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Bridge Deck Research at The University of Tennessee: A Summary Thesis

Lindsey Brooke Phelps
University of Tennessee, Knoxville, lphelps6@vols.utk.edu

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I am submitting herewith a thesis written by Lindsey Brooke Phelps entitled "Bridge Deck Research at The University of Tennessee: A Summary Thesis." 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:

Z. John Ma, Timothy Truster

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Bridge Deck Research at The University of Tennessee: A Summary Thesis

A Thesis Presented for the

Master of Science

Degree

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Lindsey Brooke Phelps

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Dedication

To my husband

Eric Phelps

and my parents

Jerry and Pauletta Gadberry

Acknowledgements

I would like to express my deepest gratitude to Dr. Edwin Burdette for his support throughout my time at the University of Tennessee. His door was always open when I had any kind of problem. He truly went above and beyond to help me with this thesis.

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Abstract

Currently, there has been no compilation of all the research the University of Tennessee has completed on chloride ion penetration in concrete bridge decks. The following thesis is a brief summary of the work that has been completed under Dr. Edwin Burdette's direction over the last six years along with some additional literature review. The testing consisted of Surface Resistivity and Rapid Chloride Ion Penetration testing. This testing showed that there is, in fact a correlation between the two test methods, though SR testing is much easier to conduct. Considerable testing was completed on bridge decks throughout the state of Tennessee, showing that chloride ion penetration is moderately high in bridge decks across the state. It was found that using supplementary cementitious materials such as ground granulated blast furnace slag along with fly ash was beneficial to the SR and RCP results. Testing was also completed on lightweight aggregate concrete bridge decks which indicated that lightweight aggregate concrete can resist chloride ion penetration at about the same levels as normal weight concrete.

Table of Contents

List of Tables

List of Figures

Chapter 1. Purpose and Scope of this Thesis

The purpose of this thesis was to bring together in summary the results of research on bridge decks conducted at The University of Tennessee (UT) between 2010 and 2016. While this thesis contains no new experimental data, considerable effort was made to glean new information from the research data available and to identify variables not presently considered which might have affected the test results. The only new information consists of literature reviews and summaries on related topics which are included in Chapter 2. The rest of the thesis is devoted to presenting the results already obtained in a way that emphasizes the important and potentially useful findings in an easily accessible way.

The work reported and discussed in this thesis was concerned with one topic: the penetration of chloride ions into concrete. The research conducted at UT involved both the measurement of chloride ion penetration and the development of a concrete mixture to produce a concrete that had a high resistance to that penetration. Chapter 2 describes methodology for measuring the ability of concrete to resist chloride ion penetration. For completeness, Chapter 2 goes beyond the scope of testing performed at UT to provide a thorough review of related literature.

Chapter 2. Summary of Pertinent Literature

The purpose of this chapter is to present information from current literature in order to give the reader a basic understanding of chloride ion penetration and its effects.

2.1 Corrosion

Corrosion is one of the biggest problems affecting America's aging concrete infrastructure. In order to prevent corrosion, one must first understand what it is. Corrosion is defined by Webster's Dictionary as "the process or effect of destroying, weakening, or wearing away little by little". Usually, the main culprit causing corrosion is the environment. Corrosion can occur anywhere the environment can come onto contact with the object being corroded [1]. In the case of interest in this thesis, people are facilitating the acceleration of the corrosion of reinforcing steel in concrete bridge decks by adding deicing salts to bridges in cold weather.

When concrete was patented by Wilkinson in 1854, it was thought that a concrete cover over steel embedded in concrete was sufficient to protect steel from the environment. This thought was due to concrete's high alkalinity. It is now known that corrosion is caused by electrochemical responses from the steel when charged ions come into contact with the steel and create a circuit [2].

Metals, compounds, and alloys can produce different potentials when coming in contact with an electrolyte. These potential values can be found in an electrochemical series table. Any metal in the series can act as a cathode to any metal beneath it in the series, causing the metal with the lower potential to dissolve. When chloride ions are present in wet concrete with steel, corrosion occurs at anodic areas. Iron compounds may also escape through the surface of the steel, leaving pits behind.

2.2 Epoxy Coated Reinforcing

Corrosion in reinforcing steel is caused by chloride ions contacting the steel, causing the steel to deteriorate. Unfortunately, the problem is only discovered after the damage has been done. In order to combat the corrosion of the reinforcing steel, it was determined that the steel should be covered somehow. Non-metallic materials were tested and powder-coated epoxy was determined to be the best to protect reinforcing steel against corrosion.

The corrosion of steel reinforcing bars was first recognized as a problem in the 1960’s. It was noticed that just a few years after bridges were being built, bridges required repair. In the 1970’s, epoxy coated reinforcing steel was beginning to come into use. Many tests were performed and it was determined that the ideal thickness of the epoxy coating on the rebar is 0.13 to 0.23 millimeters thick [3].

Imperfections in the epoxy coating can occur when it becomes damaged after transportation and handling, leading to the need for enhanced specifications regarding the care of the reinforcement. It was decided that, since a perfect coating was not achievable, a maximum of six "holidays" (defects not visible to the naked eye) every meter would not damage the coating excessively [3]. Initially, it was required that any visible defect be filled with a liquid epoxy.

Tests were conducted by the FHWA in which epoxy was intentionally damaged. These bars did not fail after 35 months, which led to a study on the relaxation of the specifications for filling defects with liquid epoxy. Most of the time, repair was not required unless defects covered over 2% of the area of a straight bar section and over 5% of a bent section of bar [3].

In 1980, the FHWA began a test to analyze the benefits of coated reinforcement and the coupling effect. The test included the use of poor quality concrete, non-specification epoxy-coated reinforcing bars (over 80 holidays per meter), and electrical coupling between mats. The reinforcement was coated in 1977 and stored outdoors for over two years. The bars were also intentionally damaged to cause defects in the coating of 0.24 to 0.86%. The test indicated that if the top mat was coated, corrosion was reduced by a factor of 11.5. If both mats were coated, corrosion was reduced by a factor of 41.

The Florida DOT began to notice that although epoxy coated reinforcement was required in their bridges, corrosion was still occurring. It was found that salt water caused disbonding between the coating and the steel. Bars that were damaged due to handling and then exposed

to salty air in the construction yard were becoming disbonded either in placing of the bars or while the concrete was being placed. By the time chloride ions have penetrated the concrete, corrosion begins on the steel beneath the epoxy imperfections and under the disbonded areas of the epoxy coating. There was no evidence that the bars examined did not meet specifications[3]. By July 1992, the Florida DOT no longer required epoxy-coated reinforcement in any of its structures[3]. They determined that epoxy-coated reinforcing does not influence long term corrosion resistance in a marine environment.

Epoxy-coated reinforcement as a whole is an effective tool in reducing the presence of corrosion. In order to effectively reduce corrosion, reasonable care must be taken so no reinforcing bars experience damage to their epoxy coating.

2.3 SR vs. RCP

The most commonly used method for testing chloride ion penetration specified by ASTM C1202 (ASTM 2010b) and AASHTO TP-11 (AASHTO 2011) had for a long time been the rapid chloride ion penetration (RCP) test. The name is deceptive; it is not rapid at all. It is simply more rapid than the ponding test, which is a much more time consuming and laborious test, but which is considered the most accurate test to determine chloride ion penetration. When testing samples using the RCP test, there is a twenty-four hour period required for preparation plus another day to complete the testing. The sample cylinders must first be cut into smaller segments for testing and subjected to various conditioning procedures. Finally, a constant

voltage is applied to the segment over a six-hour period. This test measures the electrical conductance of the concrete, which is taken as an appropriate measure of chloride ion penetration. A lower measured conductance denotes a lower penetration, which is desired. The length of time and tedious preparation required for this test can often lead to human error and can skew test results [11].

The main source of chloride ions in bridge decks is deicing salt. In cold months, deicing salt solutions are spread over bridge decks. As the snow melts, a solution of melting snow, chloride ions, and salt diffuses into the concrete surface. When the chloride ions reach the reinforcing steel, spalling and corrosion of the steel occur.

Slight changes in a concrete mixture can cause large changes in the RCP values of concrete. One mix variable that influences the RCP value of concrete is the type of aggregates used in the concrete mixture. Aggregates that are more porous typically allow more water flow in concrete and allow chloride ions to move more freely. Also, a “richer” mixture, that is one with more cementitious paste, leads to the penetration of more chloride ions [4].

Another very common factor that affects the RCP value of concrete is the water-cement ratio. It is not uncommon for water to be added to concrete shortly before it is placed in order to increase slump. Unfortunately, this has been shown to increase the penetration of chloride ions into the concrete [4].

There are some potential weaknesses, not only in the performance of the RCP test, but also in the interpretation of the test results. One criticism is that “permeability” and “penetrability” are frequently used interchangeably [4]. The RCP test is really a test of the penetrability of chloride ions. However, some mistake the RCP test for a measure of permeability. Permeability refers to the movement of any material through the concrete, whereas the RCP test measures only the movement of chloride ions through the concrete.

Another criticism of the RCP test is that it is potentially inaccurate when the concrete being tested contains supplementary cementitious materials such as fly ash, silica fume, or slag cement. The more accepted method, the ponding test, involves ponding a sodium chloride solution on the surface of the concrete for a period of 90 days. Samples are taken from various depths of the concrete and analyzed for chloride ion content. The RCP and ponding test methods correlate very well when there have been no supplementary cementitious materials (SCMs) added to the concrete. There has been essentially no research completed relating the ponding and RCP tests using concrete with SCMs. Many believe, without proof, that there is a weak correlation between RCP and ponding tests in cases with concrete containing SCMs. Because, as shown later herein, the SR test is the indirect inverse of the RCP test, this same criticism also accompanies the SR test.

The last criticism of the RCP test is that it generates heat in the concrete being tested. As a current is applied to a sample, heat is generated in the sample, potentially increasing its conductance. This heat, in turn, creates a higher RCP value. ASTM C1202 (ASTM 2010b)

specifies a maximum temperature of 190 degrees F. If this temperature is exceeded, the test is to be terminated and the samples characterized as having a high chloride ion penetration.

A method that has been recommended to replace the RCP test method is the Surface Resistivity (SR) test. SR values represent a resistance to the penetration of chloride ions into concrete. The test is an indirect inverse of the RCP method as it measures a concrete sample's resistance to an electrical current [4]. This test method is less time consuming and is also non-destructive, which means the samples that are tested using the SR method can also be tested for strength; whereas the RCP test is destructive in that the cylinder is cut into 1-inch thick disks for testing.

The SR test consists of using, a handheld Wenner probe comprised of four electrodes which measure a sample's electrical conductivity. After surface moisture is removed from a sample, the probe is placed longitudinally to the surface of the sample with all the electrodes making contact with the surface. The two outer electrodes emit a constant electrical current while the inner two electrodes measure the difference in the electrical current. This test is conducted a total of eight times around the circumference of the sample and the results averaged. As this method measures a resistance to electrical current, a higher value is desired to indicate a higher resistance to the penetration of chloride ions. The chloride ion penetration classifications found in AASHTO and ASTM can be found below in Table 1.

Table 1: Chloride Ion Penetration Classification [13]

Chloride Ion Penetrability Classification	ASTM C1202 56 day RCP Charge Passed (Coulombs)	AASHTO TP 95-11 28 day SR Surface Resistivity (kohm-cm)
High	> 4,000	< 12
Moderate	2,000 – 4,000	12 – 21
Low	1,000 – 2,000	21 – 37
Very Low	100 – 1,000	37 – 254
Negligible	< 100	> 254

2.4 Related Topics

This section of Chapter 2 explains the effects of chloride ion penetration when concrete is changed either by constituents or by the addition of stress on the concrete.

2.4.1 Chloride Ion Penetration of Recycled Aggregate Concrete:

Deterioration of aging infrastructure in the United States continues to become a larger problem. Often, the infrastructure is destroyed in order to make space for newer infrastructure, leading to large amounts of waste. A smaller environmental footprint is left when reusing some of this waste for future infrastructure.

In order to use recycled aggregates obtained from demolition, the aggregates must first go through a beneficiation process. After this process, the aggregate is ready to be used in new construction. There will be three different kinds of aggregates that are obtained from demolition waste: crushed concrete, crushed masonry, and mixed demolition debris [8].

In order to be considered recycled concrete aggregate, the aggregate must contain at least 90% Portland cement paste and natural aggregate. Recycled masonry aggregate must be composed of a minimum of 90% of a summation of concrete blocks, ceramic bricks, blast-furnace slag bricks and blocks, ceramic roofing tiles and shingles, and sand-lime bricks. Mixed recycled

aggregates are a blend of crushed and graded concrete and masonry rubble composed of less than 90% Portland cement fragments and natural aggregates [8].

It is typical to find recycled aggregates with a higher chloride ion content than that of natural aggregates, particularly if the original location of the recycled aggregates was somewhere with a high chloride ion environment. Since the aggregates are usually porous, they can be washed, reducing their chloride ions. Typically, if they are soaked in water for at least two weeks, the chloride content decreases enough to be used in reinforced concrete.

As more recycled aggregates are used in place of natural aggregates, the chloride ion content of the material increases. It was found that increasing the amount of fine recycled aggregate increases the chloride ion migration in the material more than increasing the amount of coarse recycled aggregate [8]. Since the permeability is higher in fine recycled aggregate when compared with coarse recycled aggregate, this chloride ion migration increase was expected. When all coarse aggregate in a mixture is coarse recycled aggregate, there is a 95% probability that the chloride ion migration coefficient will increase by 1.65 times. If all fine aggregate in a mixture is replaced with fine recycled aggregate, there is a 95% probability that the chloride ion migration coefficient will increase by almost a factor of three [8].

There was a study completed by Gomes and Brito[10] that studied the different types of recycled aggregate and their effects on chloride ion migration. The mixed recycled aggregate contained 30% recycled masonry aggregate and 70% recycled concrete aggregate. When using 50% coarse recycled concrete aggregate, 37.5% coarse mixed recycled aggregate, or 25% coarse recycled

masonry aggregate, the chloride ion migration coefficient increased by 5.6%, 15.1%, or 18.8%, respectively. Since recycled masonry aggregate is more porous than the other materials, it was expected to have a higher chloride ion content. It was also found that as the amount of recycled masonry aggregate in a mix increased, the amount of water absorbed increased, which decreased the chloride ion resistance.

It is possible that crushing concrete creates micro-cracks, which can increase a concrete's penetrability to chloride ions. If recycled concrete aggregate is subjected to crushing that creates a more rounded shape and decreases the amount of mortar attached to the surface of the aggregate, concrete's penetrability can be reduced compared to that of aggregate with a less round shape and more mortar adherence [8].

Generally, the inclusion of recycled aggregates will significantly increase the chloride ion penetration in concrete. Recycled masonry aggregates proved to produce the highest penetrability when used in concrete. The use of fly ash, silica fume, or metakaolin can help combat this by decreasing the penetration of chloride ions in the concrete. Although penetration values are increased in the beginning of the lifetime of a bridge when utilizing recycled aggregate, they are essentially the same as natural aggregate concrete after about ten years [8]. In an area where the penetration of chloride ions is considered detrimental, such as Tennessee, the use of recycled aggregate concrete for bridge decks is questionable at best.

2.4.2 Chloride Ion Penetration in Stressed Concrete:

Generally, concrete is tested for chloride ion penetrability in an unstressed state. Since most bridges in use today are in a stressed state, at least to some degree, these results are somewhat inaccurate. Some studies have shown that chloride ions more quickly penetrate concrete in tension than in unstressed concrete [9]. Also, the penetration rate was slower for concrete in compression than for unstressed concrete. Testing confirmed that resistance to chloride ions could be improved by increasing the compressive strength of the concrete. No test data measuring chloride ion penetration was found.

Chapter 3. Background

Replacing deficient concrete bridge decks is at once an inconvenience for the traveling public and a significant expense to the Department of Transportation. Being painfully aware of this fact, the Tennessee Department of Transportation (TDOT) sponsored research at The University of Tennessee (UT) to develop a more durable concrete mix. Work to develop a concrete mix that is efficient and affordable with the potential to enhance the quality of the concrete in Tennessee bridge decks was completed in 2008. The results of that early study indicated that the current TDOT Class D mix design was not capable of achieving a resistance to chloride ion penetration, as measured by the Rapid Chloride Ion Penetration (RCP) test, that was considered any better than, at best, “moderate.” The UT study showed that a ternary blend mix consisting of cement, fly ash, and ground granulated blast furnace slag (referred to herein simply as slag) was far more efficient in achieving high resistance to chloride ion penetration than a typical binary mix. The “best” mix developed in that study was a ternary blend mix with a dense graded aggregate consisting of both #7 and #57 limestone. The mix developed was referred to as the “UT 565” mix with mix proportions shown in Table 2. As a part of that research, a few tests were made with the SR meter, and a reasonable correlation with RCP results was obtained.

Table 2: UT-565 Mix Proportions

W/C Ratio		0.4
Total Cementitious Material Content (lb/yd^3)		565
Cement (lb/yd^3)		283
Fly Ash (lb/yd^3)		113
Slag (lb/yd^3)		169
Water (lb/yd^3)		226
Combined Aggregates (lb/yd^3)	#57	1109
	#7	792
	Natural Sand	1216

While the UT 565 mix had high strength and low chloride ion penetration values, the use of slag necessitates an additional bin. The use of two coarse aggregates, on the other hand, is not perceived to cause any particular inconvenience. And the “dense graded” mix proved to be effective in lowering chloride ion permeability.

At the time that the early work on mix designs was winding down, there was serious interest expressed in a “performance based specification” whereby certain performance criteria would be specified, and a contractor would have a free hand in developing his own mix and be responsible for meeting these criteria. The FHWA representatives on the research advisory group were particularly enthusiastic about this approach. In a meeting at TDOT headquarters, while this potential type of specification and the use of a ternary blend were being discussed, the question was raised, “How good are our current decks?” The answer was simple: we don’t know.

At that time the accepted method of assessing resistance of concrete to chloride ion penetration was the Rapid Chloride Ion Penetration Test (RCP Test), a method that belied its name; it was “rapid” only as compared to the supposed “gold standard”, the ponding test. But a new method was being developed, a method being pushed by the Florida DOT, called the Surface Resistivity Method (SR), a method which in essence measured the inverse of that measured by the RCP Test. A few SR tests had been performed at UT and a large number of these tests had earlier been performed by the Florida DOT, all of which showed good correlation between SR and RCP tests.

The decision was made in the meeting at TDOT referenced above to initiate research that accomplished two specific things: (1) assess the durability of the concrete in the decks of bridges currently being built in Tennessee and (2) assess the feasibility of using the SR method to measure resistance of chloride ions into concrete versus the accepted RCP method.

From these discussions an unusual research project was born. Samples were collected from bridge deck placements all over the state of Tennessee and sent to Region 1 headquarters where they were subsequently picked up by personnel of the Civil Engineering Department. Both RCP and SR tests were performed with the dual purpose of evaluating the correlation between the two test methods and evaluating the quality of concrete being placed on Tennessee bridge decks. This research project and the succeeding projects which occupied six years of research at UT are summarized in the following chapters.

Chapter 4. Testing Phases 1, 2, and 3

The purpose of this chapter is to explain the three phases of testing the University of Tennessee performed and the results of this testing.

4.1- Phase 1: 2009-2011

Working on a two-year research contract, on September 1, 2009, the University of Tennessee began work on research to determine a correlation between SR and RCP testing with samples being collected from concrete bridge decks being placed throughout the state. At these concrete bridge deck placements, thirteen extra 4-in. by 8-in. cylinders were cast by the contractor. The cylinders were cast and cured according to ASTM C31 for at least 48 hours before transport. The cylinders were placed in large marine coolers with dense Styrofoam holders for the cylinders. The coolers then made their way to the TDOT Region Headquarters located in Nashville and then to the Region 1 office in Knoxville by TDOT personnel as soon as possible. The cylinders from bridge decks located in Region 1 were taken directly to Region 1 headquarters. All cylinders were picked up by UT Civil Engineering Department personnel and taken to the University of Tennessee where they were immediately placed in a lime water bath.

Since the cylinders were from all across the state, the time period in which the samples were in the coolers varied but was usually between 7 and 21 days. Before the samples were picked up,

they were kept in a moisture room as specified by ASTM C511 with their caps still on. When the cylinders arrived at the University of Tennessee, the caps were removed, the forms were stripped, and they were immediately placed in a lime water bath.

Of the thirteen cylinders, six cylinders were used for compressive strength testing. Three of them were tested at seven days while the other three were tested at twenty eight days. Six cylinders were used for SR and RCP testing. Three were tested at twenty eight days and the other three were tested at fifty six days. The one remaining cylinder was an extra in case one cylinder was damaged. If it was not needed, it was used to measure the SR value at ninety one days. Since the SR test method is nondestructive, this test was performed on the cylinders before RCP tests. The results of this testing can be found in Table A1. The results can be condensed into Tables 3 and 4 to illustrate the quality of the concrete as determined from SR and RCP testing.

It should be noted that the AASHTO specifications for SR specify samples to be tested at 28 days where ASTM specifies RCP samples to be tested at 56 days. If one compares high and moderate samples tested by SR and RCP at 28 days, the tests seem quite comparable. The same can be said for those tested at 56 days.

Since the SR test measures the resistivity of an electrical current and the RCP test measures the conductivity of an electrical current, the two are essentially the inverses of one another. Testing sample cylinders using both the SR and RCP test methods showed a high correlation between

Table 3: A Summary of Test Results by Penetration Classification: SR

(1 56-day SR value was not recorded due to errors in testing)

Penetration Classification	**28 day SR Value by Classification**	**Samples Tested (28 day SR) (kohm-cm)**	**Samples Tested (56 day SR) (kohm-cm)**
High	<12	41	12
Moderate	12-21	66	51
Low	21-37	3	43
Very Low	37-254	0	3
Negligible	>254	0	0

Table 4: Summary of Test Results by Penetration Classification: RCP

(2 28-day and 5 56-day RCP values were not recorded due to errors in testing)

Penetration Classification	**56 day RCP Value by Classification**	**Samples Tested (56 day RCP) (Coulombs)**	**Samples Tested (28 day RCP) (Coulombs)**
High	>4000	21	59
Moderate	2000-4000	48	44
Low	1000-2000	31	5
Very Low	100-1000	5	0
Negligable	<100	0	0

the two tests [5]. The tests produced a coefficient of determination (R^2) value of 0.882. The results of this testing are shown in Figure 1. A coefficient of determination value represents how comparable two sets of data are from values of zero to one, with one being the most similar a data set can be to one another; in other words perfect correlation. The sample tests completed confirm that the SR method can reasonably be used to replace the RCP test.

4.2- Phase 2: 2011-2013

The years of 2011 to 2013 consisted of more of the same SR and RCP research along with creating a performance based specification and researching a ternary blend mix to be used on concrete bridge decks across Tennessee [16]. Concrete cylinders continued to be received from across the state until near the end of the project.

The argument for implementing a performance based specification was that such a specification encouraged contractors to provide a better product while possibly also reducing their cost. Implementing this specification would replace the current Class D specification which was viewed as restrictive and not conducive to contractor innovation. Other states, including Virginia, New Mexico, Texas, and Pennsylvania have implemented a performance-based specification with good results. Indiana Department of Transportation and Purdue University have completed research for a possible inclusion of a performance-based specification in the future. New Hampshire and Nebraska have also performed research on a potential performance-based specification [16].

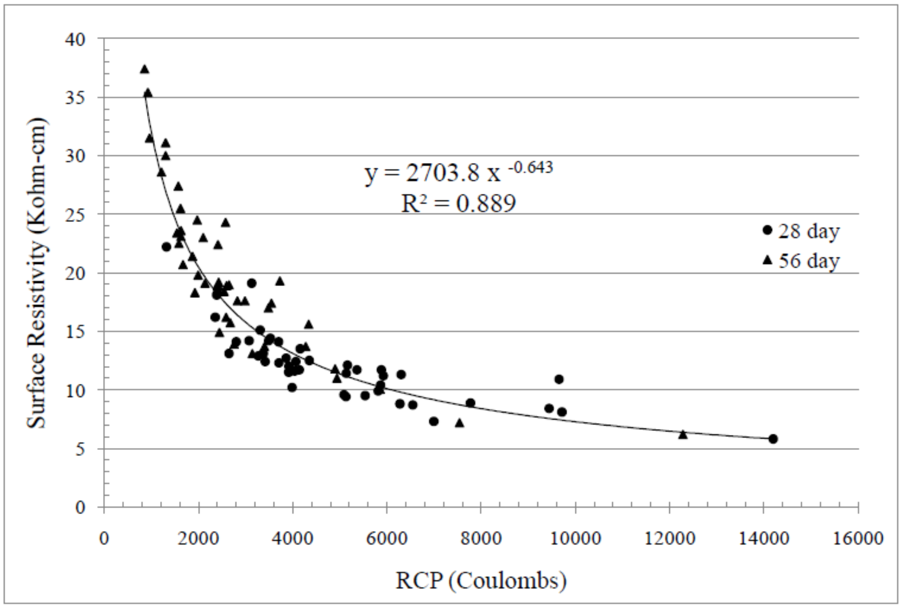

Figure 1: SR vs. RCP Combined 28 and 56 Day Data [4]

At a meeting at TDOT headquarters in December 2011, the development of a performance based specification was discussed in detail and rejected. Thus, development of such a specification was discontinued.

At this time, the Tennessee Department of Transportation only requires the use of a Class D binary concrete mixture containing cement and fly ash in their projects. The specifications are shown in Table 5. SR and RCP testing on bridges across Tennessee have resulted in values that indicate a need for a concrete mixture with a lower penetrability than the mixture currently in use. This lower penetrability can be achieved through the use of a ternary blend mixture.

Table 5: TDOT Class D Mixture [11]

Current Class D Mixture				
Minimum 28 Day Compressive Strength (psi)	Minimum Cementitious Material (lbs/c.y.)	Maximum Water/Cem. Material Ratio (lb/lb)	Air Content % (Design ± Production Tolerance)	Slump (in.)
4,000	620	0.40	6	8 max

Ternary blend concrete mixtures contain cement and two types of supplementary cementitious materials. Fly ash and ground granulated blast furnace slag are commonly used in ternary blend mixtures. Since fly ash is a by-product of coal production and slag is a by-product of iron production, it is both economically and environmentally friendly to use these in place of simply portland cement.

There are many other advantages to using a ternary blend mixture in addition to its resistivity to chloride ions. These advantages include improved workability, final strength gain, freeze-thaw resistance, and increased sustainability [6]. Of course, there are also some disadvantages to the use of a ternary blend concrete as well. The disadvantages include an increased setting time and erratic changes in time between the initial and final sets. Since the setting time is increased, the strength gain is slower, which discourages some companies from using a ternary blend concrete mixture, especially during colder weather. The availability of slag can become an issue if concrete plants do not have adequate storage for the material. Many concrete producers have storage bins for cement as well as fly ash but lack a third bin for slag. Ternary blend mixtures also have a longer setting time as well as a slower strength gain.

While concrete's resistance to chloride ion penetration is important, it becomes relatively less important if the concrete decks, due to primary shrinkage, crack extensively. If a concrete is comprised of material that is resistant to chloride ions and yet develops extensive cracks, chloride ions are provided ready access to penetrate the concrete and eventually reach the steel. The lab samples that were tested for chloride ion penetration were also tested for shrinkage using shrinkage prisms. It has been suggested that the percentage of length changed of a concrete sample should be no more than .0400 at twenty eight days and .0500 at ninety days. All of the samples tested for shrinkage were well within these values [7].

When conducting SR and RCP tests on ternary blend laboratory samples, low values of chloride ion penetrability were obtained [12]. Testing of binary blend laboratory mixtures resulted in

moderate to high chloride ion penetrability values. Based on these results, UT researchers concluded that a mixture of 50% cement, 30% slag, and 20% fly ash will consistently produce significantly lower chloride ion permeability values than that in concrete cast with the commonly used binary mixture [6]. The current binary Class D mixture contains either 75% cement and 25% fly ash or 80% cement and 20% fly ash.

Fly ash, which is both inexpensive and readily available, is widely used in concrete mixtures for structures ranging from slabs-on-grade in a parking lot to bridge decks to nuclear plants. A ternary mix adds one cementitious material [6]. Silica fume, in terms of measured chloride ion penetrability, is probably the most effective material to reduce penetrability. However, silica fume is expensive and is a bit "tricky" to use. Thus, ground granulated blast furnace slag is the recommended cementitious material to combine with cement and fly ash to produce a concrete mixture with a high resistance to the penetration of chloride ions [6].

4.3- Phase 3: Lightweight Aggregate Concrete

In 2013, the Hurricane Bridge on SR 56 in DeKalb County was undergoing a deck replacement. In order to decrease dead loads and increase durability, this replacement was to be of lightweight aggregate, ternary blend concrete with cementitious material consisting of 60% Portland cement, 20% Class C fly ash, and 20% Grade 100 slag cement [15]. At the same time as this bridge deck was being replaced, the I-40 Bridge deck over the French Broad River was specified to be replaced with a ternary blend lightweight mix concrete and a reduced amount of

cementitious material. The need for more information on lightweight ternary blend concrete mixes became apparent. This need led to the two-year research project completed in July 2015.

Structural lightweight concrete is defined by ACI as concrete comprised of low-density aggregate such that the concrete has a dry density of no more than 115 lb/ft^3 and a compressive strength of more than 2500 psi (ACI 2000). It contains lightweight coarse aggregate, and in some cases, a lightweight fine aggregate for a portion –or even all- of the fine aggregate. The resulting unit weight is between 90 and 115 lb/ft^3. Most often only a lightweight coarse aggregate is used with a corresponding unit weight of approximately 115 lb/ft^3. Such concrete is sometimes referred to as “sand-lightweight” concrete. The term “lightweight” in this thesis refers to “sand-lightweight”. Lightweight concrete can significantly reduce the dead load on a bridge, increasing the span length and the distance between girders, which translates to fewer girders used and lower construction costs. The lightweight aggregate can consist of expanded shale, expanded slate, or expanded clay. TDOT limits aggregate absorption to 10% or less, making slate the only possibility for use on bridges in Tennessee[17].

The fact that the lightweight aggregates are more porous than normal weight aggregates might be expected to lead to a decrease in the concrete’s resistance to penetration of chloride ions. However, resistance to the penetration of chloride ions can be increased by the use of SCMs, achieving an appropriate water-cement ratio, and using an effective curing method [15]. Even though lightweight aggregates tend to be more porous than normal weight aggregates, research has shown that lightweight concrete typically has an equal or smaller permeability-

not necessarily penetrability- than normal weight concrete. As in normal weight concrete, adding fly ash, silica fume, and slag cement have been proven to lower the penetrability of lightweight concrete [15].

In 2011, during Phase II work, contractors cast two batches of field-cast lightweight concrete for the University of Tennessee to test. The lightweight Class L concrete has similar requirements to the Class D normal weight concrete that TDOT normally uses, but the maximum water-cement ratio was required to be .39 as opposed to .40. The cementitious material was also modified to contain 25% Class C fly ash and 75% Portland cement [15]. The cylinders exceeded the 4000 psi minimum 28-day strength but the SR and RCP results revealed high chloride ion penetration values. Both batches had 28-day SR and RCP values of less than 9 kOhm-cm and above 7,300 coulombs, and 56-day SR and RCP values were under 12 kOhm-cm and above 4,100 coulombs[15]. All of these values are considered high penetration values by ASTM and AASHTO.

In 2012, the University of Tennessee was continuing their research on the normal weight Class D samples arriving from across the state as well as beginning testing on laboratory cast normal weight ternary blend concrete and lightweight binary and ternary concretes. The normal weight and lightweight ternary blend concretes contained a cementitious material comprised of 20% Class F fly ash, 30% slag cement, and 50% Portland cement. The lightweight binary mix contained cementitious material that consisted of 25% Class F fly ash and 75% Portland cement. All of the samples were cured in a lime water bath. As shown in Table 6, the test results for the

Table 6: University of Tennessee Laboratory Mix Penetrability Results

Mix Design	NWT	LWB	LWT
W/CM ratio	0.37	0.40	0.40
Cementitious Material (lb/yd^3)	620	620	620
Cement (lb/yd^3)	310	456	310
Class F Fly Ash (lb/yd^3)	124	155	124
Grade 100 Slag Cement (lb/yd^3)	185	0	185
Water (lb/yd^3)	247	247	247
#57 Lightweight (lb/yd^3)	1854	0	0
#57 Limestone (lb/yd^3)	0	930	930
Natural Sand (lb/yd^3)	1203	1298	1298
28 day compressive strength (psi)	7585	7440	7904
28 day SR (kOhm-cm)	46.1	25.8	77.6
28 day RCP (Coulombs)	766	2,077	550
56 day SR (kOhm-cm)	60.6	60.3	125.1
56 day RCP (Coulombs)	520	1,471	361

*NWT= Normal Weight Ternary Blend
*LWB= Lightweight Binary Blend
*LWT= Lightweight Ternary Blend

lightweight ternary blend achieved greater SR and lower RCP values than the normal weight ternary and lightweight binary concretes.

The main purpose of this early work on lightweight concrete was to recommend a mix design to be used on the Hurricane Bridge in DeKalb County, Tennessee. UT researchers recommended the use of the mix design used for the lightweight ternary blend mix to be 50% Portland cement, 30% slag, and 20% fly ash. For unknown reasons, the mix was slightly altered to contain 60% Portland cement, 20% slag, and 20% fly ash[15]. Even though the mix was altered a bit, improvements in SR and RCP values were expected.

Sample cylinders collected from eight bridge deck placements were sent to the University of Tennessee to be tested. The results from these sample cylinders can be found in Table 7. All of the cylinders exceeded the required 28-day minimum f'c of 4000 psi. The 28-day SR and RCP test results reflect a moderate chloride ion penetration while the 56-day results produce a low chloride ion penetration. While this mix achieved a moderate chloride ion penetration, the University of Tennessee's lightweight ternary concrete mixes in the lab produced a very low chloride ion penetration, which is more desirable.

This early research led to a project which focused on the I-40 Bridge over the French Broad River. The purpose of this research was to assess the durability of the concrete placed on that bridge and select a reasonable SR lower limit expectation for lightweight bridge deck concrete[17]. However, due to

Table 7: Hurricane Bridge Field-Cast Cylinder Test Results[15]

Placement Date	28-day SR (kOhm-cm)	28-day RCP (Coulombs)	28-day f'c (MPa)	56-day SR (kOhm-cm)	56-day RCP (Coulombs)
9/24/2012	13.2	2789	44.4	26.9	1514
9/25/2012	13.9	2804	42.1	29.1	1527
10/3/2012	12.4	2790	41.8	24.3	1613
10/5/2012	15.1	2498	50.0	29.8	1254
11/28/2012	11.6	3906	46.3	25.8	1578
12/6/2012	15.4	3075	53.4	27.1	1333
12/14/2012	N/A	N/A	N/A	24.1	1532
2/11/2013	15.1	3295	48.4	33.9	1155
Average	13.6	2977	46.3	27.2	1470

Note: N/A= Not Applicable due to testing conflict or insufficient aging

different variables affecting the SR of a sample coupled with generally inconsistent results, the specification of a lower limit never became possible.

Proper aggregate saturation of lightweight concrete aggregate is essential for pumping. If the aggregate is not properly saturated, water is forced into the pores of the aggregate and there is less water available for the lubrication of the cementitious material[14]. Improper aggregate saturation can also impact the water/cement ratio, thus affecting the ability of the concrete to resist chloride ion penetration[17]. The results from samples collected from the bridge deck are shown in Table 8. It is clear from Table 8 that the initially specified mix design with 50% cement, 30% slag, and 20% fly ash was essentially never used. The contractor anticipated problems pumping that mix and, after pumping problems occurred, abandoned the mix. Pumping problems continued to occur, raising questions about the adequacy of the soaking procedure of the lightweight aggregate.

Bridge inspection was completed on five lightweight concrete bridge decks after placement. The only concern that came from this inspection was the fact that the bridge decks had been subjected to grinding in order to meet traction requirements. Lightweight aggregate tends to float at the top of the mix, so the grinding of the bridge decks allowing their pores to become penetrated for the depth of the aggregate[17]. This is not a problem for normal weight concrete since its aggregate is usually not porous.

Table 8: Summary of Results in Lime Bath: I-40 Bridge

SUMMARY OF RESULTS FOR LIME BATH SAMPLES						
Casting Date	Mix Site	Cement Brand	Mix Design (Cement,Slag, FA)	f'c (psi)	SR (kohm-cm)	
				28-day	28-day (LB)	56-day (LB)
4/17/2014	UTK Lab	Buzzi	50-30-20 (620)	4765	40.8	-
5/14/2014	Field	Cemex	50-30-20 (620)	-	10.2	14.5
5/14/2014	Field	Cemex	50-30-20 (620)	-	5.7	-
6/5/2014	UTK Lab	Buzzi	50-30-20 (620)	6820	53.6	72.2
6/19/2014	Field	Cemex	50-30-20 (620)	5209	16.9	32.7
6/24/2014	Field	Cemex	60-20-20 (670)	6713	9.3	17.7
6/26/2014	UTK Lab	Buzzi	50-30-20 (620)	4557	25.6	40.4
7/7/2014	Field	Cemex	85-15 (670)	5641	6	8.9
7/10/2014	UTK Lab	Cemex	50-30-20 (620)	3898	10.7	19.7
7/10/2014	Field	Cemex	60-20-20 (670)	7402	18.5	29.5
7/15/2014	UTK Lab	Buzzi	50-30-20 (620)	6099	29.3	48.9
7/17/2014	Field	Cemex	60-20-20 (670)	4985	9.7	16.8
7/24/2014	UTK Lab	Cemex	50-30-20 (620)	4871	13.5	24.3
(1) 7/29/2014	UTK Lab	Buzzi	50-30-20 (620)	6498	29.3	47.9
(2) 7/31/2014	UTK Lab	Buzzi	50-30-20 (620)	6330	28.6	44.4
8/5/2014	Field	Cemex	60-20-20(670)	4372	8.1	15.2
8/12/2014	UTK Lab	Buzzi	50-30-20 (620)	5290	31.7	49.7
8/21/2014	UTK Lab	Cemex	50-30-20 (620)	5610	14.5	26.6

Table 8 Continued

Casting Date	Mix Site	Cement Brand	Mix Design (Cement,Slag, FA)	f'c (psi)	SR (kohm-cm)	
				28-day	28-day (LB)	56-day (LB)
8/26/2014	Field	Cemex	60-20-20(670)	5344	10.2	18.2
9/11/2014	UTK Lab	Cemex	50-30-20 (620)	6564	15.6	31.3
9/16/2014	UTK Lab	Cemex	50-20-30 (620)	6616	17.7	32.2
10/2/2014	UTK Lab	Cemex	50-20-30 (575)	6784	16.4	27.5
(4) 10/21/2014	Field	Cemex	60-20-20 (670)	7349	15.5	19.3
10/22/2014	Field	Cemex	60-20-20(670)	6343	10.8	22
10/30/2014	UTK Lab	Cemex	60-20-20	6550	16.3	22.9
1/7/2015	UTK Lab	Cemex	50-30-20 (620)	6821	21.6	36.7
1/14/2015	UTK Lab	Cemex	50-30-20(620)	6499	21.7	36.5
1/21/2015	UTK Lab	Cemex	50-30-20(620)	6615	17.9	32.7
1/21/2015	Field	Cemex	85-0-15(670)	4143	8.2	13.1
(2) 3/18/2015	Field	Cemex	80-0-20(565)	4336	7.2	
(2) 3/20/2015	Field	Cemex	80-0-20(565)	5494	7.3	
4/9/2015	Field	Cemex	60-20-20(670)	3788	7.7	
4/9/2015	UTK Lab	Cemex	50-30-20 (620)	5114	23.1	

Lightweight aggregate concrete can have a higher shrinkage than normal weight concrete due to the thicker cementitious paste developed when the aggregate absorbs water from the mixture. Autogenous shrinkage, which is caused by the volume change during cement hydration, is the main concern when trying to prevent shrinkage in lightweight concrete.

Autogenous shrinkage is controlled by water-cement ratio, fly ash use, and aggregate saturation[17]. It can cause early cracks which will later decrease the durability of the bridge deck. If the aggregate is not properly saturated, the aggregates will absorb some of the water in the mixture and lower the water-cement ratio. It was found that a higher water-cement ratio can lead to less autogenous shrinkage. This can be difficult to accomplish since a higher water-cement ratio also decreases strength. Finally, the addition of fly ash helps prevent autogenous shrinkage because of its fineness. It fills pores in the concrete and creates a stronger micro-structure, which leads to less autogenous shrinkage[17].

Nine sets of shrinkage prisms were taken and tested. The following variables affecting shrinkage were studied: cement amount, cement brand, and mix location. Figure 2 shows that as the amount of cement increases, shrinkage will also increase, although not radically. Figure 3 shows the comparison between Cemex and Buzzi cement. For unknown reasons, samples that contained Cemex brand cement had higher shrinkage values than samples with Buzzi cement. Figure 4 shows the difference in shrinkage in samples cast in the lab and samples cast in the field. The samples in the lab had a slightly lower shrinkage than that cast in the field, which is believed to be due to the amount of aggregate saturation in the field.[17]

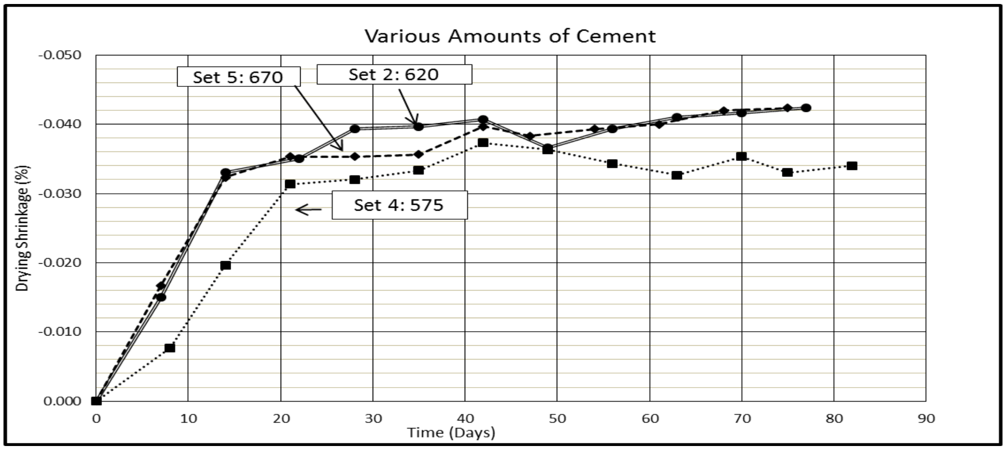

Figure 2: Variation in Shrinkage due to Cement Amount[17]

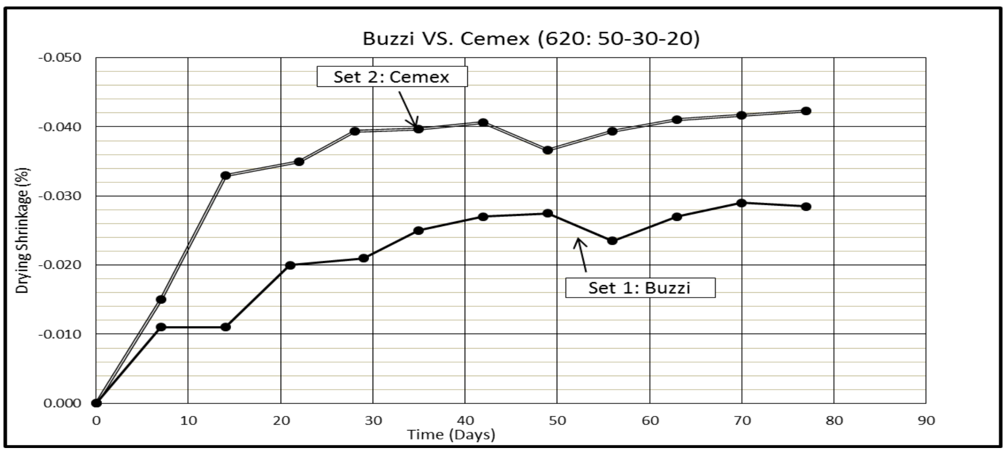

Figure 3: Variation in Shrinkage due to Cement Brand[17]

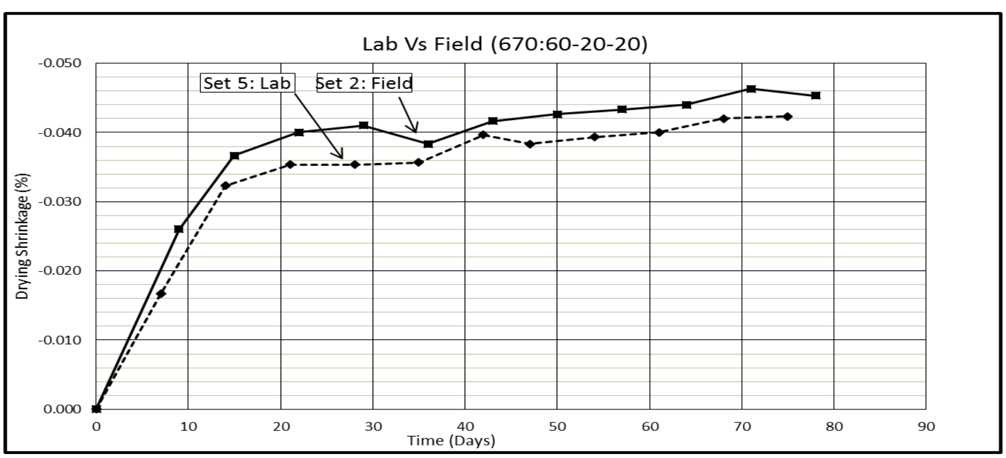

Figure 4: Variation in Shrinkage due to Mix Location[17]

Chapter 5. Additional Test Results

When the author of this thesis, Lindsey Phelps, began her career at the University of Tennessee as a graduate research assistant, she took on the task of attempting to find another variable that affects SR and RCP results, using the data already collected. This effort led only to dead ends. In fact, if anything was learned from the analysis of data, it would be what did NOT affect SR and RCP values. An attempt was made to find some relationship between SR and RCP results and the mix temperature. A mix design spreadsheet found in the mountains of information accumulated was used to compare the mix temperatures with their respective RCP values. Table A2 provides a summary of the information found. The reasoning was that, since temperature affects the rate at which the concrete hydrates, it might also affect the final hydration of the concrete and thus affect the SR values. However, there was essentially no correlation between temperature and SR (or RCP) as shown in Figure A1.

The next variable checked was the air content. The thinking was that, since air could not conduct an electrical current, a higher air content might decrease the SR values. This testing also led nowhere, showing no direct correlation between SR and air content as shown in Figure A2.

The last variable that was available in the spreadsheets was slump. While there was no reason to expect to learn anything meaningful from these data, the data were there to use. Again, there were no meaningful results obtained from the data. The results can be seen in Figure A3.

The R^2 value can be seen on each graph. The R^2 value is a value that represents how alike two sets of data are. The value is between zero and one. A value close to one represents that there is a good correlation between two sets of data. As shown in the figures, the R^2 results are very close to zero, meaning the two variables tested are likely unrelated.

After these three explorations found nothing new, a comparison was made between the cement brands and the SR vales they produced. The several Progress Reports and the Final Report on lightweight concrete research submitted to TDOT in July 2015 clearly showed that Buzzi cement out-performed Cemex cement on a consistent basis. But no comparison had ever been made between SR values and cement brand for normal weight concrete. After a lengthy search, SR values for concrete across the state made with different cement brands were obtained. The results are shown Figures A4 and A5. Tables A3-A8 show SR values separated by cement brand. To say that Cemex “held its own” compared to other cements is to understate the fact that it appeared to significantly outperform other cements. However, the results should not be given too much credibility because of the low number of samples made with Cemex cement.

Chapter 6. Results and Discussion

The purpose of this thesis was to summarize the results of bridge deck research completed by UT researchers between 2010 and 2016. This research began with a need for an accurate yet less time consuming way to test samples for chloride ion penetration. The most commonly accepted method for this testing has for a long time been the RCP test. Research had indicated that the SR test produces results that are essentially inverses of RCP test results. This testing confirmed that SR testing can be used in place of RCP testing.

Currently, TDOT requires the use of a Class D binary concrete mixture for uses on bridge decks across the state. Research completed shows that a ternary blend mixture that would contain cementitious material of 50% cement, 30% slag, and 20% fly ash would considerably improve the resistance to chloride ion penetration in bridge decks.

Lightweight concrete bridge decks can decrease dead loads on a bridge, which in turn can increase the span length and decrease construction costs. Based on testing results, UT researchers recommended a mix consisting of 20% Class F fly ash, 30% slag, and 50% portland cement for use on bridge decks with lightweight concrete.

Due to an undetected malfunction of the moist room, higher SR values than expected were obtained in early tests before a vat for a lime bath was available. The samples improperly cured showed that improper curing can lead to a falsely high measured impedance of chloride ions

when using SR testing, but a falsely low impedance based on RCP testing. Thus, SR test results can be said to produce an upper bound of resistance to chloride ion penetrability, and RCP test results will produce a lower bound to impedance of chloride ion penetration into concrete. In other words, if an SR test is conducted on an improperly cured cylinder, the reading can be expected to be artificially high, indicating an incorrectly high impedance to chloride ion penetrability. On the other hand, if an RCP test is incorrectly performed on a cylinder that has been improperly cured, one can, again, expect artificially large RCP readings, but now indicating a lower than actual impedance to penetration of chloride ions.

Chapter 7. Conclusion

The breadth of the concrete testing project makes the drawing of succinct conclusions difficult. But, logically, any conclusions should be separated into those relating to normal weight concrete and those relating to lightweight concrete.

For normal weight concrete the primary conclusion is that the concrete in Tennessee bridge decks is neither resistant to the penetration of chloride ions as one would wish, but it is not alarmingly bad. Most of the tested cylinders were in the moderate range of penetration resistance as specified by AASHTO (SR) and ASTM (RCP). The research clearly showed that the use of a ternary blend mix containing of 50% cement, 30% slag, and 20% fly ash led to significantly better resistance to the penetration of chloride ions.

The research on lightweight concrete led to generally uncertain conclusions. Due to pumping concerns, the originally specified mix was never used on the bridge deck. While obtaining the desired level of penetration resistance was difficult, nothing emerged from the research to suggest that the use of lightweight concrete is not appropriate. Pumpability is an issue that must be dealt with but one that can be addressed with proper aggregate soaking. Lightweight decks currently in use appear to be performing adequately.

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Appendix

Table A1: Summary of SR and RCP Test Data from Bridge Decks in Tennessee

				SR (kohm-cm)			RCP (Coulombs)	
Date	Region	County	28 day f'c (psi)	28 day SR	56 day SR	(28/56) Ratio	28 day RCP	56 day RCP
2/22/2010	4	Carroll	6239	9.8	17.1	0.57	6829	2347
3/13/2010	4	Henderson	5570	10.5	20.9	0.50	4468	2325
3/15/2010	2	Hamilton	5488	8.0	11.1	0.72	6146	5142
3/16/2010	1	Cocke	5351	12.7	21.0	0.60	3438	1876
3/17/2010	1	Knox	6737	14.4	25.8	0.56	2325	1351
3/30/2010	2	Hamilton	5096	11.4	12.9	0.88	5152	4303
4/6/2010	1	Carter	5358	13.4	19.2	0.70	4532	3114
4/22/2010	1	Blount	5576	17.8	31.5	0.57	2066	1062
5/3/2010	1	Knox	4230	15.5	26.8	0.58	3249	2259
5/25/2010	4	Haywood	4249	12.0	21.2	0.57	8483	3273
6/9/2010	2	Coffee	4653	8.9	12.1	0.74	8536	4337
6/10/2010	2	Clay	6740	21.0	26.9	0.78	2748	1731
6/23/2010	1	Union	4840	14.9	24.7	0.60	3653	2118
7/2/2010	3	Williamson	3604	12.6	19.4	0.65	4511	2479
7/2/2010 (2)	2	Polk	5610	12.3	17.2	0.72	5204	3809
7/6/2010	3	Davidson	3743	13.6	18.6	0.73	3570	3058
7/15/2010	4	McNairy	4729	6.4	6.9	0.93	N/A	N/A
7/27/2010	4	Madison	4305	12.8	20.8	0.62	5167	2278
8/10/2010	3	Davidson	4155	12.8	21.1	0.61	4710	2129

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
8/14/2010	4	Henderson	4117	9.3	15.2	0.61	8298	N/A
8/19/2010	4	McNairy	4898	7.0	8.1	0.87	N/A	N/A
9/1/2010	4	Lake	4393	12.8	23.6	0.54	3562	1642
9/3/2010	1	Sevier	6483	20.7	34.6	0.60	2111	841
9/8/2010	4	Gibson	4751	14.2	28.1	0.50	2870	1419
9/11/2010	2	Hamilton	3835	14.4	30.1	0.48	2964	1378
9/14/2010	1	Sevier	6076	19.9	38.9	0.51	2094	810
9/21/2010	3	Davidson	4887	11.2	15.3	0.73	3502	2418
9/28/2010	2	Warren	4884	12.9	21.8	0.59	3637	1747
10/5/2010	2	Warren	5114	15.5	22.7	0.68	2460	1465
10/12/2010	2	Warren	5219	13.7	25.4	0.54	3824	1426
10/14/2010	2	Warren	4765	10.4	20.1	0.52	4844	1687
10/21/2010	3	Williamson	5125	14.0	25.3	0.55	3390	1842
10/27/2010	3	Montgomery	8948	24.4	41.1	0.59	1158	748
11/2/2010	4	Decatur	4101	8.8	20.2	0.43	N/A	2231
11/19/2010	4		5260	10.2	19.4	0.53	N/A	2620
12/22/2010	2	McMinn	5891	12.5	15.0	0.83	5537	3756
1/4/2011	4	Haywood	4443	10.9	17.8	0.61	5105	2269

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
1/19/2011	4	Gibson	5272	9.5	N/A	N/A	5754	N/A
1/28/2011	2	Polk	6131	15.6	15.1	1.04	3064	2984
1/28/2011 (2)	2	Warren	4547	16.6	24.8	0.67	2906	1388
1/29/2011	2	Warren	5728	15.6	34.2	0.46	2699	1141
2/22/2011	2	Marion	4650	7.8	7.5	1.03	N/A	N/A
3/4/2011	1	Knox	6547	13.2	14.4	0.9	3444	2758
3/9/2011	4	Crockett	5203	15.9	33.0	0.5	3096	1141
3/11/2011	4	Dyer	6799	8.3	16.4	0.5	N/A	2145
3/15/2011	4	McNairy	6557	6.0	7.2	0.8	N/A	N/A
3/16/2011	2		7393	13.7	17.5	0.8	2999	N/A
3/29/2011	2	White	5712	10.5	12.0	0.9	4865	4060
3/29/2011 (2)	2		5854	13.5	16.0	0.8	3254	2927
4/12/2011	4	Hardeman	3850	9.7	19.4	0.5	5513	2256
4/21/2011	2	Rhea	3650	10.5	17.4	0.6	6018	4262
5/18/2011	1	Blount	6222	16.9	23.9	0.7	1848	1139
5/19/2011	Lab		N/A	12.6	15.9	0.8	4323	2591
5/23/2011	2		5094	12.2	13.7	0.9	4205	3884
5/26/2011	Lab		6027	19.0	32.1	0.6	2265	1137

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
5/26/2011 (2)	Lab		5780	14.6	24.1	0.6	3295	2016
6/3/2011	4	Tipton	5002	9.9	15.4	0.6	5709	2960
6/7/2011	2	Warren	4375	12.5	21.4	0.6	3173	1920
6/9/2011	2		5291	9.6	11.7	0.8	5157	4233
6/9/11 (2)	2	Warren	4830	13.8	20.3	0.7	3367	2248
6/21/2011	4	Gibson	4745	10.7	18.6	0.6	4850	2441
6/23/2011	2		4433	13.4	21.4	0.6	3843	2388
8/18/2011	4		4956	21.7	34.3	0.6	2031	1391
8/23/2011	4	Haywood	3798	11.9	17.2	0.7	7430	3519
8/25/2011	3		3771	15.1	21.5	0.7	3197	2062
8/29/2011	1	Blount	5019	14.9	22.7	0.7	2644	1490
9/1/2011	3	Williamson	4751	10.9	14.0	0.8	6068	4563
9/1/11 (2)	3	Williamson	4566	11.1	13.5	0.8	6185	LEAKED
9/7/2011	4	Gibson	5704	12.0	12.6	0.95	5421	4974
9/28/2011	4	McNairy	4875	6.7	7.1	0.9	N/A	N/A
10/5/2011	1		6358	12.9	22.8	0.6	4085	1971
10/11/2011	4	Hardeman	4739	10.9	12.3	0.9	6658	5127
10/20/2011	2	McMinn	6630	11.7	16.2	0.7	5512	4044

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
10/21/2011	Lab		6664	12.9	23.3	0.6	4027	2005
10/21/2011 (2)	Lab		5587	11.8	19.0	0.6	4540	2325
10/21/2011 (3)	2		4930	N/A	N/A	N/A	N/A	N/A
11/3/2011	1	Roane	7038	15.5	25.2	0.6	2999	1748
11/8/2011 C	2	Dekalb	5501	7.3	10.4	0.7	N/A	4866
11/8/2011 S	2	Dekalb	5659	8.8	11.5	0.8	7308	4196
12/20/211	1	Unicoi	5368	10.0	17.8	0.6	4585	N/A
1/20/2012	1	Johnson	4979	12.4	12.4	1.0	4701	2260
2/14/2012 (2)	4	Hardeman	5916	8.6	11.0	0.8	7330	3996
2/21/2012	4	Shelby	5833	10.5	16.9	0.6	4896	2198
3/6/2012	4	Weakley	4715	13.1	28.1	0.5	4583	1585
3/6/2012 (2)	1	Carter	4805	9.1	13.9	0.7	6578	3183

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
3/9/2012	2	Warren	6367	15.5	24.2	0.6	2607	1658
3/12/2012	1	Washington	5808	12.8	25.9	0.5	3893	2003
3/20/2012	4	Shelby	5198	18.3	25.5	0.7	1563	864
4/9/2012	4	Shelby	5804	14.3	23.7	0.6	2173	1450
4/10/2012	4	Hardeman	4945	11.0	12.2	0.9	5035	4619
4/18/2012	2	Franklin	4002	13.4	19.9	0.7	3879	2374
4/27/2012	2	Hamilton	4205	7.7	N/A	N/A	N/A	N/A
5/11/2012	4	Obion	4036	12.3	12.4	1.0	5940	4032
5/15/2012	1	Cocke	5487	16.1	27.8	0.6	2954	1280
5/15/2012 (2)	4	Hardeman	4566	8.6	10.0	0.9	7731	5795
5/24/2012	1	Hawkins	5964	12.8	20.6	0.6	3381	1934
6/7/2012	4	Shelby	5456	23.3	38.6	0.6	1922	928
6/14/2012	4	Hardeman	4668	12.0	14.1	0.8	4720	3494
6/14/2012 (2)	4	Shelby	4001	19.7	27.9	0.7	1907	1305
7/6/2012	4	Henderson	N/A	13.3	18.3	0.7	4957	2746
7/11/2012	4	Henderson	4352	12.0	17.9	0.7	5275	3189
7/24/2012	4	Henderson	5562	12.4	19.0	0.7	5018	2429
7/31/2012	2		4011	10.5	20.7	0.5	4138	2375

Table A1 Continued

Date	Region	County	28 day f'c (psi)	SR (kohm-cm) 28 day SR	56 day SR	(28/56) Ratio	RCP (Coulombs) 28 day RCP	56 day RCP
8/2/2012	1	Hamblen	4600	12.0	22.2	0.5	3236	2148
8/20/2012	1	Knox	4015	11.9	18.5	0.6	4393	2038
8/22/2012	1	Washington	4871	12.8	23.1	0.6	3960	2463
10/24/2012	1	Sevier	6395	19.9	30.0	0.7	2201	1373
10/24/2012 (2)	1	Hamblen	3665	10.7	16.4	0.7	5203	3010
11/15/2012	1	Knox	5208	15.0	21.3	0.7	3072	1639
12/18/2012	1	Morgan	6055	20.3	30.4	0.7	2618	1065
3/19/2013	4	Hardeman	6277	12.4	21.9	0.6	4043	2264

***__All SR values__ in this report incorporate a 10% increase to account for lime-water curing (AASHTO TP 95-11)*

***__All RCP values__ in this report incorporate a 12.1% reduction to account for the use of 4” cylinders instead of 3.75” cylinders (ASTM C1202)*

Table A2: SR Values Compared to Temperature, Air Content, and Slump

SR 28 day	SR 56 day	Mix Temperature (degrees F)	Air Content (%)	Slump
11.5	19.1	61	7.5	5
13.1	23.4	44	7.6	3.25
12.1	17.4	73	6.8	5.5
16.2	28.6	70.0	5.5	2.25
14.1	24.3	79	7.3	7
13.5	22.4	78	6.7	5.8
18.8	31.5	75	7	6
18.1	35.4	68	5.8	6
12	13.1	66	7.2	8
15.3	21.8	70	6.2	5.75
7.3	10.1	59	7	6.6
10.4	11.8	60.5	6.7	6.5
8.1	11.0	82	7.3	6.8
19.1	24.5	77	6.4	7.6
11.2	15.6	84	7.1	7.4
13.1	27.4	81.3	8	6.5
11.7	19.8	73	7	7
14.1	20.7	60	7.6	8
12.5	23.1	68	6.8	5.75
9.4	18.3	70	8	8.25
11.3	13.7	62	5.3	3.5
14.2	13.7	58	6.8	7
14.2	31.1	60	7.5	6
7.1	6.8	67	6.2	5.5
12.4	15.9	61	6	5.25
9.5	11	56	8.5	7
12.3	14.6	59	6.8	6.5
9.6	15.8	63	6.8	8
11.4	17.6	70	8	7.5
12.4	17.0	76.5	7.25	6.5
11.7	19.2	81.0	6.2	4.25
10.2	13.9	81	5.5	6
12.7	23	72.0	7.6	4.5
22.2	37.4	80	5.9	4.25
8.9	15.7	62	7	4
9.6	19.0	58	7.3	5.75
10.9	19.3	79	6.6	6.75

Table A2 Continued

SR 28 day	SR 56 day	Mix Temperature (degrees F)	Air Content (%)	Slump
	7.2	86	5.1	5
5.8	6.2	85	6.1	6.5
11.7	18.9	81	6	7
8.4	13.8	84	6.5	7.5
6.4	7.4	86	6	6
11.6	21.4	84	7	7.25
12.9	25.5	84	7.8	4.75
8	18.4	65	7.1	4
14.1	23.6	60	2.8	7
9.3	17.6	55	6.6	7
9.9	16.2	50	7.8	6
8.7		50	7.5	6.5
14.4	30	59	8	4.5
7.6	14.9	61	6.1	4
5.5	6.6	57	6.9	7
	26.2	67	6.4	6
8.8	17.6	63	6	4
9	14	83	7	6.25
9.7	16.9	86	6.6	5.5

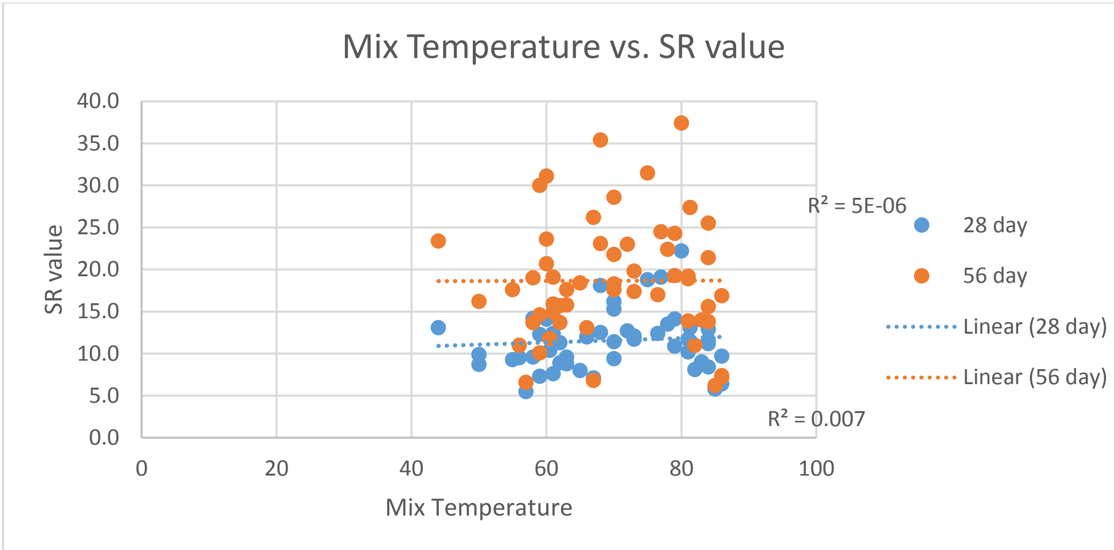

Figure A1: Mix Temperature vs. SR Value

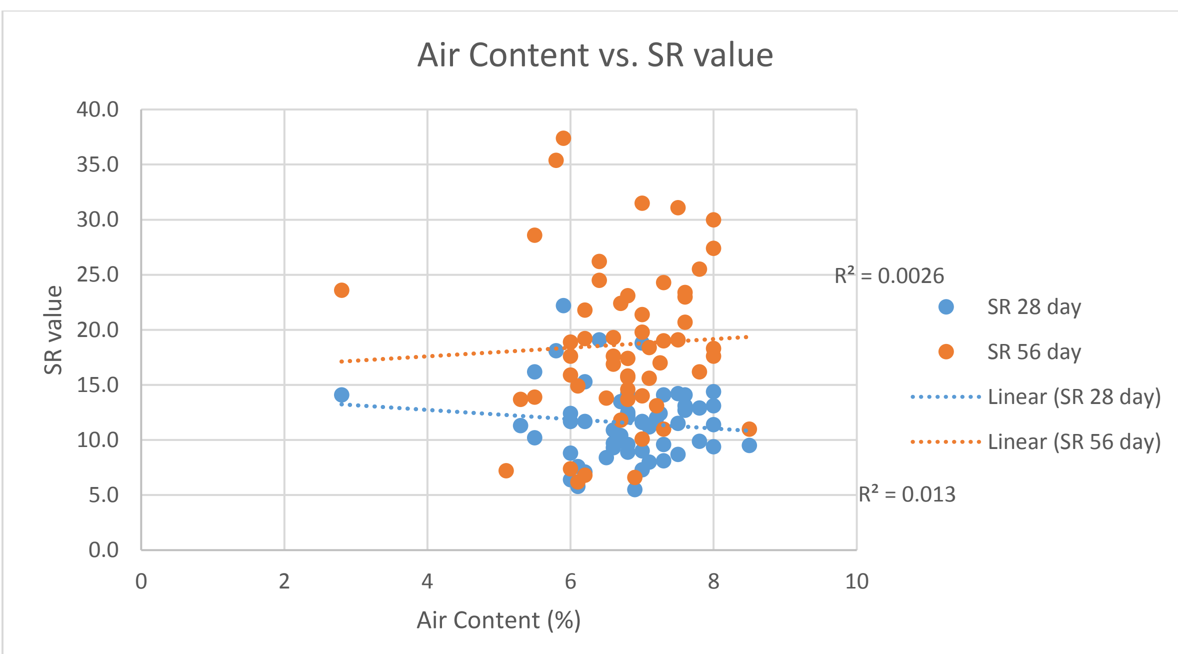

Figure A2: Air Content vs. SR Value

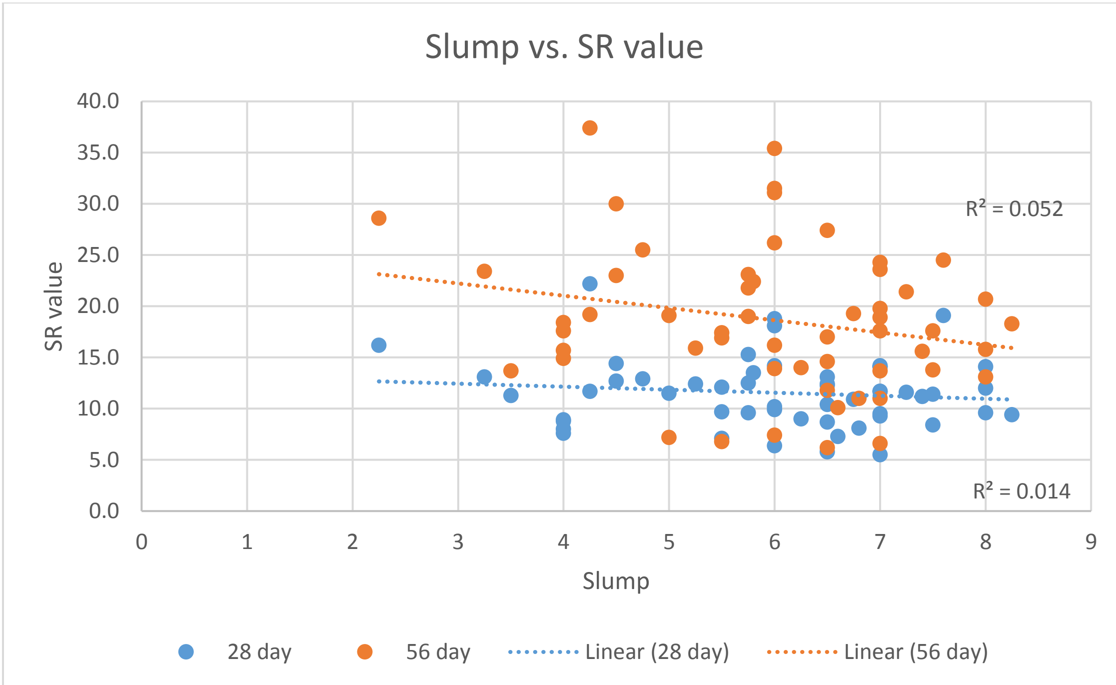

Figure A3: Slump vs. SR Value

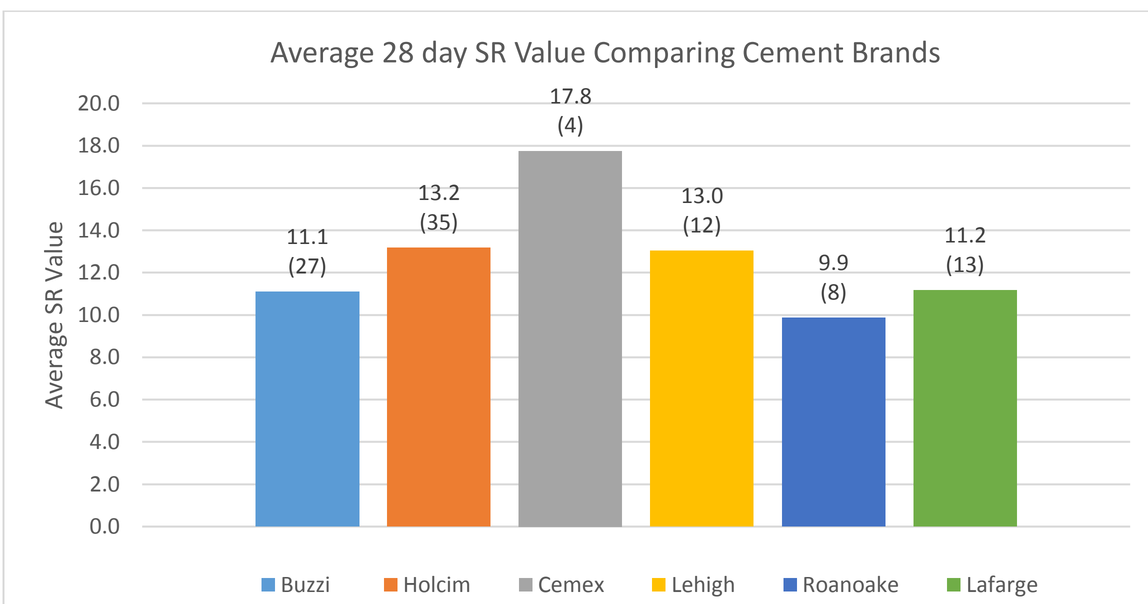

Figure A4: Average 28 day SR Value Comparing Cement Brands

(Numbers in parenthesis indicate number of samples)

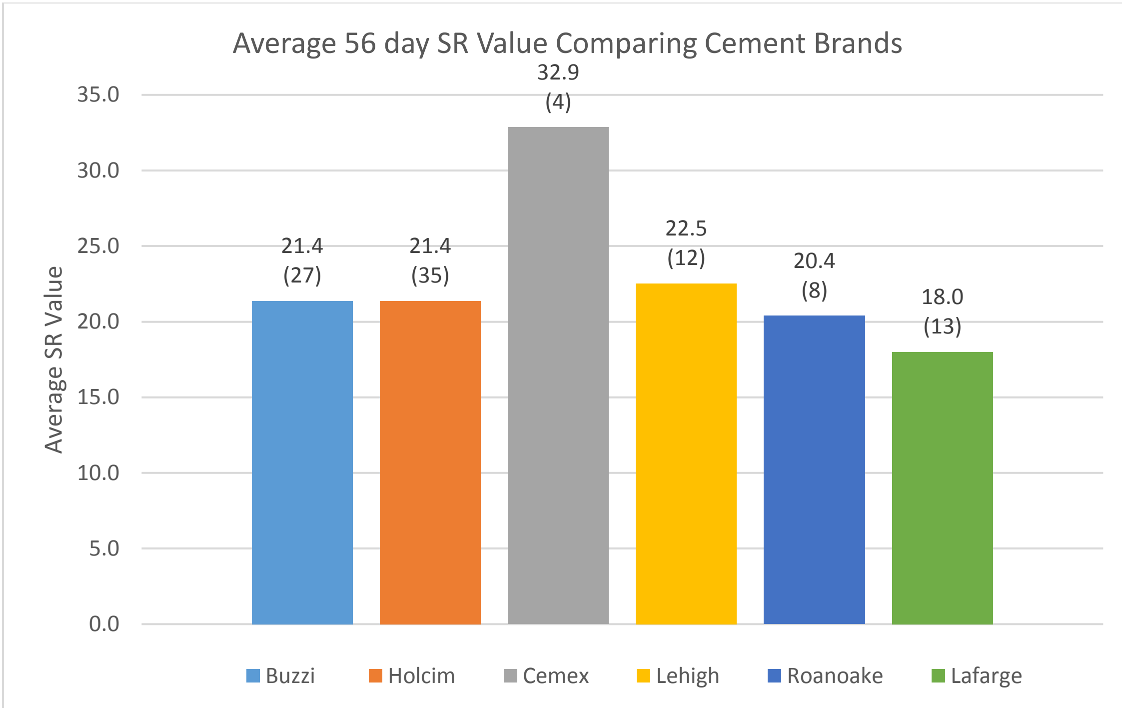

Figure A5: Average 56 day SR Value Comparing Cement Brands

(Numbers in parenthesis indicate number of samples)

Table A3: Buzzi Cement

	Region	County	28 day SR	56 day SR	Job
	2	Hamilton		12.9	CNF 114
	1	Knox	15.5	26.8	CNH 166
	3	Williamson	12.6	19.4	CNG 840
	2	Polk			CNH 645
	4	Henderson	9.3	15.2	CDR 091
	4	Lake	12.8	23.6	CNH 147
	3	Williamson	14.0	25.3	CNG 840
	2	McMinn	12.5	15.0	CNH 243
	2	Polk	15.6	15.1	CNH 645
	2	Marion	7.8	7.5	CNJ 232
	1	Knox	13.2	14.4	CNH 166
	4	Dyer	8.3	16.4	CNJ 168
	1	Blount	16.9	23.9	CNJ 934
	4	Carroll		9.9	CNH 246
	2		13.4	21.4	CNJ 039
	1	Blount	14.9	22.7	CNJ 934
	3	Williamson	10.9	14.0	CNG 840
	3	Williamson	11.1	13.5	CNG 840
	2	McMinn	11.7	16.2	CNH 243
	1	Roane	15.5	25.2	CNH 252
	1	Blount		29.6	CNJ 278
	4	Shelby	10.5	16.9	CNG 065
	4	Shelby	14.3	23.7	CNJ 516
	2	Hamilton	7.7		CNJ 395
	2			10.2	CNH 645
	2		10.5	20.7	CNK 233
	1	Hamblen	10.7	16.4	CNK 014
Average			12.3	18.2	

Table A4: Holcim Cement

	Region	County	28 day SR	56 day SR	Job
	4	Madison		7.9	CNJ 031
	4	Madison	12.8	20.8	CNH 280
	4	Gibson	14.2	28.1	CNH 677
	4	Shelby	15.5	26.0	CNH 248
	4	Naywood	10.9	17.8	CNH 041
	4	Gibson	9.5		CNJ 911
	4	Crockett	15.9	33.0	CNH 191
	4	Shelby		28.9	CNH 248
	2	White	10.5	12.0	CNJ 236
	4	Hardeman	9.7	19.4	CNJ 237
	4	Hardeman		12.1	CNJ 237
	4	Gibson	10.7	18.6	CNJ 911
	4		21.7	34.3	CNH 248
	4	Haywood	11.9	17.2	CNH 041
	4			18.5	CNJ 031
	4	Gibson	12.0	12.6	CNJ 911
	4				CNJ 281
	4	Hardeman	10.9	12.3	CNJ 237
	4	Shelby		24.0	CNH 248
	4	Fayette		26.5	CNJ 276
	4	Hardeman	8.64	11.0	CNJ 202
	4	Shelby		40.3	CNH 248
	4	Haywood		18.1	CNJ 286
	4	Shelby	18.3	25.5	CNF 178
	4	Hardeman	11.0	12.2	CNJ 202
	4	Fayette		39.0	CNJ 276
	4	Shelby			Pin 101615
	4	Hardeman	8.6	10.0	CNJ 202
	4	Shelby	23.3	38.6	CNH 248
	4	Hardeman	12.0	14.1	CNJ 202
	4	Shelby	19.7	27.9	PIN 101615
	4	Gibson		24.5	CNH 677
	4	Shelby		32.0	PIN 101615
	4	Hardeman		20.2	CNJ 202
	4	Hardeman	12.4	21.9	CNJ 202
Average			13.3	22.0	

Table A5: Cemex Cement

	Region	County	28 day SR	56 day SR	Job
	1	Sevier	20.7	34.6	CNH 594
	2	Hamilton	14.4	30.1	CNJ 132
	1	Sevier	19.9	38.9	CNH 138
	1	Cocke	16.1	27.8	CNL 068
Average			17.8	32.9	

Table A6: Lehigh Cement

	Region	County	28 day SR	56 day SR	Job
	2	Coffee	8.9	12.1	CNH 625
	2	Warren	12.9	21.8	CNH 204
	2	Warren	15.5	22.7	CNH 204
	2	Warren	13.7	25.4	CNH 204
	2	Warren	10.4	20.1	CNH 204
	2	Warren	16.6	24.8	CNH 581
	2	Warren	15.6	34.2	CNH 581
	2	Rhea	10.5	17.4	CNJ 135
	2	Warren	12.5	21.4	CNH 153
	2	Warren	13.8	20.3	CNH 153
	1		12.9	22.8	CNJ 171
	2			27.5	CNH 153
Average			13.0	22.5	

Table A7: Roanoake Cement

	Region	County	28 day SR	56 day SR	Job
	1	Unicoi	10.0	17.8	CNK 931
	1	Johnson	12.4	20.8	CNJ 161
	1	Carter	9.1	13.9	CNK 021
	1	Washington	12.8	25.9	CNJ 314
	1	Hawkins	12.8	20.6	CNK 408
	1	Sullivan		18.8	CNK 244
	1	Hamblen	12.0	22.2	CNK 802
	1	Washington		23.1	CNJ 314
Average			11.5	20.4	

Table A8: Lafarge Cement

	Region	County	28 day SR	56 day SR	Job
	2	Clay	21.0	26.9	CNH 158
	4	McNairy	6.4	6.9	CNH 716
	4	McNairy	7.0	8.1	CNH 716
	4	Decatur	8.8	20.2	CNH 217
	4		10.2	19.4	CNJ 257
	4	McNairy	6.0	7.2	CNH 716
	4	Tipton	9.9	15.4	CNH 643
	4	Henderson	11.8	26.7	CNJ 311
	4	Weakley	13.1	28.1	CNK 124
	2	Franklin	13.4	19.9	CNK 315
	4	Henderson	13.3	18.3	CNJ 311
	4	Henderson	12.0	17.9	CNJ 311
	4	Henderson	12.4	19.0	CNJ 311
Average			11.2	18.0	

Vita

Lindsey Phelps, daughter of Jerry and Pauletta Gadberry and younger sister to Lucas, was born in 1992 in Somerset, KY. She attended Pulaski County High School in Somerset, KY where she graduated in 2010. She first attended Somerset Community College where she was a pre-engineering major. After two years, she transferred to Western Kentucky University in Bowling Green, KY to pursue her Bachelor's Degree in Civil Engineering. After receiving her Bachelor's Degree, she began her Master's Degree at the University of Tennessee, Knoxville. While at the University of Tennessee, she worked under the direction Dr. Edwin Burdette. After graduating, she plans to pursue a career in industry.

While at Western Kentucky University, Lindsey became involved in Omega Phi Alpha (national service sorority) and the American Society of Civil Engineers (ASCE) where she was a member of the steel bridge team in 2015 and completed 25th in the nation. In 2014, she married Eric, an Eastern Kentucky University Agricultural Livestock Production Graduate. They currently reside in Somerset, KY. Lindsey enjoys camping, embroidery, and riding her motorcycle.