Influence of Changes in Water-to-Cement Ratio, Alkalinity, Concrete Fluidity, Voids, and Type of Reinforcing Steel on the Corrosion Potential of Steel in Concrete

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 Research on steel corrosion has demonstrated that the concentrations of chloride and hydroxide ion at the concrete/steel interface influence the susceptibility of the steel to corrosive attack. This study used electrochemical means and changes in mix design to increase the alkalinity and improve consolidation of the concrete against the steel to determine if this would increase the corrosion resistance of the reinforcing steel without compromising the properties of the concrete. To understand these effects better, the following concrete properties were evaluated: compressive strength, splitting tensile strength, modulus of elasticity, and length change (shrinkage).

 The evaluation involved the casting of different types of concrete samples, all of which contained artificial voids, for corrosion testing. These samples were composed of one of two concrete mixtures: (1) the Virginia Department of Transportation's (VDOT) Class A4 General Bridge Deck Concrete with Straight Portland Cement (A4), or (2) a self-consolidating concrete (SCC). Selected A4 and SCC mixtures were electrochemically treated 135 days after samples were cast. Some samples were left untreated and functioned as control samples.

 There were no significant differences in the concrete properties between the short-term treatment (less than 7 hr) and control samples tested in this study. It was determined that alkalinity, water-to-cement ratio, and steel type all influence the corrosion potential of reinforcing steel when reinforced concrete is subjected to saltwater. In addition, introducing small voids adjacent to the steel created a greater spread between the 25th and 75th percentile of the half-cell potential measurements when compared to locations without voids; however, these same voids have little influence on the average value measured. A study is underway to perform cyclical saltwater ponding on selected samples to allow for future evaluation of corrosion resistance.

 This study showed that alkalinity, water-to-cement ratio, concrete fluidity during placement, and steel type all influence the corrosion potential of the reinforcing steel when reinforced concrete is subjected to saltwater. The study recommended that the Virginia Center for Transportation Innovation and Research (VCTIR) continue performing saltwater exposure on these specimens until corrosion becomes evident and then autopsy them and characterize the corrosion of the steel reinforcement. In addition, VCTIR should work with VDOT's Materials Division to compare various concrete mix designs that would be considered acceptable to VDOT and assess how each influences the corrosion potential on embedded steel. Further, more emphasis should be placed on mix designs, such as SCC mixtures, that could provide VDOT with greater corrosion resistance and reduced labor during placement.

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FINAL REPORT

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ABSTRACT

Research on steel corrosion has demonstrated that the concentrations of chloride and hydroxide ion at the concrete/steel interface influence the susceptibility of the steel to corrosive attack. This study used electrochemical means and changes in mix design to increase the alkalinity and improve consolidation of the concrete against the steel to determine if this would increase the corrosion resistance of the reinforcing steel without compromising the properties of the concrete. To understand these effects better, the following concrete properties were evaluated: compressive strength, splitting tensile strength, modulus of elasticity, and length change (shrinkage).

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INTRODUCTION

In the last 30 years, the substantial cost associated with highway bridge corrosion has caused many transportation agencies in the United States to search for methods that mitigate this problem. A significant amount of research has focused on the conventional reinforced concrete bridge. For new construction, this is achieved through the use of improved concretes with lower slump, increased cover thickness, reduced permeability through the addition of pozzolans, and the replacement of conventional carbon steel reinforcing bars (rebar) with epoxy-coated or galvanized rebar. Although solid stainless steel, stainless steel clad, and other types of metallic bars have emerged as a means of mitigating corrosion of reinforcing steel (Clemeña and Virmani, 2004; Hartt et al., 2004; Koch et al., 2002), concrete must have sufficient alkalinity and adequate consolidation when placed.

Early research into the corrosion of reinforcing steel demonstrated that the chloride and hydroxide ion concentrations adjacent to the steel significantly influenced the susceptibility of the steel to corrosive attack (Hausmann, 1967). Hausmann concluded that a corrosion threshold value existed and should not exceed 0.61 based on the following relationship between the chloride and hydroxide ion concentrations (Hausmann, 1967):

$$\frac{[Cl^-]}{[OH^-]} \leq 0.61 \qquad\qquad [\text{Eq. 1}]$$

As it became clear that corrosion often played a significant role in the life of a reinforced concrete bridge structure, work began on ways to mitigate this problem. In 1973, the Kansas Department of Transportation performed a study on the electro-stabilization of clayey soils (Morrison et al., 1976). This work inspired experiments involving the electrochemical removal of chloride ions from concrete, which would become known as electrochemical chloride extraction (Virmani and Clemeña, 1998). A similar electrochemical process arose for increasing the alkalinity of carbonated concrete, which is known as re-alkalization (Banfill, 1997).

Currently, both electrochemical techniques are used to mitigate corrosion. In 2000, Glass and Buenfeld suggested that the resistance of the structure to corrosion could be improved by applying the electrochemical process before chloride ions had a chance to initiate corrosion. Based on this idea, rather than reducing the chloride concentration, the concentration of hydroxide ions is increased, which therefore increases the chloride threshold, as shown in Equation 1. An illustration of this approach is provided in Figure 1.

Now, when current flow through concrete is sufficient, not only does the alkalinity increase near the reinforcing steel, but other changes are also occurring within the concrete (Andrade et al., 1998; Clemeña and McGeehan, 1993; Clemeña and Virmani, 2004; Marcotte et al., 1999; Ryu and Otsuki, 2002; Tritthart, 1996). Based on the previous electrochemical research, electrochemically treating a reinforced concrete structure prior to use could potentially reduce the corrosion susceptibility by the following:

- reducing the permeability of cracks by electrodeposition of insoluble products
- reducing the concrete permeability by altering the pore size distribution
- increasing the pH adjacent to the reinforcing steel by decomposing water
- increasing the cation concentration (Na^+ and K^+) at the rebar surface.

The benefit of reduced corrosion susceptibility, however, must not compromise the properties of the concrete or steel reinforcement. To understand better how this treatment influences concrete, the durability, shrinkage characteristics, and physical properties must be evaluated.

The main concern regarding durability is the issue of changing the pore size and pore size distribution. The system may be impacted in a detrimental manner if the moisture is not accommodated by the remaining voids during freezing and thawing because the system has tightened up following treatment. This can cause cracking and other deterioration problems in the concrete.
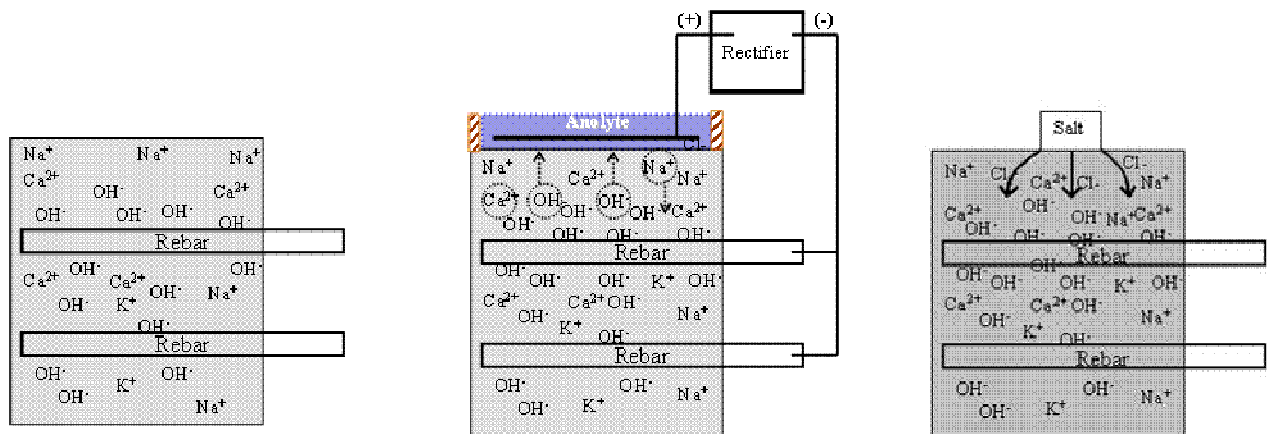

Figure 1. Schematic Illustrating Alkalization Treatment to Inhibit Corrosion. *Left:* **Concrete is placed and allowed to cure.** *Center:* **A temporary electrochemical system is constructed and the alkalization treatment is applied for 1 day.** *Right:* **The alkalization treatment apparatus is removed and salt exposure begins. The salt reaches the steel, but corrosion is inhibited by the treatment, resulting in a higher pH.**

The drying shrinkage of concrete involves the removal of moisture over time. This is usually due to the drying and curing of the concrete. The initial loss of moisture is from the larger voids, so this loss is free water that is not bound. There is little to no shrinkage associated with this initial water loss other than plastic shrinkage. The shrinkage occurs when bound water in the capillary voids is removed, which creates tensile stresses in the concrete and causes shrinkage. These stresses are sometimes great enough to cause cracking in the concrete. The main concern regarding this research as it relates to shrinkage is that the void structure may be altered.

This research investigated particular factors, such as voids, water-to-cement ratio (w/c ratio), and alkalinity, that can influence the corrosion susceptibility of the embedded reinforcing steel. Therefore, approaches to reduce the corrosion susceptibility of the steel while monitoring for changes in the concrete were performed. These approaches focused on increasing the corrosion resistance of the reinforced concrete samples by reducing the detrimental influence attributable to the formation of voids between the concrete and steel. It is known that the formation of voids at the surface of the reinforcing steel can be strongly influenced by the type of concrete and placement procedures, such as consolidation of the concrete. The two approaches studied were:

1. *Altering the concrete mixture ingredients to reduce the formation of voids adjacent to the steel and improving the concrete flow characteristics.* For this study, this operation occurred prior to concrete placement.

2. *Electrochemically treating the concrete to increase the alkalinity adjacent to the steel, especially in regions where voids adjacent to the steel have formed that might contain bleed water.* For this study, this operation occurred after concrete placement using a DC rectifier.

Test samples were exposed to saltwater for years, and this report discusses the effect each approach had on the concrete as well as the current status regarding the corrosion resistance of the samples.

PURPOSE AND SCOPE

The purpose of this study was to determine the influence the w/c ratio, concrete fluidity during placement, and alkalinity have on the corrosion potential of different types of reinforcing steel embedded in concrete when small voids are adjacent to the surface of the steel. By better understanding this, the Virginia Department of Transportation (VDOT) can determine if it should investigate optimizing concrete mixtures for different applications.

The evaluation was performed on laboratory samples of concrete mixtures from a local Virginia ready-mix concrete producer. The mixtures were of one of two concrete mix designs: (1) VDOT's Class A4 General Bridge Deck With Straight Portland Cement (A4) or (2) self-consolidating concrete (SCC). The ready-mix produced concrete was used to allow testing of mixtures that can be received in the field. The ease of placement was also evaluated between the

two mixtures, with the amount of labor required to place the concrete monitored. After casting, the samples remained outside as they cured and during testing. Cyclic exposure to saltwater was used to introduce chlorides into the concrete, and then the steel was monitored for indications of corrosion using the ASTM half-cell potential method for uncoated reinforcing steel (ASTM C876) as a guideline (ASTM, 1999).

METHODS

Overview

The evaluation involved the casting of different types of concrete samples, all of which contained artificial voids, for corrosion testing. These samples were composed of one of two concrete mix designs: (1) A4 (VDOT, 2002), or (2) SCC. The SCC mixture was designed to have a higher cement content and lower w/c ratio when compared to the A4 mixture, which would result in the SCC mixture having increased alkalinity and lower permeability in addition to better consolidation characteristics. This was done to assess how strongly these changes would affect the corrosion susceptibility of the embedded steel. Although VDOT traditionally uses pozzolanic materials in the concrete mixtures, they were not used during this study in an attempt to minimize the time required to perform this study.

Some of the samples were electrochemically treated using a DC rectifier, which would also alter the alkalinity adjacent to the steel. Various measurements were made on both fresh and hardened concrete samples to characterize the concrete and assess the influence of voids, changes in mix design, and electrochemical treatment.

The following are described in this section:

- test samples for corrosion testing
- electrochemical treatment of selected samples
- concrete material properties testing
- corrosion testing.

Description of Test Samples

Artificial Crevices

During this study, it was necessary to create regions adjacent to the reinforcing steel that would have a greater susceptibility to corrosion attributable to a lack of contact between the surface of the steel and the alkaline concrete mixture. This was done by creating small mortar wedges containing voids and then tightly affixing those wedges to the reinforcing steel bars.

To maintain consistent dimensions for each void, carefully sized foam inserts were used during the wedge casting operations. The foam insert for creating the larger void was approximately twice as long as the foam for the smaller void. These foam inserts were removed

before the wedges were placed against the reinforcing steel. The wedges were placed and then fastened to the steel with the use of nylon ties. An example of a foam insert, wedges with smaller and larger void sizes, and a wedge fastened to the steel are shown in Figures 2 through 6.

Figure 2. Wedges After Casting But Before Separation Into Individual Units

Figure 3. Single Wedge Before Placement Showing Small Void (approximately 1 cm by 1 cm by 1 cm)

Figure 4. Single Wedge Before Placement Showing Larger Void (approximately 2 cm by 1 cm by 1 cm)
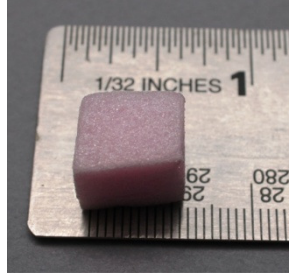
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Figure 5. Foam Insert Used to Create Smaller Void in Wedge. Foam is removed from wedge after curing to ensure void area is not damaged during removal process.
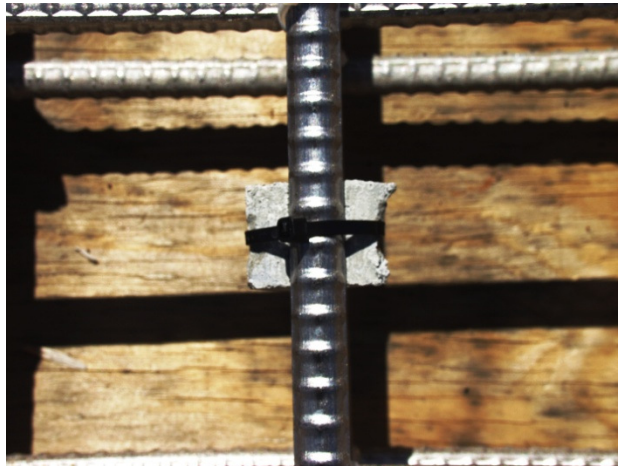

Figure 6. Example of Wedge in Place and Secured With Plastic Tie Before Samples Are Cast

Specimen Design

The samples, shown in Figure 7, were blocks 24 in by 24 in by 8 in with a 1.6875-in cover depth. As discussed previously, these samples consisted of two mix designs: A4 and SCC. Both mix designs are shown in Table 1. As discussed previously, although VDOT routinely uses pozzolanic materials, they were not used in either mixture in order to expedite the study since it is known that these materials can increase the time required for chlorides to diffuse through concrete.

Each specimen contained one of three types of reinforcement: carbon steel; low carbon, chromium, steel rebar that met the requirements of ASTM A1035 (ASTM, 2005); or 316LN stainless steel clad rebar. Each specimen contained two mats of reinforcing steel. For the samples listed in Table 2 that contain either a large or small artificial void, three artificial voids of similar size were placed along a diagonal line, which can be seen in Figure 7. After these samples were cast, they were cured for 135 days before an electrochemical treatment was applied for less than 7 hr. Table 2 provides an overview of the concrete mix design, reinforcing steel type, treatment condition, current density applied, and number of samples covered by these conditions.
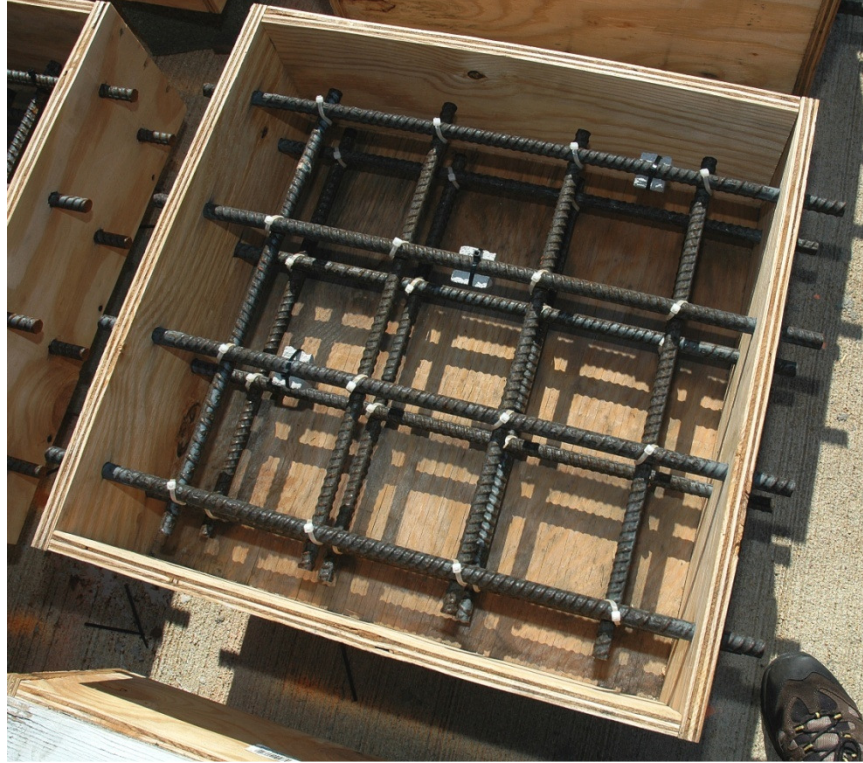
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Figure 7. Sample Prior to Concrete Placement With Artificial Crevices Attached. Artificial crevice wedges and black nylon tie connecting them to the reinforcement are visible.

Table 1. Proposed Mix Design for A4 and SCC Samples

Ingredient	A4	SCC
Coarse aggregate, lb	1,918	1,445
Fine aggregate, lb	1,125	1,377
Cement, lb	636	752
Water, lb	275	286
Water/cement ratio	0.43	0.38

A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; SCC = self-consolidating concrete.

Electrochemical Treatment of Selected Samples

During this study, reinforcing steel was polarized for a brief period to increase the alkalinity near the steel in an effort to improve the corrosion resistance of the reinforcing steel, all of this being done prior to chloride exposure. To polarize the steel, a DC power supply was used to negatively polarize the embedded steel while positively polarizing an anode mat that was placed in an aqueous solution contained on the external surface of the concrete. An illustration of this arrangement is shown in Figure 1. During polarization, the current was monitored over time to provide a means of calculating the amount of charge passed during the treatment process.

The samples were polarized using DC power supplies that operated in a constant current mode delivering a current density of 1.5 A/m^2, which was based on the surface area of the concrete. The concrete surface area was used to calculate the applied current density rather than the steel surface area because some of the test samples did not contain steel.

Table 2. Overview of Sample Test Blocks and Electrochemical Treatment Details

Mix Design	Steel Type	Void Size	Treatment Condition	Current Density, A/m²	No. of Samples
A4	CS	None	Untreated	0	6
A4	CS	Small	Untreated	0	8
A4	CS	Large	Untreated	0	6
A4	CS	None	Treated	1.5	3
A4	CS	Small	Treated	1.5	1
A4	CS	Large	Treated	1.5	3
A4	A1035	None	Untreated	0	6
A4	A1035	Small	Untreated	0	8
A4	A1035	Large	Untreated	0	6
A4	A1035	None	Treated	1.5	3
A4	A1035	Small	Treated	1.5	1
A4	A1035	Large	Treated	1.5	3
A4	316LN	None	Untreated	0	3
A4	316LN	Large	Untreated	0	2
SCC	CS	None	Untreated	0	3
SCC	CS	Small	Untreated	0	5
SCC	CS	Large	Untreated	0	3
SCC	CS	None	Treated	1.5	3
SCC	CS	Small	Treated	1.5	1
SCC	CS	Large	Treated	1.5	3
SCC	A1035	None	Untreated	0	3
SCC	A1035	Small	Untreated	0	3
SCC	A1035	Large	Untreated	0	5
SCC	A1035	None	Treated	1.5	3
SCC	A1035	Small	Treated	1.5	1
SCC	A1035	Large	Treated	1.5	3
SCC	316LN	None	Untreated	0	3
SCC	316LN	Large	Untreated	0	2

A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; CS = carbon steel; A1035 = low carbon, chromium, steel rebar; 316LN = 316LN stainless steel clad rebar; SCC = self-consolidating concrete.

To ensure good conductivity with the samples, the concrete was ponded with water 24 hr before the treatment process was initiated. The anolyte used during the treatment process was initially a 0.5 M sodium carbonate solution. Then, as the treatment progressed and the pH decreased, sodium carbonate was periodically added to the anolyte to ensure the pH remained alkaline. The remaining untreated samples were used to provide a baseline during the corrosion comparison between treated and untreated samples.

Concrete Material Properties Testing

A variety of tests were performed on treated and untreated samples to determine if the electrochemical treatment had an effect on the material properties of the concrete. Testing was performed to determine the compressive strength, modulus of elasticity, splitting tensile strength, and unrestrained length change of samples, both treated and untreated, from all batches fabricated for the study.

Samples were fabricated from each batch to allow for testing at various ages after samples were cast. In general, one-half of the samples were treated electrochemically and the other half of the samples were used as control samples. Other than the electrochemical treatment, all samples were cured in a similar manner.

Compressive strength testing was performed in accordance with ASTM C39 (ASTM, 2001a). The modulus of elasticity and splitting tensile strength testing was performed in accordance with ASTM C469 (ASTM, 2001b) and ASTM C496 (ASTM, 2001c), respectively.

For the first set of batches fabricated in 2006, A4 and SCC mixtures, testing was performed on samples at 1, 7, 28, 90, 180, 240, 270, and 365 days after casting for the control samples. Treated samples were tested at 180, 240, 270, and 365 days after casting, as the treatment did not occur until 135 days after casting.

Length change measurements were performed on samples in accordance with ASTM C157 (ASTM, 2001d). Three samples were tested each test day for each batch for the compressive and splitting tensile strengths testing. For the modulus of elasticity testing, six samples were tested for each test day for each batch. For the length change samples, nine samples were tested.

Corrosion Testing

To initiate corrosion, all samples were exposed to salt using cyclical ponding with a 3% sodium chloride solution. To determine if there was a high probability of corrosion initiation, half-cell potential measurements were routinely made on the samples. This was done in accordance with ASTM C876 (ASTM, 1999). Each data point in the box charts of the corrosion potential data in this report represents the average of multiple data values. The averages were determined by using data gathered for different times (i.e., on four different test dates) from two different locations for each sample. Upon receipt of an indication of corrosion, an autopsy of the specimen was to follow to confirm corrosion and characterize the corroded area of the specimen.

RESULTS AND DISCUSSION

Placement of Test Samples

Weather Conditions

Both the SCC and A4 mixtures were cast and cured at an outdoor exposure site. The SCC samples were cast at VDOT's Boyd Tavern Area Headquarters on April 11, 2006, and the A4 samples were cast at the same location on April 13, 2006. Daily weather data from the Freeman Field Louisa, Virginia, weather station, which is approximately 12.5 mi from the exposure site, were captured to show the conditions leading up to, during, and following placement of the SCC and A4 mixtures (Weather Underground, 2013).

The mixtures were placed in accordance with the weather conditions specified by VDOT:

> Concrete shall not be placed against surfaces whose temperature is below 40 degrees F. Concrete shall be protected from freezing by approved coverings and, when necessary, heating the surrounding air in such a manner that the concrete will not dry (VDOT, 2002).

The temperature was acceptable for both mixtures, with the temperature range and maximum wind speed higher on the A4 casting date than on the SCC casting date. There was no precipitation for at least 2 days prior to placement of the mixtures, and there was a small amount of rain the day after the A4 mixture was placed. It is unlikely that any of the variability in the weather during the placement period would strongly alter either concrete mix design. The temperature, precipitation, and wind speed data for the days leading up to and following the casting dates are provided in Figure 8.
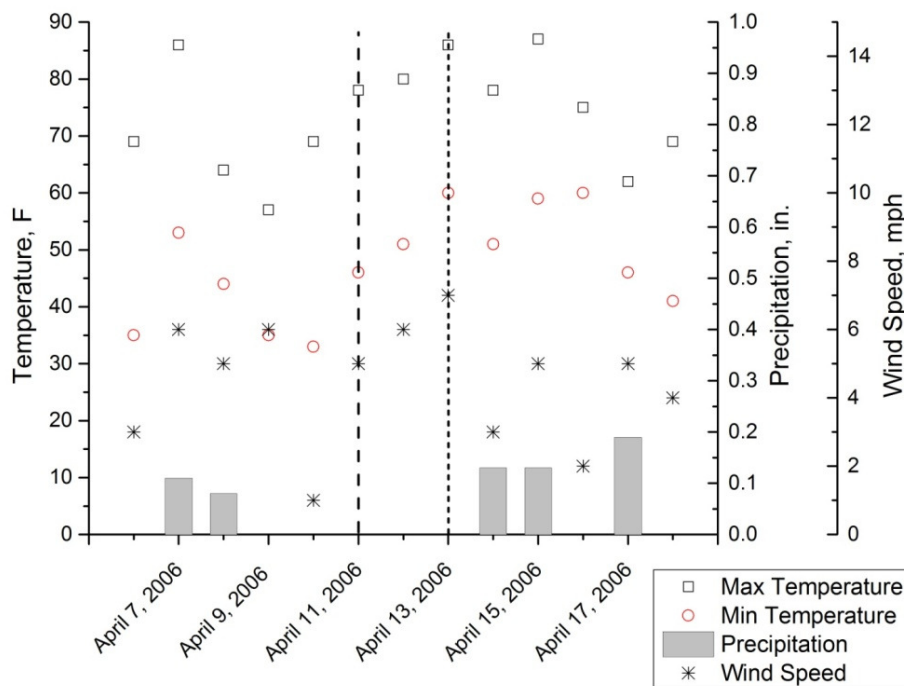

Figure 8. Weather Data for Region During Casting of Samples (Weather Underground, 2013)

SCC Mixture

For the SCC samples, the actual composition varied slightly from what was originally proposed, as shown in Tables 1 and 3. As discussed previously, both fresh and hardened concrete properties were measured. The fresh concrete properties are given in Table 4, and the hardened concrete properties are discussed in the section on "Electrochemical Treatment." In general, the final mix design resulted in a good flowing concrete that was easy to work with and had a w/c ratio of 0.38 and an air content of 6.7%.

Table 3. Composition of Actual Mixture for SCC Samples

Ingredient	Amount
Coarse aggregate (No. 18 stone "pea gravel")	1,393 lb
Fine aggregate	1,377 lb
Cement	752 lb
Water	286 lb
Air-entraining admixture	0.07 oz
High-range water-reducing admixture	4.2 oz

SCC = self-consolidating concrete.

Table 4. Fresh Concrete Test Results for SCC Mixture

Test	Measured Value
Spread, in (time, sec)	26 (4.0)
Air content, %	6.7
Temperature, °F	73
Relative humidity, %	36
Density, lb/ft^3	138.8

SCC = self-consolidating concrete.

A4 Mixture

The mix design for the A4 mixture is given in Table 1, with 0.75 oz/cwt of air-entraining admixture (AEA) and 8.0 oz/cwt of a high-range water-reducing (HRWR) admixture also added to the initial mixture. Initially the mixture was too stiff and the air content too low, so 2 gal of HRWR admixture was added to improve the workability and 20 oz of AEA was added to increase the air content. This resulted in multiple measurements being made before the concrete was placed. The fresh concrete properties for the initial ready-mix truck are given in Table 5, and the hardened concrete properties are discussed later. The blocks that contain this mixture are labeled A4-A in this report.

After some of the concrete was placed, the researchers decided the mixture was too stiff, and 1.75 gal of HRWR admixture was added. Although the slump and air content were not measured after the addition of the admixture, these blocks were labeled A4-B to help with evaluating the influence of the change on the corrosion resistance of the blocks. Finally, because of difficulties in consolidating and working with mixtures A4-A and A4-B, a second ready-mix truckload of A4 mixture was required to complete the casting of samples; these samples were labeled A4-C. The fresh concrete test results for the A4-C mixture are given in Table 6. In general, the final mix design resulted in a poorly flowing concrete that was difficult to work with and had a w/c ratio of 0.43 and an air content that ranged from 4.7% to 11.5%.

Table 5. Fresh Concrete Test Results for Samples A4-A

Test	Initial Measurement	Second Measurement After Mix Was Adjusted	Final Measurement After Mix Was Adjusted
Slump, in	7.25	7.75	-----
Temp, °F	79	80.5	-----
Air, %	-----	11.5	10.4
Density, lb/ft^3	-----	142	-----

Table 6. Fresh Concrete Test Results for Samples A4-C

Test	Measured Value
Slump, in	6.5
Temperature, °F	79.5
Air, %	4.7
Density, lb/ft^3	148

Upon completion of the two days of casting, since changes in concrete mix designs could influence the response of the samples during corrosion testing, the researchers decided to track separately the half-cell potential behavior of the three A4 mixtures (i.e., A4-A, A4-B, and A4-C) and the one SCC mixture.

Observations During Casting

As a first observation, it was noticed during the casting of the samples that the SCC samples required fewer workers than did the A4 samples. In general, three people were required to place the SCC and five or six people were required to place the A4. This was a result of the high fluidity of the SCC and the fact that the SCC did not require a person to consolidate the concrete through external vibration. The SCC also autogenously fit the shape of the forms as it was placed, evenly filling the forms because of its self-leveling nature, thus not requiring an additional person to come back and place additional concrete to ensure it was flush with the top of the form. The lower labor need for placing the SCC is evident in Figures 9 through 11. This is an important observation since the additional costs that could be incurred for the SCC material and changes in formwork could be offset by labor savings during placement.

Figure 9. Placement of SCC in Sample. SCC = self-consolidating concrete.

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Figure 10. Striking Off of SCC. SCC = self-consolidating concrete.

Figure 11. High Flow of SCC Makes Placement Work Easier. Concrete is placed in a second specimen without the need for vibrator while previous specimen is quickly screeded. SCC = self-consolidating concrete.

The second observation had to do with how the SCC and A4 mixtures faired according to selected requirements in the 2002 VDOT *Road and Bridge Specifications* (Table 7). As shown in Table 8, although the 2002 specifications do not have a requirement for SCC mixtures, the SCC used in this study would meet the requirements for minimum cement content, maximum w/c ratio, and air content in the 2002 VDOT *Road and Bridge Specifications*.

The A4 mixtures would meet the 2002 minimum cement content and maximum w/c ratio requirements. However, not all of them would meet the slump and air requirements, as shown in Table 8. A4-A would have too much entrained air, and A4-C would have too little. Nevertheless, even though the air content in the A4 mixtures would not meet the specification requirements, none of the samples had durability issues as a result of outdoor exposure to weather-related freeze cycles in Virginia. Because of the difference in A4 slump measurements, the A4-C mixture would meet the requirements and the A4-A mixture, and most likely the A4-B mixture since it was basically an A4-A mixture with additional HRWR, would not have met the requirements because of the too large slump measurement. Therefore, it was expected that the A4-A and A4-B mixtures would flow better, more like the SCC flowed, when compared to the A4-C mixture.

Table 7. Selected VDOT Specification Requirements for an A4 Mixture

Specification	2002 Requirement[a]
Minimum cement content, lb/yd^3	635
Maximum water/cement ratio	0.45
Slump, in	2 to 4 (if HRWR used, up to 7-in slump acceptable)
Air content, %	6 ± 1 (if HRWR used, can increase upper limit by 1%)

A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; HRWR = high-range water-reducing admixture.
[a] Requirement in 2002 VDOT *Road and Bridge Specifications.*

Table 8. Comparison of SCC and A4 Mixtures With Regard to Selected 2002 VDOT Specification Requirements

Specification	SCC	A4-A	A4-B	A4-C
Minimum cement content	Meets	Meets	Meets	Meets
Maximum water/cement ratio	Meets	Meets	Meets	Meets
Slump	N/A	Does not meet (too high)	---	Meets
Air content	Meets	Does not meet (too high)	---	Does not meet (too low)

Source: 2002 VDOT *Road and Bridge Specifications* (VDOT, 2002).
SCC = self-consolidating concrete; A4-A = first A4 mixture Placed; A4-B = second A4 mixture placed; A4-C = third A4 mixture placed.

Results of Electrochemical Treatment

While subjecting all the blocks to similar current densities, on average a larger applied voltage was required for the SCC samples than for the A4 samples. However, in both cases the average voltage decreased while current density remained constant. The average voltage and current density response of the A4 and the SCC samples are shown in Figures 12 and 13, respectively.
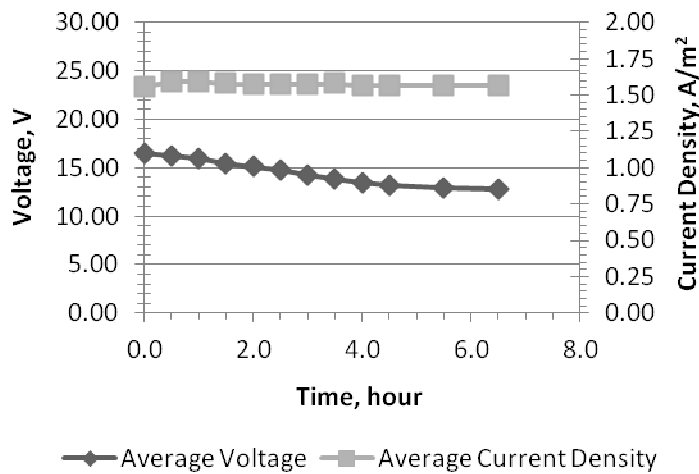

Figure 12. Average Voltage and Current Density Measurements for A4 Samples. A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement.
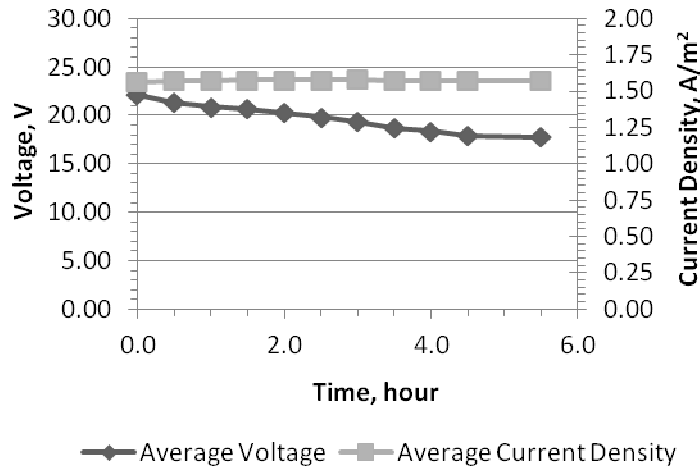
Figure 13. Average Voltage and Current Density Measurements for SCC Samples. SCC = self-consolidating concrete.

Table 9. Charge Passed During Treatment of Samples

A4 Mix Design			SCC Mix Design		
Rebar Type	Void Size	Charge Passed, C	Rebar Type	Void Size	Charge Passed, C
CS	Small	9836	CS	Small	8935
A1035	Small	9971	A1035	Small	8964
CS	Large	11622	CS	Large	9436
CS	Large	9760	CS	Large	9725
CS	Large	6534	CS	Large	7160
A1035	Large	8568	A1035	Large	8818
A1035	Large	10512	A1035	Large	6438
A1035	Large	9604	A1035	Large	10819
CS	None	9549	CS	None	9585
CS	None	11253	CS	None	8328
CS	None	8322	CS	None	8808
A1035	None	13297	A1035	None	9053
A1035	None	7863	A1035	None	7498
A1035	None	7945	A1035	None	10312

A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; SCC = self-consolidating concrete; A1035 = low carbon, chromium, steel rebar; CS = carbon steel.

A two-sample independent *t*-test was performed on the charge passed values shown in Table 9 to determine if the difference of the population means were significantly different. This was done to determine if the various samples had received similar treatments. Three scenarios were evaluated: A4 vs. SCC mix design, large voids vs. no voids, and carbon steel vs. ASTM A1035 steel. It was determined for each scenario that at the 0.05 level, the difference of the population means was not significantly different than the test difference. This result was expected since an attempt was made to maintain a constant current flow while the voltage was allowed to fluctuate.

Concrete Material Properties

As mentioned previously, the A4 and SCC samples were cast in 2006. Some of the samples from each mixture were electrochemically treated whereas others were not and were used as control samples. Samples were tested for compressive strength, modulus of elasticity, splitting tensile strength, and length change. Figure 14 presents the average compressive strength, splitting tensile strength, and modulus of elasticity for the treated and untreated samples fabricated from the A4 mixture, respectively. Although early data varied slightly, over time there were no significant differences between the untreated and treated samples. All tested values after 1 year were within 5% of each other.

Figure 15 presents the average compressive strength, splitting tensile strength, and modulus of elasticity for the treated and untreated samples, respectively, fabricated from the SCC mixture. Again, the data showed slight variability early, but over time there were no significant differences between the untreated and treated samples. All tested values after 1 year were again within 5% of each other.
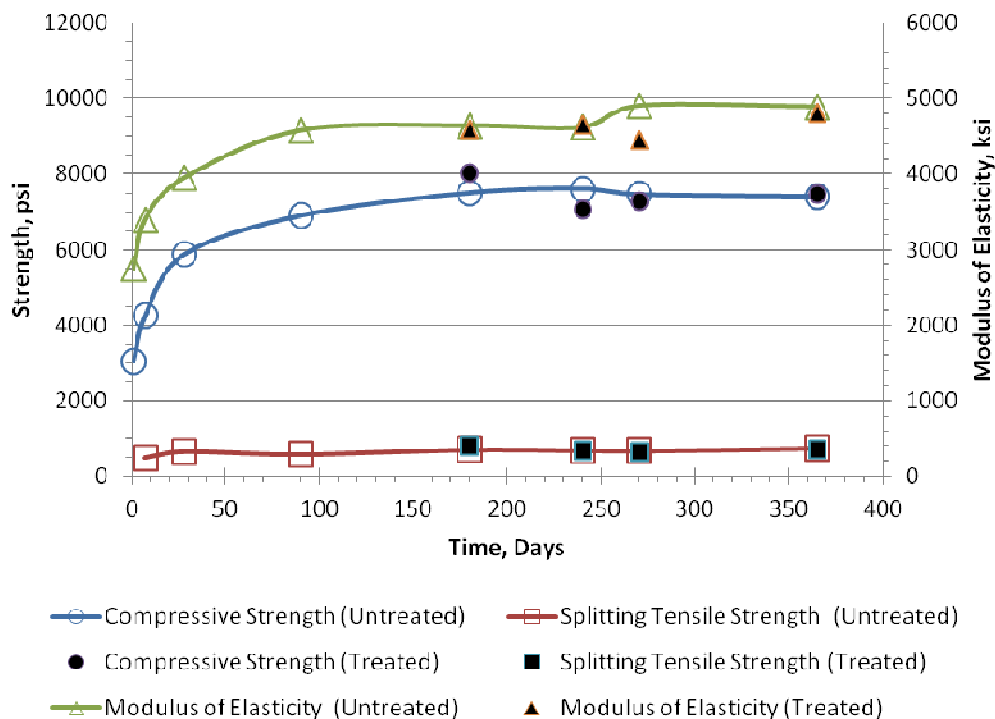

Figure 14. Material Properties for Treated and Untreated A4 Samples. A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement.
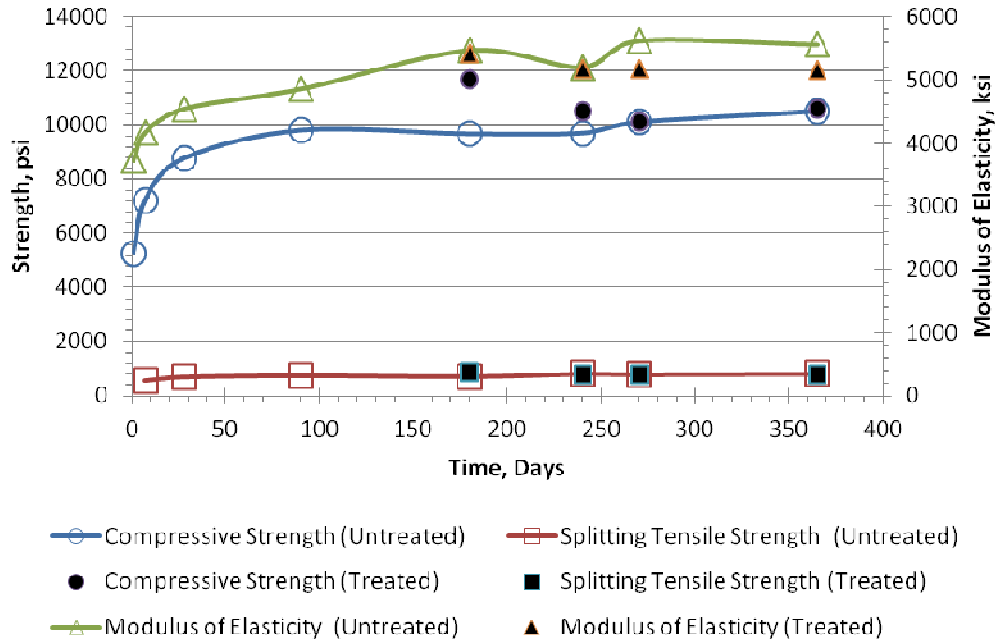
16

Figure 15. Material Properties for Treated and Untreated SCC Samples. SCC = self-consolidating concrete.

Figure 16 presents the length change data for the A4 samples. The data are presented in microstrain, with the negative sign meaning shrinkage. The data show that although the treated samples show some swelling after treatment because of moisture ingress during treatment, the overall shrinkage adjusts back to the original shrinkage as the samples dry. Therefore, from the data it does not appear that the electrochemical treatment affected the shrinkage of the samples.
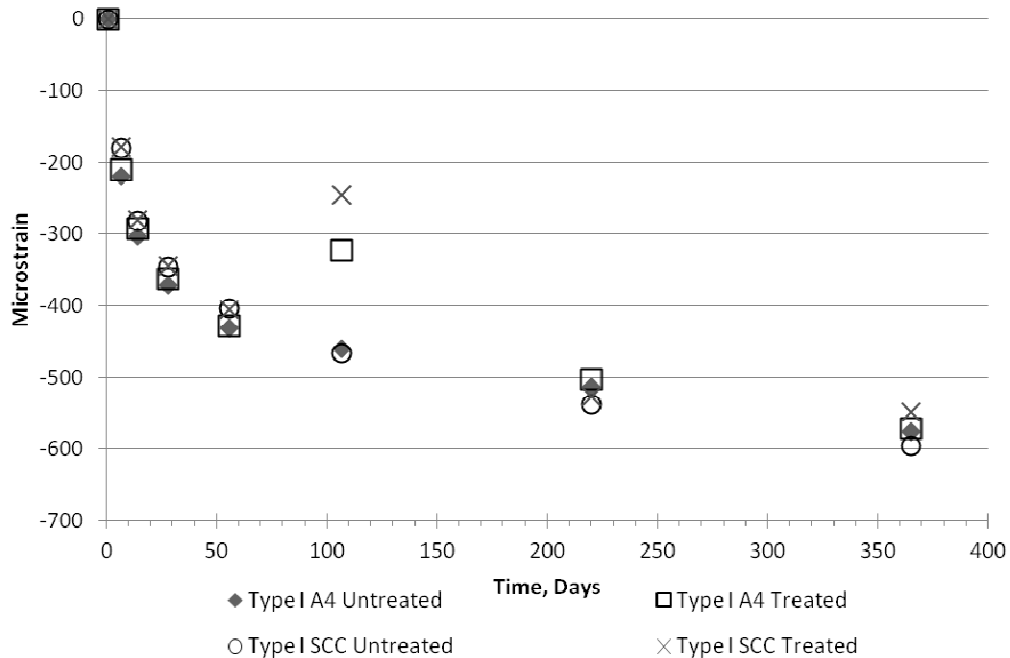
Figure 16. Length Change Data for Treated and Untreated A4 and SCC Mixtures. A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; SCC = self-consolidating concrete.

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Figure 16 also presents the length change data for the SCC mixtures. Again, the treatment produced some swelling in samples, but the length change went back to normal as the samples dried. This is an indication that the treatment did not affect the length change of the samples.

Corrosion Evaluation

Based on the most recent half-cell potential measurements, gathered in September 2013, several interesting trends were found. These trends are discussed for each type of sample cast for this study.

In an untreated (i.e., not electrochemically treated) concrete, after the median, mean, and spread of the most recent half-cell data shown in Figure 17 were compared, it was clear that the creation of artificial void spaces against the bar did not strongly alter the median or mean; however, the data spread was smaller in blocks without voids. Upon evaluating the influence of the SCC vs. A4 mixtures (Figure 18), in general the SCC mixtures appeared to be performing better than the A4 mixtures. Even the "No Void SCC" samples had a more negative median and mean potential value; however, these values were still in the potential region of low corrosion probability according to ASTM C876 (ASTM, 1999).

As mentioned earlier, the A4 mixtures were from two different ready-mix batches that had different fresh concrete properties. Figure 19 separates the responses of the different A4 mixtures (including the SCC mixture as a point of reference). Clearly, the A4-C mixture was responding differently from the other mixtures. Further, the values measured for the A4-C samples were indicative of a higher probability of corrosion compared to the SCC, A4-A, and A4-B mixtures. Upon visual assessment of the samples, cracking was found in eight blocks, of which seven were cast using the A4-C mixture (the other one was a A4-B mixture), which supports the observations regarding the half-cell potential data. This was also consistent with the fact that the SCC, A4-A, and A4-B mixtures all had better flow characteristics (for example, higher slump) and so they would consolidate better. It is ironic, however, that in this case because of its high slump, the A4-A mixture would not have met the VDOT specification whereas the A4-C mixture would have met the slump requirement even though the A4-A mixture was outperforming the A4-C mixture. In addition, the higher cement content, lower w/c ratio, and improved distribution of cement particles in the SCC mixture were expected to improve the corrosion resistance of the mixture.

Finally, cracking was not observed in any of the treated samples. In general, these samples also had half-cell values that indicated a low probability of corrosion. The average of the four last measurements over a void location resulted in a median value of -134 mV vs CSE (copper / copper sulfate electrode); mean value of -132 mV vs CSE; standard deviation of 69 mV; minimum value of 18 mV vs CSE; and a maximum value of -267 mV vs CSE. Therefore, additional chloride exposure was required to induce corrosion in the treated samples.
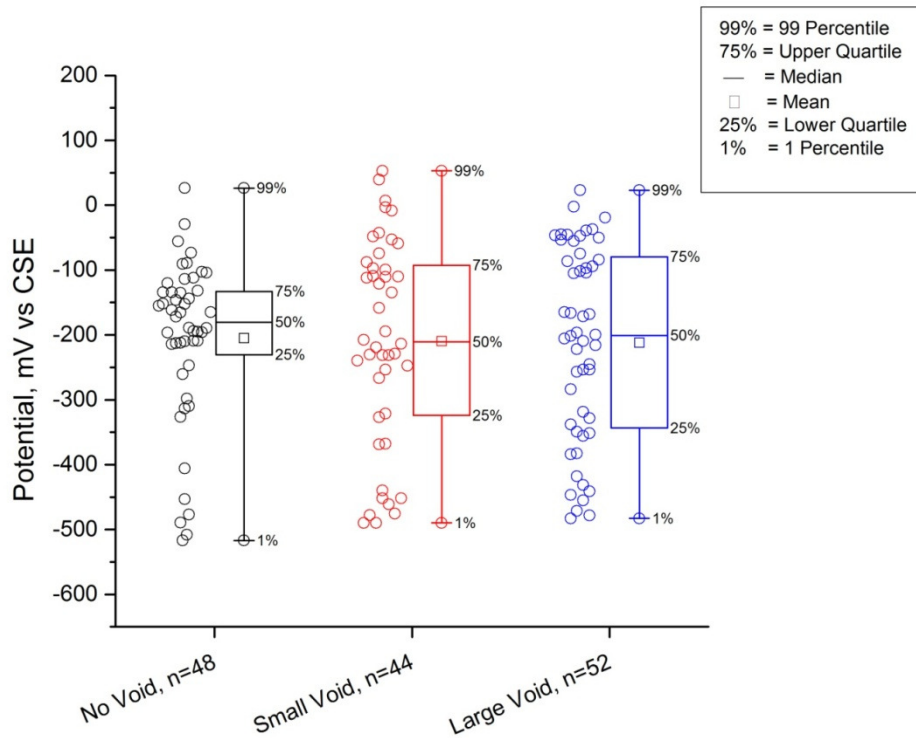
18

Figure 17. Comparison of Void Influence on Corrosion Potential in Untreated Samples
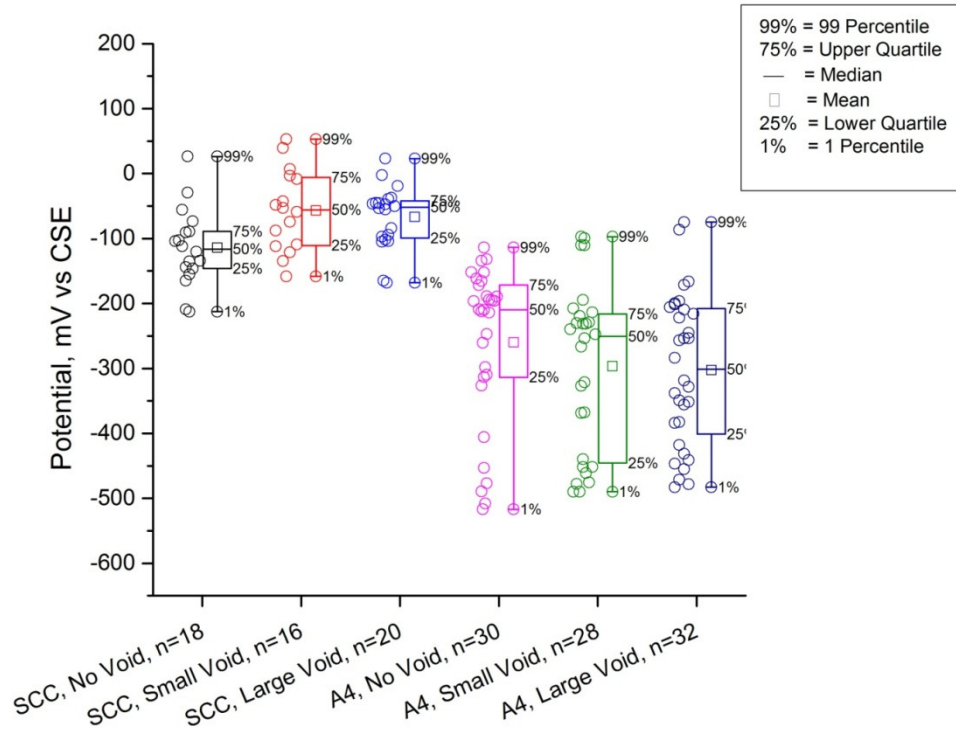

Figure 18. Influence of Concrete Type and Presence of Voids on Corrosion Potential of Untreated Samples. SCC = self-consolidating concrete; A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement.
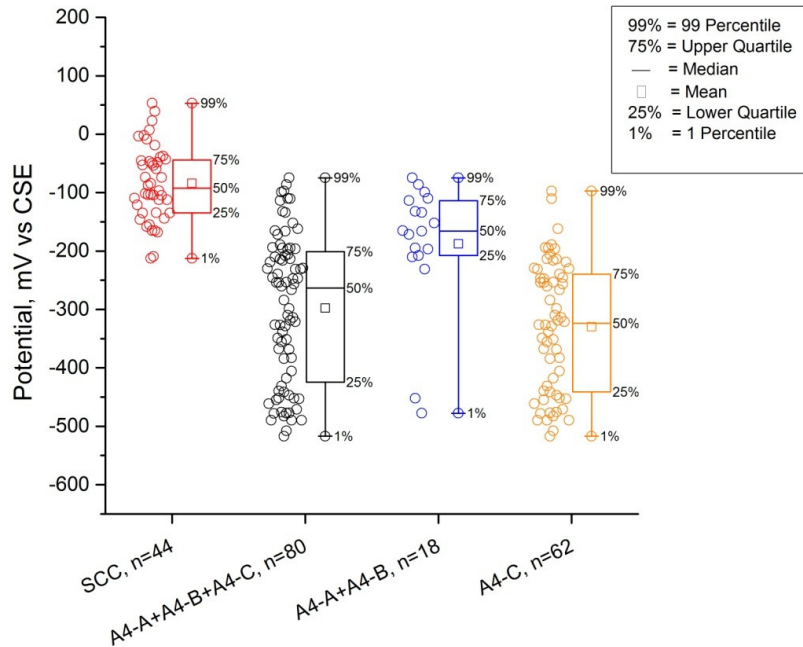
19

Figure 19. Half-cell Potential Measurement Responses on Untreated Samples. SCC = self-consolidating concrete; A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; A4-A+A4-B +A4-C = Combining Data From First, Second, and Third A4 Mixtures Placed; A4-A+A4-B = Combining Data From First and Second A4 Mixtures Placed; A4-C = Data From Third A4 Mixture Placed.

The samples also contained different types of steel reinforcement. Figure 20 again shows that the SCC mixture was performing better than the A4 mixture regardless of the reinforcing steel. Upon comparison of the steels in the A4 mixtures, the carbon steel has the greatest spread in the data and the most negative median and mean values. This is consistent with what would be expected since this type of steel is the least corrosion resistant. This would indicate a high probability of corrosion relative to the other samples. In contrast, the 316LN stainless steel clad rebar exhibited the best performance to date, showing the most positive corrosion potential and tightest distribution of data. This is also consistent with what would be expected when comparing carbon steel with stainless steel rebar.

It was interesting to note the response the blocks have had to the electrochemical treatment; however, only the data for the A4-A and A4-B blocks were included in the analysis since none of the A4-C blocks received treatment. The corrosion potential behavior is shown in Figure 21, which shows that the untreated blocks on average had a more positive potential but also the greatest variability. Upon visual examination of the blocks, the untreated blocks also had a single sample with a crack whereas the treated blocks did not. To assess better the influence that the treatment has had, additional ponding cycles and monitoring are required for these blocks.

After the half-cell potential data and observed cracking of some A4 samples were evaluated, it is clear that an autopsy is warranted for some samples. Therefore, these samples will be autopsied in the near future to characterize the corrosion. However, the ponding process will continue and routine corrosion measurements will be gathered until corrosion is evident in the other samples.
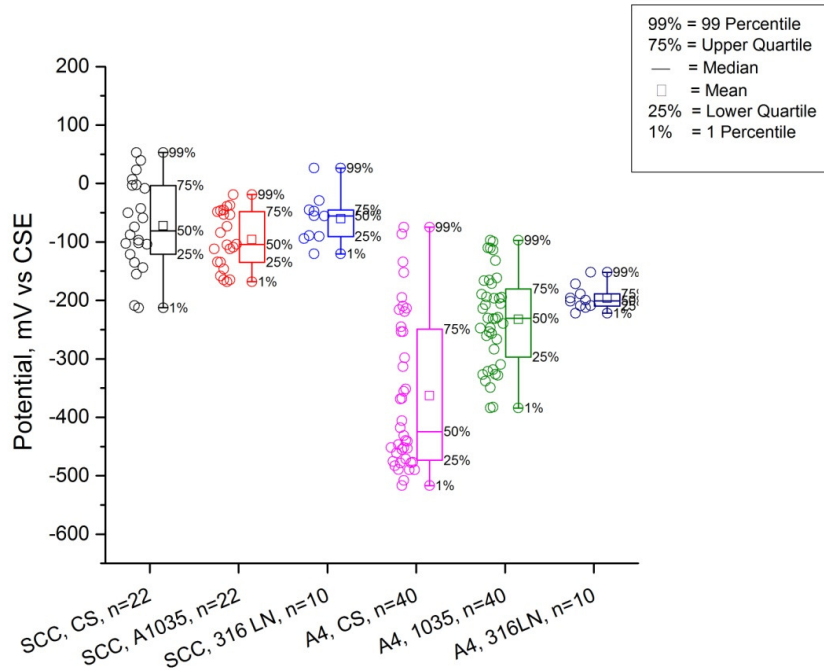
20

Figure 20. Steel Type and Mix Design Half-cell Potential Measurement Responses for Untreated Samples With Different Void Conditions That Were Exposed to Chlorides. SCC = self-consolidating concrete; CS = carbon steel rebar; A1035 = low carbon, chromium, steel rebar; 316 LN = 316LN stainless steel clad rebar; A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement.
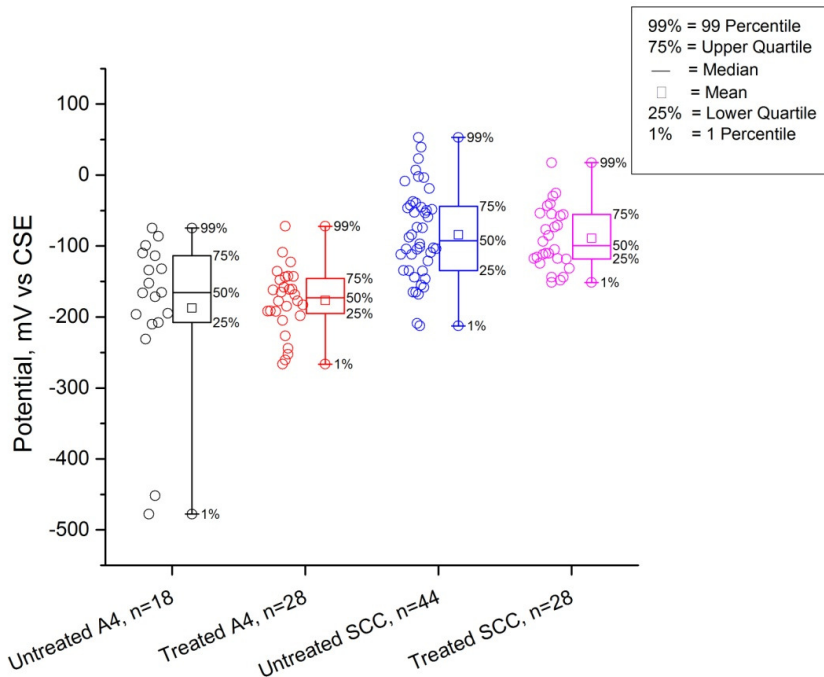

Figure 21. Mix Design Half-cell Potential Measurement Responses for Treated and Untreated Samples. Untreated = not electrochemically treated; treated = electrochemically treated; A4 = VDOT Class A4 General Bridge Deck Concrete With Straight Portland Cement; SCC = self-consolidating concrete. The data for A4-C blocks are not included in the plot.

SUMMARY OF FINDINGS

- Varying the concrete mix design resulted in considerable differences in corrosion potential behavior.

- When compared to the A4 mixture, the SCC mixture, even with a mix design with a lower w/c ratio, required fewer personnel to place.

- To induce equivalent current densities in the SCC and A4 mix designs, the SCC samples required larger applied voltages.

- Strength-related properties were not influenced by short-term electrochemical treatment of 3-month-old samples.

- The shrinkage response changed during the treatment because of the ingress of moisture from testing, but the change was not permanent and the length change returned to normal as the samples dried.

- The SCC provided indications of being a more corrosion-resistant concrete as compared to the non-pozzolanic A4 mixture.

- A comparison of the corrosion potential data, independent of mix design, showed that the probability of corrosion for the three types of steel evaluated would be as follows (least to greatest probability of corrosion):

  316LN Stainless Steel Clad Rebar < ASTM A1035 Rebar < Carbon Steel Rebar

- The corrosion potential measurements indicated that a greater spread between the 25th and 75th percentile of the half-cell data occurred when voids were present, but the samples must be autopsied to confirm the influence of the voids on the corrosion behavior at the steel.

- The corrosion potential measurements indicated that a greater spread in the overall half-cell data and between the 25th and 75th percentile of the half-cell data occurred with lower corrosion-resistant steel (carbon steel) as compared to higher corrosion-resistant steel (316LN stainless steel clad).

- Corrosion potential measurements indicated that a greater spread in the overall half-cell data and between the 25th and 75th percentile of the half-cell data occurred with the untreated samples when compared to the treated samples; however, the medians and means were similar for a given mixture.

CONCLUSIONS

- *Alkalinity, w/c ratio, concrete fluidity during placement, and steel type all influence the corrosion potential of the reinforcing steel when reinforced concrete is subjected to saltwater.*

- *Of the two void sizes evaluated during this study, small voids adjacent to the steel create a greater spread between the 25th and 75th percentile of the half-cell potential measurements when compared to locations without voids; however, these small voids have little influence on the average value measured when compared to the larger voids.*

- *The behavior of a mixture during placement can strongly influence the amount of labor required during placement; therefore, a more expensive mixture could provide labor savings during placement.*

RECOMMENDATIONS

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1. *VCTIR should continue performing saltwater exposure on these samples until corrosion becomes evident. An autopsy of these samples should then follow to characterize corrosion of the steel reinforcement.*

2. *VCTIR should compare different acceptable concrete mix designs to see how each influences the corrosion potential of the embedded reinforcing steel.*

3. *VDOT's Materials Division should work with VCTIR to investigate areas where cost savings could be realized for VDOT by reducing labor requirements through the use of SCC.*

BENEFITS AND IMPLEMENTATION PROSPECTS

This study showed that alkalinity, w/c ratio, and steel type all influence the corrosion potential of the reinforcing steel when reinforced concrete is subjected to saltwater. The study recommended that VCTIR continue performing saltwater exposure on these specimens until corrosion becomes evident and then autopsy them and characterize the corrosion of the steel reinforcement. In addition, VCTIR should compare various concrete mix designs that would be considered acceptable to VDOT and assess how each influences the corrosion potential on embedded steel. In addition, this effort should place more emphasis on mix designs, such as SCC mixtures, that could provide VDOT with greater corrosion resistance and reduced labor during placement.

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