8-2007

“Parametric Study of the Effects of Water to Cementitious Materials Ratio and Cementitious Materials Content on the Durability Properties of High Performance Concrete

Andrew T. Tinsley
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Andrew T. Tinsley entitled ""Parametric Study of the Effects of Water to Cementitious Materials Ratio and Cementitious Materials Content on the Durability Properties of High Performance Concrete." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Edwin G. Burdette, Major Professor

We have read this thesis and recommend its acceptance:

J. Harold Deatherage, Quihong Zhao

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Parametric Study of the Effects of Water to Cementitious Materials Ratio and Cementitious Materials Content on the Durability Properties of High Performance Concrete

A Thesis Presented for
the Master of Science
Degree
The University of Tennessee, Knoxville

Andrew Tinsley
August 2007

Dedication

To my Father, Tom Tinsley, for all of the inspiration you have offered in my life.

ACKNOWLEDGEMENTS

I would like to acknowledge the Tennessee Department of Transportation for their financial support and project guidance. I would also like to thank the University of Tennessee College of Civil and Environmental Engineering for the guidance and technical knowledge they provided throughout the project. I would also like to thank the professors in charge of this project, Dr. Ed Burdette and Dr. Hal Deatherage. Without them, none of this project and thesis could have been possible. My fellow graduate research assistants: Ross Shaver and Andy Ford were also supremely helpful in this project. Rohi Salem also provided an irreplaceable amount of guidance throughout the project. I would also like to thank my wife for putting up with my busy schedule and the time away from her to excel in my academic career.

Thanks to all.

ABSTRACT

This study takes a detailed look at the factors that affect the durability of concrete and how they can be applied to the development of a useful performance specification and help to extend the life of bridge decks and other concrete structures exposed to the elements of nature. A series of fifteen mixes (with varying cement contents and water/cement ratios) were performed in order to determine exactly which of these factors have a significant effect on the durability of a concrete mix. Controlling the water/cement ratio is necessary in order to control strength and permeability. Cement content was found to have little bearing on strength while the amount of cement affected the shrinkage significantly. Shrinkage is also dramatically affected by the amount of water in the mix. The results of the mixes were then used to develop a new specification for a bridge deck mix that will potentially improve the lifespan of bridge decks. Prescriptive versus performance specifications were also explored with the benefits and deficiencies of each form of specification looked at in detail.

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List of Abbreviations

ACI	American Concrete Institute
AEA	Air Entraining Agent
ASTM	American Society for Testing and Materials
CPV	Cementitious Paste Volume
DOT	Department of Transportation
FHWA	Federal Highway Administration
HPC	High Performance Concrete
HRWRA	High Range Water Reducing Agent
RCPT	Rapid Chloride Permeability Test
SHRP	Strategic Highway Research Program
TDOT	Tennessee Department of Transportation
VDOT	Virginia Department of Transportation
W/C	Water to Cementitious Material Ratio or Water to Cement Ratio

1.0 Background and Introduction

1.1 Research Background

The Tennessee Department of Transportation (TDOT) has been funding a research project through the University of Tennessee over the past four years that has focused on the design and development of a new high performance bridge deck concrete mix for use throughout the state. Many options were explored including the use of supplementary cementitious materials (SCM), different aggregate gradations, and reduced cement contents. One of the properties observed with the variance of cementitious materials content and water to cement (W/C) ratios was the drastic effect on the durability properties of the mix as measured by the amount of shrinkage and the chloride ion permeability. Research of this subject showed that there is very little information on the simultaneous effects of these mix properties on the durability performance of a high performance concrete mix.

These effects come into mainstream concern in the ready mix concrete delivery system currently used in the United States. A common problem noted throughout the project was a tendency to add water to a mix in order to obtain the appropriate slump as opposed to using extra high range water reducing agent. The watering down of these concrete mixes produces a noticeably less durable mix and will often shorten the life of a bridge deck well below its design service life.

In order to address this issue, the research team at the University of Tennessee tested a series of mixes that would vary either the water to cement ratio or the cementitious materials content individually to allow for the comparison of the effects on the strength and durability of the concrete.

1.2 Research Objective

The objective of this thesis was to monitor the effects of water to cementitious material ratio and cementitious materials content on the durability of concrete. As stated above, the main driving factor behind this research was to show that the commonly accepted practice of "watering down" concrete has a drastically negative effect on the durability of the concrete while still allowing the concrete to meet the strength requirements that many departments of transportation use to evaluate the quality of concrete. With the increased amount of research and design emphasis shifting toward more durable mixes as opposed to increased strength, it is important to understand the effects of the water/cementitious materials ratio and the cementitious materials content as these two items are often the basis of mix design in the current prescribed concrete mix specifications used in the United States.

Another objective of this study was to show the usefulness of a performance specification as opposed to a prescribed specification. Use of a performance specification allows the ready-mix producers to create mix designs that will optimize their profitability and efficiency while providing the construction industry with the durability and performance that today's technology demands.

1.3 Organization of the Report

This report begins with a literature review of the different factors that affect the durability of concrete. The next section outlines the materials, material properties, equipment, and test methods used to perform the research necessary for completion of the analysis. The next chapter reports and discusses the data obtained throughout the experiment. The final chapter includes conclusions and recommendations to aid in the development of more durable mixes and also to give departments of transportation a reference as to how much damage can be done to the infrastructure if water content is increased. All of the tables and figures referred to in this report are located in the appendices at the back of the paper in the order they are first referred to in the text. For the purposes of this paper, water/cement ratio is synonymous with water/cementitious materials ratio since all mixes contained supplementary cementitious materials. Also, cement content is equivalent to cementitious materials content for similar reasoning.

2.0 Literature Review

2.1 High Performance Concrete

An appropriate definition of high performance concrete (HPC) has been argued within the concrete industry throughout the last few decades. Many agencies including the Strategic Highway Research Plan (SHRP), American Concrete Institute (ACI), and the Federal Highway Administration (FHWA) all have their own definitions and they differ significantly.

2.1.1 ACI Definition of HPC

The American Concrete Institute defines HPC as "concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices" [26]. The requirements may involve enhancements of placement and compaction without segregation, long-term mechanical properties, early-age strength, volume stability, or service life in severe environments. HPC is often high-strength, but high-strength concrete may not necessarily be high-performance.

2.1.2 SHRP Definition of HPC

The Strategic Highway Research Plan defined HPC as “any concrete which satisfies certain criteria proposed to overcome limitations of conventional concretes.” SHRP then subdivides HPC into the categories given in Table A-1. The acceptance criterion for each subdivision is also given in Table A-1 [28].

2.1.3 FHWA Definition of HPC

The Federal Highway Administration [19] has broken down HPC into different grades. Table A-2 shows each grade along with its characteristics.

2.2 Effects of Cementitious Materials Content

The effects of cementitious materials content have long been investigated as a driving force behind concrete strength and performance. Recent studies have found that increased cement content may not only hurt the durability of the concrete, but may actually be detrimental to the strength of the concrete.

2.2.1 Effects on Strength

Several studies have shown that for a particular water/cementitious materials ratio, an increase in cementitious materials content will increase the strength (insignificantly) to a certain point. After this point, the addition of cement is detrimental to the strength of the concrete. The point at which the addition of cement has a negative effect on strength is subject to change from mix to mix. This point can be affected by aggregate type, aggregate gradation, supplementary cementitious materials contents, and water/cementitious materials ratio [27]. The decrease (or increase) in strength is generally negligible and tends to show a downward trend [18]. Neville states that cementitious materials content has little to do with the actual strength gain of a given mix [23]. Again, the effects on strength are highly variable and tend to depend on several different variables, making the prediction of the effects on strength difficult to predict.

2.2.2 Effects on Permeability

The direct effect of the cementitious materials content on the permeability of concrete is hard to determine. Increased cementitious materials content tends to increase the number of cracks in a particular casting which will result in rapid chloride ingress [21]. Also, the chemical composition of the cement plays a large role in the permeability of a mix. It has also been shown that the chlorides are incapable of traveling through aggregates; therefore, a mix with less paste will slow the ingress of chloride ions to a certain extent. As a general rule, the permeability tends to go down with a decrease in cement paste if the water/cement ratio is kept low (less than .45) [24].

2.2.3 Effects on Shrinkage

A study performed by Dhir et al. shows that an increase in cement content will generally lead to an increase in drying shrinkage. At a water to cement ratio of .55 and cement contents varying from 600 lb/yd^3 to 415 lb/yd^3, the study indicated a decrease in drying shrinkage from 744 microstrain to 542 microstrain respectively [18]. Neville states that the drying shrinkage of a mix is largely proportional to the amount of water the mix contains. It can then be concluded that at constant water/cement ratios the shrinkage will be higher with an increase in cementitious materials since there is more water in the mix [23].

2.3 Effects of Water/Cementitious Materials Ratio

2.3.1 Effects on Strength

It is widely known that one of the best ways to increase the strength of a concrete mix is to lower the water/cementitious materials ratio. This increase in strength is a direct result of a reduction of the porosity of the hydrated cement paste which occurs with removal of water from the mix [2]. Neville states that the strength of concrete at a given age and cured in water at a prescribed temperature is dependent upon primarily the water/cement ratio and the degree of compaction [23]. While there are other factors that affect the strength of concrete including the type of cement, supplementary materials content, air void percentage, and aggregate types, the main factor is the water/cement ratio for non-high strength concrete (less than 8,000 psi). In a “high strength” mix, having almost everything essentially perfect becomes critically important.

2.3.2 Effects on Permeability

As discussed previously, the permeability of a concrete mixture has a lot to do with the porosity and pore structure of the cement. Chloride attack occurs when chloride ions enter the interstitial spaces in the cement paste and react with the C_3A to cause the formation of monochloroaluminates [2]. These monochloroaluminates cause cracking, spalling, and corrosion of reinforcement. Entrance and travel through the interstitial spaces is made much more difficult with the decrease in porosity caused by a lower water/cement ratio [2]. Neville also reports similar findings in that the coefficient of permeability (and permeability itself) is drastically increased as the water/cement ratio is increased [23].

2.3.3 Effects on Shrinkage

As discussed earlier, the drying shrinkage is largely affected by the amount of water in the mix. Drying shrinkage is directly related to the amount of excess water being removed from the pore spaces in the concrete. A decreased water/cement ratio will lead to less excess water and, therefore, a decrease in drying shrinkage [23]. The ACI Committee 318 also reports that a decrease in water/cement ratio will result in a less permeable concrete [1].

2.4 Performance vs. Prescriptive Specifications

The differences between performance and prescriptive specifications have been discussed in the concrete production community for some time now. Both forms of specifications have advantages and disadvantages, some of which are discussed here. With the performance requirements for concrete shifting from strength alone to more in-depth durability requirements, specification changes will be a necessity to facilitate the implementation of high durability mixes in the field.

Prescriptive specifications are currently in use in most states in the United States. Lobo defines a prescriptive specification as "…one that includes clauses for methods and means of construction and composition of the concrete mix rather than defining performance requirements." Some of the items often specified include the water/cement ratio, type of cement, minimum cement content, limits on quantity of supplementary cementitious materials, brand of admixture, and aggregate gradation [22]. By regulating these essential components of any concrete mix, one assumes that the durability of the concrete will be similar to that of research mixes. This is usually true when the mixes are properly batched and cured. However, it is still possible to meet the strength requirements of a given specification and still have a decreased durability resulting from deviation from the prescribed mix. Prescribed mixes also discourage innovation and often result in higher costs to the consumer [22].

Lobo defines a performance specification as "…a set of instructions that outlines the functional requirements for hardened concrete depending on the application." A performance specification concentrates on the performance side of the concrete. This type of specification will encourage innovation, improve the quality of concrete, and often lower the cost to the consumer. This type of specification also allows for the "specialization" of concrete. For example, an interior column and an exterior bridge column may need the same compressive strength, but they do not need the same freeze-thaw or permeability capabilities [22]. Generally, performance specifications will avoid specifying the means and methods, but will focus on the performance criteria along with the specific acceptance criteria and testing methods.

3.0 Materials and Methods

3.1 Materials

3.1.1 Portland Cement

Commercially available Type I Portland cement meeting ASTM C 150 [9] was used in this study. A specific gravity of 3.15 was assumed for the purpose of mix proportioning. Table E-1 in Appendix E gives the chemical composition of the Type I Portland cement used in the mixes.

3.1.2 Fly Ash

The Class F fly ash used in this study conformed to ASTM C 618 [14]. The specific gravity of the fly ash used was assumed as 2.3. Figure B-1 shows a picture of the fly ash used in the concrete mix. Table E-2 in Appendix E gives the chemical composition of the class F fly ash used in the mixes.

3.1.3 Coarse Aggregates

There were two different types of coarse aggregates used in the formulation of the test mix. The major coarse aggregate was the #57 limestone with a nominal maximum size of 1-inch, the standard coarse aggregate for TDOT Class D mixes. Table B-1 gives the general properties, while Table B-2 provides the sieve analysis of the #57. Figure B-2 is also provided, which is a visual representation of the #57 *limestone.*

The second coarse aggregate used in this study was the #7 limestone with a nominal maximum size of ¾-inch. Table B-3 gives the general properties and Table B-4 provides the sieve analysis of the #7 limestone. Figure B-3 provides a picture of the #7 limestone.

3.1.4 Fine Aggregate

The fine aggregate was Ohio River Valley natural sand. This aggregate was used in each of the 5 Group Mixes. The properties of the natural sand are given in Table B-5. The sieve analysis is given in Table B-6. A picture of the natural sand used is provided in Figure B-4.

3.1.5 Mixing Water

The water used for mixing was tap water. The unit weight of water was assumed to be 62.4 lbs/yd^3.

3.1.6 Chemical Admixtures

There were two chemical admixtures used in the mixes of this study. One was high range water reducing agent (HRWRA), and the other was air entraining agent (AEA). The HRWRA used conformed to ASTM C 494 type F and G [14]. The AEA used conformed to ASTM C 260 [13].

3.2 Mixing and Curing Methods

3.2.1 Mix Design

The mix design was performed volumetrically with the specific gravities given above used in the design sheet. All quantities were corrected for moisture content prior to each of the mixes to maintain positive control of the water/cement ratio. Although the cementitious materials content and the water/cement ratio varied in each of the mixes, the percentage of materials was kept the same for consistency throughout the series of mixes. Table B-7 shows the percentages used in calculating the individual mix proportions.

3.2.2 Mixing Procedure

All mixing was performed in a standard laboratory mixer with a 7.5 cubic feet capacity. A picture is provided in Figure B-5. Before mixing, moisture contents were obtained for all aggregates used in the particular mix. These values were used to adjust the amount of water used in the mix. Water was added for dry aggregates, while water was subtracted for wet aggregates.

The mixing procedure is listed as follows:

1. Coarse aggregates were added to the mixer.
2. Chemical admixtures (HRWRA and AEA) were mixed in with half of the water, while the fine aggregate was added simultaneously.
3. Aggregates were well mixed before moving to step 4.
4. Cementitious material was added. This included cement and fly ash. The other half of the water was added at the same time to reduce the amount of cementitious material escaping as dust particles.
5. The mixer was left rotating for 3-5 minutes, and then stopped for 1-2 minutes. Upon restarting the mixer, HRWRA was added if needed to control slump values.

The mixer was left rotating for another 3-5 minutes, and then fresh cement properties (slump, temperature, air content, and unit weight) were taken consistent with the relevant ASTM and AASHTO standards.

3.2.3 Sampling Procedure

All specimens were cast according to ASTM C192 [11]. Four cylinders measuring 6 in. diameter by 12 in. long were cast for compressive strength testing in accordance with ASTM C 192 [11]. Beams measuring 4 in. x 4 in. x16 in. long were cast for shrinkage (two beams). Four cylinder specimens measuring 4" in. diameter by 8 in. long were cast for chloride ion permeability testing in accordance with ASTM C 1202 [17].

Specimens were covered with plastic immediately after casting, and then covered with wet burlap bags. Specimens were left to cure for 24 ± 8 hours, at which time they were removed from the molds. All specimens were then placed in a lime water bath. A picture of the specimens after casting is presented as Figure B-6, while a picture of the lime water bath is given in Figure B-7. The regular limewater bath was kept at 72^{o}F ± 2 ^{o}F. A hot limewater bath was kept at 100 ±2 ^{o}F to use for accelerated curing of chloride ion specimens

Compressive strength specimens were kept in the bath for 28 days before testing. Shrinkage specimens were kept in the bath for seven days and air-dried at a temperature of 70^{o}F ±5 ^{o}F and a humidity of 40% ± 6%. Chloride permeability specimens were cured for either 28 or 56 days until testing depending on the method of curing performed.

3.3 Testing of Fresh Concrete

3.3.1 Slump

The slump of the fresh concrete mixture was measured according to ASTM C143 [8]. Figure B-8 shows a picture of the slump test in progress.

3.3.2 Air Content

The air content was determined by the pressure method according to ASTM C231 [12]. Figure B-9 shows a picture of the air content apparatus.

3.3.3 Temperature

The temperature of concrete was measured with a standard thermometer, with an accuracy of ± 1 ^{o}F. The measurements were made according to ASTM C 1064 [16].

3.3.4 Unit Weight

The unit weight of the concrete mixture was measured according to ASTM C138 [7].

3.4 Testing of Hardened Concrete

3.4.1 Compressive Strength

The compressive strength of each mix was tested according to ASTM C39 [5] using a 400,000 lb. capacity hydraulic loading compression machine. Each mix was tested for compressive strength at 28 days of age. Three specimens were tested from each mix. A fourth cylinder was tested if the results from the first three showed significant variation. A picture of the compression machine after a test is shown in Figure B-10.

3.4.2 Rapid Chloride Ion Permeability

The chloride ion permeability test was performed on each mix according to ASTM C1202 [17]. Each test specimen consisted of the top 2” slice from a 4” diameter x 8” long specimen. Specimens were allowed to air dry for one hour. After air-drying, specimens were coated with an epoxy sealant and allowed to dry. Specimens were then subjected to 3 hours under vacuum before de-aired water was added. After addition of the water, the vacuum was run for 1 more hour, and then specimens were opened to the atmosphere. The specimens were then left to soak in water for 18 ± 2 hours. The vacuum apparatus is shown in Figure B-11. The ends of each specimen were then sealed into a Plexiglas mold. A close-up of a sample can be seen in Figure B-12. One end of the specimen was submerged in a 3% sodium chloride solution, while the other was subject to a 0.3N sodium hydroxide solution. An electric current of 60.0 volts DC was applied to each specimen through copper screens attached to the Plexiglas molds. The current was applied for 6 hours with the apparatus taking current and Coulomb measurements every 30 minutes. The apparatus is shown in Figure B-13. The Coulomb value after 6 hours is related to the permeability of the concrete.

3.4.3 Free Drying Shrinkage

The volume or length change (free shrinkage) of each mix was tested according to ASTM C157 [10]. Two specimens were tested for each mix. Readings were taken at 1, 2, 3, 4, 5, 6, 7, 14, 21, 28, and 56 days after the seven-day curing process. A picture of the test being performed is given in Figure B-14.

4.0 Test Results and Discussion

4.1 HPC Mix Design

The mix proportions used for each of the fifteen mixes are given in Tables C-1 thru C-3. As discussed earlier, the main differences in the mixes were the various cementitious materials contents along with the varying W/C ratios. In order to keep the mixes as consistent as possible, the percentages of cementitious materials and aggregates were kept consistent throughout each of the mixes. These proportions can be found in Table B-7.

4.2 Effects on Fresh Properties of Concrete Mixes

The effects of the varied W/C ratios and cementitious materials contents on the fresh properties of concrete were monitored throughout the course of the research. Table C-4 gives a summary of the fresh properties of the concrete by mix.

Little can be learned from the fresh properties of the mix as recorded since high range water reducing agents and air entraining agents were used in each of the mixes. The slumps and air contents were highly affected by the use of these additives. The temperature was a function of the ambient temperature on the day the mix was performed. The unit weight saw a variance of approximately 5 pounds per cubic foot throughout the experiment. The only notable information that came from this portion of the experiment was that mixes with low cement contents and low W/C ratios will generally require more HRWRA. Mixes with high cement contents will generally require more AEA. The amount of AEA required appeared to be independent of the W/C ratio. Figures C-1and C-2 present graphical representations of these conclusions.

4.3 Effects on Hardened Properties of Concrete Mixes

In an effort to provide the most accurate analysis possible, the data obtained were analyzed using several different correlations including their relationship to water content, cementitious materials content, cementitious paste volume, and water/cementitious materials ratio. While some of these values are not directly related to the main focuses of the paper, there can be indirect ties made to each of them. The definition of cementitious paste volume (CPV) is the sum of the volumes of the water, cementitious materials, and air divided by the total volume of the mix.

4.3.1 Effects on Compressive Strength

The compressive strength values obtained through the course of this study are summarized in Appendix F. As can be seen in Figures C-3 thru C-6, compressive strength shows little correlation to any varied properties of the mix other than the W/C ratio. While related directly to the W/C ratio, the water content of the mix has very little bearing on the compressive strength of the mix. Another interesting finding is that the generally accepted fact that adding cement will increase the strength of the mix tends to be disproven by Figure C-4. As shown in this figure, the cementitious materials content of the mixes proved to have little bearing on the compressive strength. The trend tends to be in the upwards direction, but no statistical significance can be found. Figure C-5 also supports the fact that the cementitious materials content has little bearing on the compressive strength. Since cementitious paste volume is directly related to the cementitious materials content of the mix, it can be concluded that neither the CPV nor cement content have a true bearing on the compressive strength of a given mix.

4.3.2 Effects on Chloride Ion Permeability

For the analysis of the permeability of the mixes, the use of the accelerated curing technique was utilized for reporting. Both the 28 day accelerated curing and the 56 day regular curing methods are summarized in Appendix F and reported individually by mix in Appendix G. While the results of the 28 day procedure are reported, the 56 day procedure yields similar results.

As can be seen in Figures C-7 thru C-10, the chloride ion permeability is highly dependent upon the W/C ratio and has a slight correlation to the water content of the mix. The water content of the mix has an effect on the pore chemistry of the mix and would therefore affect the permeability. The cement content of a mix is generally accepted to affect the permeability of the mix. However, there appears to be no correlation whatever with the cement content of the mix, which was unexpected since the chlorides need the paste in order to migrate through hardened concrete. The main factor that affected the permeability of the mix was the W/C ratio. With an r-square value of .802, it can be almost guaranteed that an increase in the W/C ratio will result in a more permeable mix.

4.3.3 Effects on Drying Shrinkage

For the analysis of the shrinkage of the mixes, the 56 day measurements were utilized for reporting due to time restraints. The shrinkage results are summarized in Appendix F while they are reported individually by mix in Appendix H.

As shown in Figures C-11 thru C-14, the drying shrinkage is largely affected by all analyzed properties except the water/cement ratio. Since the drying shrinkage of a mix is caused by the release of excess moisture from the pore spaces of the mix, it would make sense that the shrinkage would be affected by the water content, cement content, and the cementitious paste volume. It is critical that the water and cement be kept to a minimum in any concrete mix in order to obtain low shrinkage values and in turn, a more durable mix.

5.0 Conclusions and Recommendations

5.1 Conclusions

In order to make a more durable mix, it is necessary to ensure that the shrinkage and permeability are kept to a minimum while allowing for the specified strength to be met. In order to control the durability properties of the mix, several facts must be recognized.

- It is possible to meet a strength criteria of 4000 psi with cement contents as low as 460 lb/yd^3 and possibly even lower. The addition of cement to a mix at a constant water/cement ratio will have little bearing on the strength and should not be considered a way to increase the strength.
- The use of supplementary cementitious materials (SCM) is a necessity to control the permeability and add to strength development. The use of SCM will also decrease the cost as opposed to using cement alone.
- The specification of a low water/cement ratio will allow for increased strength and decreased permeability; the W/C ratio should therefore be kept as low as practical.
- The water and cement contents of a mix should be kept as low as practical to control permeability and shrinkage. The cement content should be as low as possible pending its ability to be pumped if required.
- The addition of unaccounted for water to any mix in the field should be discouraged and monitored since this water may have significant derogatory effects on the performance and life of the mix.

5.2 Recommendations

In order to guarantee the production of a durable mix for use in bridge decks, it is recommended that a performance specification be implemented. A performance specification will allow the ready mix industry to take advantage of the advancements made by research projects and product suppliers. Today's admixture producers are able to produce water reducers that allow for low water/cement ratios. The quarries are able to create aggregates to specification as opposed to specifications being written around aggregate gradations. The use of supplementary cementitious materials will allow for better performing, cheaper concrete and is also environmentally friendly since many of the SCM currently used are byproducts of industrial processes.

This research was funded through a project whose main goal was to revamp the TDOT specification for their bridge deck mix. Table D-1 below, shows the current prescriptive specification compared to the proposed performance specification submitted by the University of Tennessee research team. As can be seen in the table, the W/C ratio is kept at a minimum. One of the large changes in the specification is the lowering of the cement content from a minimum of 620 lb/yd^3 to a maximum of 570 lb/yd^3. The gradation of the aggregate is left up to the supplier in an effort to allow for development of a more efficient mix. The use of SCM is opposed to optional required as. The addition of a shrinkage and permeability requirement is a large advancement in assuring the durability of the mix. While the shrinkage specification has turned out to be a bit controversial, it is possible to leave it out if there is adequate quality control on site to ensure that water is not added to the mix. The air content and slump requirements remain the same for freeze thaw durability and workability purposes, respectively.

While the industry may take some time to get used to the new performance specifications, such specifications have the potential to dramatically increase the life of the bridge decks and other concrete structures if applied appropriately. The addition of water to any mix in the field should be discouraged due to the derogatory effects on the durability properties of the mix. If all of the above guidelines are followed in the development of a performance specification and the DOT backs it with sufficient penalties, the implementation of this specification can lead to a dramatic improvement in the life of bridge their bridge decks.

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Appendix A: Chapter 2 Graphs and Figures

Table A-1 SHRP High-Performance Concrete Criteria

Category of HPC	Minimum Compressive Strength	MaximumWater/ Cement Ratio	Minimum Frost Durability Factor
Very early strength (VES)			
Option A (with Type III cement)	2,000 psi in 6 hours	0.40	80%
Option B (with PBC-XT cement)	2,500 psi in 4 hours	0.29	80%
High early strength (HES) (with Type III cement)	5,000 psi in 24 hours	0.35	80%
Very high strength (VHS) (with Type I cement)	10,000 psi in 28 hours	0.35	80%

Table A-2 FHWA Performance Grades in US Units [18]

Performance Characteristic	FHWA HPC Performance Grades			
	1	2	3	4
Freeze-thaw durability[1] (x = relative dynamic modulus of elasticity after 300 cycles)	60% ≤ x < 80%	80% ≤ x		
Scaling Resistance[2] (x = visual rating of the surface after 50 cycles)	x = 4, 5	x = 2, 3	x = 0, 1	
Abrasion resistance[3] (x = avg. depth of wear in inches)	2/25 > x ≥ 1/25	1/25 > x ≥ 1/50	1/50 > x	
Chloride Penetration[4] (x = coulombs)	3000 ≥ x > 2000	2000 ≥ x > 800	800 ≥ x	
Strength[5] (ksi) (x = compressive strength)	6 ≤ x < 8	8 ≤ x < 10	10 ≤ x < 14	x ≥ 14
Elasticity[6] (psi) (x = modulus of elasticity)	4 ≤ x < 6 x10^6	6 ≤ x < 7.5 x10^6	x ≥ 7.5 x10^6	
Free Shrinkage[7] (x = micro-strain)	800 > x ≥ 600	600 > x ≥ 400	400 > x	
Creep[8] (per psi) (x = micro-strain/pressure unit)	0.52 ≥ x > 0.41	0.41 ≥ x > 0.31	0.31 ≥ x > 0.21	0.21 ≥ x

[1] *Test in accordance with AASHTO T 161 (ASTM C 666 Procedure A)*
[2] *Test in accordance with ASTM C 672*
[3] *Test in accordance with ASTM C 944*
[4] *Test in accordance with AASHTO T 277 (ASTM C 1202)*
[5] *Test in accordance with AASHTO T2 (ASTM C 39)*
[6] *Test in accordance with ASTM C 469*
[7] *Test in accordance with ASTM C 157*
[8] *Test in accordance with ASTM C 512*

Appendix B: Chapter 3 Graphs and Figures

Figure B-1: Class F Fly Ash

Table B-1 General Properties of Coarse Aggregate (#57 Limestone)

Properties	Value
Nominal Size (in)	1
Absorption (%)	0.49
SSD Specific Gravity	2.79
Oven-Dry Specific Gravity	2.78
Apparent Specific Gravity	2.82

Table B-2 Sieve Analysis of Coarse Aggregate (#57 Limestone)

	TDOT Specifications		Percent Passing
Sieve Size	Low	High	Rinker Materials (#57)
1"	95	100	100.0
3/4"	--	--	87.7
1/2"	25	60	35.2
3/8"	--	--	14.5
#4	0	10	0.9

Figure B-2 #57 Coarse Aggregate

Table B-3 General Properties of Coarse Aggregate (#7 Limestone)

Properties	Value
Nominal Size (in)	3/4
Absorption (%)	0.35
SSD Specific Gravity	2.84
Oven Dry Specific Gravity	2.83
Apparent Specific Gravity	2.85

Table B-4 Sieve Analysis of Coarse Aggregate (#7 Limestone)

	Percent Passing
Sieve Size	Rinker Materials (#7)
3/4"	100.0
1/2"	89.1
3/8"	54.6
#4	2.0
#8	2.6
#16	1.4
#30	2.3
#50	2.2
#100	2.0
#200	1.1

Figure B-3 #7 Coarse Aggregate

Table B-5 General Properties of Fine Aggregate (Ohio River Valley Sand)

Properties	Value
Nominal Size (in)	3/8
Absorption (%)	0.62
SSD Specific Gravity	2.6
Oven Dry Specific Gravity	2.58
Apparent Specific Gravity	2.63

Table B-6 Sieve Analysis of Fine Aggregate (Ohio River Valley Sand)

	Specifications		Percent Passing
Sieve Size	Low	High	Ingram (N.S.)
3/8"	100	100	100.0
#4	95	100	99.0
#8	--	--	92.0
#16	50	90	78.0
#30	--	--	62.0
#50	5	30	15.0
#100	0	10	1.5
#200	0	5	1.0

Figure B-4 Ohio River Valley Natural Sand used as Fine Aggregate

Table B-7 Material Proportioning Percentages

W/C Ratio		Varied Depending on Mix
Total Cementitious Material Content		Varied Depending on Mix
Cement		75% Total Cementitious Content
Fly Ash		25% Total Cementitious Content
Water		Varied Depending on Mix
Combined Aggregates	#57	36% Total Aggregate Volume
	#7	26% Total Aggregate Volume
	Natural Sand	38% Total Aggregate Volume

Figure B-5 Laboratory Mixer (7.5 ft^3 capacity)

Figure B-6 Specimens After Casting

Figure B-7 Lime Water Bath

Figure B-8 Slump Test in Progress

Figure B-9 Air Content Apparatus

Figure B-10 Compressive Strength Machine After Test

Figure B-11 Vacuum Apparatus

Figure B-12 Close Up of Specimen Ready for Testing

Figure B-13 Chloride Ion Testing Apparatus

Figure B-14 Shrinkage Measurements Being Performed

Appendix C: Chapter 4 Graphs and Figures

Table C-1 Mix Proportions for W/C Ratio of .4

Mix ID		A-1	A-2	A-3	A-4	A-5
W/C Ratio		0.4	0.4	0.4	0.4	0.4
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		184	200	224	248	280
Combined Aggregates (lb/yd^3)	#57	1214	1184	1146	1103	1045
	#7	877	856	828	797	755
	Natural Sand	1218	1189	1161	1117	1059
Air Entrainment (oz/yd^3)		1	1	1.2	1.4	1.6
HRWRA (oz/yd^3)		70	65	61	45	23

Table C-2 Mix Proportions for W/C Ratio of .45

Mix ID		A-6	A-7	A-8	A-9	A-10
W/C Ratio		0.45	0.45	0.45	0.45	0.45
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		207	225	252	279	315
Combined Aggregates (lb/yd^3)	#57	1196	1165	1119	1073	1011
	#7	864	841	808	775	730
	Natural Sand	1211	1180	1133	1086	1024
Air Entrainment (oz/yd^3)		1	1	1.1	1.2	1.5
HRWRA (oz/yd^3)		52	45	41	38.6	9

Table C-3 Mix Proportions for W/C Ratio of .50

Mix ID		A-11	A-12	A-13	A-14	A-15
W/C Ratio		0.5	0.5	0.5	0.5	0.5
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		230	250	280	310	350
Combined Aggregates (lb/yd^3)	#57	1173	1141	1091	1042	977
	#7	847	824	788	753	705
	Natural Sand	1189	1155	1105	1056	989
Air Entrainment (oz/yd^3)		1	1	1.2	1.3	1.7
HRWRA (oz/yd^3)		49	24	16	11	0

Table C-4 Summary of Fresh Properties by Mix

Mix	W/C Ratio	Cement Content	Slump (in)	Air Content (%)	Unit Weight (lb/ft^3)	Temperature (F)
A-1	0.4	460	7.25	5.25	149	64
A-2	0.4	500	8	6.5	147	64
A-3	0.4	560	8.5	7	145	64
A-4	0.4	620	8.75	5	147	67
A-5	0.4	700	6.5	4	147	59
A-6	0.45	460	7	6	147	76
A-7	0.45	500	6.5	6	146	76
A-8	0.45	560	8	6	144	80
A-9	0.45	620	7.5	4.75	147	80
A-10	0.45	700	6.5	6	146	55
A-11	0.5	460	7.5	7	145	76
A-12	0.5	500	7	4.25	148	71
A-13	0.5	560	7.5	5	146	73
A-14	0.5	620	8	4.5	145	68
A-15	0.5	700	8.5	4.5	146	59

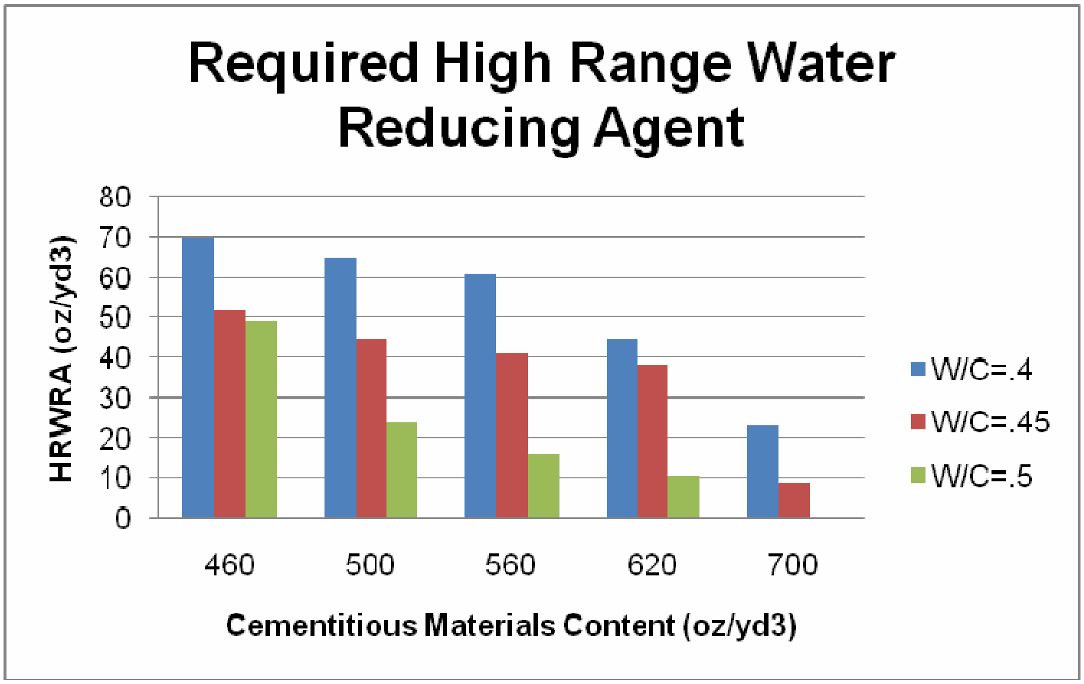

Figure C-1 Required High Range Water Reducing Agent

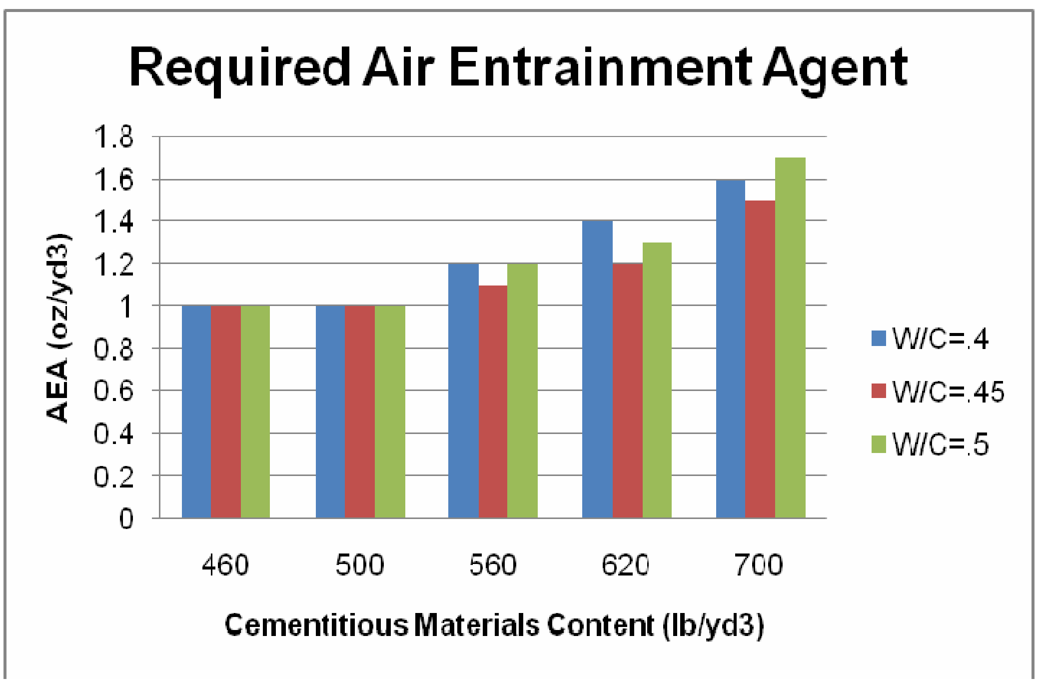

Figure C-2 Required Air Entrainment Agent

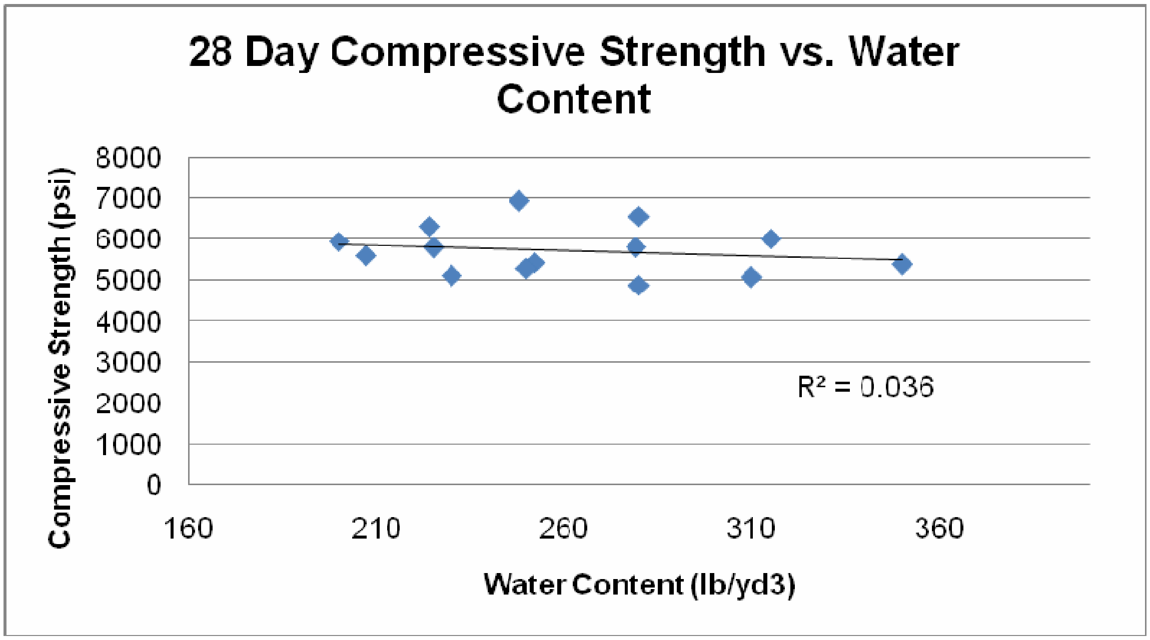

Figure C-3 28 Day Compressive Strength vs. Water Content

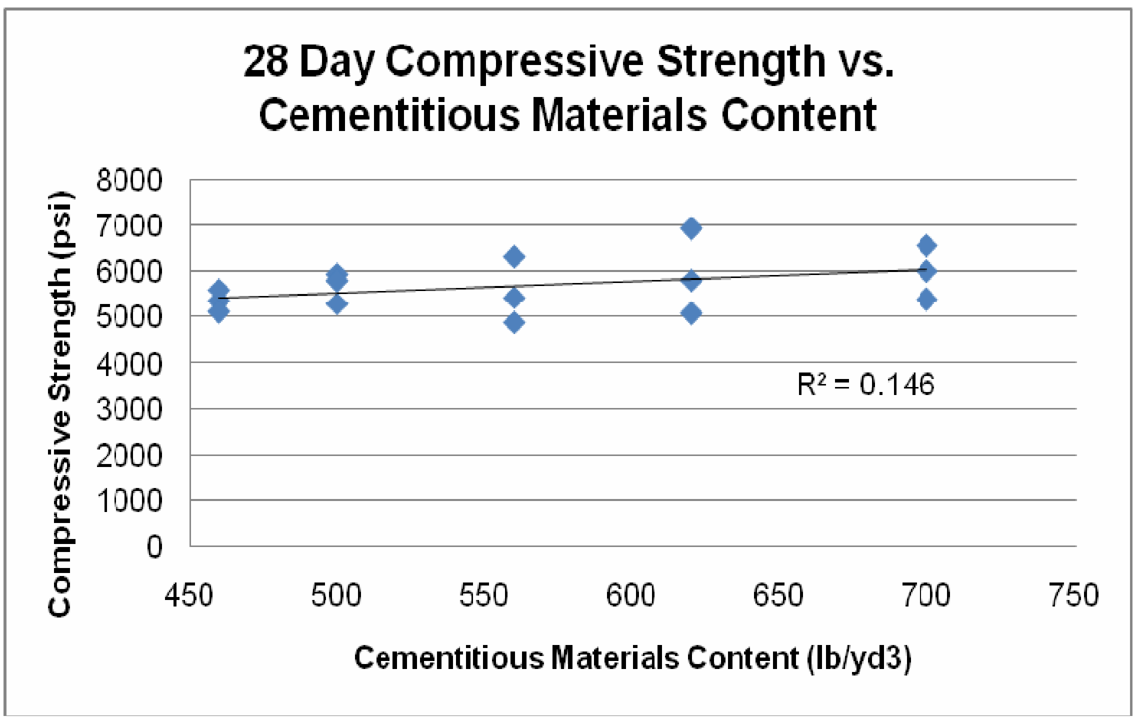

Figure C-4 28 Day Compressive Strength vs. Cementitious Materials Content

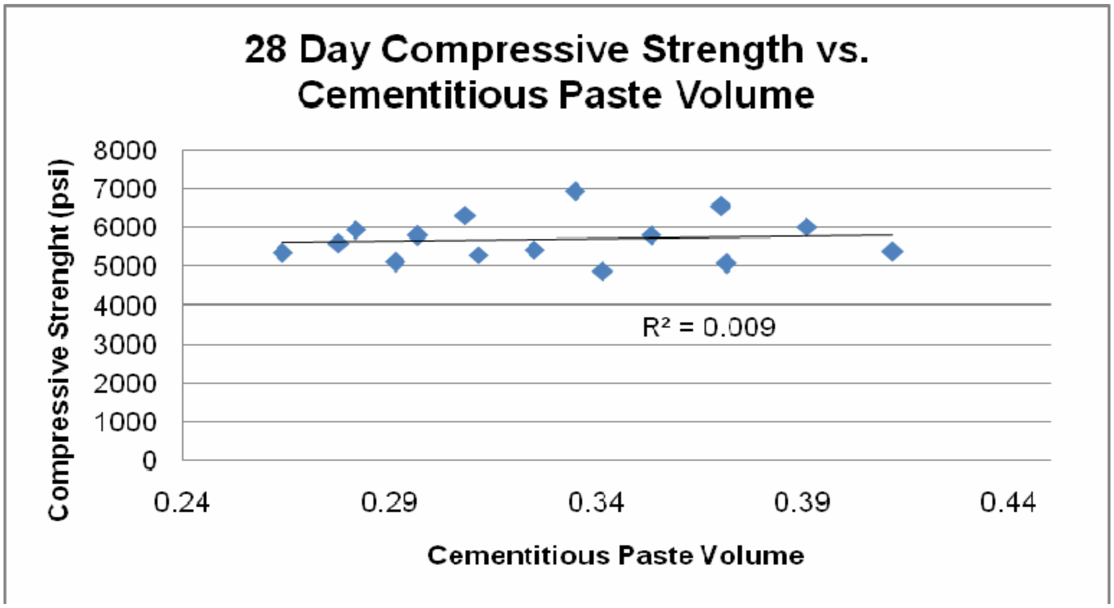

Figure C-5 28 Day Compressive Strength vs. Cementitious Paste Volume

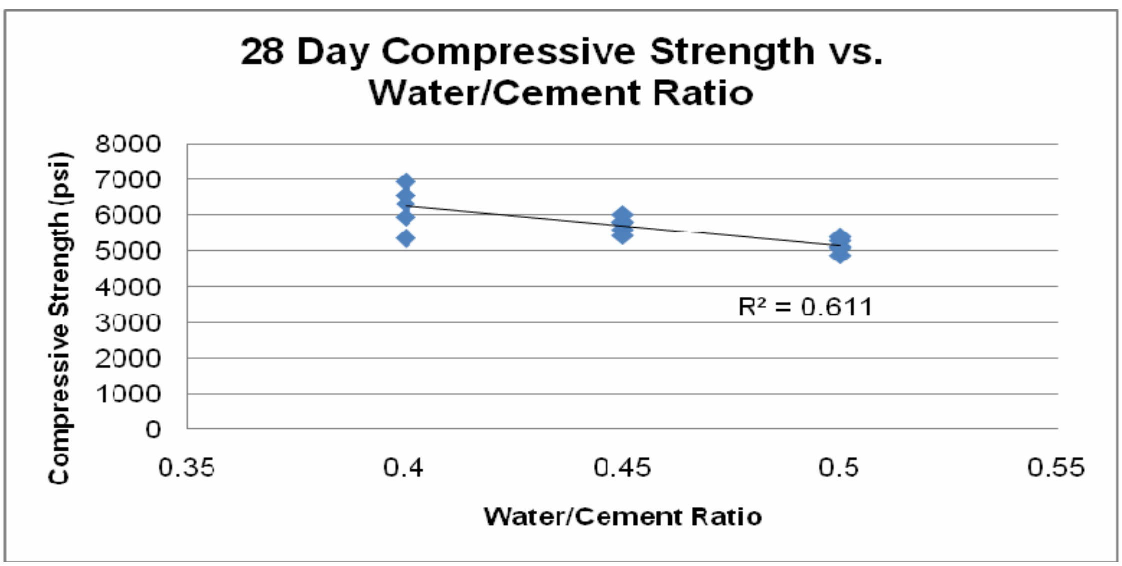

Figure C-6 28 Day Compressive Strength vs. W/C Ratio

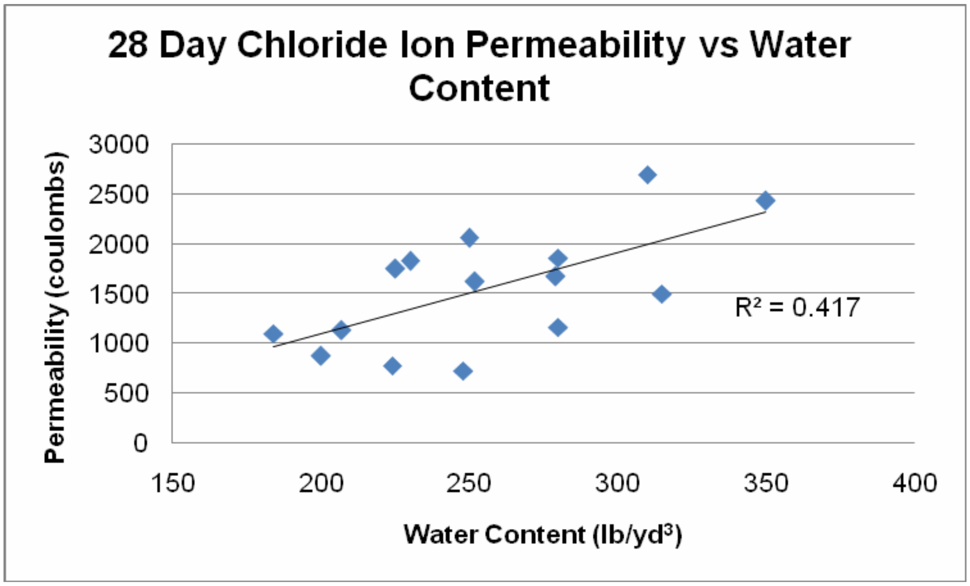

Figure C-7 28 Day Chloide Ion Permeability vs. Water Content

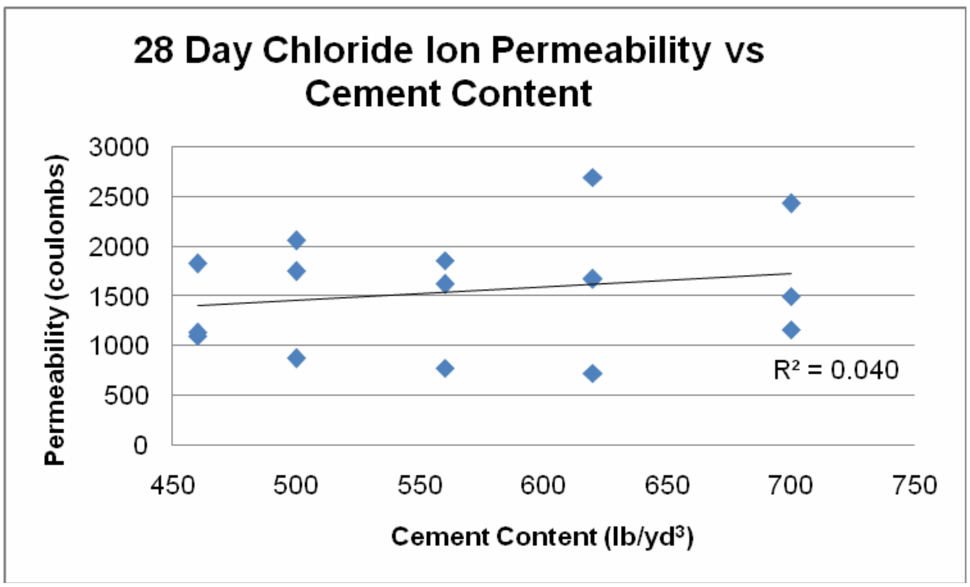

Figure C-8 28 Day Chloride Ion Permeabilty vs. Cement Content

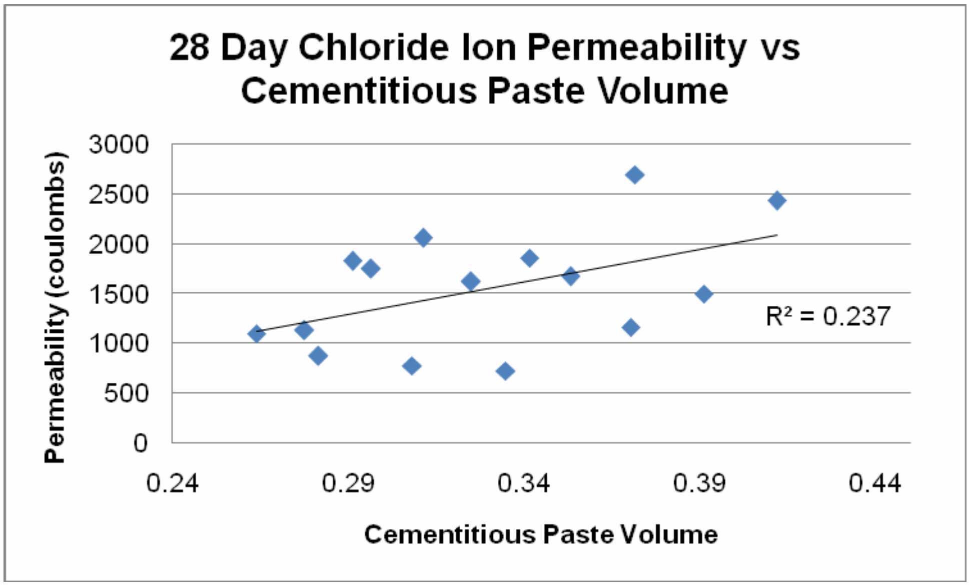

Figure C-9 28 Day Chloride Ion Permeability vs. Cemetitious Paste Volume

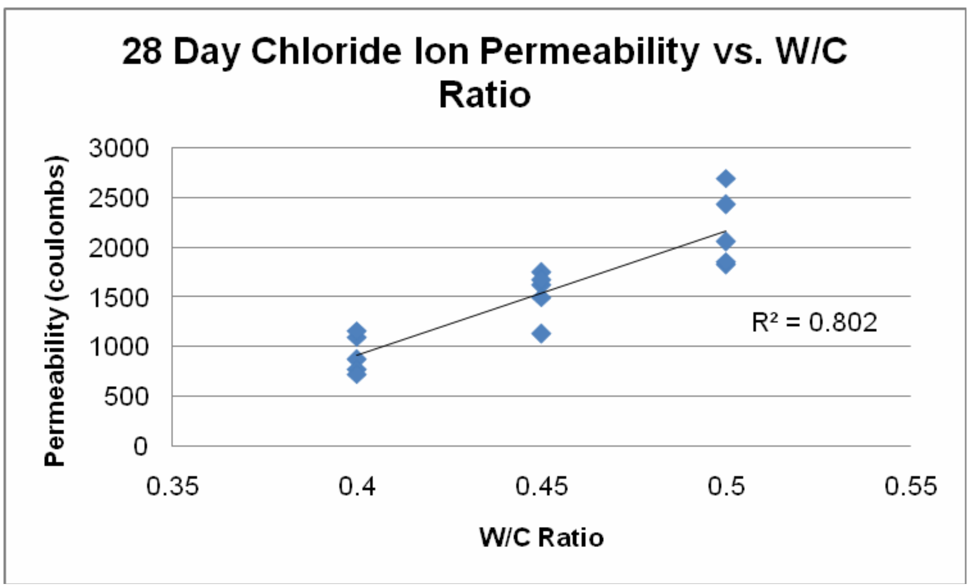

Figure C-10 28 Day Chloride Ion Permeability vs. W/C Ratio

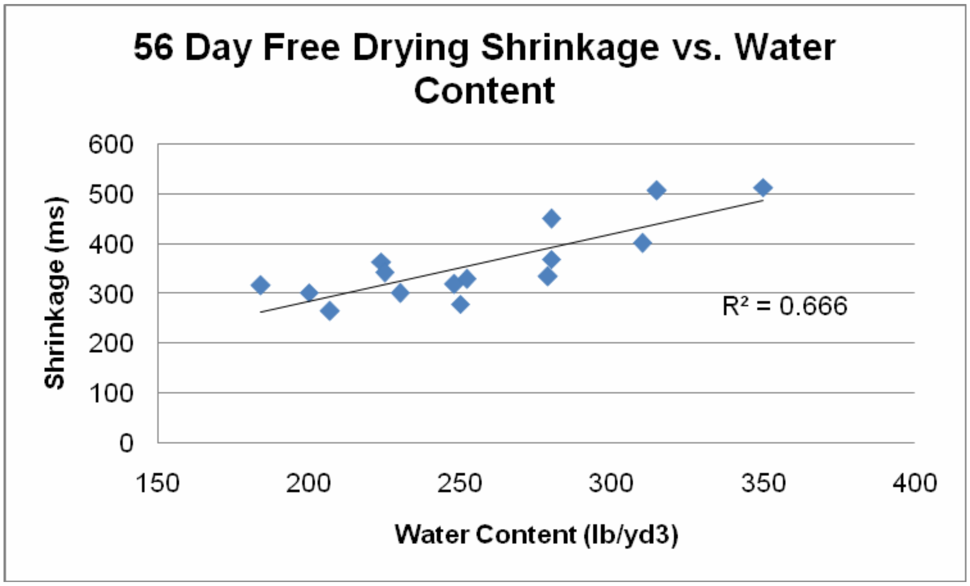

Table C-11 56 Day Free Drying Shrinkage vs. Water Content

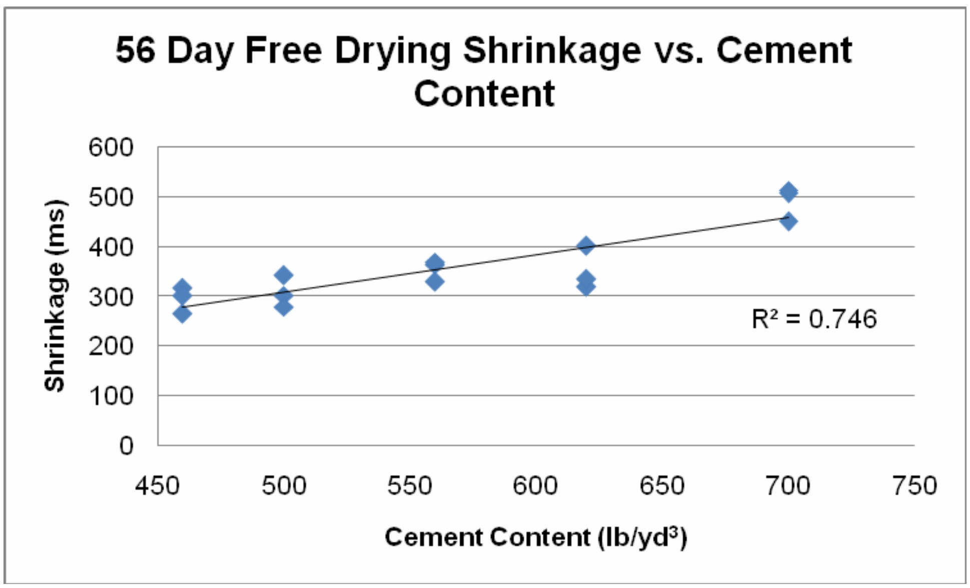

Table C-12 56 Day Free Drying Shrinkage vs. Cement Content

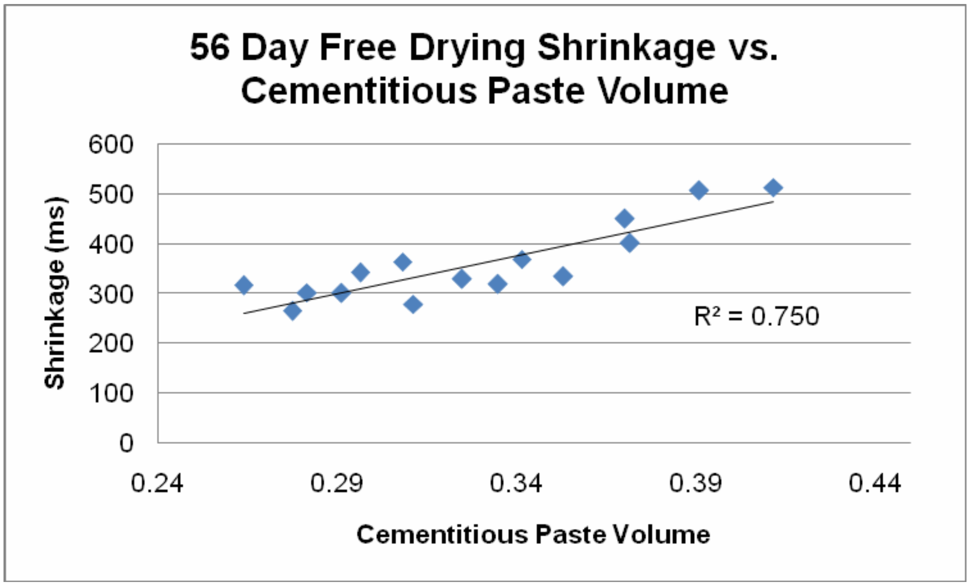

Table C-13 56 Day Free Drying Shrinkage vs. Cementitious Paste Volume

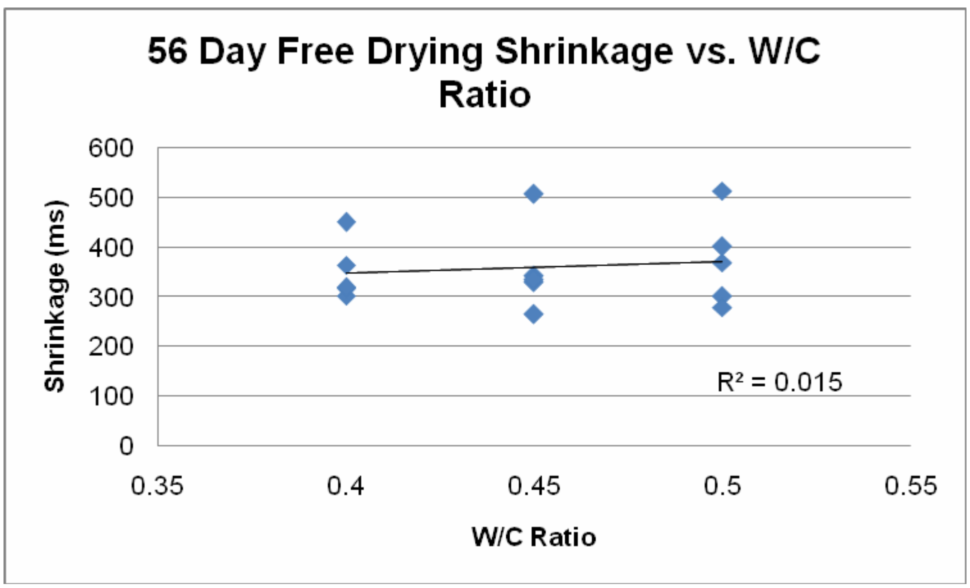

Table C-14 56 Day Free Drying Shrinkage vs. W/C Ratio

Appendix D: Chapter 5 Graphs and Figures

Table D-1 Current and Proposed Specifications for TDOT HPC Bridge Deck Mix

Proposed Specification for HPC Bridge Deck Mix		
Specification Type	Prescriptive	Performance
Status	Current	Proposed
Max W/CM Ratio	0.4	0.4
Total Cementitious Material	>620 lb/yd3	<570
Supplementary Cementitious Material	Optional	Required
28 Day Strength	>4000 psi	>4000 psi
Rapid Chloride Permeability	---	<1000 Coulombs
56 Day Shrinkage	---	<400 microstrains
Air Content	4%-8%	4%-8%
Slump	4"-8"	4"-8"

Appendix E: Physical and Chemical Properties of Cementing Materials

Table E-1: Material Composition of Type I Portland Cement

[Buzzi Unicem USA, INC., Signal Mountain Plant]

Composition	Percent (mass)
Silicon Dioxide	20.3
Aluminum Dioxide	4.9
Ferric Oxide	3.6
Calcium Oxide	63.3
Magnesium Oxide	3.1
Sulfur Trioxide	2.9
Loss in Ignition	1.4
Insoluble Residue	0.21
Total	**100.0**

Table E-2: Chemical Properties of Class F Fly Ash

	Element	Typical Range of Concentration
1	Silica (SiO_2)	41 - 58%
	Amorphous	42 - 53.5
	Crysalline	3.0 - 7.0
2	Alumina (Al_2O_3)	18.1 - 28.6%
3	Iron oxide (Fe_2O_3)	9.9 - 26%
4	Calcium oxide (CaO)	0.8 - 4.5%
5	Magnesium oxide (MgO)	0.7 - 1.4%
6	Sodium oxide (Na_2O)	0.2 - 0.6%
7	Potassium oxide (K_2O)	1.5 - 3.3%
8	Titanium dioxide (TiO_2)	1.0 - 1.9%
9	Sulfur trioxide (SO_3)	0.1 - 2.2%
10	Phosphorus pentoxide (P_2O_5)	nil - 1.5%
11	Loss on ignition	1.9 - 8.0%
12	pH	4.1 - 9.5

Appendix F: Summary Tables

Table F-1: Mix ID and Proportions by W/C Ratio

Mix ID		A-1	A-2	A-3	A-4	A-5
W/C Ratio		0.4	0.4	0.4	0.4	0.4
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		184	200	224	248	280
Combined Aggregates (lb/yd^3)	#57	1214	1184	1146	1103	1045
	#7	877	856	828	797	755
	Ingram Sand	1218	1189	1161	1117	1059
Air Entrainment (oz/yd^3)		1	1	1.5	1	1.4
HRWRA (oz/yd^3)		70	65	61	61	23

Mix ID		A-6	A-7	A-8	A-9	A-10
W/C Ratio		0.45	0.45	0.45	0.45	0.45
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		207	225	252	279	315
Combined Aggregates (lb/yd^3)	#57	1196	1165	1119	1073	1011
	#7	864	841	808	775	730
	Ingram Sand	1211	1180	1133	1086	1024
Air Entrainment (oz/yd^3)		1	1	1	1.2	1.5
HRWRA (oz/yd^3)		52	45	41	38.6	9

Mix ID		A-11	A-12	A-13	A-14	A-15
W/C Ratio		0.5	0.5	0.5	0.5	0.5
Total Cementitious Material Content (lb/yd^3)		460	500	560	620	700
Cement (lb/yd^3)		345	375	420	465	525
Fly Ash (lb/yd^3)		115	125	140	155	175
Water (lb/yd^3)		230	250	280	310	350
Combined Aggregates (lb/yd^3)	#57	1173	1141	1091	1042	977
	#7	847	824	788	753	705
	Ingram Sand	1189	1155	1105	1056	989
Air Entrainment (oz/yd^3)		1.2	0.8	1.6	4.5	1.7
HRWRA (oz/yd^3)		49	24	16	11	0

Table F-2: Fresh Properties Summary Table

Mix	Slump (in)	Air Content (%)	Unit Weight (lb/yd^3)	Temperature (F)
A-1	7.25	5.25	4014	64
A-2	8	6.5	3972	64
A-3	8.5	7	3921	64
A-4	8.75	5	3981	67
A-5	6.5	4	3977	59
A-6	7	6	3967	76
A-7	6.5	6	3954	76
A-8	8	6	3897	80
A-9	7.5	4.75	3979	80
A-10	6.5	6	3955	55
A-11	7.5	7	3903	76
A-12	7	4.25	3987	71
A-13	7.5	5	3942	73
A-14	8	4.5	3905	68
A-15	8.5	4.5	3953	59

Table F-3: Compressive Strength Summary Table

Mix	W/C Ratio	Cement Content (lb/yd^3)	Compressive Strength (psi)			
			Specimen			
			1	2	3	Average
A-1	0.4	460	5356	5349	5348	5351
A-2	0.4	500	5817	5953	6100	5957
A-3	0.4	560	6206	6209	6601	6339
A-4	0.4	620	6943	7202	6692	6946
A-5	0.4	700	6774	6540	6404	6573
A-6	0.45	460	5519	5761	5550	5610
A-7	0.45	500	5846	5856	5688	5797
A-8	0.45	560	5405	5400	5540	5448
A-9	0.45	620	5732	5783	5952	5822
A-10	0.45	700	5964	5885	6230	6026
A-11	0.5	460	5013	5126	5184	5108
A-12	0.5	500	5345	5221	5330	5299
A-13	0.5	560	4979	4965	4732	4892
A-14	0.5	620	5113	5057	5076	5082
A-15	0.5	700	5379	5685	5133	5399

Table F-4: Chloride Ion Penetration Summary Table

Mix	W/C Ratio	Cement Content (lb/yd^3)	28 Day Permeability (Coulombs)		
			Specimen		
			1	2	Average
A-1	0.4	460	1165	1030	1098
A-2	0.4	500	789	959	874
A-3	0.4	560	804	752	778
A-4	0.4	620	705	747	726
A-5	0.4	700	1132	1197	1165
A-6	0.45	460	1182	1090	1136
A-7	0.45	500	1997	1508	1753
A-8	0.45	560	1636	1603	1620
A-9	0.45	620	1651	1688	1670
A-10	0.45	700	1494	1503	1499
A-11	0.5	460	1841	1818	1830
A-12	0.5	500	2131	1983	2057
A-13	0.5	560	1867	1855	1861
A-14	0.5	620	2589	2805	2697
A-15	0.5	700	2259	2611	2435

Table F-5: Drying Shrinkage Summary Table

Mix	W/C Ratio	Cement Content (lb/yd^3)	56 Day Drying Shrinkage (microstrains)		
			Specimen		
			1	2	Average
A-1	0.4	460	327	307	317
A-2	0.4	500	310	293	302
A-3	0.4	560	320	407	364
A-4	0.4	620	320	317	319
A-5	0.4	700	454	447	451
A-6	0.45	460	247	283	265
A-7	0.45	500	344	340	342
A-8	0.45	560	330	327	329
A-9	0.45	620	344	323	334
A-10	0.45	700	490	524	507
A-11	0.5	460	293	310	302
A-12	0.5	500	280	277	279
A-13	0.5	560	374	364	369
A-14	0.5	620	424	380	402
A-15	0.5	700	527	500	514

Appendix G: Individual Mix Permeability Data

Table G-1: Mix A-1 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	48	2	43	2
30	49	87	43	77
60	50	176	44	157
90	51	267	45	237
120	52	360	46	319
150	53	456	47	403
180	54	553	47	489
210	54	651	48	576
240	55	751	49	664
270	56	852	50	754
300	57	954	50	845
330	58	1058	51	937
360	59	1165	52	1030

Table G-2: Mix A-1 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	60	3	59	3
30	62	110	62	109
60	65	225	64	223
90	68	345	66	342
120	70	470	67	463
150	72	600	71	587
180	75	733	73	717
210	76	870	74	849
240	78	1010	75	985
270	79	1153	76	1122
300	80	1297	77	1261
330	81	1444	78	1402
360	82	1591	78	1543

Table G-3: Mix A-2 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	34	2	40	2
30	34	62	41	73
60	34	124	42	148
90	35	187	42	224
120	35	251	43	302
150	36	316	43	380
180	36	382	44	460
210	37	448	44	541
240	37	515	45	622
270	37	582	46	705
300	38	651	46	789
330	38	719	47	873
360	38	789	47	959

Table G-4: Mix A-2 56 Day Chloride Ion Permeability

	Specimen 1		**Specimen 2**	
Time	**Current**		**Current**	
(min)	**(mA)**	**Coulombs**	**(mA)**	**Coulombs**
1	50	3	46	2
30	52	92	50	89
60	54	188	53	183
90	55	287	55	280
120	57	389	56	381
150	59	494	55	483
180	60	601	56	584
210	61	710	56	688
240	61	820	58	792
270	62	932	58	896
300	62	1045	58	1001
330	63	1159	58	1106
360	64	1274	58	1211

Table G-5: Mix A-3 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	33	2	38	2
30	33	59	35	65
60	33	120	34	127
90	34	180	33	187
120	35	242	33	248
150	36	306	34	309
180	37	372	34	371
210	38	440	34	433
240	39	510	35	496
270	39	581	35	559
300	40	654	35	623
330	41	728	35	687
360	42	804	35	752

Table G-6: Mix A-3 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	44	2	41	2
30	41	76	40	73
60	41	151	41	147
90	41	226	41	222
120	42	302	41	297
150	43	379	41	371
180	43	458	42	447
210	44	538	43	523
240	45	619	43	602
270	45	700	44	681
300	45	782	44	761
330	46	865	44	841
360	46	949	44	922

Table G-7: Mix A-4 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	32	2	34	2
30	31	57	33	61
60	31	113	32	121
90	31	170	32	180
120	31	226	33	240
150	32	283	34	301
180	32	342	34	363
210	33	401	34	425
240	33	460	35	488
270	33	521	35	552
300	33	582	36	617
330	34	643	36	682
360	34	705	36	747

Table G-8: Mix A-4 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	49	3	44	2
30	46	84	41	76
60	46	167	41	151
90	46	250	41	226
120	47	335	42	301
150	48	421	42	377
180	48	508	42	453
210	49	596	42	529
240	49	685	42	606
270	50	774	43	683
300	50	865	43	761
330	50	956	43	839
360	50	1047	43	916

Table G-9: Mix A-5 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	55	3	59	3
30	51	95	54	100
60	51	187	53	197
90	51	280	53	293
120	51	372	54	390
150	51	465	54	488
180	52	559	55	587
210	52	653	55	687
240	52	748	56	788
270	53	843	56	889
300	53	939	56	991
330	53	1035	57	1093
360	53	1132	57	1197

Table G-10: Mix A-5 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	131	8	120	7
30	132	234	124	219
60	140	481	133	451
90	147	740	140	698
120	153	1012	147	957
150	158	1293	152	1227
180	164	1584	157	1507
210	168	1883	162	1796
240	171	2190	167	2093
270	175	2504	171	2397
300	180	2824	174	2707
330	183	3151	176	3023
360	185	3484	179	3345

Table G-11: Mix A-6 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	101	6	111	6
30	108	191	115	203
60	114	392	122	416
90	118	603	129	643
120	124	823	134	880
150	129	1051	138	1125
180	130	1284	141	1375
210	132	1522	140	1630
240	134	1763	143	1887
270	136	2009	145	2148
300	139	2256	146	2411
330	140	2508	148	2676
360	142	2762	148	2944

Table G-12: Mix A-6 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	Unreadable		Unreadable	
30	Unreadable		Unreadable	
60	115	397	121	411
90	119	608	127	636
120	124	829	131	870
150	129	1059	136	1112
180	132	1296	138	1358
210	134	1537	141	1608
240	137	1782	140	1861
270	137	2028	142	2116
300	138	2276	141	2371
330	139	2527	142	2627
360	143	2782	142	2883

Table G-13: Mix A-7 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	82	4	84	5
30	84	149	89	155
60	88	305	92	319
90	95	470	95	488
120	97	644	99	663
150	94	816	102	845
180	96	988	104	1030
210	93	1159	68	1191
240	93	1328	36	1285
270	93	1496	32	1346
300	92	1663	30	1403
330	93	1831	29	1456
360	91	1997	28	1508

Table G-14: Mix A-7 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	62	3	65	3
30	62	112	65	118
60	62	224	66	235
90	64	338	68	356
120	65	455	70	480
150	66	573	71	608
180	67	694	73	739
210	68	817	75	873
240	69	941	76	1009
270	70	1067	78	1148
300	71	1194	79	1290
330	71	1323	80	1434
360	72	1453	81	1579

Table G-15: Mix A-8 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	87	5	97	5
30	89	157	99	177
60	94	323	104	361
90	100	499	109	553
120	105	684	114	755
150	109	877	118	965
180	113	1078	123	1183
210	117	1287	128	1409
240	121	1503	132	1643
270	125	1725	136	1885
300	128	1954	140	2135
330	131	2188	144	2391
360	134	2428	147	2653

Table G-16: Mix A-8 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	107	6	102	6
30	112	197	104	185
60	121	407	111	380
90	132	636	119	588
120	139	881	126	810
150	146	1140	133	1044
180	154	1412	140	1290
210	162	1697	149	1551
240	170	1998	157	1827
270	181	2314	164	2117
300	190	2649	169	2420
330	197	2998	175	2732
360	207	3361	181	3054

Table G-17: Mix A-9 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	68	4	69	4
30	66	121	69	124
60	70	245	71	251
90	71	372	74	382
120	72	503	76	517
150	74	636	77	655
180	76	773	79	796
210	77	914	80	940
240	79	1058	81	1086
270	81	1203	82	1234
300	83	1350	83	1384
330	83	1500	84	1535
360	84	1651	85	1688

Table G-18: Mix A-9 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	79	4	83	5
30	78	140	84	151
60	81	285	87	306
90	84	435	91	468
120	87	590	94	635
150	89	749	97	808
180	91	912	99	984
210	93	1079	100	1164
240	94	1249	102	1347
270	96	1421	103	1532
300	97	1595	104	1720
330	98	1772	105	1909
360	99	1951	106	2100

Table G-19: Mix A-10 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	67	4	67	4
30	63	117	63	117
60	64	232	64	233
90	65	348	65	350
120	54	390	68	470
150	68	590	69	594
180	69	714	69	719
210	70	840	70	846
240	71	968	71	975
270	72	1097	72	1105
300	73	1228	73	1237
330	73	1361	74	1369
360	74	1494	74	1503

Table G-20: Mix A-10 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	138	8	147	9
30	143	251	157	273
60	153	519	170	569
90	160	801	182	886
120	168	1098	191	1223
150	174	1407	200	1576
180	179	1726	209	1945
210	184	2054	217	2328
240	188	2390	224	2726
270	192	2734	232	3138
300	197	3085	241	3565
330	200	3443	250	4008
360	204	3807	257	4466

Table G-21: Mix A-11 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	72	4	71	4
30	72	130	71	129
60	75	262	73	260
90	78	401	78	396
120	79	544	80	540
150	84	693	82	687
180	86	846	85	837
210	88	1003	87	993
240	89	1164	89	1152
270	90	1327	91	1315
300	94	1494	92	1479
330	96	1666	93	1647
360	98	1841	95	1818

Table G-22: Mix A-11 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	65	3	69	4
30	65	117	72	127
60	67	235	74	259
90	69	758	79	398
120	72	486	81	543
150	74	617	83	693
180	75	752	86	847
210	77	891	88	1006
240	79	1032	91	1168
270	81	1178	92	1333
300	83	1326	94	1503
330	85	1478	97	1676
360	86	1633	98	1852

Table G-23: Mix A-12 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	77	4	68	4
30				
60	84	288	44	161
90				
120	91	604	77	514
150				
180	98	948	84	804
210				
240	106	1318	96	1125
270				
300	113	1713	118	1509
330				
360	118	2131	54	1102

Table G-24: Mix A-12 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	100	6	104	6
30	109	188	109	192
60	117	392	119	398
90	125	611	127	621
120	133	845	136	858
150	140	1091	141	1107
180	145	1348	147	1367
210	149	1613	151	1636
240	152	1885	155	1912
270	156	2163	158	2193
300	159	2447	161	2480
330	161	2735	163	2772
360	163	3028	164	3068

Table G-25: Mix A-13 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	73	4	69	4
30	75	133	72	128
60	77	271	74	259
90	80	414	78	398
120	83	562	81	543
150	85	714	84	692
180	87	870	87	847
210	89	1029	89	1006
240	91	1192	91	1169
270	92	1358	94	1336
300	93	1526	96	1506
330	94	1695	97	1680
360	95	1867	98	1855

Table G-26: Mix A-13 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time (min)	Current (mA)	Coulombs	Current (mA)	Coulombs
1	112	6	118	7
30	114	203	123	215
60	122	415	132	446
90	129	640	141	693
120	134	878	148	953
150	141	1126	155	1226
180	146	1384	161	1511
210	151	1652	166	1806
240	155	1928	171	2111
270	157	2211	175	2423
300	161	2498	177	2741
330	162	2789	179	3064
360	166	3085	182	3391

Table G-27: Mix A-14 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	94	5	94	5
30	97	172	97	172
60	102	352	102	352
90	108	543	108	543
120	114	743	121	767
150	118	952	127	990
180	122	1168	130	1222
210	126	1392	138	1465
240	129	1622	143	1718
270	132	1858	147	1979
300	134	2099	151	2248
330	136	2343	156	2524
360	137	2589	158	2805

Table G-28: Mix A-14 56 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	135	8	134	8
30	148	254	148	254
60	161	533	163	534
90	176	837	178	842
120	186	1164	191	1175
150	198	1510	202	1529
180	207	1875	211	1901
210	215	2255	220	2290
240	224	2651	229	2696
270	231	3059	238	3116
300	235	3481	248	3552
330	244	3915	261	4011
360	248	4359	279	4499

Table G-29: Mix A-15 28 Day Chloride Ion Permeability

	Specimen 1		Specimen 2	
Time	Current		Current	
(min)	(mA)	Coulombs	(mA)	Coulombs
1	79	4	85	5
30	84	148	92	161
60	87	303	98	331
90	92	466	104	514
120	96	637	110	707
150	102	816	115	911
180	105	1003	121	1125
210	108	1196	127	1349
240	112	1396	131	1583
270	116	1602	137	1826
300	119	1815	143	2079
330	123	2034	147	2341
360	126	2259	152	2611

Table G-30: Mix A-15 56 Day Chloride Ion Permeability

Not Reported

Appendix H: Individual Mix Shrinkage Data

Table H-1: Mix A-1 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-1			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	67	63	65
2	87	70	78
3	87	73	80
4	87	67	77
5	87	73	80
6	93	80	87
7	93	87	90
14	173	153	163
21	187	170	178
28	277	230	253
56	327	307	317
112	374	323	349

Table H-2: Mix A-2 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-2			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	70	67	68
2	90	77	83
3	90	77	83
4	83	73	78
5	87	77	82
6	93	83	88
7	100	90	95
14	187	170	178
21	203	187	195
28	267	257	262
56	310	293	302
112	360	347	354

Table H-3: Mix A-3 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-3			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	43	53	48
2	60	80	70
3	73	107	90
4	90	137	113
5	110	157	133
6	130	180	155
7	150	207	178
14	183	243	213
21	253	323	288
28	263	337	300
56	320	407	364
112	380	474	427

Table H-4: Mix A-4 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-4			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	43	33	38
2	57	53	55
3	80	73	77
4	100	93	97
5	127	117	122
6	133	127	130
7	143	140	142
14	213	207	210
21	243	237	240
28	263	260	262
56	320	317	318
112	404	380	392

Table H-5: Mix A-5 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-5			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	63	60	62
2	103	97	100
3	130	123	127
4	150	143	147
5	163	157	160
6	160	157	158
7	200	190	195
14	223	220	222
21	344	320	332
28	384	377	380
56	454	447	450
112	Not Reported		

Table H-6: Mix A-6 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-6			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	57	60	58
2	73	73	73
3	87	83	85
4	103	93	98
5	110	100	105
6	117	110	113
7	117	123	120
14	163	183	173
21	177	207	192
28	203	233	218
56	247	283	265
112	360	404	382

Table H-7: Mix A-7 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-7			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	67	60	63
2	87	77	82
3	100	93	97
4	113	110	112
5	130	127	128
6	140	140	140
7	147	150	148
14	193	223	208
21	230	230	230
28	280	260	270
56	344	340	342
112	384	377	380

Table H-8: Mix A-8 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-8			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	70	60	65
2	70	70	70
3	97	97	97
4	110	107	108
5	117	117	117
6	123	123	123
7	130	130	130
14	187	177	182
21	220	213	217
28	230	237	233
56	330	327	328
112	464	454	459

Table H-9: Mix A-9 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-9			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	60	53	57
2	83	70	77
3	97	87	92
4	107	100	103
5	113	107	110
6	137	127	132
7	130	120	125
14	187	167	177
21	220	203	212
28	270	257	263
56	344	323	334
112	424	390	407

Table H-10: Mix A-10 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-10			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	63	67	65
2	107	107	107
3	133	127	130
4	153	143	148
5	167	157	162
6	160	170	165
7	203	220	212
14	240	257	248
21	357	364	360
28	414	454	434
56	490	524	507
112	Not Reported		

Table H-11: Mix A-11 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-11			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	60	47	53
2	60	53	57
3	67	67	67
4	80	80	80
5	93	90	92
6	103	100	102
7	110	107	108
14	150	147	148
21	177	183	180
28	200	227	213
56	293	310	302
112	394	390	392

Table H-12: Mix A-12 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-12			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	50	40	45
2	63	50	57
3	77	60	68
4	83	70	77
5	90	77	83
6	100	97	98
7	103	100	102
14	147	143	145
21	187	183	185
28	210	203	207
56	280	277	278
112	414	410	412

Table H-13: Mix A-13 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-13			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	57	57	57
2	53	60	57
3	93	97	95
4	93	90	92
5	113	110	112
6	133	127	130
7	150	137	143
14	160	150	155
21	207	203	205
28	237	233	235
56	374	364	369
112	404	387	395

Table H-14: Mix A-14 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-14			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	80	77	78
2	87	97	92
3	107	110	108
4	123	120	122
5	137	130	133
6	147	137	142
7	153	143	148
14	220	197	208
21	267	240	253
28	307	270	288
56	424	380	402
112	554	554	554

Table H-15: Mix A-15 Drying Shrinkage Measurements

Shrinkage Calculations Mix A-15			
Time (day)	Specimen 1	Specimen 2	Average
0	0	0	0
1	47	43	45
2	97	93	95
3	143	143	143
4	170	170	170
5	183	183	183
6	197	193	195
7	210	203	207
14	290	280	285
21	384	370	377
28	470	450	460
56	527	500	514
112	Not Reported		

VITA

Andrew Tinsley was born in 1983 to Tom and Denice Tinsley in Knoxville, TN. He lived in several locations after being born, but wound up back in Knoxville at the age of four. He attended Karns from k-12 and graduated high school in December of 2001. His father, who was a large inspiration to his academic career, met his untimely death in 1994. His mother remarried to Willis Freeman a few years later. At this point, he began his college career at Pellissippi State Technical Community College with the intent of transferring to the University of Tennessee to obtain his B.S. in Civil Engineering. After obtaining his B.S., he began pursuing his M.S. degree and plans to follow with his Ph.D. After graduation, he plans to pursue a career in consulting and litigation support.

Andrew has been active in his community for a number of years. He began in the cub scouts which eventually led to the boy scouts where he received the rank of Eagle Scout. Once in college, he became active with the local volunteer fire department. Andrew was recently promoted to lieutenant at the main station and will continue to serve there for as long as he is able. He married in 2006 to Amanda and they currently reside in the community of Karns in Knox County. He has many hobbies including fishing, hunting, boating, golfing, and the fire department.