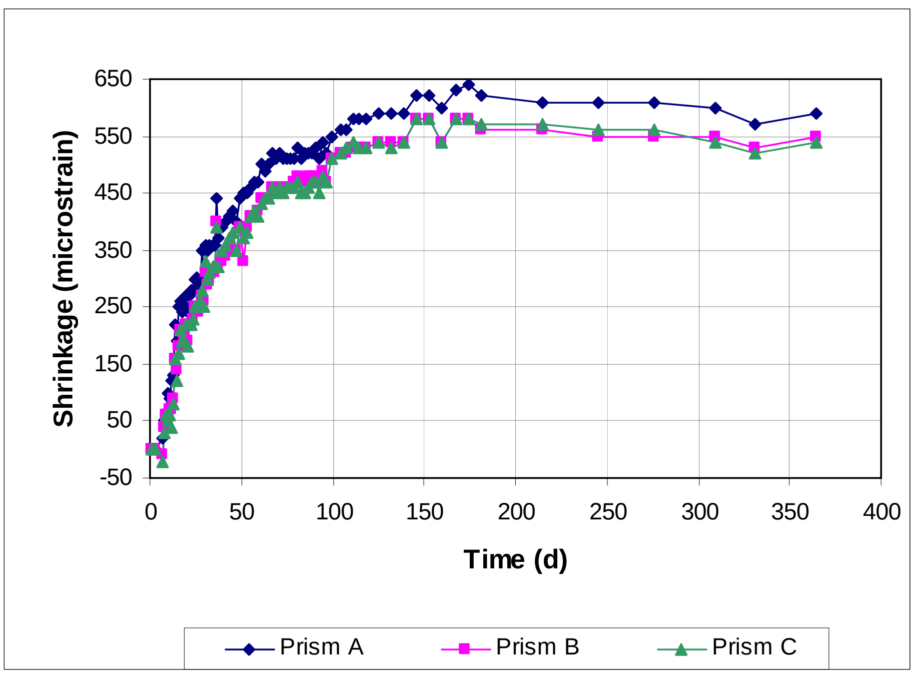

Figure A3.42 - Free Shrinkage, Batch 165, 7-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 7 days.

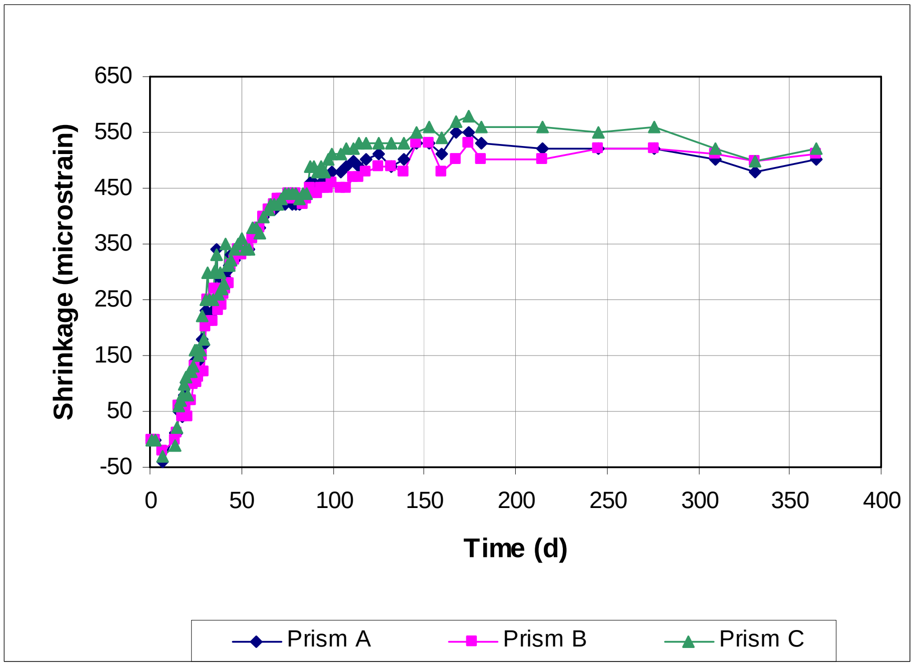

Figure A3.43 - Free Shrinkage, Batch 165, 14-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 14 days.

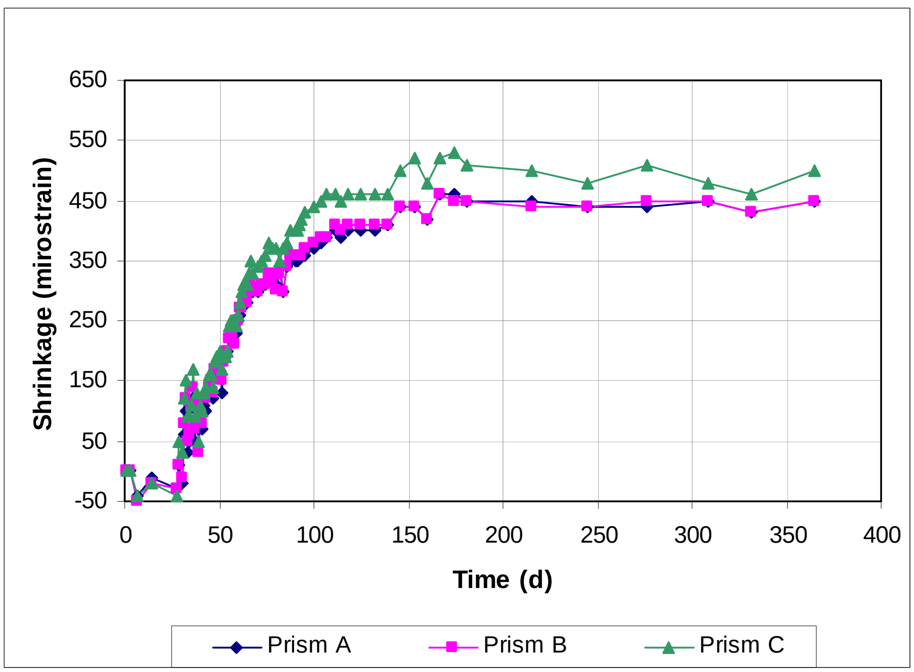

Figure A3.44 - Free Shrinkage, Batch 165, 28-day cure. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 28 days.

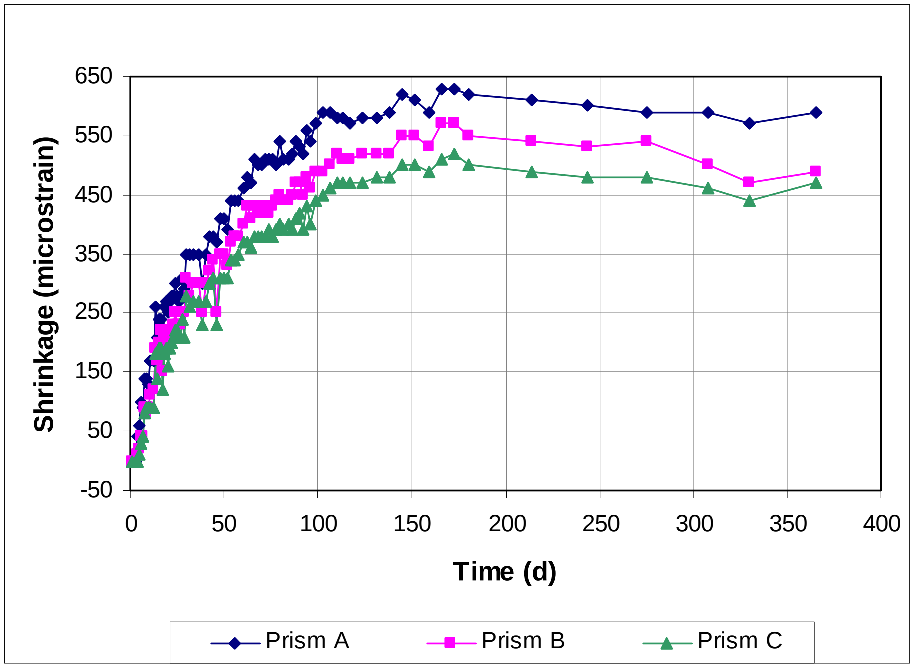

Figure A3.45 - Free Shrinkage, Batch 166, 3-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 3 days.

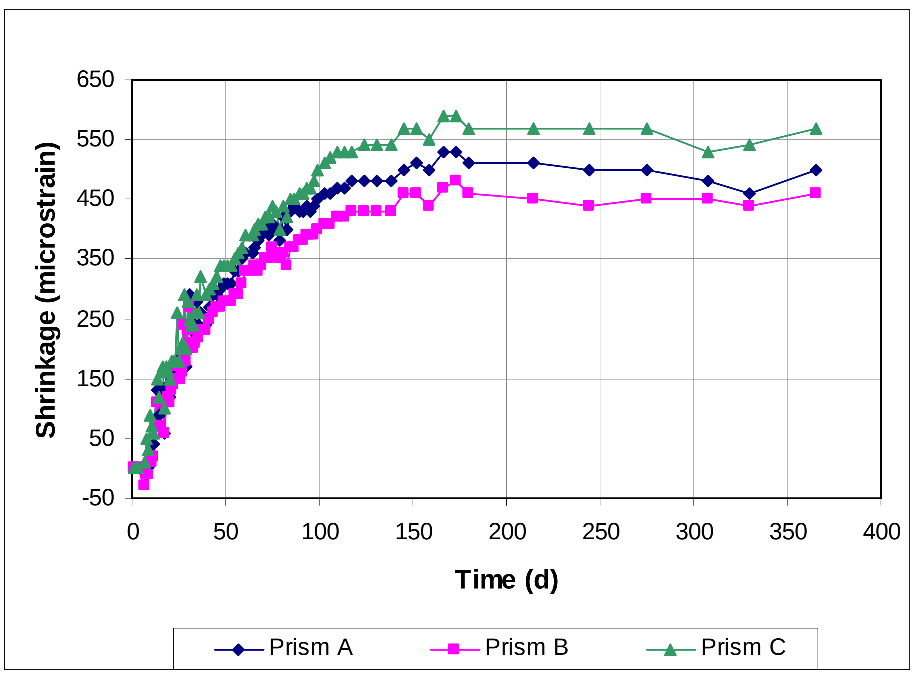

Figure A3.46 - Free Shrinkage, Batch 166, 7-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 7 days.

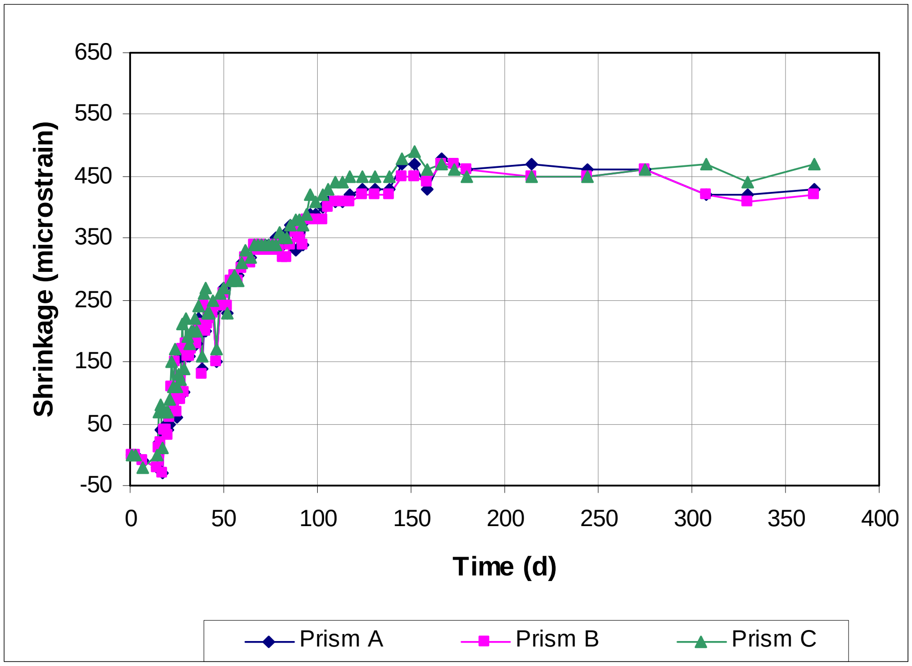

Figure A3.47 - Free Shrinkage, Batch 166, 14-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 14 days.

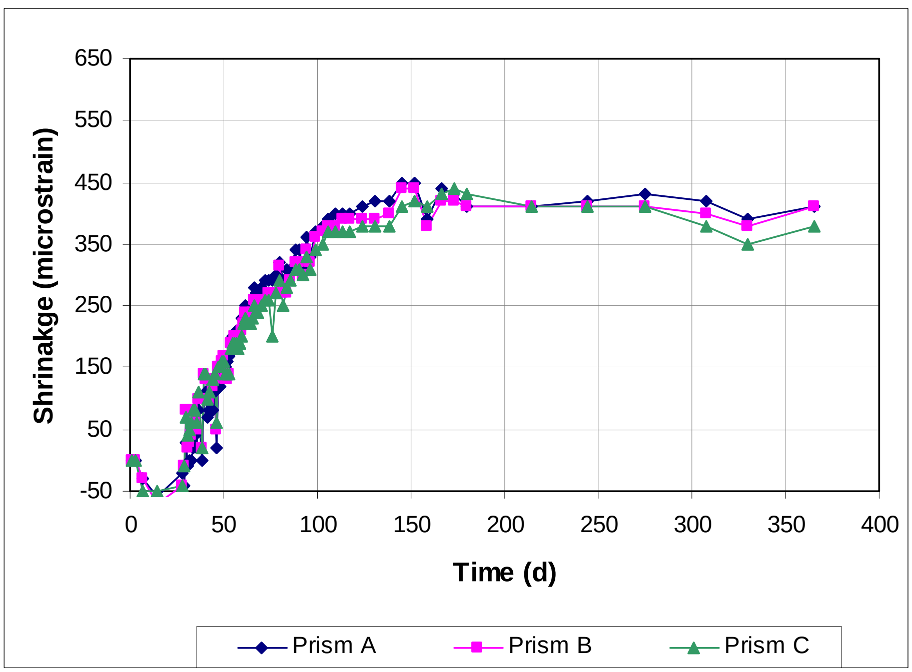

Figure A3.48 - Free Shrinkage, Batch 166, 28-day cure. 70% Aggregate, 0.45 w/c. Type II coarse ground (CG) cement. Drying begins at 28 days.

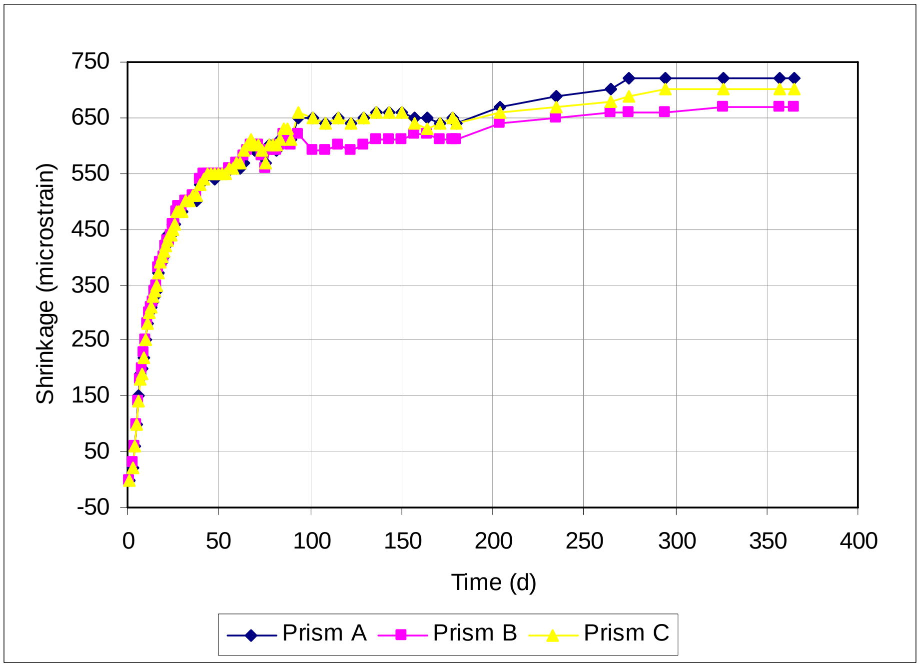

Figure A3.49 Free Shrinkage, Batch 201(3-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement. Drying begins at 3 days.

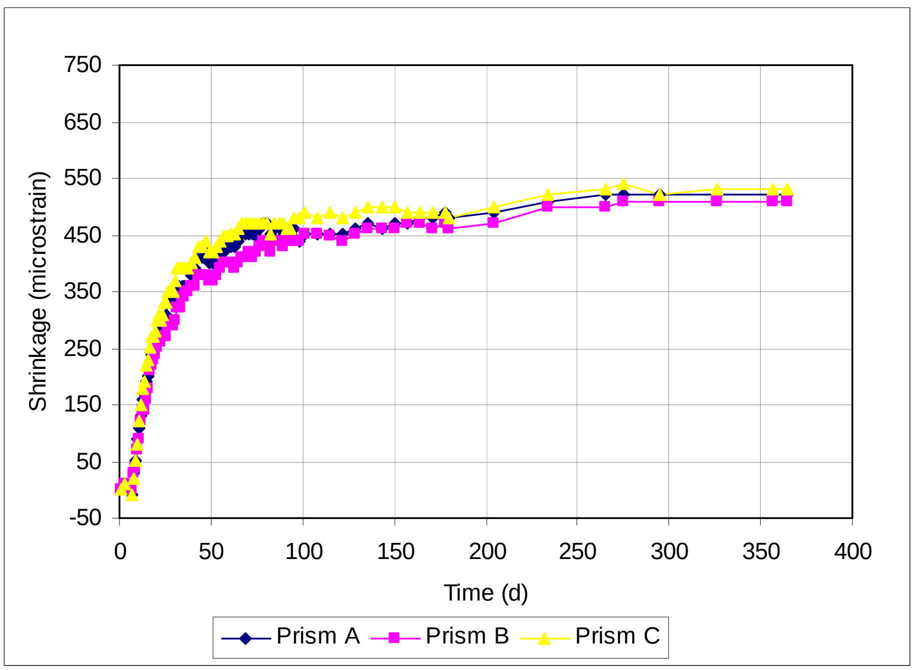

Figure A3.50 Free Shrinkage, Batch 201(7-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement. Drying begins at 7 days.

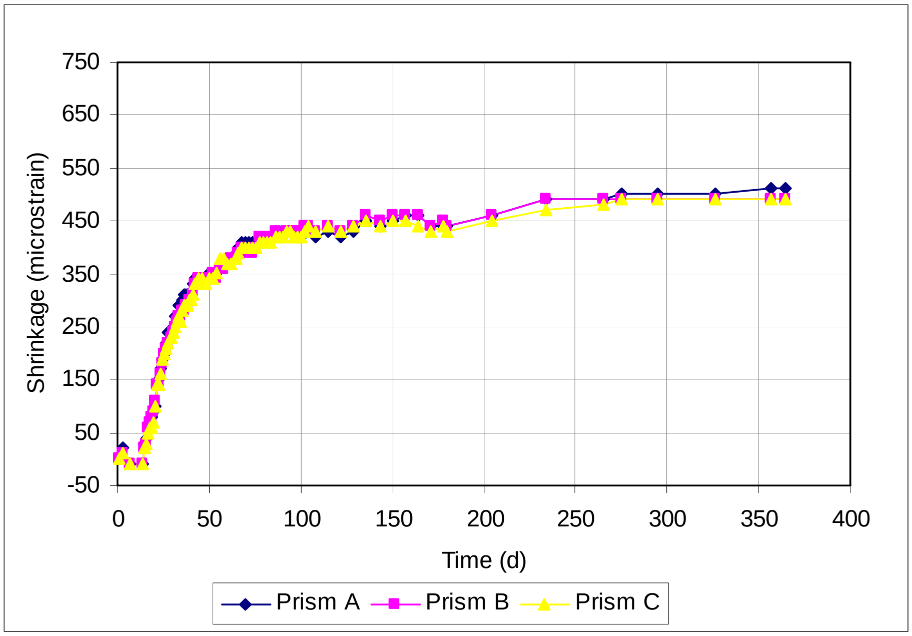

Figure A3.51 Free Shrinkage, Batch 201(14-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement. Drying begins at 14 days.

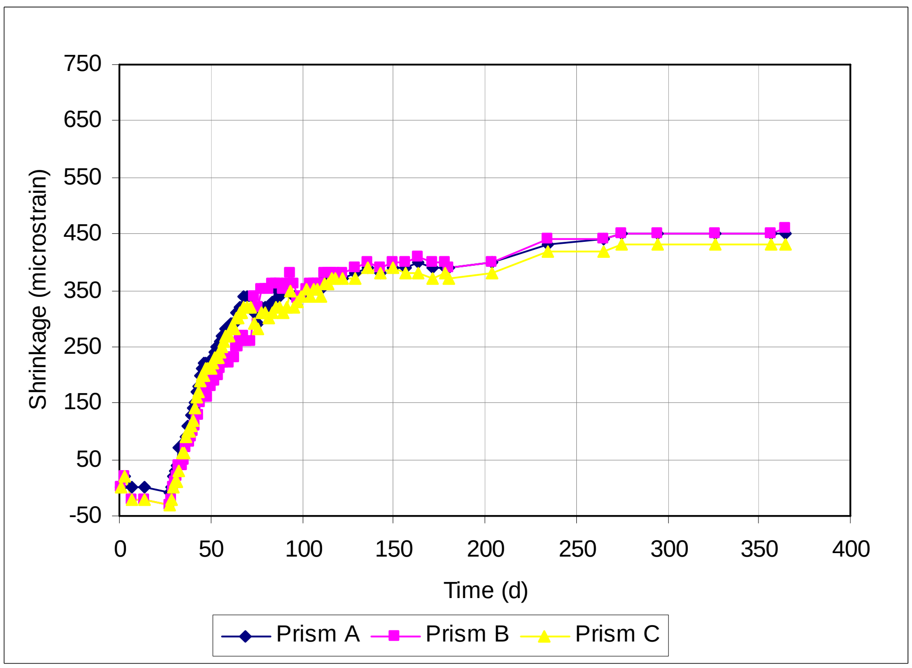

Figure A3.52 Free Shrinkage, Batch 201(28-days-cured), 70% Aggregate, 0.45 w/c ratio, Type I/II Cement. Drying begins at 28 days.

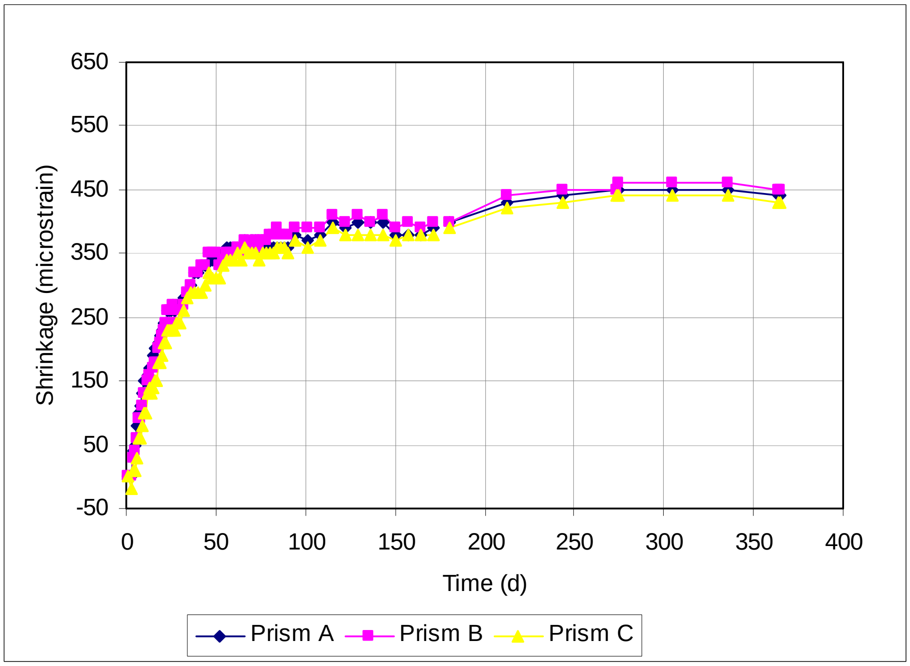

Figure A3.53 Free Shrinkage, Batch 207(3-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 3 days.

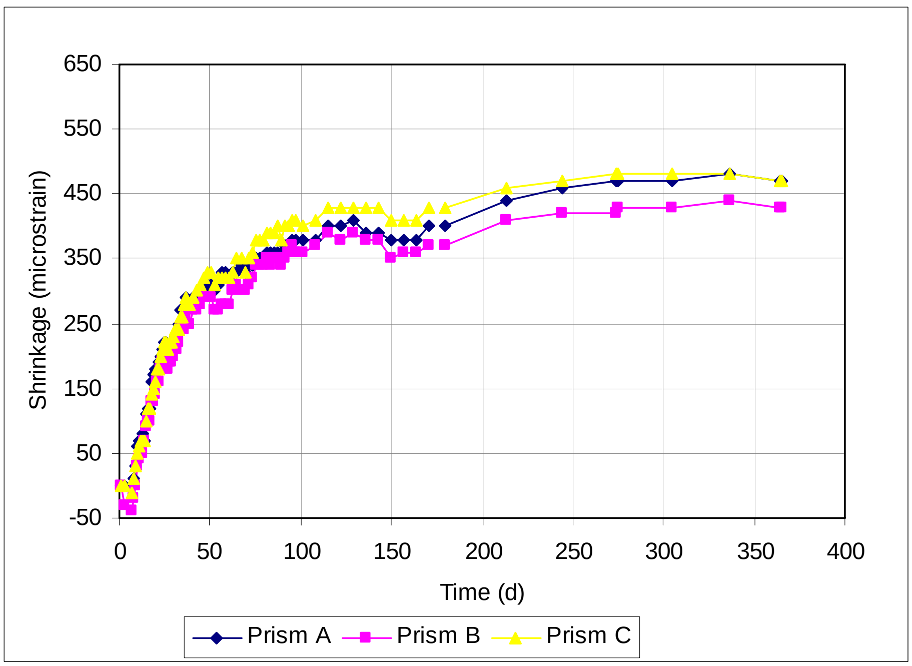

Figure A3.54 Free Shrinkage, Batch 207(7-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 7 days.

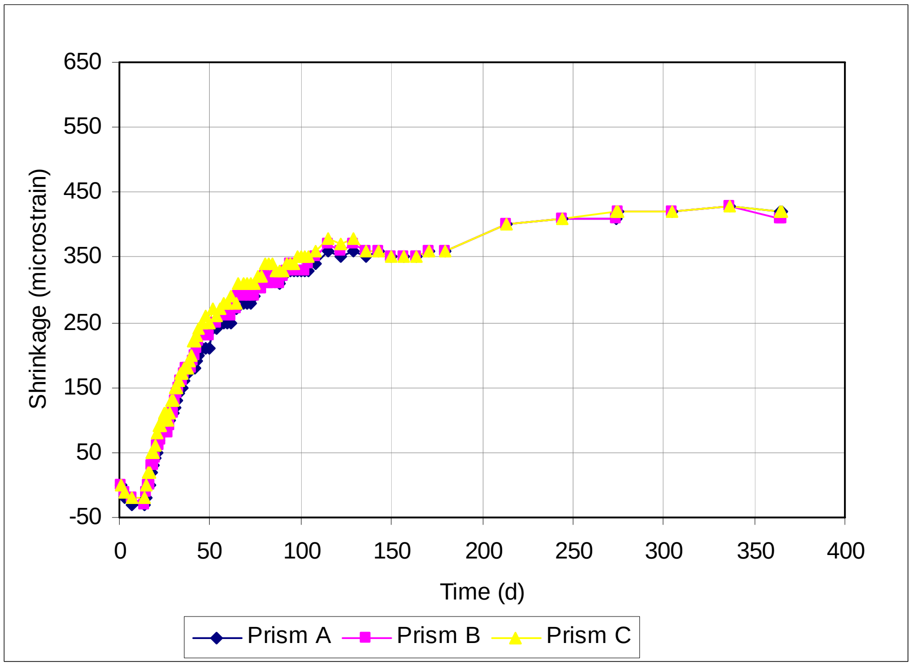

Figure A3.55 Free Shrinkage, Batch 207(14-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 14 days.

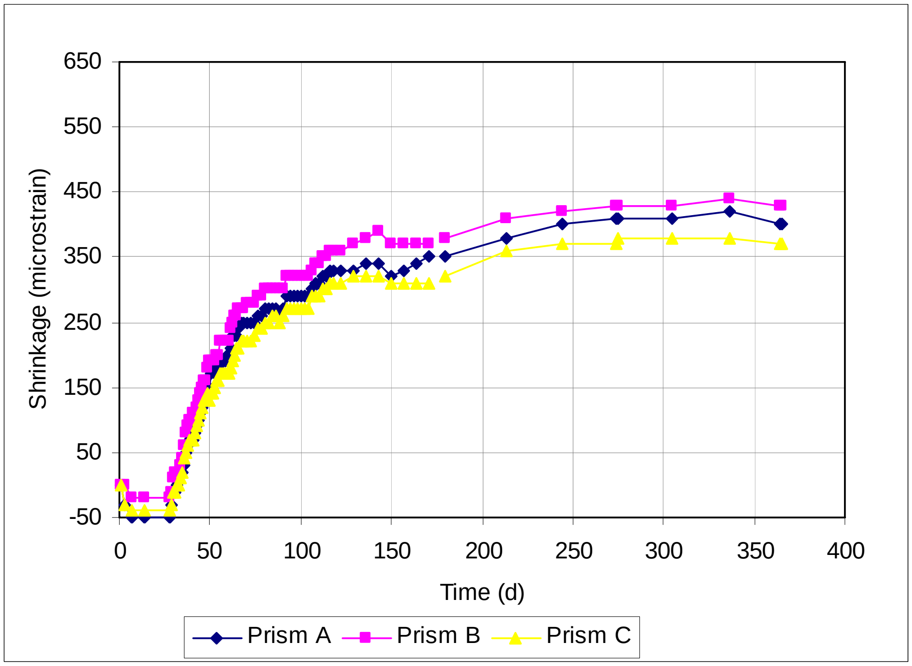

Figure A3.56 Free Shrinkage, Batch 207(28-days-cured), 70% Aggregate, 0.45 w/c ratio, Type II coarse ground (CG) cement. Drying begins at 28 days.

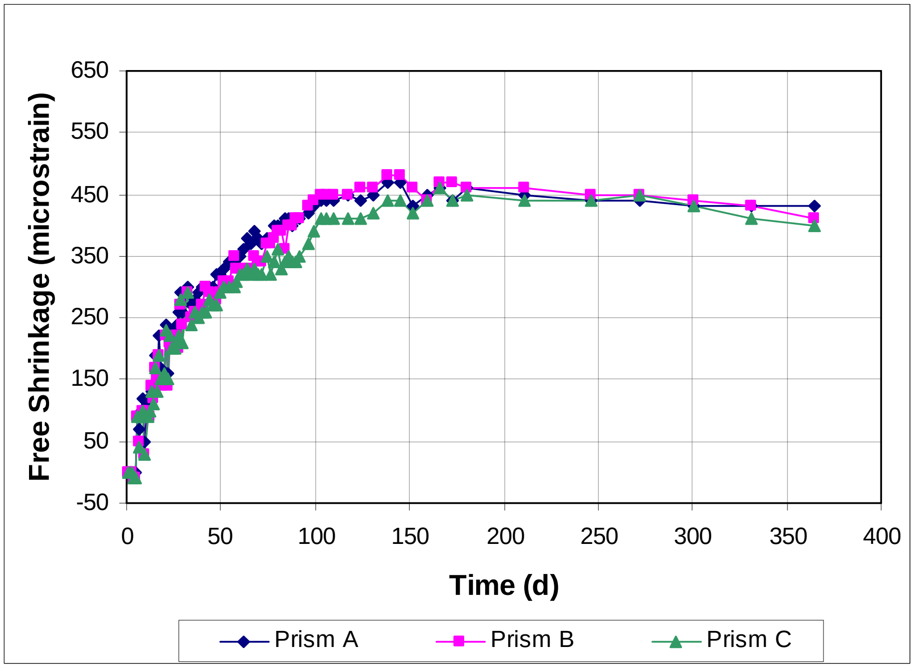

Figure A3.57 - Free Shrinkage, Batch 167. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures.

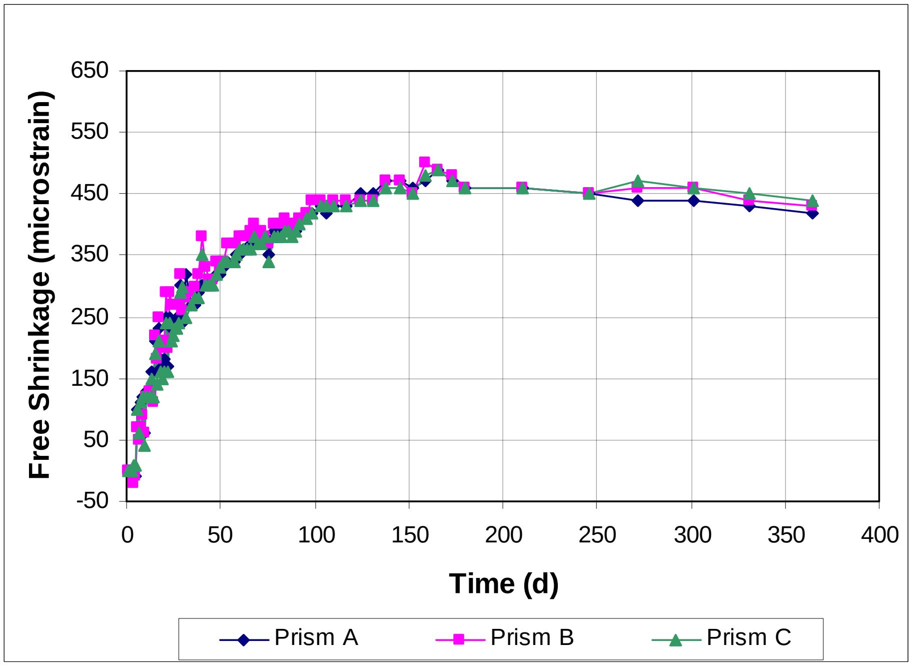

Figure A3.58 - Free Shrinkage, Batch 168. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Glenium 3000NS.

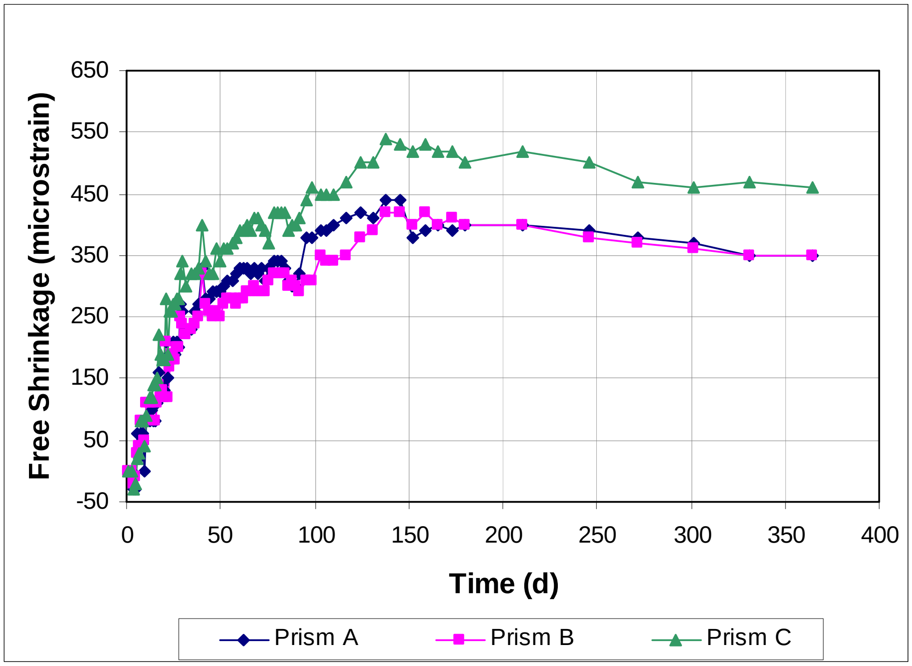

Figure A3.59 - Free Shrinkage, Batch 169. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Glenium 3000NS.

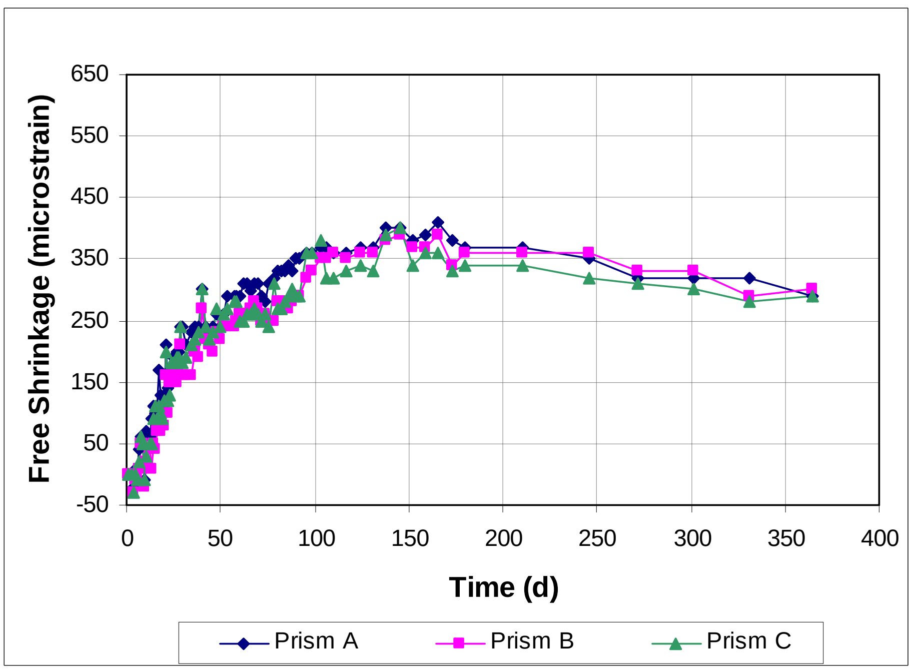

Figure A3.60 - Free Shrinkage, Batch 170. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS.

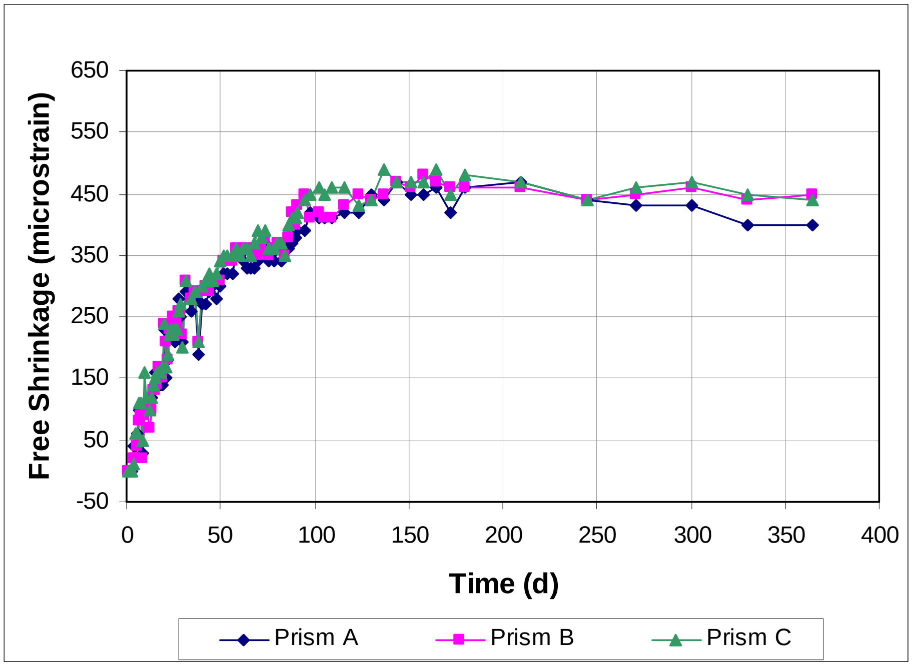

Figure A3.61 - Free Shrinkage, Batch 171. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Rheobuild 1000.

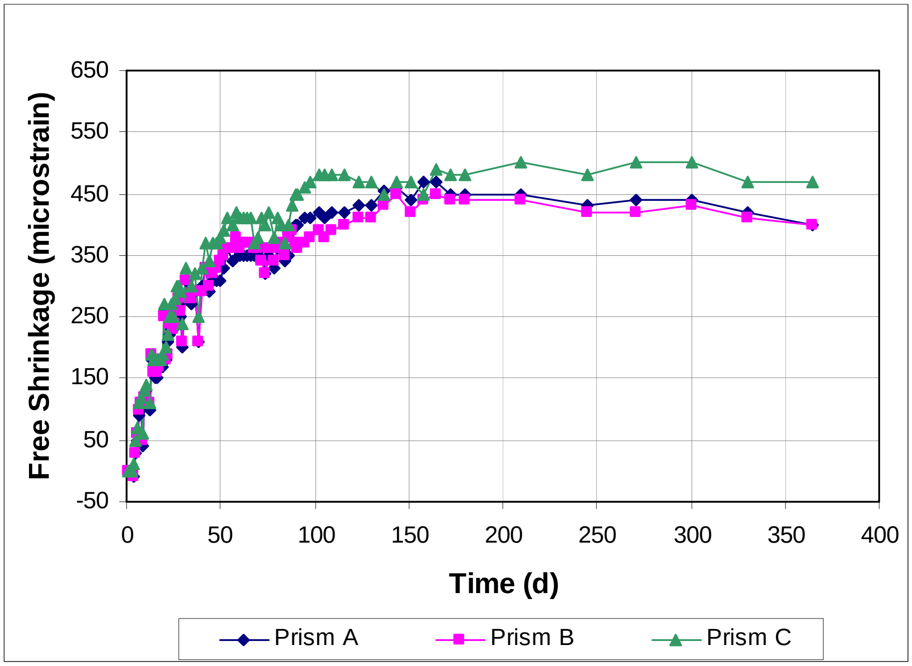

Figure A3.62 - Free Shrinkage, Batch 172. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Rheobuild 1000.

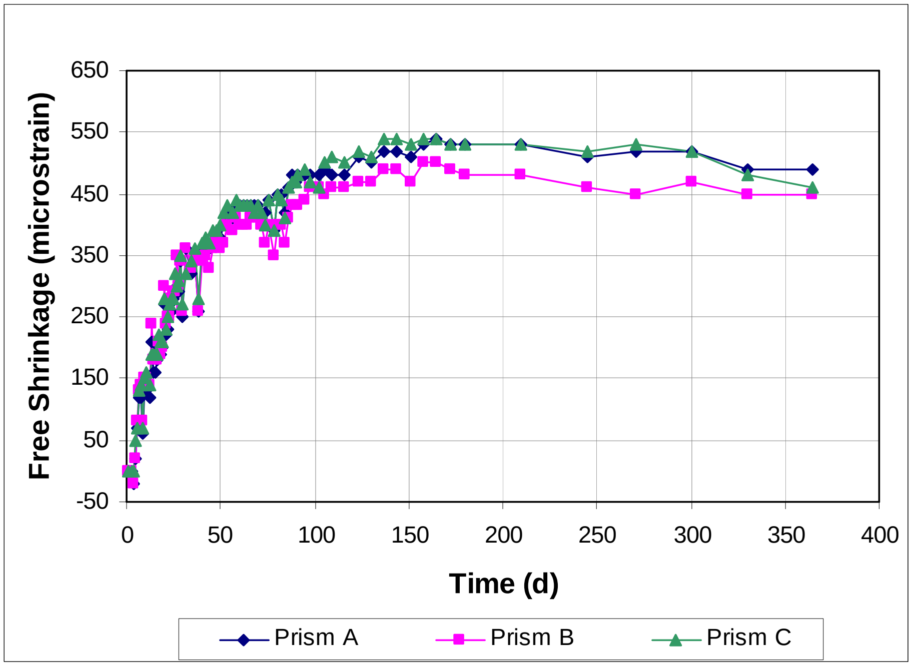

Figure A3.63 - Free Shrinkage, Batch 173. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000.

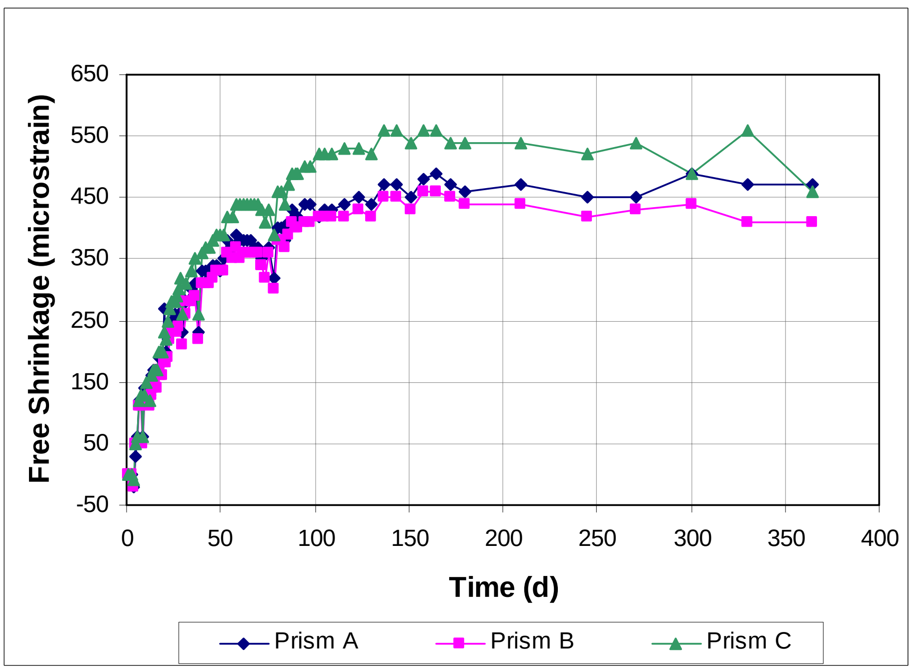

Figure A3.64 - Free Shrinkage, Batch 174. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS.

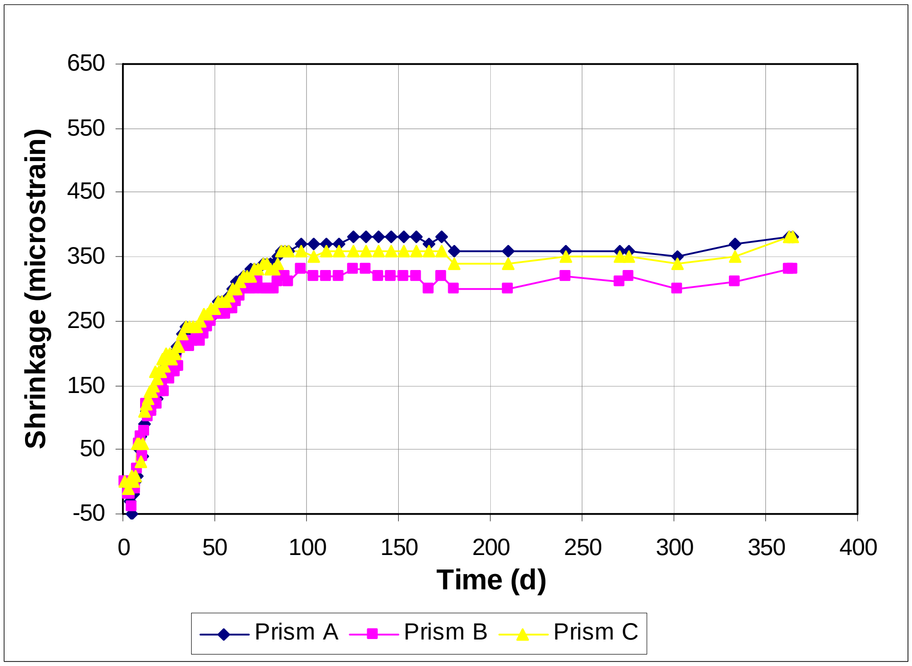

Figure A3.65 - Free Shrinkage, Batch 175. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures.

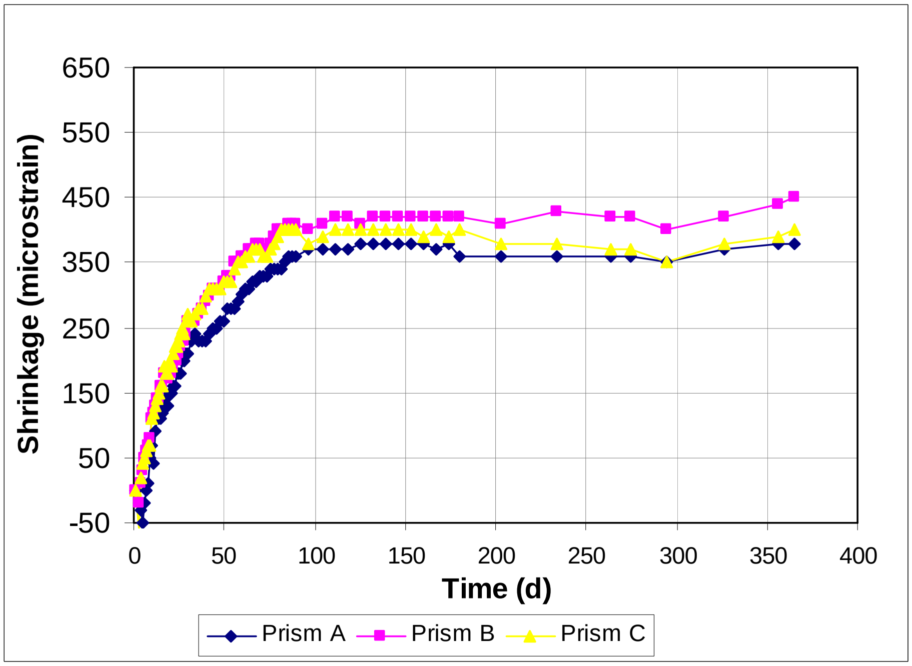

Figure A3.66 - Free Shrinkage, Batch 176. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Glenium 3000NS.

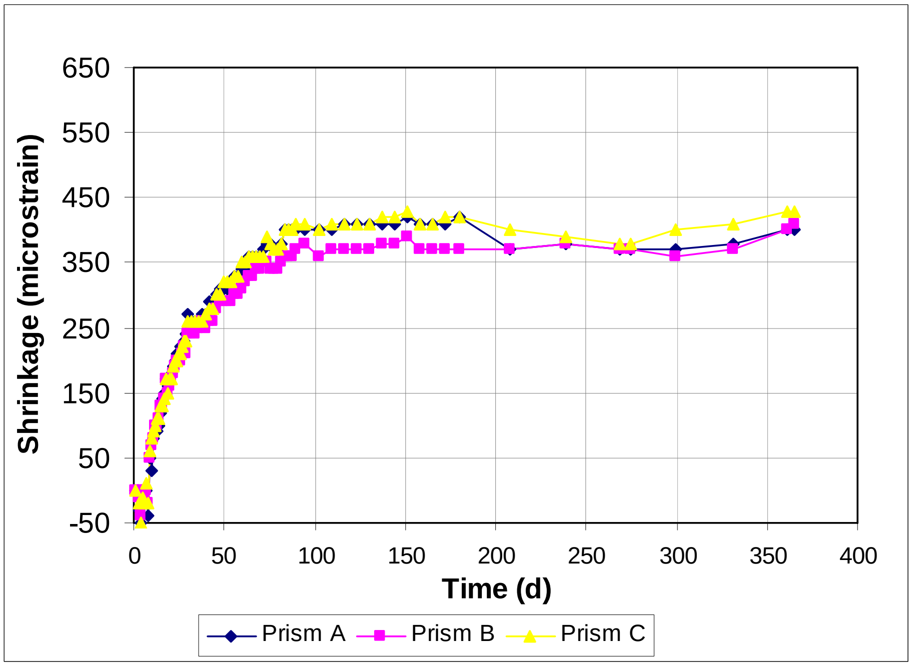

Figure A3.67 - Free Shrinkage, Batch 177. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Glenium 3000NS.

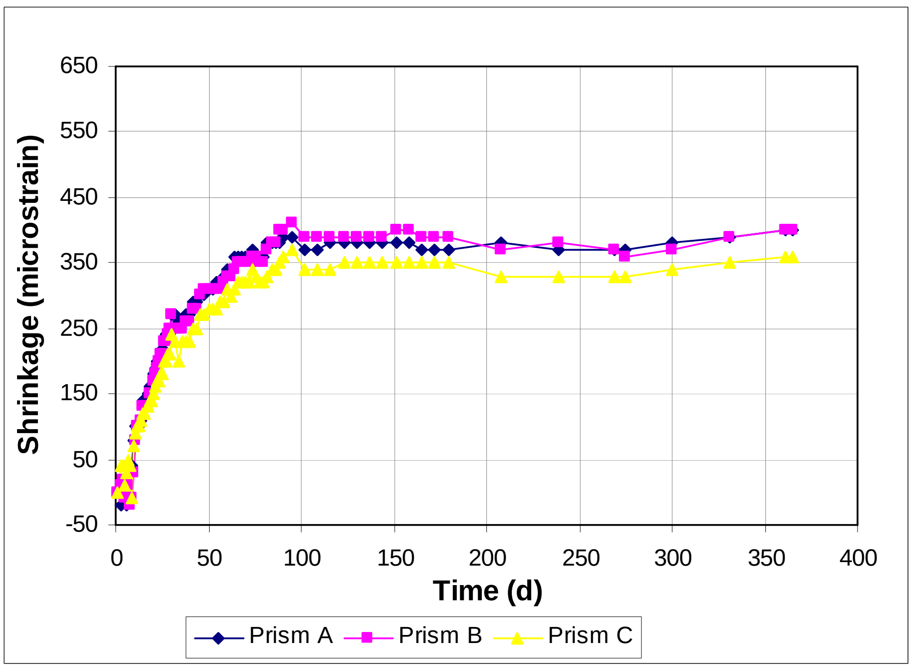

Figure A3.68 - Free Shrinkage, Batch 178. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Glenium 3000NS.

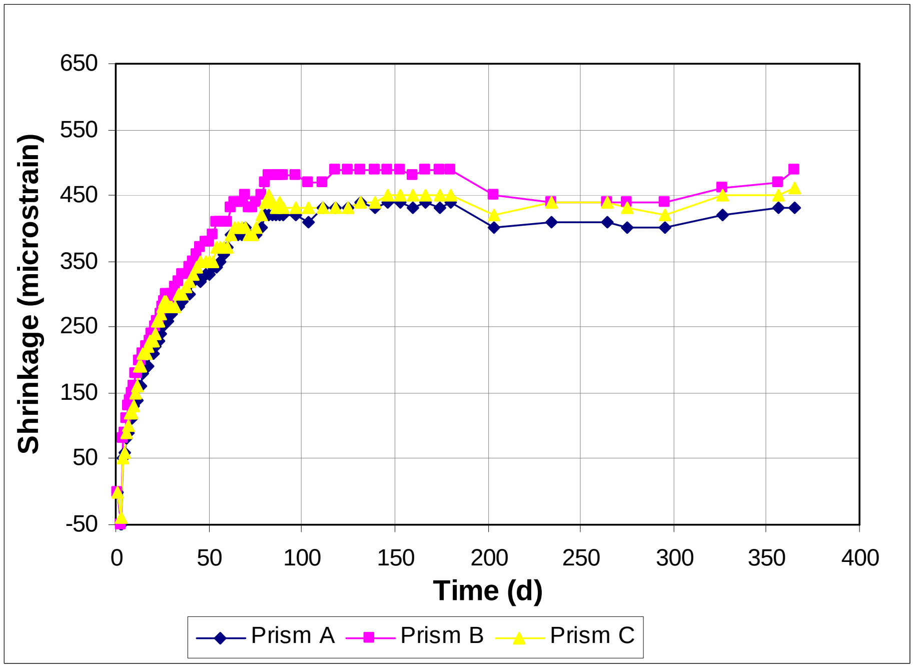

Figure A3.69 - Free Shrinkage, Batch 179. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Rheobuild 1000.

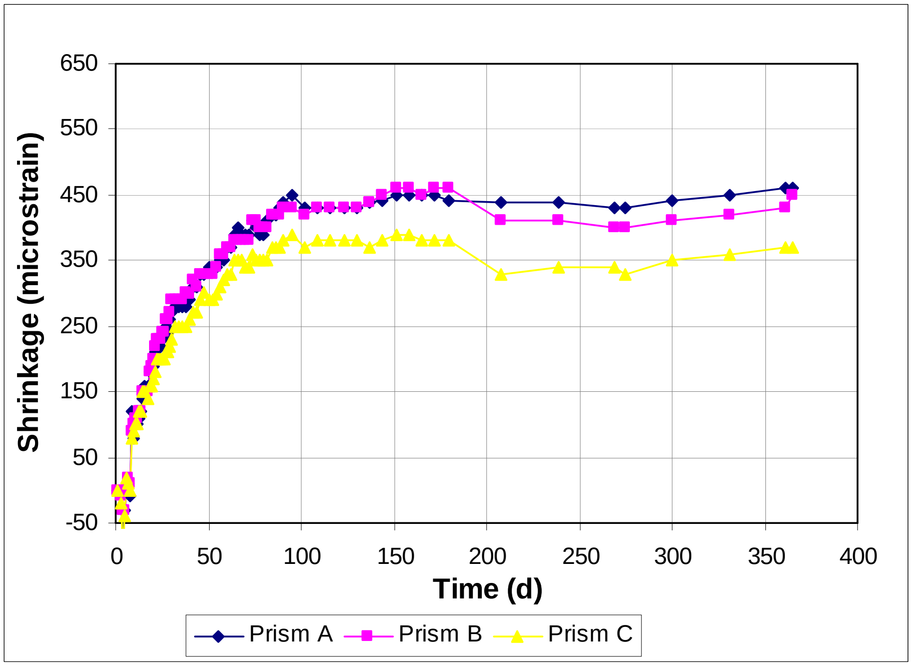

Figure A3.70 - Free Shrinkage, Batch 180. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Rheobuild 1000.

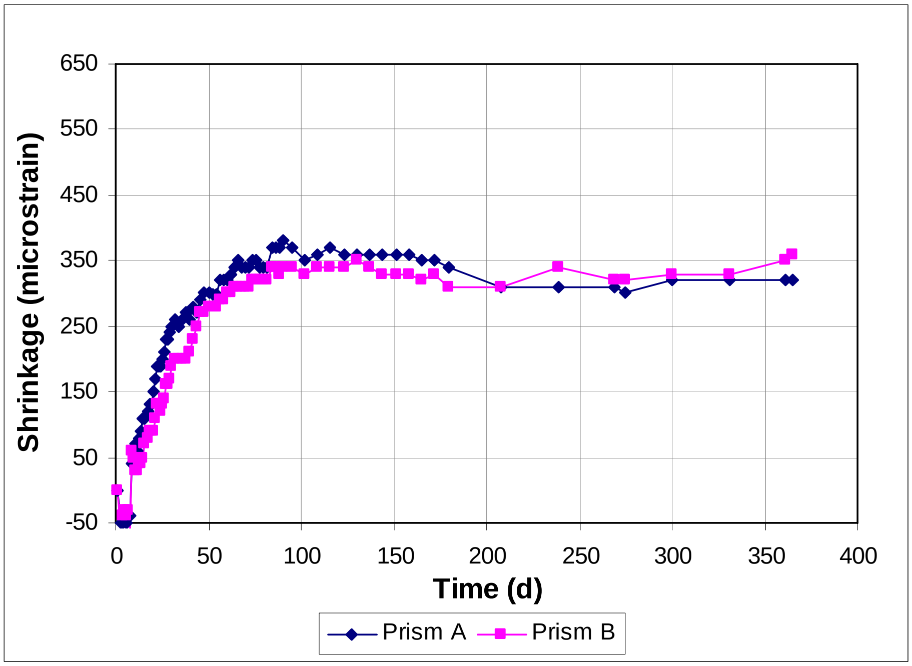

Figure A3.71 - Free Shrinkage, Batch 181. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000.

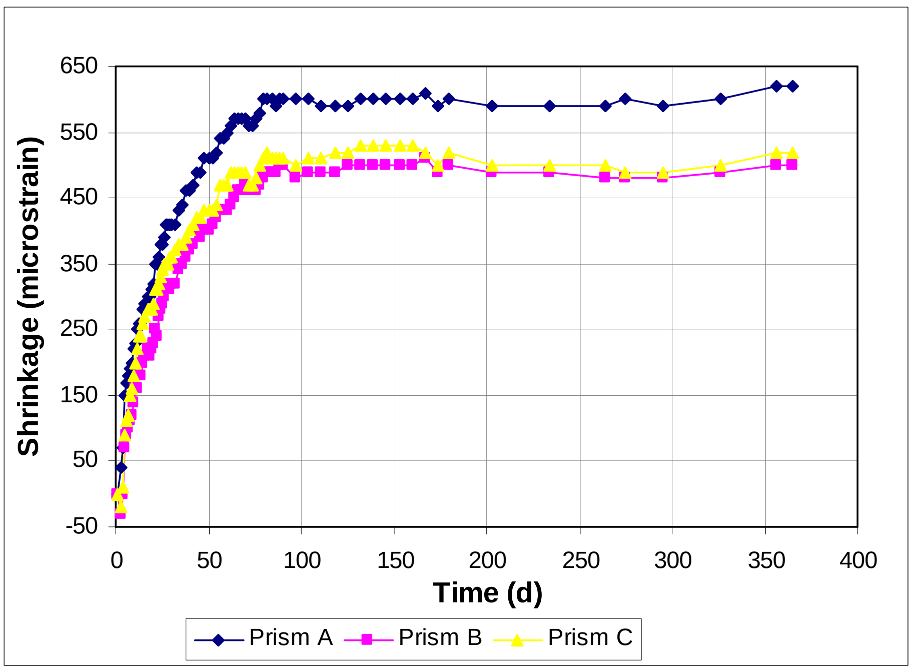

Figure A3.72 - Free Shrinkage, Batch 182. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Rheobuild 1000.

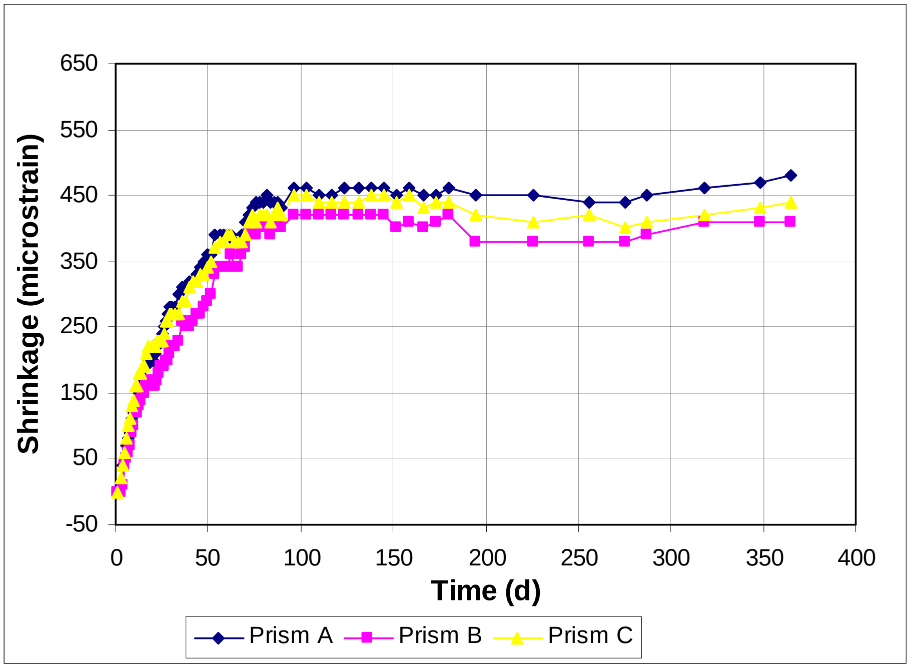

Figure A3.73 - Free Shrinkage, Batch 183. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures.

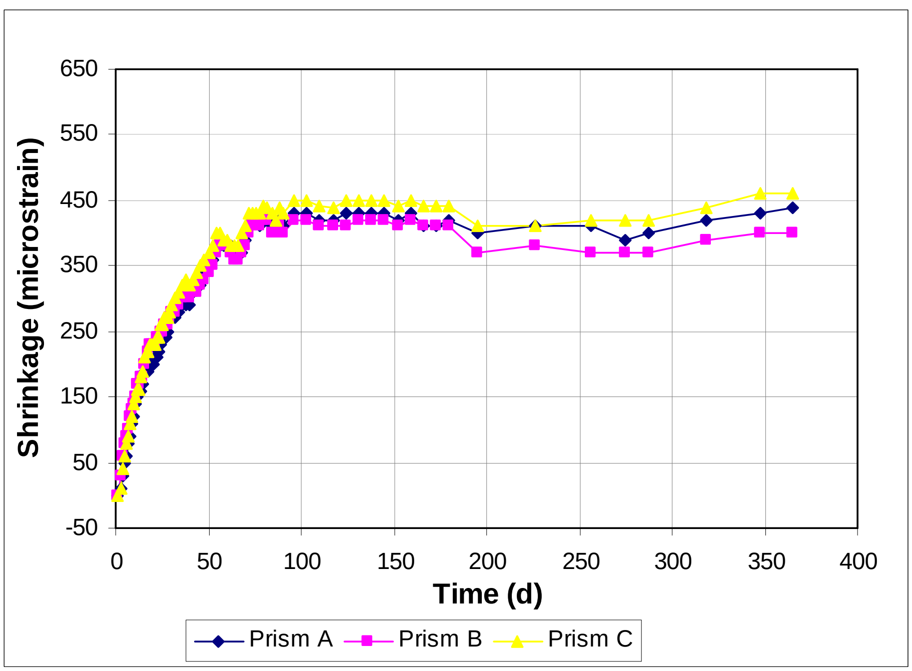

Figure A3.74 - Free Shrinkage, Batch 184. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Adva 100.

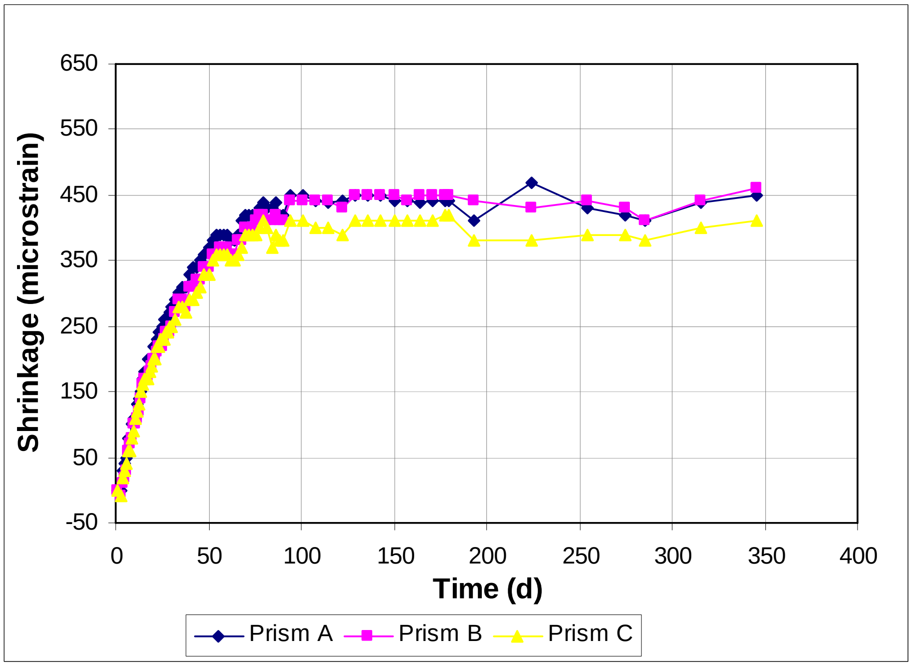

Figure A3.75 - Free Shrinkage, Batch 185. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Adva 100.

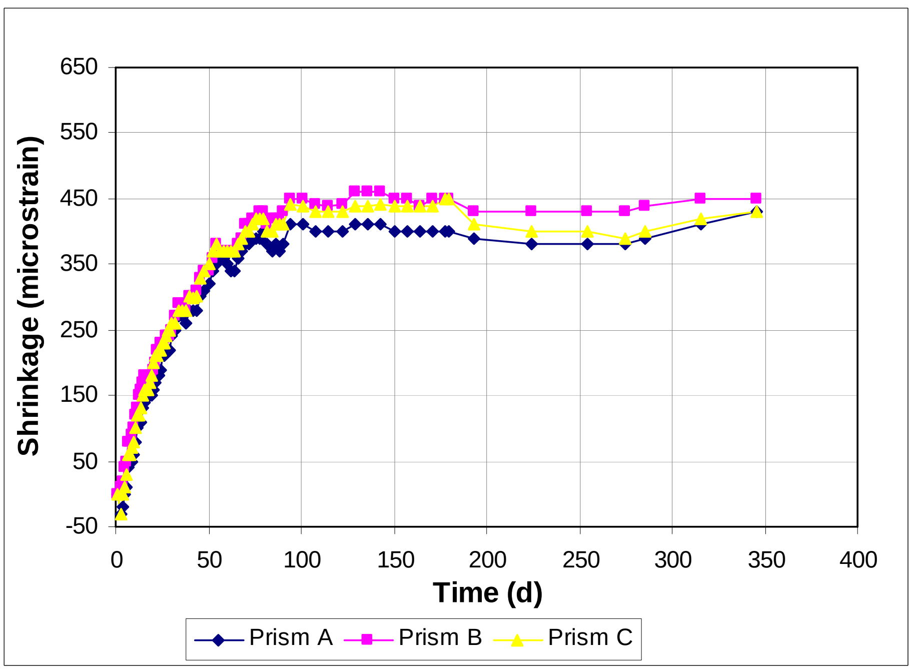

Figure A3.76 - Free Shrinkage, Batch 186. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Adva 100.

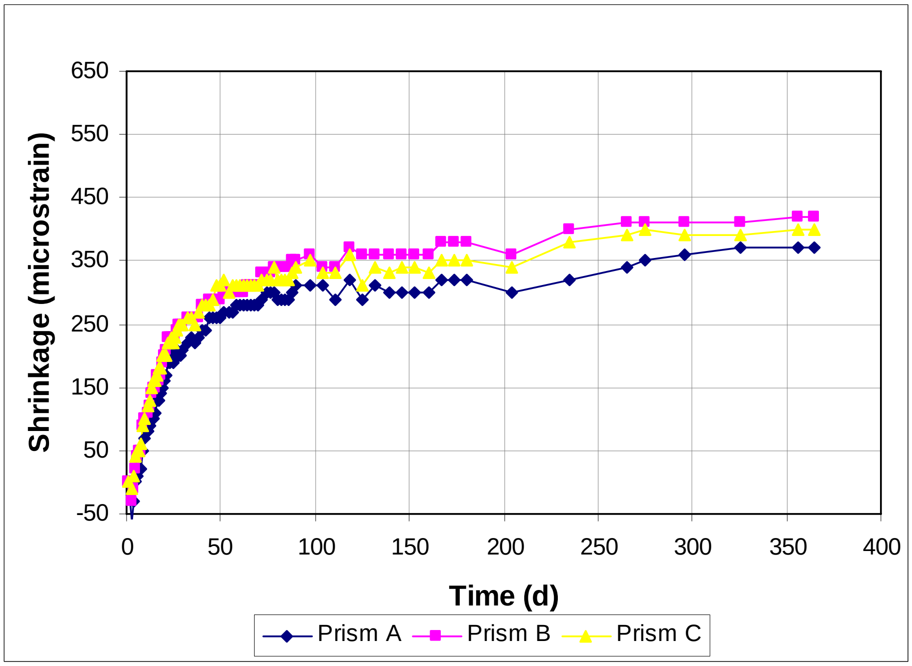

Figure A3.77 - Free Shrinkage, Batch 190. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Low dosage of Adva 100.

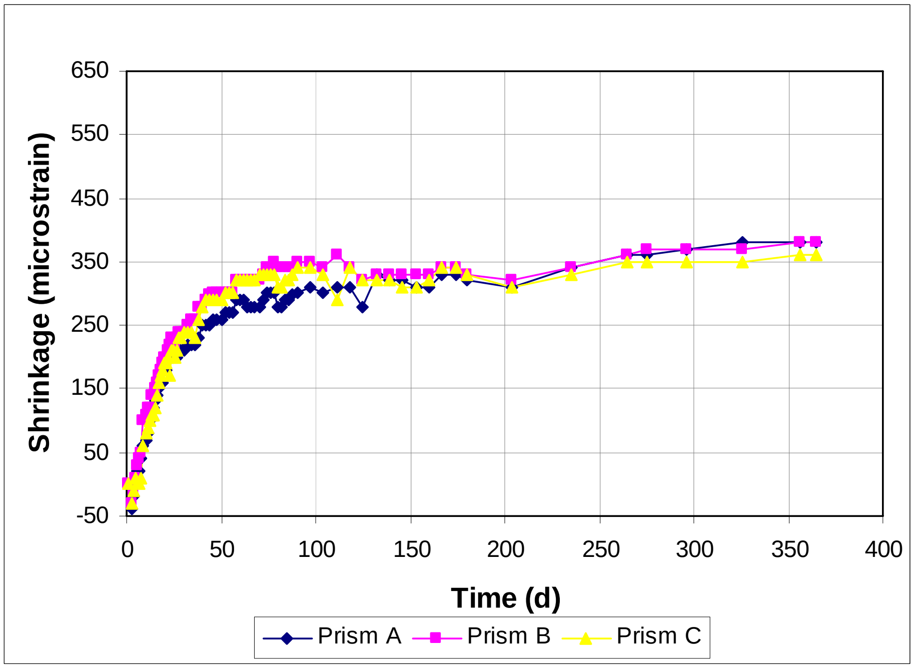

Figure A3.78 - Free Shrinkage, Batch 191. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Medium dosage of Adva 100.

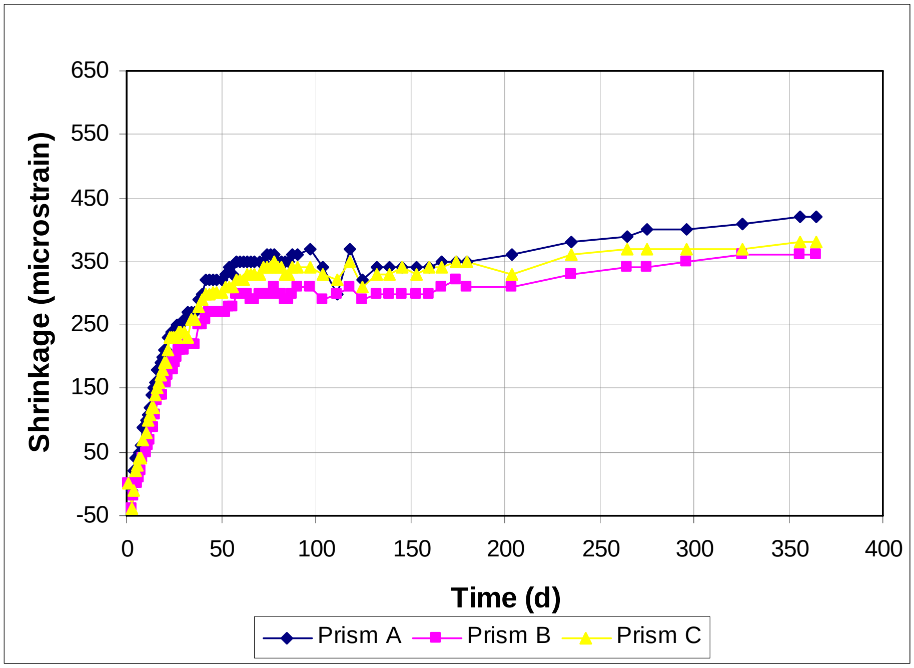

Figure A3.79 - Free Shrinkage, Batch 192. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. High dosage of Adva 100.

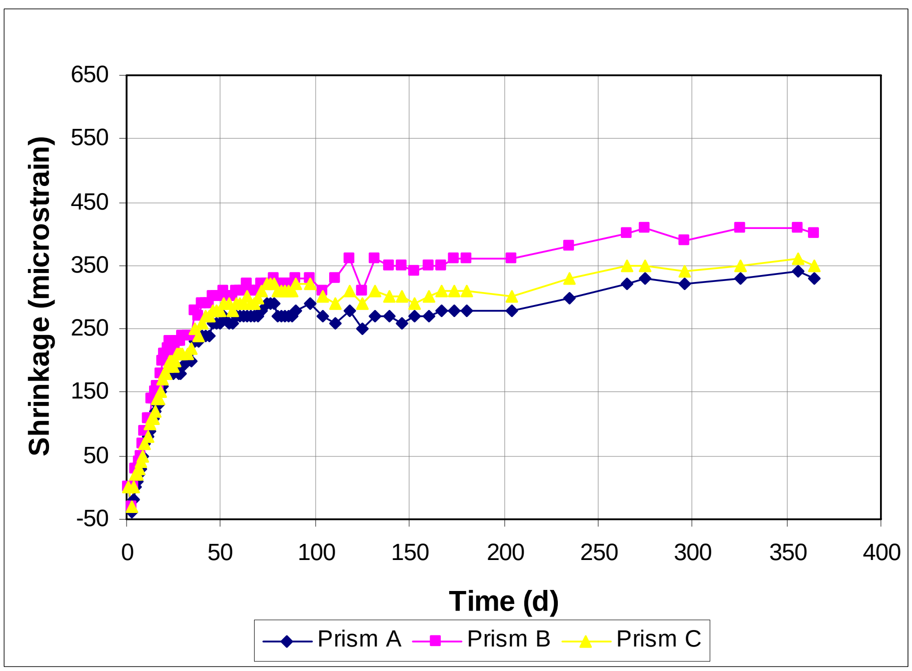

Figure A3.80 - Free Shrinkage, Batch 193. 75% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixture.

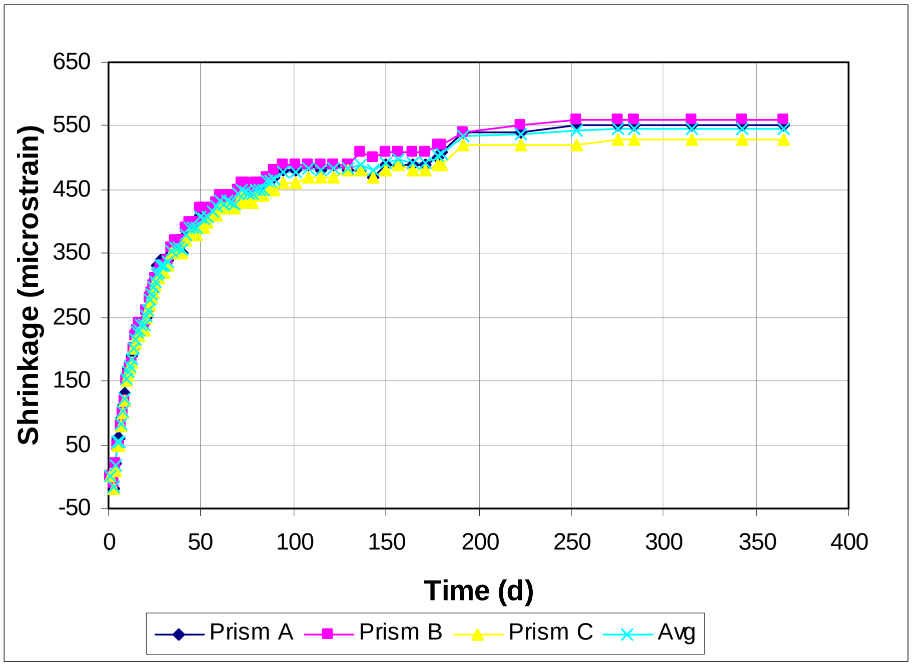

Figure A3.81 - Free Shrinkage, Batch 208. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days. Control, no chemical admixtures.

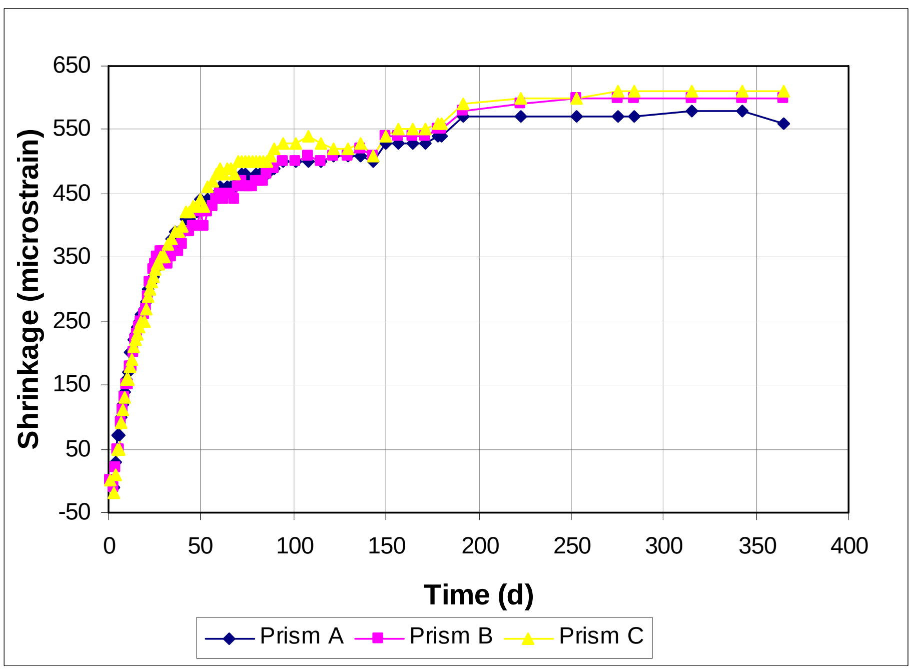

Figure A3.82 - Free Shrinkage, Batch 209. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Adva 100.

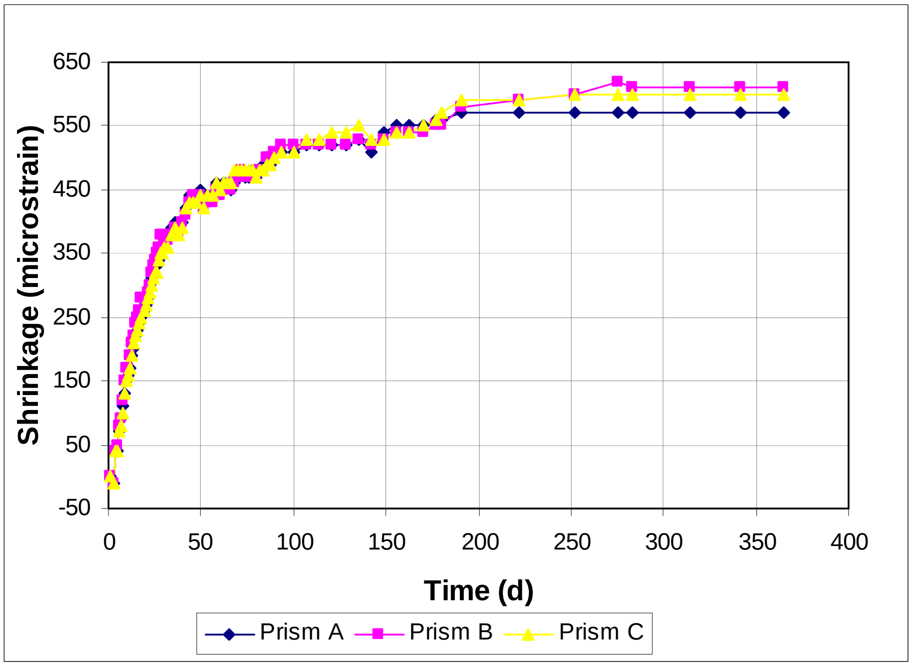

Figure A3.83 - Free Shrinkage, Batch 210. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Glenium 3000 NS.

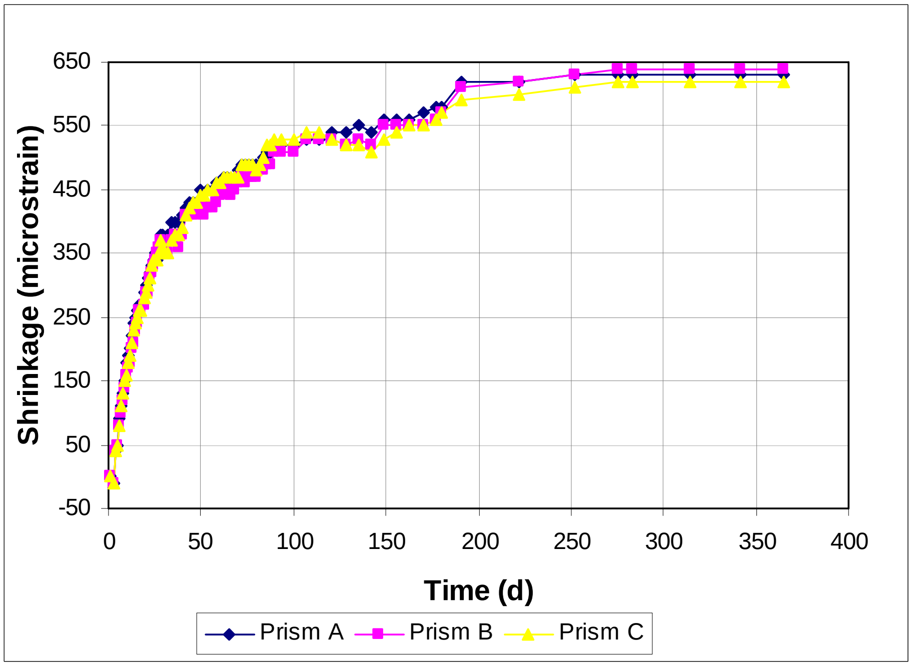

Figure A3.84 - Free Shrinkage, Batch 211. 70% Aggregate, 0.45 w/c. Type I/II cement. Drying begins at 3 days, Rheobuild 1000.

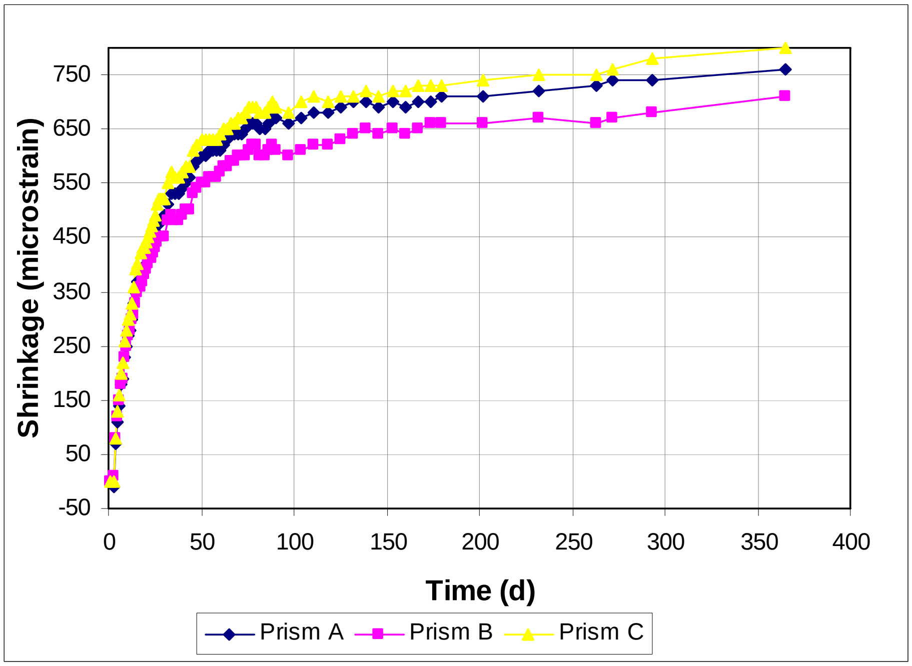

Figure A3.85 - Free Shrinkage, Batch 260. 63.5% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Control, no superplasticizer, increased paste content for same slump.

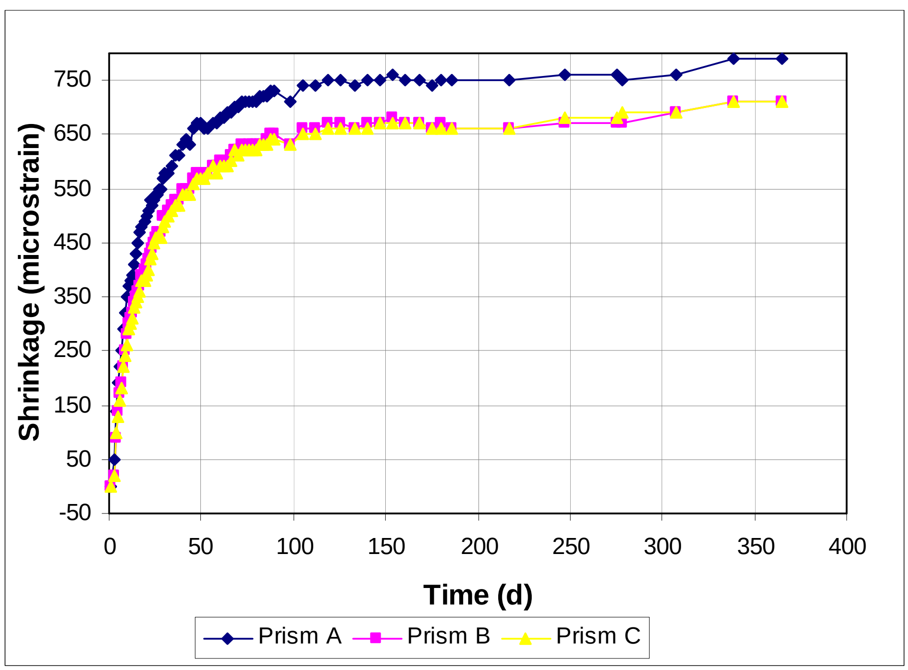

Figure A3.86- Free Shrinkage, Batch 249. 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Glenium 3000 NS.

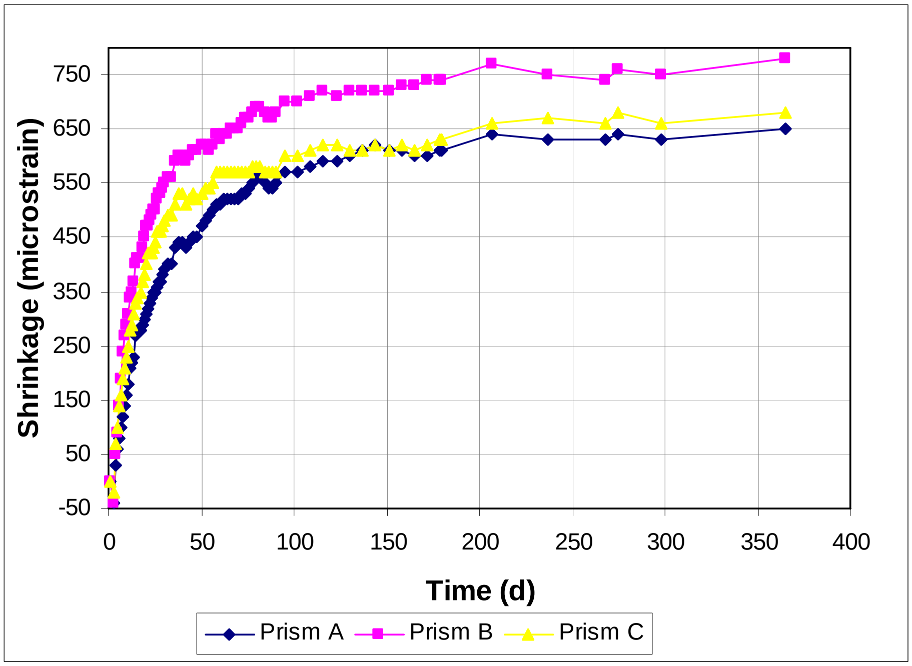

Figure A3.87 - Free Shrinkage, Batch 256. 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Rheobuild 1000.

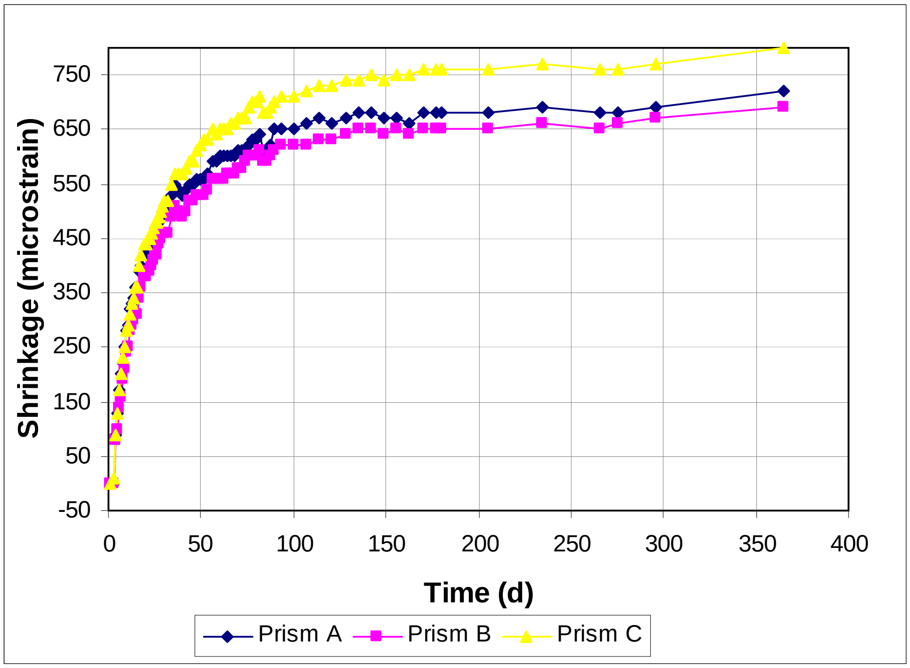

Figure A3.88 - Free Shrinkage, Batch 259 67.8% Aggregate, 0.45 w/c. Type I/II cement. Air-entrained concrete. Drying begins at 3 days. Adva 100.