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Performance Specification for Tennessee Bridge Decks

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I am submitting herewith a thesis written by Brian Ray Buchanan entitled "Performance Specification for Tennessee Bridge Decks." 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.

Dr. Ed Burdette, Major Professor

We have read this thesis and recommend its acceptance:

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Performance Specification for Tennessee Bridge Decks

A Thesis
presented for the Master of Science
degree

The University of Tennessee, Knoxville

Brian Ray Buchanan

December 2011

Dedication

This thesis is dedicated to my son, Braden, and wife, Melissa, who continue to inspire and challenge me on a daily basis and also to my parents whose support and work ethic make all things possible.

Acknowledgements

I would like to express my deepest gratitude to my mentor, professor, and friend Dr. Ed Burdette and also Dr. Dayakar Penumadu who together made this wonderful opportunity possible. Their sincerity and caring speak volumes about the character of the university that I have come to call home. I am also forever indebted to my fellow researcher, student, and friend, Eric Ryan, for all of his support and understanding throughout my education. Thanks must also be expressed to the personnel at the Tennessee Department of Transportation (TDOT), Ed Wasserman in particular, whose support made this research possible. All of my fellow students and professors at the University of Tennessee have made a real impression on my life and I will forever strive to maintain the integrity they have all instilled in me. Special appreciation also goes out to Robby Nidiffer who will carry on this research and has been instrumental in the closing of this chapter.

Abstract

In today's world of ever increasing demand on a weakening infrastructure, concentration is being firmly placed on increasing the sustainability of that infrastructure. Tennessee's bridges and the concrete decks, on which the public travels, require a large part of the state's infrastructure spending. Research has shown the current durability standards of Tennessee's bridge decks could be significantly improved which would both increase service life and reduce maintenance costs of these structures. This research concentrates on greatly increasing the lifespan of these bridge decks, throughout the state, through an improved construction specification which will encourage the increased use of supplementary cementitious materials. These improved construction specifications would be performance based in nature and would give suppliers increased freedom to provide a more durable product while simultaneously reducing costs. This new performance based specification will remove the current stringent prescriptive requirements and will use the measurement of surface resistivity (SR) as a key variable to be assessed as a measure of performance. The ultimate goal of implementing a performance based specification is to achieve more durable bridge deck concrete. The proposed

specification presented herein grew out of two years of research related to assessing the current situation regarding bridge deck concrete in Tennessee and the development of methodology to perform this assessment.

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Chapter 1: Introduction

1.0 Background

In September of 2009, research began at the University of Tennessee (UT) for the Tennessee Department of Transportation (TDOT) using concrete samples that were taken from the construction of bridge decks as they were placed throughout the entire state. The purpose of this research was two-fold: first to establish a correlation between the current accepted method for forecasting the resistance of bridge deck concrete to penetration of chloride ions and a newer, much less user sensitive, test that is quickly seeking acceptance in the concrete testing field; second, to establish a reasonable acceptable value of this new test for use in a performance based specification to be implemented on all Tennessee bridge decks throughout the state. Through September 1st, 2011 tests have been performed on 67 sets of samples at ages of 28, 56, and 91 days to establish the current state of Tennessee bridge deck concrete. Tests so far have found chloride ion penetration values higher than initially expected.

The current industry accepted test to predict concrete’s ability to resist chloride ion penetration is ironically known as the

Rapid Chloride Ion Penetration Test (RCP) and is described in ASTM C1202. The irony is that there is nothing about this test that could be considered “rapid”. Standard age of test specimens is 56 days, and the test requires a labor intensive 30 hours to complete during which there is ample opportunity for technician-induced variation of the results. A test method that has been introduced in recent years and is quickly gaining industry acceptance is the Surface Resistivity (SR) Test. The results from the SR test show a strong correlation to the RCP test and can be completed easily in less than half an hour once the specimen has been gathered and with minimal opportunity for error. This new, easier, more reliable test opens up a large avenue into the durability testing of Tennessee bridge deck concrete and the potential use of a durability standard in a performance based concrete specification.

The average value of the currently accepted 56 day RCP test for all the samples taken from across the state of Tennessee as of September 1st, 2011 is 2811 coulombs (1). This average statewide value does not include the readings from five sets of samples that had extremely high values such that they surpassed the capabilities of the testing apparatus and had to be terminated early to prevent damage. When compared to Table 1 from ASTM

C1202, one can see that this value is considered “moderate” for Chloride Ion Penetrability (2).

Table 1: Chloride Ion Penetrability Based on Charge Passed (2)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

Tennessee results are consistent with research that was concluded in 2003 by the Federal Highway Administration (FHWA) into the use of high performance concrete in bridge construction (3). This FHWA research produced some highly variable results. Permeability of cast-in-place bridge decks from 10 different states was recorded; for the same prescriptive mix designs, results ranged from a “very low” reading of 461 to a “high” reading of 5597 coulombs (3). Obviously, there is adequate room for improvement to justify a change in current practice.

1.2 Testing Program

On September 1st, 2009, research started at the University of Tennessee, Knoxville (UTK) to determine the feasibility of replacing the currently accepted test to measure the resistance of concrete to penetration of chloride ions. This research, which is continuing at UTK, was performed for the Tennessee Department of Transportation (TDOT) in which thirteen 4x8 inch cylindrical samples were taken from bridge deck placements throughout the state by TDOT personnel in the Materials and Testing Division.

Once the samples had been collected by TDOT personnel, they were field cured by placement near the bridge deck in an area that would afford similar exposure to environmental conditions as experienced by the bridge deck for 24 hours. The samples were then placed into wheeled marine coolers and transported to regional offices by TDOT personnel where they were stored in the moist room to await transport to TDOT headquarters in Nashville, TN. The samples were then picked up by Region 1 personnel from headquarters and transported to the Region 1 office located in Knoxville. The samples were again stored in a moist room to await pickup by UT personnel who transported the samples back to UT for the actual testing.

Upon arrival at UT the samples were immediately removed from the molds and placed into a lime water tank, as described in ASTM C511, for curing until the test date, and the sample properties were collected and placed onto data collection sheets (10). Normally three of the specimens would be tested at a specimen age of 7 days by TDOT personnel for compressive strength according to ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) prior to arriving at UT (11). At a specimen age of 28 days, 7 samples were removed from the tank. Three of these specimens were tested for compressive strength according to ASTM C39. One sample was tested only for resistivity according to Florida Department of Transport test method FM 5-578 (Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability) for comparison to its resistivity at a specimen age of 56 and 91 days (12). The remaining three specimens were also tested for resistivity according to FM 5-578, but after resistivity testing the specimens were prepped and tested for conductivity according to ASTM C1202 (Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration) which encompassed two days of testing. The remaining three specimens were similarly tested according to FM 5-578 and ASTM C1202 at a specimen age of 56 days. The mix design information for each set of samples was also gathered for the purpose of comparing the variations in the different mixes to their surface resistivity and conductivity values. This mix design data has been included in the Appendix.

Chapter 2: Literature Review

This section briefly describes some of the necessary background to be considered in the development of a performance based specification. Section 1 describes the determining factor of durability in cast in place concrete decks. The different methods by which chloride ions penetrate concrete bridge decks are then discussed followed by the details of the Surface Resistivity (SR) and Rapid Chloride Ion Penetration (RCP) tests. Also herein discussed is the correlation between the two tests and the relationship between 56 day and 28 day SR testing

2.1 Durability of Concrete Bridge Decks

One of the hurdles for implementing a performance based concrete specification which includes a durability component has been the decision of which of the concrete properties actually determines the durability of the final product. On the subject of concrete bridge decks, there exists a multitude of researchers that agree that the corrosion of reinforcing steel due to chloride penetration of concrete is the leading cause of damage (4; 5; 6; 7). While limiting shrinkage, and likewise cracking, of the concrete deck could be argued as an important factor in its overall durability, many of the same parameters that contribute to a less permeable concrete also result in lower shrinkage values. Cracking in bridge structures has also been mainly attributed to moisture loss and temperature change which can only be controlled to a small degree (8). Therefore permeability of the bridge deck concrete was the only variable considered in the scope of this research.

2.2 Methods of Chloride Penetration

Corrosion of the steel due to chloride ions has long been considered the chief cause behind frequent expensive maintenance and repairs for reinforced concrete structures. The corrosion of the steel causes expansion of the metal which likewise causes cracking and spalling in the cover concrete which in turn allows for more rapid corrosion if not addressed in a timely manner (7). Within concrete bridge decks there are two main avenues by which chloride ions can access the reinforcing steel and cause this corrosion. One avenue is through the capillary action caused by the voids in the concrete, and the other, larger, concern is through the diffusion of chloride ions that exist in surface water and diffuse to the area of lower concentration within the voids in the concrete. Capillary action has been shown to increase with increased amounts of cement paste and water which cause larger, more defined air voids (10). The use of supplementary cementitious materials (SCMs) such as Fly Ash, Granulated Ground Blast Furnace Slag (GGBFS), or Silica Fume in place of a percentage of Portland cement has been shown to greatly reduce this capillary action by reducing the size of the air voids and likewise reducing the capillary action caused by the voids (10). Lowering the water-cementitious material ratio (w/cm) also decreases both the potential for shrinkage and damage from freeze/thaw cycles (12).

2.3 Surface Resistivity Testing

The electrical resistivity (ρ) of a material is found by multiplying the resistance (R) of that material by the cross-sectional area (A) which is then divided by the length (*l*) of the sample (1).

—— **Equation 1 (1)**

The above equation results in a reading of ohm-length which for ease of comparison to other research has been converted to kilo ohm-centimeter (kohm-cm). In order to minimize the effect of varying densities close to the surface of a concrete sample, four equally spaced probes known as a Wenner probe are employed when dealing with concrete samples. A current is driven across the outer two probes, and the voltage drop is measured across the inner two probes. Figure 1, in the AASHTO Specification which is currently being revised, illustrates this design.

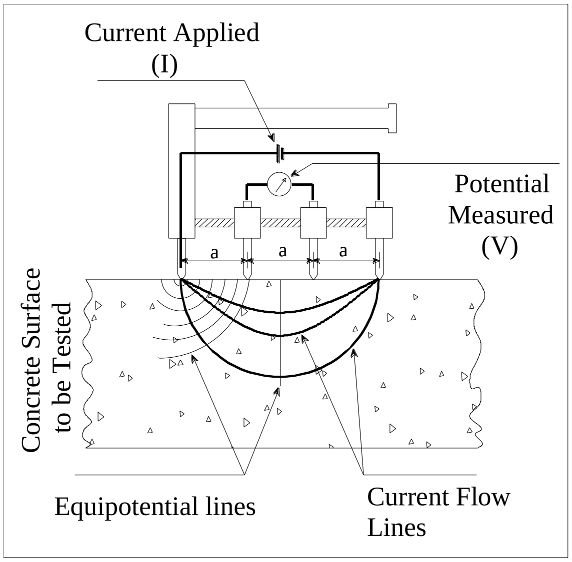


Figure 1: Four Point Wenner Probe (13)

2.4 Rapid Chloride Ion Penetration (RCP) Testing

As outlined in ASTM C1202 the RCP test is a conductivity test which has been well correlated to AASHTO T259 (salt ponding test) which is an extended duration test that measures the physical ingress of chloride into a test slab onto which salt water is ponded for a period of 90 days after curing. AASHTO T259 is an often used test, but the lengthy time required to administer the test precludes its use in a performance based specification. During the RCP test a 2 inch thick, four inch diameter sample is prepped and placed between two testing cells, one containing sodium chloride (NaCl), and the other containing sodium hydroxide (NaOH). Once the sample has been properly sealed and cured to prevent leakage of the solutions during the six hour test, a constant current from a 60V power supply is applied to the sample and the amount of charge passed, or the conductivity (σ), through the sample is measured at thirty minute intervals in Coulombs. The total amount of charge passed after six hours of testing has been shown to correlate well with the results from AASHTO T259. Figure 2 illustrates the test set-up of the RCP test (9).

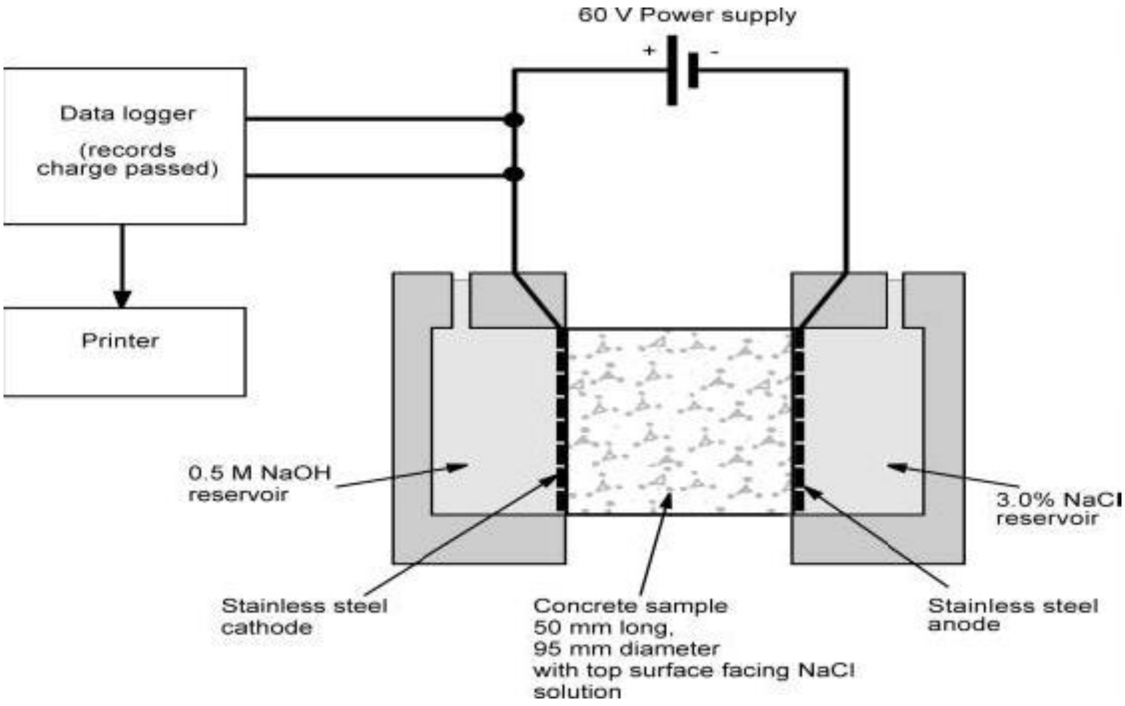


Figure 2: ATSM C1202 Test Setup (9)

The RCP test, while considerably shorter than the salt ponding test, requires 56 days (typically) to cure the sample and approximately 2 days to properly prep the sample and conduct the test. The RCP test also suffers from several criticisms (10):

1) There is a relatively high coefficient of variation between tests.
2) Results on samples of marginal quality are skewed by heating that occurs during testing.
3) Total charge passed is due to all ions present in the sample, not only the chloride ions present in the solution.

These criticisms of the RCP test, coupled again with an unacceptable amount of time required to perform the test from the construction standpoint, have been the major points of understandable reluctance to its use in a performance-based specification.

2.5 Correlation between RCP and SR Testing

The electrical conductivity (σ) of any material is simply the inverse of the material's electrical resistivity (ρ) as shown by the equation 2 (14):

$$- \qquad \textbf{Equation 2}$$

It is therefore understandable that the conductivity of a concrete sample should correlate well with its resistivity. This correlation has been the subject of recent research here at the University of Tennessee (UT) and by the Florida Department of Transportation (FDOT). Fifteen months of research that included

64 separate field samples supplied by the Tennessee Department of Transportation (TDOT) tested at UT have shown a strong correlation between SR and RCP regardless of the age of the specimen (1). Results from research by Ryan (2010) are shown graphically in Figure 3.

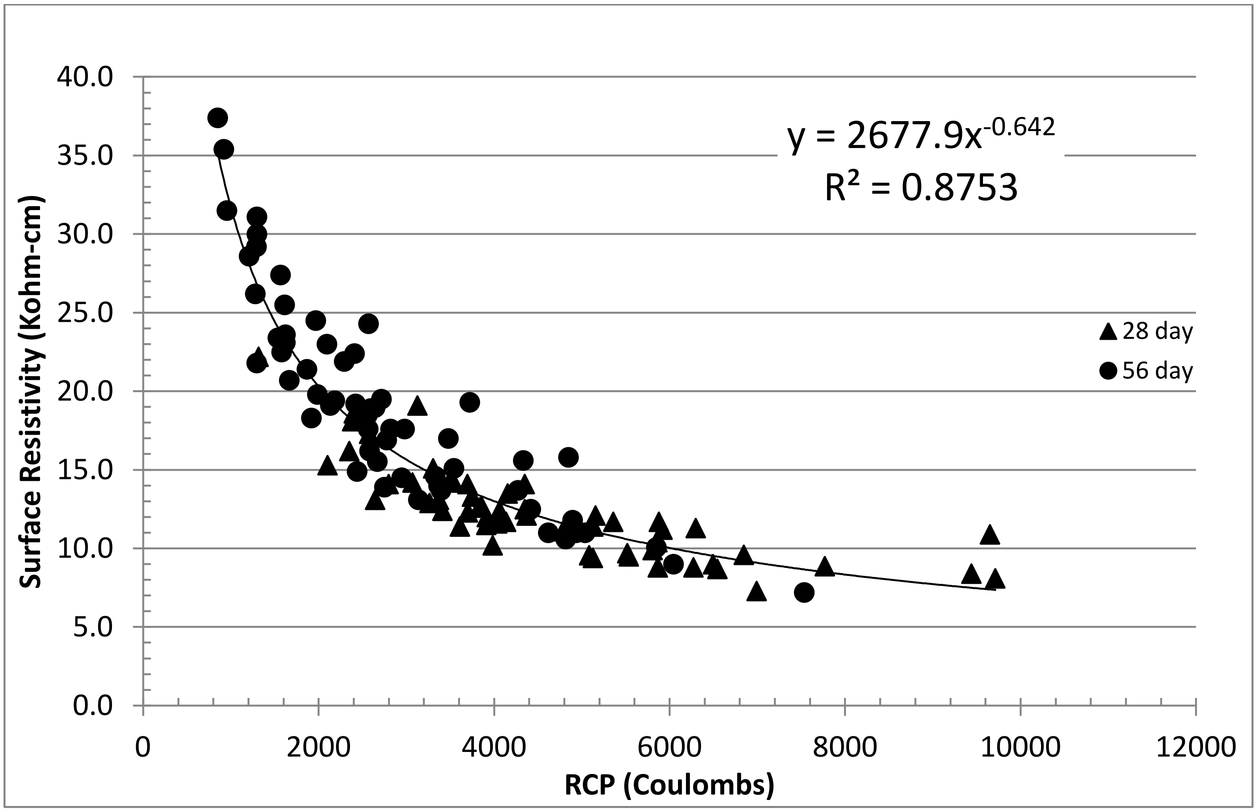


Figure 3: SR vs. RCP (Combined 28 and 56 Day Data) (1)

While research into this correlation continues at UTK, the R^2 value of 0.88 thus far demonstrates that a sufficient correlation exists between the two tests to warrant the use of the faster, more reliable SR test in the formulation of a performance-based specification.

2.6 Correlation of 56 Day and 28 Day Surface Resistivity

The initial challenge of this research program was the establishment of a correlation between RCP and SR test results for concrete produced in across Tennessee by many different producers, with that challenge having been met to a relatively high confidence level; the next challenge is to relate the SR results at 56 days to a 28 day value. Using 28 day measurements will minimize the interference to construction schedules while still insuring a durable final product with a reasonable level of confidence. In this way an acceptable level of RCP at 56 days, once established, can be correlated to an SR value, also at 56 days, and then that 56 day SR value can be predicted using a 28 day SR value. Figure 4 shows this 28 vs. 56 day SR relationship on the field samples taken from bridge deck construction throughout Tennessee.

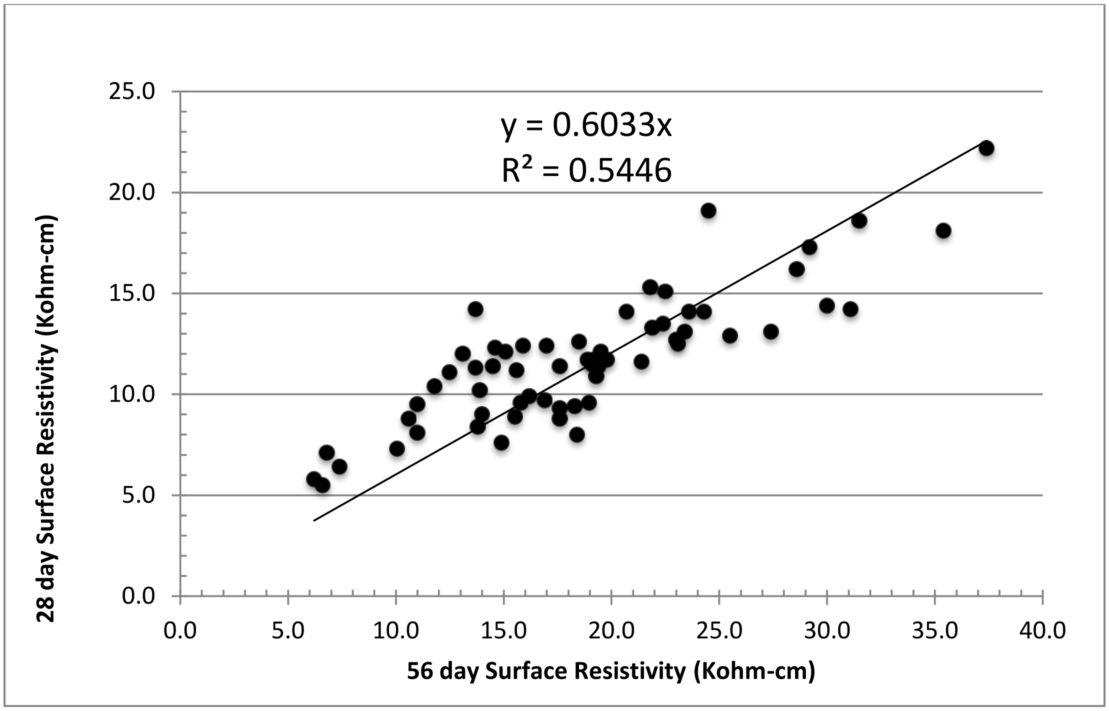


Figure 4: 28 day Surface Resistivity vs. 56 day Surface Resistivity

As noted by Ryan in his research, the coefficient of determination (R^2) value of 0.54 seems low in that only 54% of the variation is explained by the regression line, but the slope of that regression line of 0.60 is consistent with similar research that shows the slope of between 0.55 and 0.6 (1). With this consistency of results, when comparing with other research on the same subject, it seems reasonable to use the correlation established in Figure 4 to predict 56 day SR values at 28 days in the state of Tennessee.

Chapter 3: Literature Review of Current Practice

3.0 Performance Based Specification Description

Rosen and Heineman (1990) define a performance based specification as "specifying an end result by formulating the criteria for its accomplishment" (13). This differs from the currently prevalent practice of specifying bridge deck concrete which is prescriptive, whereby the materials to be used are supplied in cookbook fashion, and the end result is implied within the "recipe". Designers who utilize prescriptive specifications inherently understand that the use of supplementary cementitious materials (SCMs) such as fly ash, in a concrete mix design, results in a less permeable bridge deck. Yet, the end result of a "prescriptively specified" product is rarely tested and verified. For example, in a performance based specification for low permeability the permeability and the means by which that permeability will be tested are clearly stated, thereby confirming, as opposed to implying, the desired result. Rosen and Heineman propose that the following three elements must exist in a performance specification (13):

a) **<u>Requirement</u>**: A qualitative statement of the desired performance.

b) **Criterion**: A quantitative statement of the desired performance.
c) **Test**: An evaluative procedure to assure compliance with the criterion.

A performance based specification for a cast-in-place (CIP) concrete bridge deck should therefore include these elements:

a) **Requirement**: A durable CIP concrete bridge deck.
b) **Criterion**: A surface resistivity (SR) reading of a specific value at a specimen age of 28 days.
c) **Test**: Florida Test Method FM-578 (or the AASHTO test method currently under review)

The specification of the final performance of a product is not innovative in and of itself. For example, in the field of specialized mechanical units, measures to assure quality are standard practice. In the use of extremely high volume water pumps, which are inherently difficult to test and extremely costly, pumps are often purchased through the use of a "performance warranty". Purdy defines a performance warranty as "a quantitative statement made by the supplier about performance, accompanied by a promise to pay a specified sum if the statement is not so" (14). The payment for a shortfall in overall performance is paid in lieu of future expenses that will be experienced due to less than optimal performance of the unit such as increased operating costs, maintenance expenses, etc.

For the example high volume water pump, a possible performance warranty would be to guarantee the pump to have a certain operating efficiency under certain conditions such as 85% efficiency based on 20 feet of applied head pressure. This warranty can be likened to a performance specification of a concrete bridge deck which is impossible to test prior to actually placement, and a percentage of payment could be withheld if the performance goals were not met in order to compensate for the increased maintenance demands required by the decreased durability.

3.1 Performance Based Specification Examples

In many different states throughout the U.S. there has been bridge projects that made use of a performance based specification, or have specified a maximum chloride ion penetration in addition to their prescriptive specifications, in the construction of the bridge deck. Many of these projects made use of the new specification in conjunction with the use of high performance concrete. This section describes some of the experiences and the reasons particular states chose to implement a performance based specification.

3.1.1 Virginia

The Virginia Department of Transportation (VDOT) has made use of a permeability requirement on several different projects that involved bridge deck construction with very good results. In all of the projects the samples were “heat cured” in a lime bath at 100° F for a period of 21 days after 7 days of room temperature curing in a lime bath. This was done in order to predict the permeability of the deck at an age of 90 days–1 year. This is important to note when comparing the values from the RCP test, which was used to predict the penetrability in all of the VDOT testing, due to the fact that the RCP results of the “heat cured” samples were on average 46% lower than room temperature cured samples (15).

The first bridge in Virginia to make use of high-performance concrete was constructed in 1995 and located in Campbell County on State Route 40 and was designed with prestressed girders and a cast-in-place deck, both of which were given limits for maximum acceptable coulomb values as determined by the RCP test at 28 days. The maximum value for the concrete deck was 2,500 coulombs using “heat cured” samples. The mix design for the deck contained a total of 658 lb/yd^3 of cementitious material which was comprised of 50% cement and 50% ground-granulated blast furnace slag (16). The design compressive strength of the deck was the standard 4,000 psi.

The results from the Route 40 Bridge were very promising; the RCP test results averaged 778 coulombs, which was less than a third of the specified value of 2,500, and the average compressive strength of 8,710 psi for the deck at 28 days was also over double the design strength of 4,000 psi (17). In his article in the Transportation Research Record, Ozyildirim credits the low permeability, in large part, to the use of slag along with a low w/cm ratio of 0.4 which was strictly monitored by the contractor (17).

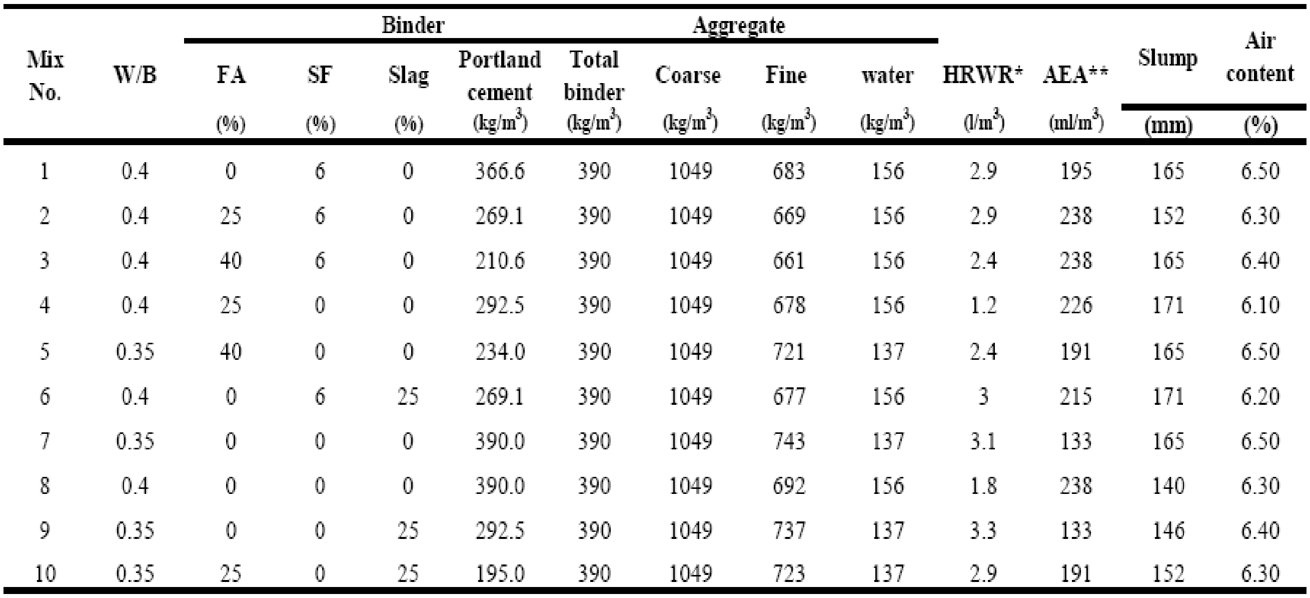
VDOT has also begun the implementation of a Performance Based Specification (PBS) in the construction and maintenance of their bridge substructures and superstructures. VDOT’s first PBS was implemented in the installation of a new concrete overlay on the bridge over the Rockfish River on Route 29, which is approximately 100 miles east of Richmond VA, in mid-year 2003 (19). The PBS contained quality limits: upper, or lower, bounds or both, for compressive strength, permeability, bond strength, and air content, all of which were reflected in a “pay factor” which was used to adjust the contactor’s pay if the limits were not met. The “pay factor” is found using a table supplied by VDOT, which is based on the standard deviation of the samples tested and the number of samples, to acquire a PWL (percentage within limits). This PWL is then compared to upper, lower, or both, quality indexes to arrive at the final “pay factor” which is applied to the bid price for the bridge deck concrete (19).

The results from this initial PBS were extremely good for both VDOT and the contractor on the project. The contractor met or exceeded all the criteria that were established in the pay factor and earned the maximum bonus of 6% for the deck installation. The compressive strength of the deck was found to be nearly double the lower quality limit and the conductivity was less than 75% of the upper limit of 1000 coulombs at 28 days. Even after the payment of the bonus, VDOT calculated that it experienced a savings of approximately 9% due to the fact that the initial bid price was 15% lower than the average bid price in that district for similar jobs (17).

3.1.2 Indiana

At the end of Phase 1 of extremely extensive research by Purdue University for the Indiana Department of Transportation and the FHWA, Olek et al. arrived at the following ten mix designs for further study and possible eventual inclusion into a performance based specification for high performance bridge decks in the state of Indiana (18).

Table 2: Mixture Proportions and Fresh Concrete Properties of 10 Concrete Mixtures Selected for Phase II Study (18)



Mix No.	W/B	Binder					Aggregate			HRWR*	AEA**	Slump	Air content
		FA (%)	SF (%)	Slag (%)	Portland cement (kg/m^3)	Total binder (kg/m^3)	Coarse (kg/m^3)	Fine (kg/m^3)	water (kg/m^3)	(l/m^3)	(ml/m^3)	(mm)	(%)
1	0.4	0	6	0	366.6	390	1049	683	156	2.9	195	165	6.50
2	0.4	25	6	0	269.1	390	1049	669	156	2.9	238	152	6.30
3	0.4	40	6	0	210.6	390	1049	661	156	2.4	238	165	6.40
4	0.4	25	0	0	292.5	390	1049	678	156	1.2	226	171	6.10
5	0.35	40	0	0	234.0	390	1049	721	137	2.4	191	165	6.50
6	0.4	0	6	25	269.1	390	1049	677	156	3	215	171	6.20
7	0.35	0	0	0	390.0	390	1049	743	137	3.1	133	165	6.50
8	0.4	0	0	0	390.0	390	1049	692	156	1.8	238	140	6.30
9	0.35	0	0	25	292.5	390	1049	737	137	3.3	133	146	6.40
10	0.35	25	0	25	195.0	390	1049	723	137	2.9	191	152	6.30

* DARACEM 19 (W. R. Grace & Co.) was used as high range water reducer (HRWR)
** DARAVAIR 1400 (W. R. Grace & Co.) was used as air entraining agent (AEA)
The quantities of HRWR and AEA were adjusted during mixing to obtain the target slump of 5.5 ± 1.5 in and air content of 6.5 ± 0.5%

FA = Fly Ash

W/B = Water to Binder Ratio

SF = Silica Fume

HRWR = High Range Water Reducer

AEA = Air Entraining Agent

The "binder" in the table simply refers to cementitious material. The authors felt that this was less confusing than referring to fly ash, silica fume, and slag as cementitious materials. Their performance parameters for the study were based on the water/binder (w/b) ratio of the mix. For a w/b of 0.4 the maximum conductivity was 1500 coulombs with 28 day strength of greater than 8500 psi, and for a w/b of 0.35 the maximum conductivity was 1000 coulombs with a minimum compressive strength of 11,000 psi (18).

3.1.3 New Mexico

The chief challenge for the New Mexico Department of Transportation (NMDOT) is the extreme reactive nature of the aggregates available in the region. For this reason NMDOT chose to concentrate the bulk of its effort controlling the Alkali-Silica Reactivity (ASR) in concrete, but during the initial rewrite of the existing prescriptive concrete specification, NMDOT realized that they had more than one issue to deal with. In order to solve multiple issues, NMDOT decided to move to a Performance Based Specification (PBS). This move to a PBS warranted the removal of many parts of the existing specification including minimum cement contents, maximum w/cm ratios, and aggregate sizes and ratios. NMDOT felt, with the wide variance in aggregate types in the region, that the removal of stipulated aggregate usage from the specification would allow the supplier to make the most efficient use of the readily available aggregates in order to meet the specified shrinkage and permeability values.

NMDOT’s Performance Based Specification includes requirements for the following (19):

1) 28 and 56 day strength
2) Minimum durability requirements for Freeze/Thaw per ASTM C 666

3) Minimum Air Void system characteristics as determined in the hardened state per ASTM C 457.
4) Compliance with NMDOT’s ASR Mitigation Evaluation Criteria
5) Maximum coulomb values per ASTM C 1202 for low, medium, and high risk zones as determined by NMDOT
6) Maximum shrinkage values per AASHTO T 160

In his article in Concrete International, Simons quotes a District Laboratory Supervisor who states:

> “Before we implemented these specifications, he dealt with approximately 150 to 200 concrete related problems a year. Since we implemented these specifications, he has had to deal with only one instance in the last 4 years. The mixtures have also become much easier to use, place, and finish. In most instances, the cost of the mixtures has been reduced. In all instances, the performance of the mixtures has been more uniform.” (20)

3.1.4 Nebraska

The Nebraska Department of Roads (NDOR) teamed with the Nebraska Center for Infrastructure Research (CIR) and the Federal Highway Administration (FHWA) to design and construct the first high performance bridge deck in Nebraska located on 120th St. and Giles Road in Omaha. While the bridge did not make use of a performance based specification, NDOR did include a supplement to the specification which required the submittal of the mix design 30 days in advance of planned placement along with the following test results; 56 day compressive strength, chloride permeability, flexural strength, alkali reactivity of aggregates, modulus of elasticity, split cylinder tensile strength, shrinkage, and abrasion resistance. Most of the results were provided only for information purposes except for the strength tests and permeability results which were the basis for overall acceptance or rejection of the mix (21). The supplied mix design made use of only 9% fly ash with Portland cement and no other supplementary cementitious materials; therefore, an extremely low w/cm ratio of 0.31 was necessary in order to meet the permeability requirements.

The results from the Nebraska HPC bridge deck were promising, but a few problems were experienced during construction. The problems were minimal prior to the finishing stage at which point a deviation from the specification was required. During the final float phase of the deck there was insufficient bleed water to avoid ripping of the surface so an evaporation retarder was applied to the surface in order to allow for proper finishing. The specification also required that the deck surface be “fogged” for 8 days after placement to insure good curing, a requirement which proved to be unrealistic as windy conditions prevented the moisture from reaching the surface. In place of fogging, a curing compound was employed to insure good curing and maintain crack control. The addition of the evaporation retarder and curing compound proved to be so successful at preventing cracking that they became an instant requirement for all future bridge deck construction in the state (21).

3.1.5 Texas

The Texas Department of Transportation (TxDOT) has also teamed with the FHWA and the Center for Transportation Research at the University of Texas Austin to develop a durability specification for concrete bridge decks in the state. These durability specifications contained a prescriptive mix design that was developed by the ready mix suppliers with support from researchers at the University of Texas Austin. These specifications were used on two separate bridge projects that made use of both a high strength HPC mix and a standard strength HPC (low permeability) mix. These two different mixes were used on both projects for the purposes of comparison. The two projects were the Louetta Road Overpass near Houston and the U.S. 67 Bridge in San Angelo. Freeze/thaw resistance is obviously not a large concern in Texas, and in some cases air entrainment is not required but is specified nonetheless in most of the state, so the concentration was on the permeability of the mix. Each of the HPC mixes made use of only fly ash as a replacement to cement and used quantities of between 28 and 32 percent of total cementitious mass. Both of the high strength

HPC mixes included high-range water reducer whereas the standard strength HPC mixes did not.

The permeability requirement of 2000 coulombs at 28 days was met by all HPC mixes on both projects, but by only a small margin on the standard strength specimens, so Texas has adopted the VDOT "heat curing" method in order to simulate higher maturity concrete at a specimen age of 28 days (22). Ralls also noted that the high strength HPC mixes required more effort to place and finish than the standard strength HPC mixes (22). Problems with cracking, possibly caused by high curing temperatures, were experienced more in the high strength HPC mix in the Louetta Bridge project than in the standard strength HPC mix in the adjoining lane (23). For this reason TxDot continues to update the construction practices in its durability specification with improved curing practices.

3.1.6 New Hampshire

In New Hampshire the New Hampshire Department of Transportation (NHDOT) teamed with researchers from the University of New Hampshire (UNH) to develop three different trial mixes that were placed into test slabs and load tested for a period of 6 months. The mix that showed the best results after testing was complete was then used for placement in the State Route 104 Bridge over the Newfound River. The best performing HPC mix design contained

7.5 percent silica fume by mass of cementitious material and had a w/cm ratio of 0.38 (24). The 28 day strength was specified at 7200 psi and the 56 day RCP test results to be performed on cores taken from the deck were specified to have a maximum of 1000 coulombs. In order to insure that they could achieve the specified performance goals, the producers were allowed to submit several refined trial batches to NHDOT for approval prior to placing. Also specified was a 4 day wet cure of the deck through the use of saturated cotton mats that were placed over the surface.

The bridge deck exceeded all of the specified performance goals by a significant margin with the exception of the air content which was specified to be between 6 and 9 percent. Test results revealed the actual air content in the deck fell between 4.0 and 5.8 percent, a shortfall that was believed to be caused by an interaction between the corrosion inhibitor and the super plasticizer that were used in the mix, but testing confirmed that the freeze/thaw durability of the deck was more than sufficient even with slightly low air content. This interaction between the two admixtures was also credited for some difficulties in maintaining the necessary slump for pumping and finishing; therefore, additional super plasticizer had to be added onsite. The RCP test results were all under the 1000 coulomb maximum and ranged from 609 to 896 coulombs, and the lowest strength test results were 8100 psi at 28 days (24).

3.1.7 Pennsylvania

In Pennsylvania the average life span of cast-in-place concrete bridge decks is 25 to 27 years. In order to extend that life expectancy to between 75 and 100 years, the Pennsylvania Department of Transportation (PennDOT) teamed with the FHWA, multiple supplier associations, and researchers from Penn State University to develop mix designs for a 26 mile section of Interstate 99 in the mountains of Pennsylvania, which contains 10 different bridge structures. Each of these ten bridge decks was placed using a different mix design that was designed to achieve the same performance goals. The performance requirements included the following (25):

1. 28 day shrinkage per ASTM 157 (Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete) less than 500 micro strains
2. Conductivity per AASHTO T277 (RCP) less than 1500 coulombs at 56 days
3. ASTM C441 (Standard Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction) must show 60 percent reduction in ASR expansions
4. 56 day strength greater than 4000 psi

5. Plastic air content 6% ± 1.5% and hardened air content between 4.5 and 8.0% with spacing factor of 0.008 inches.

Penn State researchers began with an initial compilation of 154 mix designs, both binary and ternary, containing varying percentages of supplementary cementitious materials (SCMs). Using lab prepared samples; the researchers reduced the list down to 25 acceptable mixes that easily met the performance parameters, which were then subjected to "full-truck" trial testing. From these 25 samples of "full-truck" trials, the final 10 mix designs were chosen for their performance and construction properties.

There was no mention of any construction issues regarding the placement of any of the decks along the corridor, and all of the actual deck placements passed all performance requirements (26). The bridge decks also easily passed their strength requirement of 4000 psi despite the fact that the total cementitious material in all of the mixes had been reduced from the standard amount by approximately 100 lbs/yd^3 to between 564 and 611 lbs/yd^3 (25). The research showed that this reduction in cementitious material was necessary in order to decrease both the shrinkage and permeability of the mix, thereby enabling them to meet the performance restrictions. Research continues at Penn State through the analysis of strain gages, thermal sensors, and corrosion clamps that were inserted into the decks during construction which continue to provide information on the durability of each of the decks.

Chapter 4: Tennessee Performance Based Specification for Bridge Deck Concrete

4.1 Changes to Current Specification

For simplicity this research suggests the addition of a new subsection to “Section 604-Concrete Structures” of the current “2006 Standard Specification for Road and Bridge Construction” (27). This new subsection would relate only to the construction of concrete bridge decks and, more specifically, to the new performance based requirements included in Section 4. The addition of this new subsection would warrant the eventual removal of many of the current prescriptive requirements contained mostly within subsections 604.02 and 604.03 pertaining to Class “D” concrete in order to prevent any confusion when the performance based requirements were implemented. One possibility is to include the two different specifications simultaneously without any penalty for not meeting the new performance standards as a 1 year trial would be enabled and could ease the transition for suppliers over to the new specification. This simultaneous use of both specifications would use the design principles from the new performance based specification to meet the current prescriptive requirements, thereby insuring that the integrity of the structures would, at a minimum, be maintained at their current levels and to some degree, be expected to improve.

4.2 Permeability Requirement

As discussed earlier, the primary factor in the determination of the durability of a concrete bridge deck is the permeability of the deck or, more specifically, the ability of the deck to resist the penetration of chloride ions. Therefore, the permeability results will be the highest priority in a performance based specification. From research, both internal at the University of Tennessee and external similar research at several locations throughout the U.S., it is obvious that an RCP value of 2,000 coulombs at 56 days is easily attainable through the reduction of overall cementitious material from current standards and the use of supplementary cementitious materials (7; 28; 29; 3). Based on the regression equation shown in Figure 3 that is derived from field research on samples taken throughout the state of Tennessee (Equation 3), an RCP value of 2000 at 56 days correlates to an SR value of 20.35 as shown below.

(*Equation 3)*

Then applying the 60% relationship of 28 day SR to 56 day SR derived from the same research produces a value of 12.21 kohm-cm at 28 days.

For the purposes of use in a performance based specification this value has been conservatively rounded down to 12 kohm-cm. This lower limit of SR will only consider lime water bath curing per ASTM C511 and will not include the "heat curing" that some departments have allowed in order to simulate later age concrete. Heat curing has been shown to greatly reduce the RCP readings which, in turn, would increase SR values (22). The only current standard reference for the Surface Resistivity test is a method developed by Florida Department of Transportation (FDOT) and is titled "Florida Method of Test For Concrete Resistivity as an Electrical Indicator of its Permeability, Designation: FM 5-578", but a similar standard is currently being reviewed by AASHTO (12).

4.3 Air Content of Fresh Concrete Requirement

The current Tennessee Standard Construction Specification requires between 6 and 8.5% air content for fresh concrete being placed by pumping when tested at the truck chute. Tests on different mix designs containing various percentages of fly ash, slag, and silica fume, have shown these requirements to still perform more than satisfactorily in tests for damage due to freeze/thaw, and the research shows no reason to make any changes to the current specification requirements for air content nor testing methods (32).

4.4 Strength Requirement

The current TDOT specification requires a minimum 28 day compressive strength of 4,000 psi for all class D concrete. There is research that suggests both the maximum w/cm and minimum compressive strength requirements can be removed from specifications in lieu of the inclusion of a maximum (or minimum) permeability value which is an indicator of both properties (32). While such a move may be justified as it further allows the supplier more freedom to deliver a more durable product at a reduced cost, the current research does not support this and suggests that a minimum compressive strength requirement should remain in place during the initial transition to a performance specification. The average 28 day compressive strength from the field samples taken for this research was 5,353 psi with a standard deviation of 1120 psi, well above the required 4,000 psi, which indicates that meeting this requirement is merely a formality and is easily accomplished by any supplier. In Figure 5 below the slight trend of higher SR values resulting in higher compressive strength can be seen, but a correlation from the present research is nonexistent; thus further research is needed before the minimum strength requirement can be excluded from the specification.

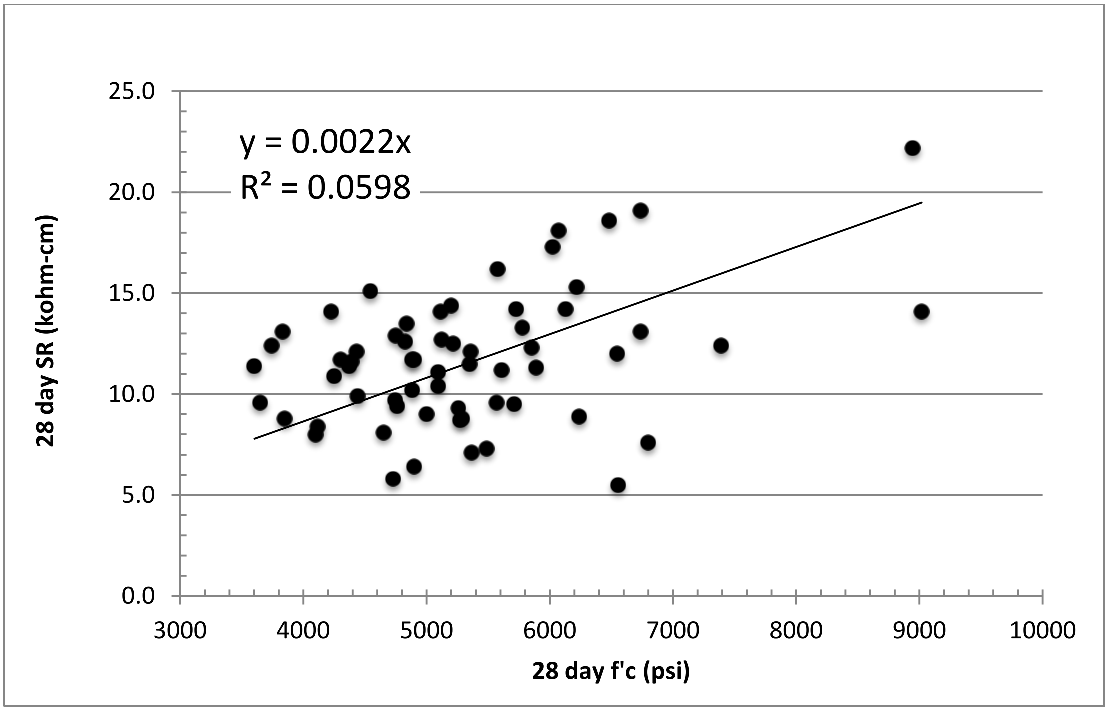


Figure 5: 28 day SR vs. 28 day f'c

4.5 Statistical Analysis

One of the advantages of using a power regression line of the form SR = constant * RCP$^{\text{exponent}}$ to describe the correlation between SR and RCP is that the logarithm of the results can be plotted on a normal scale and the power relationship will become a linear relationship which lends itself readily to a statistical analysis of the data including the creation of the confidence intervals. The following statistical variables were calculated from the field data in Microsoft Excel and then used to establish 95% confidence intervals.

# of samples (n)	60
slope of trendline (m)	-0.64796
y -intercept of regression line (b)	3.460954
Standard error in estimate (Syx)	0.054336
Average RCP (Log)	3.4
Sum of Squares (Ssx)	2.759744
95% t-value	2.001717

Figure 6 and 7 show the plot of the 95% confidence intervals for the regression line on both the Logarithmic and the original data respectively.

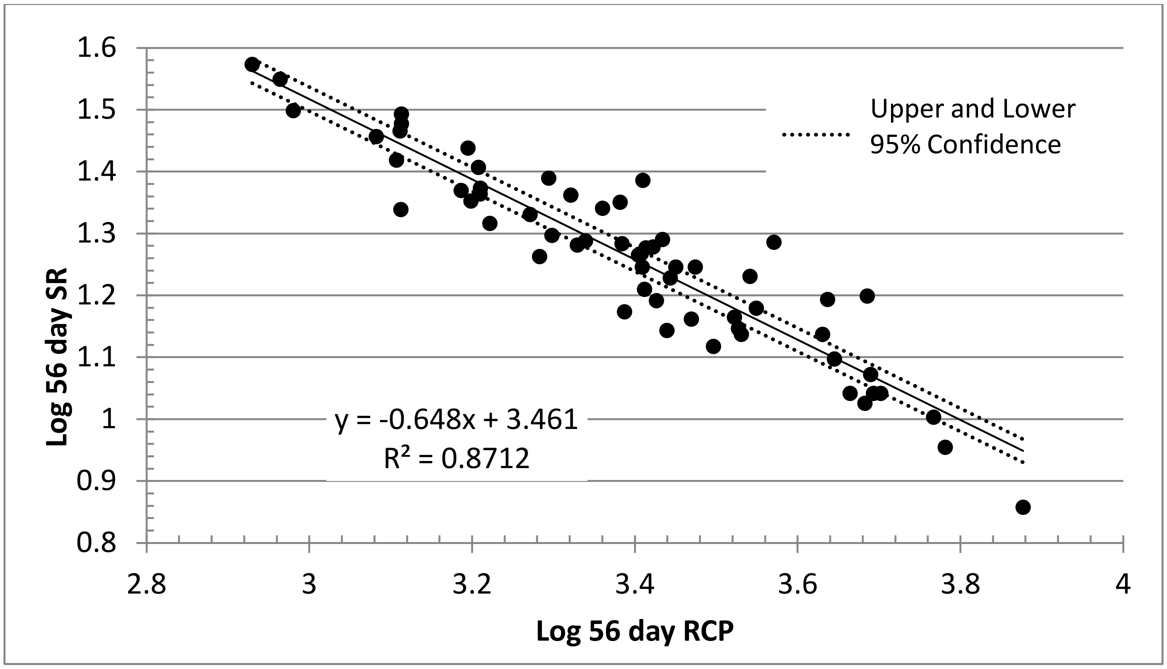


Figure 6: Log Plot for 56 day SR vs. 56 day RCP w/95% Confidence Interval

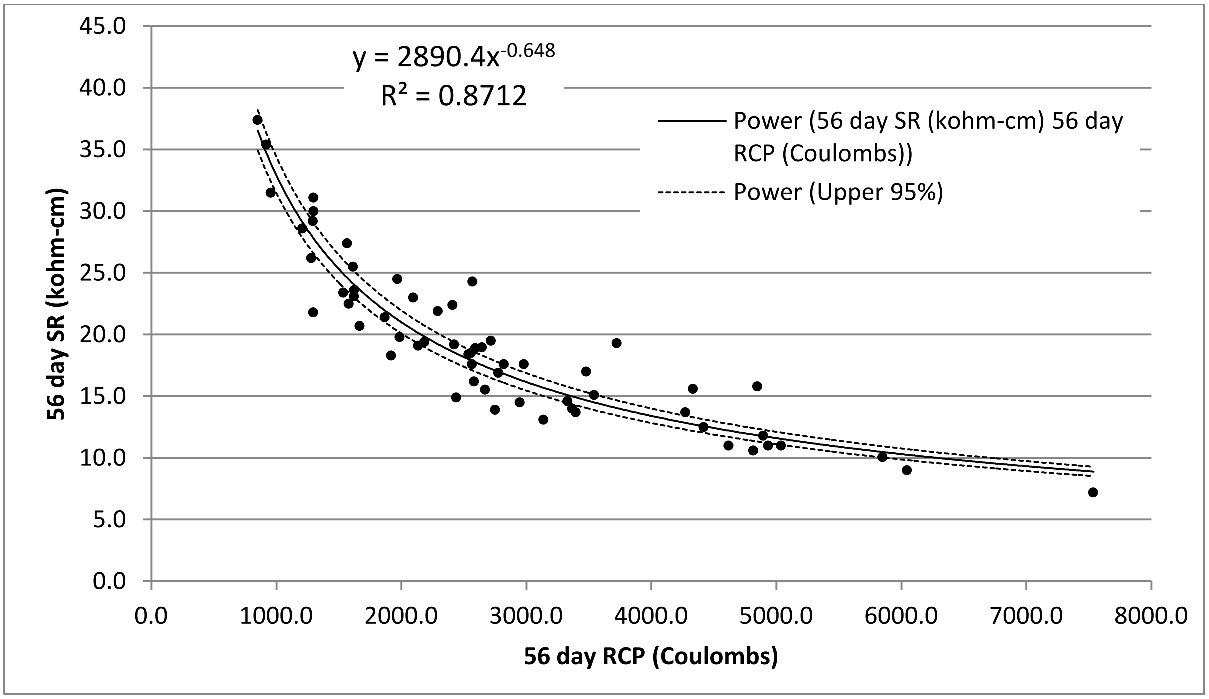


Figure 7: 56 day SR vs. 56 day RCP w/95% Confidence Interval

In order to establish a lower bound for the regression equation, the equation for a confidence interval for a fitted value was used with the required 56 day RCP value of 2000 (31).

Then the 56 day SR value was calculated using the regression equation:

Then the lower bound of the 95% confidence interval was calculated:

Then the ratio of .6 for the 28/56 day SR value, as discussed earlier, can be applied:

This result can logically be rounded to 12. As an admittedly over simplistic trial, the samples from the field data with a 28 day SR value of less than 12 were removed and the average 56 day RCP values for the remaining samples was recalculated. The average 56 day RCP value of these samples is 1994 Coulombs, this value would represent a marked improvement from the present conditions, in view of the fact that the present average for all the samples is 2811. As discussed earlier, this number is artificially low due to the restrictions of the testing equipment. As explained earlier herein, approximately 8% of the samples had to be discontinued because of overheating of the equipment due to what would have turned out to be extremely high RCP values. Thus, the actual average value of RCP for all the samples is larger than 2811 by some indeterminate amount, a fact illustrating the need for steps to assure that Tennessee bridge decks have more durable concrete than that currently being provided.

4.6 Payment Adjustments

Section 604.31 of the current specification contains the following table for use in calculating the percentage of pay for concrete that does not meet the required strength.

Table 3: Percent of Price Adjustment for Less than Required Strength Concrete for Tennessee Bridge Construction (27)

PERCENT BELOW SPECIFIED STRENGTH	PERCENT OF BID PRICE TO BE PAID*
0.1 – 3.3	95
3.4 – 6.7	90
6.8 – 10.0	80
10.1 – 13.3	70
13.4 – 16.7	60
16.8 – 20.0	50
20.1 – 23.3	45
23.4 – 26.7	40
26.8 – 30.0	35
30.1 – 33.3	30
> 33.3	25

This table would remain in place in the performance based specification and would take priority over the permeability price adjustment. Therefore, there would be a possibility of two bid price adjustments in the new specification with the strength adjustment being made first, followed by the permeability adjustment, which would be based on a table similar to Table 4.

Table 4: Permeability Percentage Price Adjustment

	Percent Above/Below Specified Resistivity	Percent of Adjusted Price* to be Paid
(Bonus)	>58	106
	46.5 - 58	105
	34.9 - 46.4	104
	23.3 - 34.8	103
	11.7 - 23.2	102
	0.1 - 11.6	101
	0	100
(Penalty)	0.1 - 3.4	95
	3.5 - 6.9	90
	7 - 10.4	85
	10.5 - 13.9	80
	14 - 17.4	75
	17.5 - 20.9	70
	21 - 24.4	65
	24.5 - 27.9	60
	28 - 31.4	55
	31.5 - 35	50
	>35	45

*Adjusted Price is Bid Price x Percent Adjustment from Table 1

This table uses a maximum 6% bonus, which was used successfully by Virginia Department of Transportation in its initial performance based specification for bridge deck construction and uses similar percentage ranges as the current Tennessee pay adjustment for strength (15). This maximum bonus is awarded for an SR value that is equivalent to an RCP value of 1000 Coulombs, a value which, according to ASTM C1202, represents the upper bound for “very low” chloride ion penetrability. Similarly, the lower limit of 35% below the required SR is equivalent to an RCP value of 4,000 which, based on the same specification, is considered “high” for chloride ion penetrability. Table 4, upon initial inspection, appears to be unduly biased towards a penalty, but this apparent “bias” is caused by the non-linear relationship between SR and the RCP values on which they are based.

4.7 Tennessee Performance Based Specification for Bridge Deck Construction

The following summarizes the primary points to consider in a performance based specification according to the current research being done by the University of Tennessee and could be considered a starting point for the development and implementation of such a specification.

1) **Strength Testing**-Average 28 day compressive strength of 4,000 psi as determined by ASTM C39 or AASHTO 22 on 6 x 12 cylinders cured according to ASTM 31 or AASHTO 23.

2) **Permeability Testing**-28 day average Surface Resistivity of 12 kohm-cm as determined by Florida Test Method FM 5-578 or AASHTO equivalent performed on three 4 x 8 cylindrical samples that have been lime water bath cured according to ASTM C511-09

3) **Air Content**-Air Content of between 6.0 and 8.5% as determined by ASTM C231 on sample taken from the truck chute per ASTM C172.

4) **Pay Adjustments**-Adjustment of pay for failure to meet strength and/or permeability requirements will be as is determined by Table 1 and Table 2 below and will be applied to the lump sum bid price for Table 1 and the adjusted price (if necessary) for Table 2.

Table 1: Percent of Price Adjustment for Less than Required Strength Concrete

PERCENT BELOW SPECIFIED STRENGTH	PERCENT OF BID PRICE TO BE PAID*
0.1 – 3.3	95
3.4 – 6.7	90
6.8 – 10.0	80
10.1 – 13.3	70
13.4 – 16.7	60
16.8 – 20.0	50
20.1 – 23.3	45
23.4 – 26.7	40
26.8 – 30.0	35
30.1 – 33.3	30
> 33.3	25

Table 2: Permeability Percentage Price Adjustment

	Percent Above/Below Specified Resistivity	Percent of Adjusted Price* to be Paid
(Bonus)	>58	106
	46.5 - 58	105
	34.9 - 46.4	104
	23.3 - 34.8	103
	11.7 - 23.2	102
	0.1 - 11.6	101
	0	100
(Penalty)	0.1 - 3.4	95
	3.5 - 6.9	90
	7 - 10.4	85
	10.5 - 13.9	80
	14 - 17.4	75
	17.5 - 20.9	70
	21 - 24.4	65
	24.5 - 27.9	60
	28 - 31.4	55
	31.5 - 35	50
	>35	45

*Adjusted Price is Bid Price x Percent Adjustment from Table 1

Conclusion

Recent research performed at the University of Tennessee has shown that the durability of Tennessee’s bridge decks presently being constructed can be vastly improved. The overall durability of concrete bridge decks has been shown to be directly related to the penetrability of chloride ions and the resulting damage caused by the corrosion of the reinforcing steel contained within the deck. Increasing the durability of the bridge decks would decrease the cost of maintaining them and would increase their lifespan. The Surface Resistivity Test (SR) is proposed as a replacement for the currently accepted Rapid Chloride Ion Penetration Test (RCP) for determining the resistance of concrete to penetration of chloride ions. This assessment at 28 days will expedite the inclusion of chloride ion penetrability into a specification and is expected to lead to improved durability of Tennessee bridge decks. Because the SR test can reliably predict durability at 28 days, it easily lends itself to inclusion into a performance based specification for Tennessee bridge decks. A performance based specification will insure the durability of the final product while also allowing concrete producers maximum flexibility to design the mixes as cost effectively as possible. This savings will ultimately be passed on to the Tennessee Department of Transportation (TDOT) through decreased bid prices by the most capable producers. The performance based specification will contain only the requirements necessary to insure a highly durable final product, namely, strength, permeability, and air content. In order to provide the producers with incentive to maximize the durability of the final product, the performance based specification will also contain provisions for a bonus to be paid for supplying concrete that exceeds the requirements. Such a bonus is clearly justified because this concrete is expected to be more durable and thus further reduce maintenance costs over the bridge decks extended life.

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Appendix

Table 5: Phase 1 Data Summary

Cast Date	Region	County	28 day f'c (psi)	Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
				28 day	56 day	(28/56)	28 day	56 day
2/22/10	4	Carroll	6239	8.9	15.5	0.57	7770	2670
3/13/10	4	Henderson	5570	9.6	19.0	0.50	5084	2645
3/15/10	2	Hamilton	5488	7.3	10.1	0.72	6993	5850
3/16/10	1	Cocke	5351	11.5	19.1	0.60	3912	2135
3/17/10	1	Knox	6737	13.1	23.4	0.56	2645	1537
3/30/10	2	Hamilton	5096	10.4	11.8	0.88	5862	4896
4/6/10	1	Carter	5358	12.1	15.1	0.80	5157	3543
4/22/10	1	Blount	5576	16.2	28.6	0.57	2351	1209
5/3/10	1	Knox	4230	14.1	24.3	0.58	3697	2570
5/25/10	4	Haywood	4249	10.9	19.3	0.56	9652	3724
6/9/10	2	Coffee	4653	8.1	11.0	0.74	9713	4935
6/10/10	2	Clay	6740	19.1	24.5	0.78	3127	1969
6/23/10	1	Union	4840	13.5	22.4	0.60	4156	2410
7/2/10	2	Polk	5610	11.2	15.6	0.72	5921	4334
7/2/10	3	Williamson	3604	11.4	17.6	0.65	5132	2821
7/6/10	3	Davidson	3743	12.4	17.0	0.73	4062	3480
7/8/10	4	Madison	7627	▨	7.2	0.00	▨	7536
7/15/10	4	McNairy	4729	5.8	6.2	0.94	▨	▨
7/27/10	4	Madison	4305	11.7	18.9	0.62	5879	2592
8/10/10	3	Davidson	4899	11.7	19.2	0.61	5359	2423
8/14/10	4	Henderson	4117	8.4	13.8	0.61	9441	▨
8/19/10	4	McNairy	4898	6.4	7.4	0.86	▨	▨
9/1/10	4	Lake	4393	11.6	21.4	0.54	4036	1868
9/3/10	1	Sevier	6483	18.6	31.5	0.59	2402	956
9/8/10	4	Gibson	4751	12.9	25.5	0.51	3265	1614
9/11/10	2	Hamilton	3835	13.1	27.4	0.48	3372	1567
9/14/10	1	Sevier	6076	18.1	35.4	0.51	2383	921
9/21/10	3	Davidson	4887	10.2	13.9	0.73	3985	2751
9/28/10	2	Warren	4884	11.7	19.8	0.59	4138	1987
10/5/10	2	Warren	5114	14.1	20.7	0.68	2799	1667
10/12/10	2	Warren	5219	12.5	23.1	0.54	4350	1622
10/14/10	2	Warren	4765	9.4	18.3	0.51	5127	1919
10/21/10	3	Williamson	5125	12.7	23.0	0.55	3857	2096
10/27/10	3	Montgomery	8948	22.2	37.4	0.59	1317	851

Table 6: Phase 1 Data Summary

Cast Date	Region	County	28 day f'c (psi)	Surface Resistivity (kohm-cm)			Rapid Chloride Ion Penetration (coulombs)	
				28 day	56 day	(28/56)	28 day	56 day
11/2/10	4	Decatur	4101	8.0	18.4	0.43	▨	2538
11/4/10	4	Shelby	9018	14.1	23.6	0.60	4350	1623
11/19/10	4	Haywood	5260	9.3	17.6	0.53	▨	2981
12/22/10	2	McMinn	5891	11.3	13.7	0.82	6299	4273
1/4/11	4	Haywood	4443	9.9	16.2	0.61	5808	2582
1/19/11	4	Gibson	5272	8.7	▨	▨	6546	▨
1/28/11	2	Polk	6131	14.2	13.7	1.04	3486	3396
1/28/11	2	Warren	4547	15.1	22.5	0.67	3306	1580
1/29/11	2	Warren	5728	14.2	31.1	0.46	3071	1298
2/22/11	2	Marion	5366	7.1	6.8	1.04	▨	▨
3/4/11	1	Knox	6547	12.0	13.1	0.9	3918	3138
3/9/11	4	Crockett	5203	14.4	30.0	0.5	3522	1298
3/11/11	4	Dyer	6799	7.6	14.9	0.5	▨	2440
3/15/11	4	McNairy	6557	5.5	6.6	0.8	▨	▨
3/16/11	2		7393	12.4	15.9	0.8	3412	▨
3/22/11	4	Shelby	▨	▨	26.2	0.0	▨	1280
3/29/11	2	White	5712	9.5	11.0	0.9	5536	4619
3/29/11	2		5854	12.3	14.6	0.8	3702	3330
4/12/11	4	Hardeman	3850	8.8	17.6	0.5	6273	2566
4/21/11	2	Rea	3650	9.6	15.8	0.6	6847	4849
5/4/11	4	Hardeman	▨	▨	11.0	0.0	▨	5038
5/18/11	1	Blount	6222	15.3	21.8	0.7	2103	1296
5/19/11	Lab	Knox	▨	11.4	14.5	0.8	4919	2948
5/20/11	4	Carroll	▨	▨	9.0	▨	▨	6046
5/23/11	2		5094	11.1	12.5	0.9	4785	4419
5/26/11	Lab	Knox	6027	17.3	29.2	0.6	2577	1293
5/26/11	Lab	Knox	5780	13.3	21.9	0.6	3749	2293
6/3/11	4	Tipton	5002	9.0	14.0	0.6	6496	3368
6/7/11	2	Warren	4375	11.4	19.4	0.6	3611	2185
6/9/11	2		5291	8.8	10.6	0.8	5867	4817
6/9/11	2	Warren	4830	12.6	18.5	0.7	3831	2558
6/21/11	4	Gibson	4745	9.7	16.9	0.6	5519	2777
6/23/11	2		4433	12.1	19.5	0.6	4372	2717

Table 7: Mix Design Proportions

Contract #	**Pour date**	**Mix Design**									
		Class	Cement Type 1 ($\mathrm{lb/yd^3}$)	Fly Ash ($\mathrm{lb/yd^3}$)	Natural Sand ($\mathrm{lb/yd^3}$)	#57 Stone ($\mathrm{lb/yd^3}$)	Water ($\mathrm{lb/yd^3}$)	Weight (pcf)	%FA of Total Agg	W/C Ratio	Air Content (%)
CNF 014	3/16/2010	D	496	124	1324	1800	248	146.4	43.39	0.34	6
CNH 239	3/17/2010	D	496	124	1179	1896	248	146	41.1	0.40	6
CNH 523	4/6/2010	D	496	124	1280	1732	248	143	44	0.40	6
CNH 538	4/22/2010	D	496	124	1216	1838	250	144	42	0.40	6
CNH 166	5/3/2010	D	496	124	1270	1800	248	145.9	43.1	0.40	6
CNH 231	6/23/2010	D	496	124	1216	1838	250	145	42	0.40	6
CNH 594	9/3/2010	D	496	124	1245	1796	248	143	42.2	0.4	6
CNH 138	9/14/2010	D	496	124	1245	1796	248	145	42.2	0.40	6
CNH 166	3/4/2011	D	620	0	1302	1800	245	146.9	43.7	0.4	6
CNJ 934	5/18/2011	D	530	113	1226	1800	250	145.5	42.1	0.39	6
Lab Mix	5/19/2011	D	465	155	1151	1786	250	141	40	0.40	6
Lab Mix #2	5/26/2011	D	465	155	1204	1854	229	145	40	0.36	6
Lab Mix #3	5/26/2011	D	496	124	1189	1800	248	142.8	40.8	0.40	6
CNF 114	3/15/2010	D	620	0	1240	1820	236	145	41.4	0.38	6
CNF 114	3/30/2010	D	620	0	1240	1820	236	145	41.4	0.38	6
CNH 625	6/9/2010	D	465	155	1151	1786	250	141	40	0.40	6
CNH 158	6/10/2010	D	465	155	1150	1830	250	142.5	39.5	0.40	6
CNJ 132	9/11/2010	D	496	124	1127	1914	248	144.8	38.1	0.40	6
CNH 204	9/28/2010	D	465	155	1170	1825	250	143	40	0.40	6
CNH 204	10/5/2010	D	465	155	1170	1825	250	143	40	0.40	6
CNH 204	10/12/2010	D	465	155	1170	1825	250	143	40	0.40	6
CNH 204	10/14/2010	D	465	155	1170	1825	250	143	40	0.40	6
CNH 243	12/22/2010	D	620		1170	1857	248	143.3	40.3	0.40	6
CNH 645	1/28/2011	D	620		1170	1875	248	145	38.4	0.4	6
CNH 581	1/29/2011	D	496	124	1237	1770	250	143.6	41.9	0.4	6
CNJ 232	2/22/2011	D	620	0	1206	1820	250	144.3	40.5	0.4	6
	3/16/2011										
CNJ 236	3/29/2011	D	800		1429	1780	258				
CNJ 160	3/29/2011	D	620		1170	1875	248	145	38.4	0.4	6
CNJ 135	4/21/2011	D	752		1430	1791	267				
CNH153	6/7/2011										
CNH 581	1/28/2011	D	496	124	1237	1770	250	143.6	41.9	0.4	6

Table 8: Mix Design Proportions

Contract #	Pour date		Mix Design								
		Class	Cement Type 1 (lb/yd^3)	Fly Ash (lb/yd^3)	Natural Sand (lb/yd^3)	#57 Stone (lb/yd^3)	Water (lb/yd^3)	Weight (pcf)	%FA of Total Agg	W/C Ratio	Air Content (%)
CNH 645	7/2/2010	D	620		1170	1875	248	145	38.4	0.40	6
CNG 840	7/2/2010	D	465	155	1204	1854	229	145	40	0.37	6
CNH 635	7/6/2010	D	465	155	1204	1854	229	145	40	0.36	6
CNH 277	8/10/2010	D	465	155	1204	1854	229	144.7	40.3	0.37	6
CNH 218	9/21/2010	D	465	155	1204	1854	229	145	40	0.36	6
CNG 840	10/21/2010	D	465	155	1204	1854	229	145	40	0.36	6
CNH 155	10/27/2010	D	463	155	1180	1824	250	143.3	40.1	0.40	6
CNH 577	2/22/2010	D	496	124	1190	1800	248	142.8	40.8	0.40	6
CDR 091	3/13/2010										
CNH 313	5/25/2010	D	496	124	1189	1800	248	142.8	40.8	0.40	6
CNJ 031	7/8/2010	D	465	155	1211	1800	248	143.7	40.8	0.4	6
CNH 716	7/15/2010	D	620		1283	1740	248	144	43	0.4	6
CNH 280	7/27/2010										
CDR 091	8/14/2010										
CNH 716	8/19/2010	D	620		1283	1740	248	144	43	0.4	6
CNH 147	9/1/2010	D	496	124	1197	1800	248	143.1	40.75	0.4	6
CNH 677	9/8/2010	D	620		1217	1800	248	143.9	41.3	0.40	6
CNH 217	11/2/2010	D	496	124	1193	1800	248	143	41	0.40	6
CNH 248	11/4/2010	P	725	140	1100	1980	244.5				
CNJ 257	11/19/2010	D	496	124	1241	1752	248	143	42.7	0.40	6
CNH 041	1/4/2011	D	496	124	1241	1756	248	143.1	42.3	0.40	6
CNJ 911	1/19/2011	D	496	124	1189	1800	248	142.8	40.8	0.4	6
CNH 191	3/9/2011	D	496	124	1161	1800	248	141.8	40.8	0.4	6
CNJ 168	3/11/2011	D	465	155	1228	1772	248	143.3	41.6	0.4	6
CNH 716	3/15/2011	D	620		1283	1740	248	144	43	0.4	6
CNH 248	3/22/2011	D	465	155	1250	1750	250	141	42.3	0.4	6
CNJ 237	4/12/2011	D	496	124	1161	1800	248	141.8	40.8	0.4	6
CNJ 237	5/4/2011										
CNH246	5/20/2011										
CNH643	6/3/2011	D	496	124	1206	1825					
CNJ911	6/21/2011	D	496	124	1189	1800	248	142.8	40.8	0.4	6

Vita

Brian Buchanan was born in Pulaski, Tennessee and spent the majority of his childhood growing up in Charleston, South Carolina. Brian graduated from Knoxville Catholic High School. After working in management for several years with the local branch of a large corporation, he returned to school to get a degree in Civil Engineering. He received his Bachelor’s degree in Civil Engineering in May of 2010 from the University Of Tennessee and accepted a graduate teaching/ research position in the Structural Engineering in the Department of Civil and Environmental Engineering department at the University of Tennessee. Brian will graduate with his Master of Science in Structural Engineering in December 2011.