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Use of Electrochemical Chloride Extraction and Associated Repairs to Extend the Beneficial Life of Reinforced Concrete Substructures

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Final Report VTRC 16-R16

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 16-R16	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Use of Electrochemical Chloride Extraction and Associated Repairs to Extend the Beneficial Life of Reinforced Concrete Substructures		5. Report Date: May 2016 6. Performing Organization Code:
7. Author(s): Stephen R. Sharp, Ph.D., P.E.		8. Performing Organization Report No.: VTRC 16-R16
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 99204
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219 Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825		13. Type of Report and Period Covered: Final 14. Sponsoring Agency Code:
15. Supplementary Notes:		

16. Abstract:

One of the biggest causes of bridge deterioration is corrosion of the reinforcement in concrete structures. Therefore, repair techniques that mitigate corrosion and extend the service life of reinforced concrete are of great value to the Virginia Department of Transportation (VDOT). One such technique is electrochemical chloride extraction (ECE), which is a temporary in situ restoration method for removing chlorides from reinforced concrete structures that are deteriorating because of corrosion.

The results of this study are based on historical and current data gathered during the evaluation of substructure elements in Virginia, i.e., the 5th Street Extended Bridge in Albemarle County and two I-95 bridges in Richmond, and on information from the literature about the earliest bridge substructure treated with ECE, i.e., the Burlington Bay Skyway in Burlington, Ontario, Canada,.

Early ECE work on the Burlington Bay Skyway showed favorable results upon reassessment of the treated area after 9 years. With regard to the ECE-treated structures in Virginia, the study determined that if additional service life beyond that provided by ECE alone is desired, the structure must be protected against the reintroduction of chlorides to the repaired elements. Further, the use of ECE techniques should be accompanied by repair or removal of overhead deck expansion joints that exposed the concrete elements to salt-laden water and application of a waterproofing sealer such as silane, methacrylate, or epoxy to the substructure elements. ECE provided an additional 15 to 20 years of service life when a post-treatment silane sealer was also applied.

The study also found that in the project specification, the criterion used for determining when to terminate ECE is often the amount of charge passed but difficulties in the field might result in unforeseen construction delays as a result of the attempt to meet this criterion. Therefore, contracts should specify that chloride concentration at the level of the reinforcing bar can be used as an alternative criterion for determining when the ECE is complete, particularly when treatment times become excessive. Specifications should also require that all ECE connections to the steel be completely removed or embedded after completion of the treatment and a highly resistive cementitious repair material should be used to patch any holes.

Another valuable outcome from this study was the discussion on how combining electrochemical techniques, such as cathodic protection and ECE, could theoretically provide additional life beyond that provided by the use of one of these techniques alone. This study gathered baseline data to assess this option. The two I-95 bridges in Richmond, one over Hermitage Road and the other over Overbrook Road, should allow a comparison of how much galvanic anode cathodic protection can extend service life beyond that of ECE treatment alone.

The study recommends that VDOT's Structure and Bridge Division incorporate the lessons learned from assessing the restoration of the substructures of the 5th Street Extended Bridge and the two I-95 bridges. In addition, the Virginia Transportation Research Council should continue to monitor the I-95 bridges to determine the value of combining different electrochemical mitigation techniques to extend service life.

17 Key Words: Corrosion, electrochemical chloride extraction, ECE, beneficial life	18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 66	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

USE OF ELECTROCHEMICAL CHLORIDE EXTRACTION AND ASSOCIATED REPAIRS TO EXTEND THE BENEFICIAL LIFE OF REINFORCED CONCRETE SUBSTRUCTURES

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In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

May 2016
VTRC 16-R16

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ABSTRACT

One of the biggest causes of bridge deterioration is corrosion of the reinforcement in concrete structures. Therefore, repair techniques that mitigate corrosion and extend the service life of reinforced concrete are of great value to the Virginia Department of Transportation (VDOT). One such technique is electrochemical chloride extraction (ECE), which is a temporary in situ restoration method for removing chlorides from reinforced concrete structures that are deteriorating because of corrosion.

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Early ECE work on the Burlington Bay Skyway showed favorable results upon reassessment of the treated area after 9 years. With regard to the ECE-treated structures in Virginia, the study determined that if additional service life beyond that provided by ECE alone is desired, the structure must be protected against the reintroduction of chlorides to the repaired elements. Further, the use of ECE techniques should be accompanied by repair or removal of overhead deck expansion joints that exposed the concrete elements to salt-laden water and application of a waterproofing sealer such as silane, methacrylate, or epoxy to the substructure elements. ECE provided an additional 15 to 20 years of service life when a post-treatment silane sealer was also applied.

The study also found that in the project specification, the criterion used for determining when to terminate ECE is often the amount of charge passed but difficulties in the field might result in unforeseen construction delays as a result of the attempt to meet this criterion. Therefore, contracts should specify that chloride concentration at the level of the reinforcing bar can be used as an alternative criterion for determining when the ECE is complete, particularly when treatment times become excessive. Specifications should also require that all ECE connections to the steel be completely removed or embedded after completion of the treatment and a highly resistive cementitious repair material should be used to patch any holes.

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The study recommends that VDOT's Structure and Bridge Division incorporate the lessons learned from assessing the restoration of the substructures of the 5th Street Extended Bridge and the two I-95 bridges. In addition, the Virginia Transportation Research Council should continue to monitor the I-95 bridges to determine the value of combining different electrochemical mitigation techniques to extend service life.

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INTRODUCTION

According to Koch et al. (2002), the annual direct cost associated with corrosion of bridges according to the Federal Highway Administration (FHWA) was estimated to be up to $8.3 billion in 2002. Therefore, repair techniques that mitigate corrosion and extend the service life of a reinforced concrete bridge are of great value to all state departments of transportation. One mitigation technique, electrochemical chloride extraction (ECE), is a temporary in situ restoration technique for reinforced concrete structures that are deteriorating because of corrosion. Although ECE is generally the focus of the repair, the value of performing other maintenance of the structure as part of the repair contract, such as joint repairs or concrete sealing, can increase the beneficial life after ECE. In addition, some have proposed installing cathodic protection (CP) on a structure after ECE to increase the beneficial life further. However, to maximize the benefit of ECE treatment on service life extension, it is important to understand how ECE works.

ECE is used to remove chloride ions from reinforced concrete while increasing the alkalinity near the reinforcing steel (Bennett and Thomas, 1993; Chatterji, 1994; Google, 2000). ECE systems apply current densities of up to $1A/m^2$ for usually 4 to 8 weeks, which reduce chloride levels while increasing the alkalinity at the reinforcement, both of which enhance the corrosion resistance of the steel (Bennett and Thomas, 1993; Clemeña and Jackson, 1997; Elsener and Böhni, 1994). A schematic showing corrosion being initiated followed by ECE treatment is shown in Figure 1.

Concrete bridge decks require traffic control during ECE treatment; however, chloride extraction of bridge piers does not generally require the extensive re-routing of traffic because the treatment can be performed without encroaching on the roadway. Examples of equipment on a bridge deck and pier are shown in Figure 2. In Figure 2a, the 34th Street Bridge that crosses I-395 in Arlington, Virginia, is having chlorides electrochemically removed from the bridge deck. In Figure 2b, the piers of the 5th Street Extended Bridge over I-64 in Albemarle County, Virginia (hereinafter 5th Street Extended Bridge), are being treated. From these photographs it is evident that the travel lane cannot be used during ECE treatment on a bridge deck. However, when the substructure is treated, the increase in circumference for each column and the pier cap after installation of the treatment system is relatively insignificant and the roadway is not encroached. Therefore, it is important to consider how treating a particular reinforced concrete element with ECE will influence the local traffic flow.

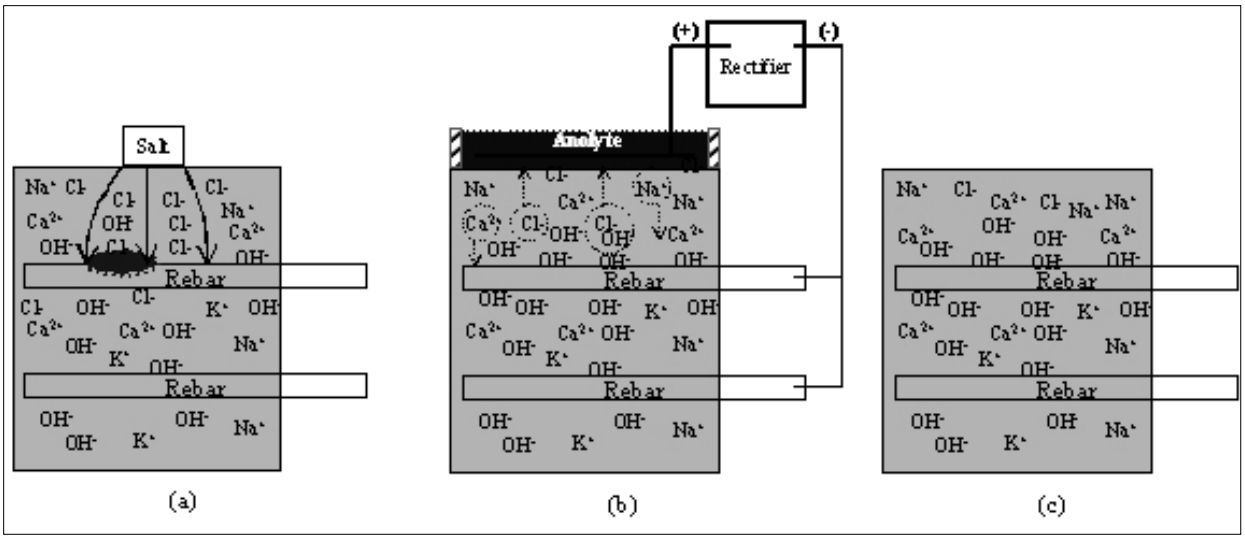

Figure 1. Illustration of Corrosion Initiation Followed by ECE Treatment on Horizontal Surface. (a) Salt penetrates uncontaminated concrete and chloride threshold is exceeded; corrosion is initiated. (b) A temporary ECE system is constructed, which reduces chloride concentration at the steel while increasing the alkalinity. (c) ECE is complete and equipment is removed. ECE = electrochemical chloride extraction.

Based on previous research on ECE (Andrade et al., 1998; Bennett and Thomas, 1993; Bennett et al., 1993a, 1993b; Clemeña and McGeehan, 1993; Ryu and Otuski, 2002; Sharp and Virmani, 2006; Sharp et al., 2002), electrochemically treating a reinforced concrete structure has the potential to reduce corrosion susceptibility by the following:

- reducing the chloride content in the concrete
- reducing the permeability of cracks by electrodeposition of insoluble products
- forming a tightly adherent deposit on the treated surface
- 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 surface of the reinforcing bar.

Most of these changes positively impact the structure and improve the durability. However, although increasing the alkalinity decreases the corrosion susceptibility of the steel, it can cause a problem if the concrete aggregate is susceptible to alkali-silica reaction (ASR). Although most aggregate is inert, some aggregates that contain certain forms of silica react with the alkaline products (Portland Cement Association [PCA], 2015). This reaction causes the formation of a gel on the surface of the aggregate that can swell and create expansive pressures, which can then lead to cracking of the concrete (PCA, 2015). Fortunately, there are certain electrolytes that can be used during ECE to mitigate ASR so that the treatment does not promote ASR in the structure. Evaluation of the aggregate for susceptibility to ASR prior to ECE treatment will ensure the correct electrolyte is selected for the treatment.

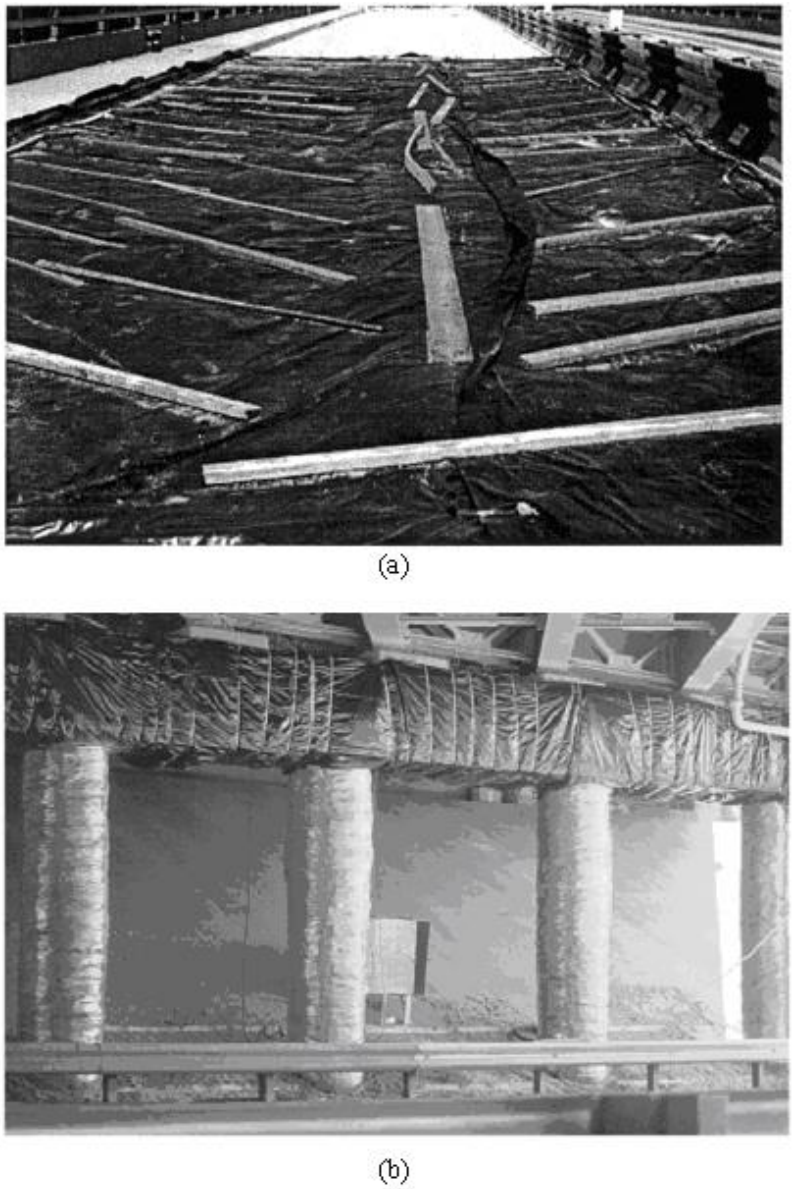

Figure 2. Chloride Removal. (a) 34th Street Bridge Deck (from Clemeña and Jackson, 1996b). (b) 5th Street Extended Bridge Piers (from Clemeña and Jackson, 2000).

Several methods of restoration are available for bridge owners in addition to ECE. However, when techniques are compared, it is important to have accurate cost values associated with each technique and a realistic value for the increase in service life. Unfortunately, with multiple factors contributing to the reduction in corrosion susceptibility after ECE treatment, the increase in beneficial life has remained unclear. Further, the beneficial life could vary for different bridge components because the saltwater contact time for the top of a pier cap (horizontal surface) can be very different than for a bridge column (vertical surface). Finally, if other repairs were made to a structure that would eliminate saltwater from contacting a bridge element (e.g., drainage repair), additional life beyond that provided by the ECE treatment would be expected.

PURPOSE AND SCOPE

The purpose of this study was to determine the beneficial life after the treatment of substructure elements using ECE and associated repair techniques by evaluating structures treated with ECE, thus leading to an increased understanding of the influence ECE and associated repair techniques can have on extending the service life of a corroding bridge substructure element.

Specifically, the results of the study are based on historical and current data gathered by the Virginia Department of Transportation (VDOT) during the evaluation of actual substructure elements in Virginia, i.e., the 5th Street Extended Bridge and two I-95 bridges in Richmond, in addition to findings from the literature about the Burlington Bay Skyway in Burlington, Ontario, Canada, which was the earliest bridge substructure treated with ECE in North America.

The study also captured critical baseline information that will be useful in understanding how combining electrochemical mitigation techniques could further extend service life beyond that provided solely by ECE. This will provide bridge engineers with the knowledge they need to make decisions regarding the incorporation of ECE as a restoration technique.

METHODS

Literature Review

Although this study focused on ECE, several supplementary techniques can potentially increase service life after its application. Bridge deck joint repair and concrete sealing would both reduce the ability of the chloride-containing saltwater solutions to penetrate the concrete and extend service life after ECE. The 5th Street Extended Bridge is an example of bridge piers being sealed after ECE, so this project was included as part of the literature review. More recently, it has been suggested that using galvanic anode CP (GACP) after ECE treatment of reinforced concrete can reduce the corrosion rate and further extend service life. The I-95 11-bridge restoration project in Richmond is an example of this mitigation approach. A review of the literature was performed before the onset of that restoration project to determine if other bridge elements had received both ECE and CP.

In addition, a review of the literature was performed to identify any physical evaluations of any of the reinforced concrete substructure elements originally treated with ECE. Of particular interest was the pier of the Burlington Bay Skyway in Burlington, Ontario, Canada. This structure was of interest because it was the first substructure element treated with ECE in North America, having undergone ECE in 1989 (Pianca et al., 2003; Sharp et al., 2002).

Field Structures Selected for Study

5th Street Extended Bridge

Overview

Built in 1969, the 5th Street Extended Bridge (VA. Str. No. 6302), shown in Figure 3, carries Route 631 (5th Street Extended) over the eastbound and westbound lanes of I-64 in Albemarle County, Virginia. The structure is a four-span multi–steel girder bridge that has a total length of 334 ft. The joints in this bridge can also be seen in Figure 3, half of which are located above each pier. The substructure consists of reinforced concrete piers and caps, which provided the main area of interest for this study as evaluating their current condition provides an evaluation of the effectiveness of ECE and subsequent silane sealing treatment after almost 20 years of service. The comparison is aided by the fact that selected piers and caps were treated with ECE and other piers and caps were selected to be controls (i.e., remain untreated).

It is also important to highlight that this bridge is exposed to salt from snow and ice removal operations that occur along both 5th Street Extended, which crosses over the bridge, and I-64, which crosses under the bridge. In 2014, the average daily traffic along 5th Street Extended was in excess of 15,000 vehicles and traffic along I-64 exceeded 20,000 vehicles. During snow and ice events, this comprises a sizable number of vehicles that subject the deck and substructure to deicing salt, so clearly this bridge is a representative candidate structure for testing and assessing the benefit of this technology.

The ECE system was energized in late April 1995, and treatment was terminated in early July of the same year. Clemeña and Jackson (1996a) stated that a silane sealer was applied to the piers after the ECE treatment was completed. The method used to treat the bridge and selected electrical measurements from this treatment were provided by Clemeña and Jackson (2000).

Current Evaluation

Review of Inspection Reports. The VDOT inspection reports for the 5th Street Extended Bridge were reviewed to assess the change in condition over time. The bridge is subject to a 24-month inspection cycle. The reports evaluated were for inspections made in 2006, 2008, 2010, 2012, and 2013.

Visual Observations. A visual survey of the substructure was performed to assess the current condition after ECE treatment. To document any areas of interest, notes were made and photographs were taken.

Chloride Samples. An analysis of the concrete samples for chlorides was performed in accordance with ASTM C1152, with the assumption that the unit weight of concrete is 3,915 lb/yd^3 (ASTM International [ASTM], 2012). Chloride samples were gathered for this study from Columns 1 (C1) and 7 (C7) in Piers 1 (P1) and 3 (P3). The plan view is shown in Figure 3, and a sketch of the general locations of the samples is shown in Figure 4. Concrete samples for analysis were gathered by horizontal drilling into the column at the following increments when permissible:

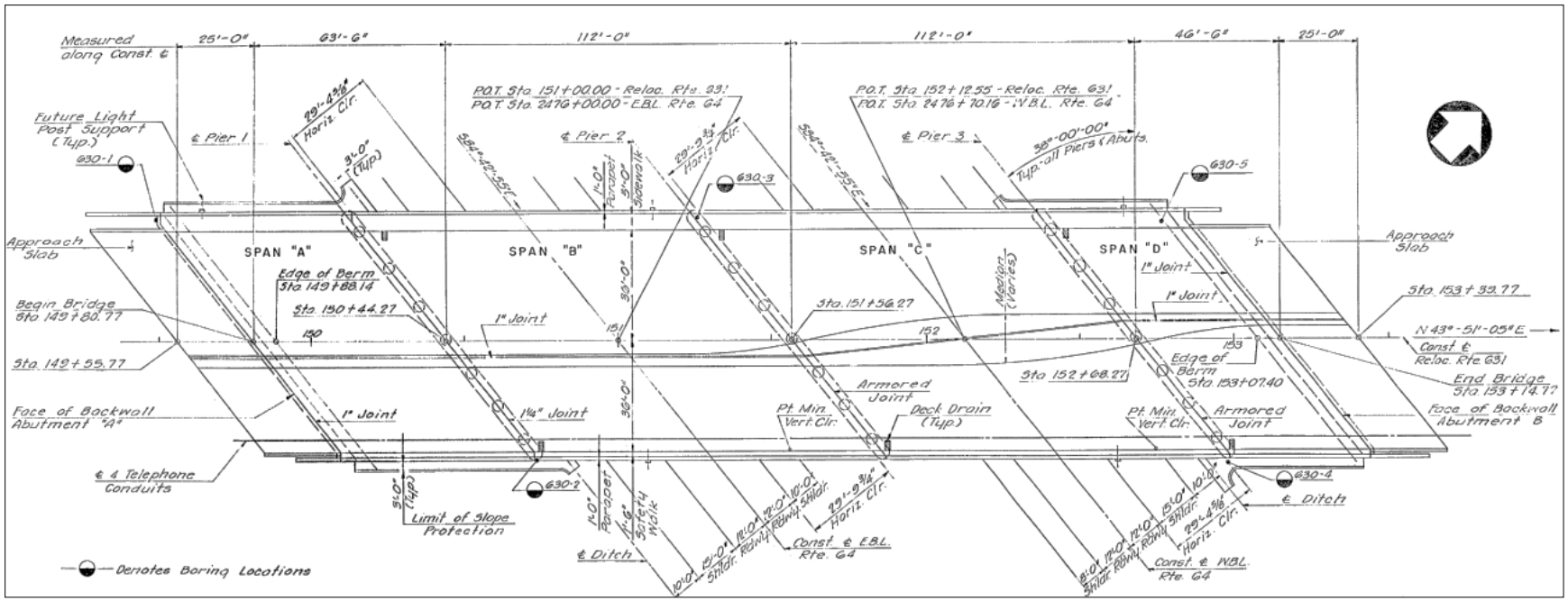

Figure 3. Plan View of 5th Street Extended Bridge

- between the surface and ¼-in depth
- between ¼-in depth and ¾-in depth
- between ¾-in depth and 1¼-in depth
- between 1¼-in depth and 1¾-in depth
- between 1¾-in depth and 2¼-in depth
- between 2¼ -in depth and 2¾-in depth
- between 2¾-in depth and 3¼-in depth
- between 3¼ -in depth and 3¾-in depth
- between 3¾-in depth and 4¼-in depth
- between 4¼-in depth and 4¾-in depth.

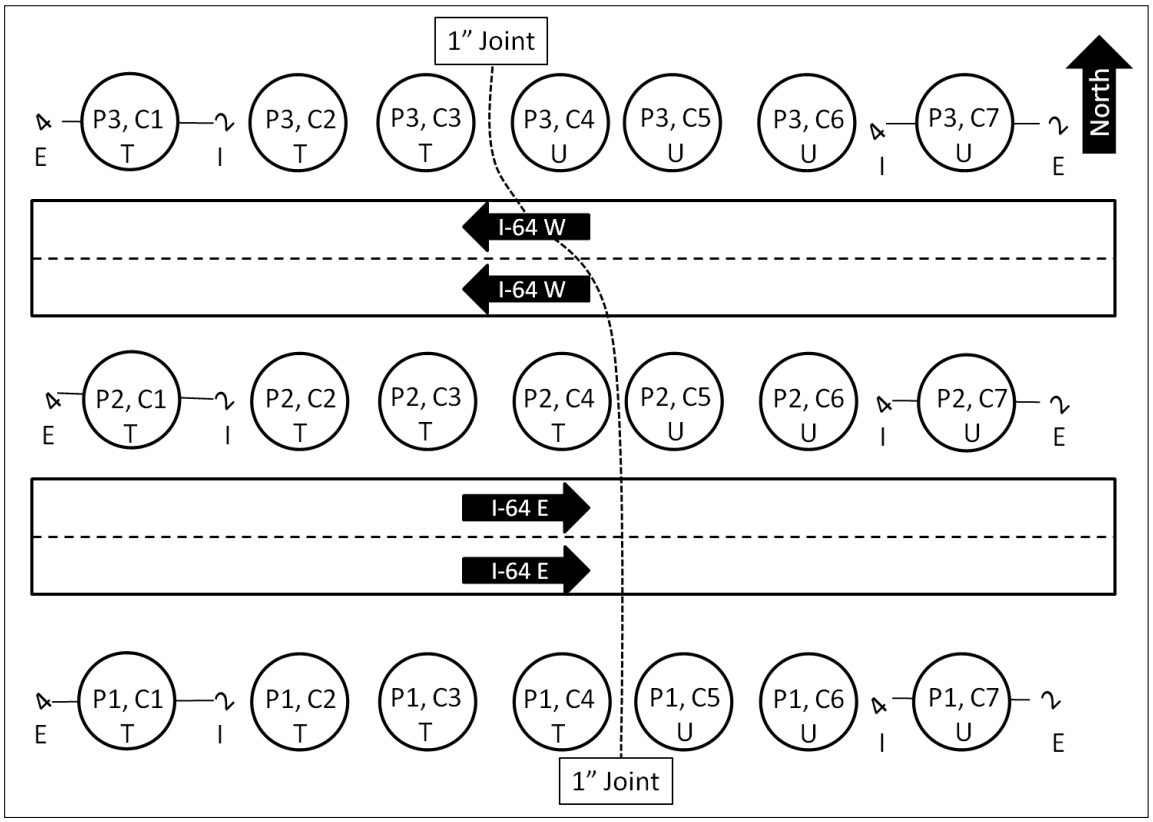

Figure 4. Plan View Illustration of Columns of 5th Street Extended Bridge Relative to Direction of Travel of I-64. Illustration shows, relative to I-64, the piers (P), columns (C), location of ECE plus seal-treated columns (T), untreated control columns (U), exterior chloride samples (E), interior chloride samples (I), and location of the 1-in bridge deck joint (pier caps were discontinuous in this location) that ensured the east and west sides of the bridge were electrically isolated. ECE = electrochemical chloride extraction.

Measurement of Delaminated Areas and Soundness of Repairs. Measurements of delaminated areas were recorded based on recent inspection reports and then visually confirmed in the field. In addition, a field visit was conducted during which the concrete around the patched regions was sounded to evaluate the quality of the repair and determine if any additional delaminations were present.

Resistivity Measurements. Resistivity measurements were made on the pier caps of Piers 1, 2, and 3 with a Proceq Resipod resistivity meter. This was done in both the ECE-treated

and untreated concrete regions and in both patched and unpatched areas. To perform this work, a four-pin resistivity meter was used with an equal spacing of 1½ in (38 mm) between each pair of pins.

Half-cell Potential Measurements. Half-cell potential measurements were made on Piers 1 and 2, Columns 1 and 7, and the pier cap area above each of these columns; these locations are illustrated in Figures 3 and 4. A copper/copper sulfate electrode (CSE) was used as a reference electrode. Measurements were made in accordance with ASTM C876 (ASTM, 2009).

Concrete Depth of Cover Measurements. An Elcometer 331 concrete cover meter was used to measure cover depths directly over the embedded steel reinforcement. Concrete depth of cover measurements were made on Piers 1, 2, and 3 on Columns 1 and 7; these locations are illustrated in Figures 3 and 4.

I-95 Bridges

Overview

In 2010, VDOT initiated a 4-year project to revitalize and extend the service life of 11 bridges that support the traffic flow along I-95 through Richmond, Virginia. Some of these bridges carry I-95 traffic along the I-95 corridor, whereas others provide ramps on and off the freeway. One of the primary durability concerns was that a superstructure designed for a 75-year service life was going to be placed on a substructure built in the late 1950s or early 1960s. It was known that this would result in the placement of new, chloride-free concrete in direct contact with older chloride-contaminated concrete, with the older contaminated concrete supporting the new uncontaminated concrete. Since this raised concerns about corrosion, the use of mitigation techniques for extending the life of the substructure was essential. VDOT worked with several consultants to develop a restoration plan, which ultimately included ECE to treat the I-95 bridges that cross over Hermitage Road (Str. No. 2842) and over Overbrook Road (Str. No. 2839) as one of the critical components.

Current Evaluation

Although it is too soon to determine the benefit of using ECE for these bridges, it is important to archive the restoration methods and current conditions for each bridge so that future investigators can evaluate the efficacy of the recent interventions. This set of bridges is especially important for evaluating long-term behavior as they are in relatively close proximity to each other and the repairs were performed under the same contractor. Further, the following restoration techniques were employed:

- elimination of leaking joints (at certain piers only)
- ECE treatment on selected substructures
- installation of CP on selected substructures
- sealing of concrete after ECE treatment.

Each of these restoration techniques when properly used can extend substructure service life. However, it is not clear exactly how much longer the service life extension will be when several of these restoration techniques are combined. Establishment of a baseline and then periodic monitoring will help in determining how various restoration techniques contribute to service life extension after the repair.

RESULTS AND DISCUSSION

Literature Review

Joint Repair

As discussed in the "Introduction" section, exposure of the steel reinforcement to salt tends to accelerate rapidly the corrosion of the steel reinforcement in the concrete elements. In Virginia, for inland structures, salt is almost always introduced from either leaking expansion joints from the deck above or salt spray from adjacent traffic, with compromised expansion joints allowing for the vast majority of this salt exposure. Accordingly, the integrity of deck joints and the ability of the deck to protect substructure elements from salt and moisture are critical for bridge durability.

Section 212 of VDOT's 2007 *Road and Bridge Specifications* (VDOT, 2007) provides guidance on joint materials, which are described as "resilient products made from various materials that are designed to accommodate the movement of rigid structures, such as component parts of hydraulic cement concrete, and seal the joint from intrusion of water or incompressibles." The requirements with regard to the various joint sealers are detailed in Section 212, with this section also indicating that approval by VDOT's Materials Division for silicone rubber joint sealer is necessary. VDOT's Materials Division maintains a list available to the public that indicates the products that are approved for use on VDOT structures. The approved silicone rubber joint and asphaltic plug joint repair materials are on this list (VDOT, 2015b).

Although sealing joints can restrict the flow of moisture and protect the underlying element, different seals can have different life expectancies. In recognition of the significance of compromised expansion joints in accelerating the corrosion of bridge elements, the forthcoming 2016 edition of VDOT's *Road and Bridge Specifications* and Part 2 of VDOT's *Manual of the Structure and Bridge Division* (VDOT, 2015c) provide stricter restrictions on the use of expansion joints. Specifically, expansion joints are allowed on new bridges only if a written design exception is provided; further, for bridges receiving rehabilitation, either the existing joints must be eliminated or more durable joint seal materials such as elastomeric expansion dams (strip seals) or seals that rely on durable adhesives must be used. Poured silicone seals will be permitted only on low volume roads, and preformed elastomeric joint sealers (compression seals) will no longer be permitted on any VDOT bridge.

The functional life performance can be dependent on whether the seal was installed during initial construction or during rehabilitation. Milner and Shenton (2015) discussed experiences and the state of the practice with regard to expansion joints that are used in the Northeast. The data collected in this work, shown in Figure 5, demonstrated that there is variability with different joint seals. This is important since in some cases after ECE treatment of a substructure element, an extension in service life could result as long as the seal restricts moisture, including saltwater, from reaching the treated element. Based on the work of Milner and Sherton (2015), 2 to 10 years can be expected on average before joint failure for maintenance or repair installations. Unfortunately, in some instances in Virginia, particularly on interstate highways, compromised joint seals have been observed within 12 months of installation. Therefore, ideally, if both joint repairs and ECE were performed on a substructure element protected from salt exposure by the deck, the additional time before failure of the joint would prolong the beneficial life as a result of both repairing the joints and performing ECE repair.

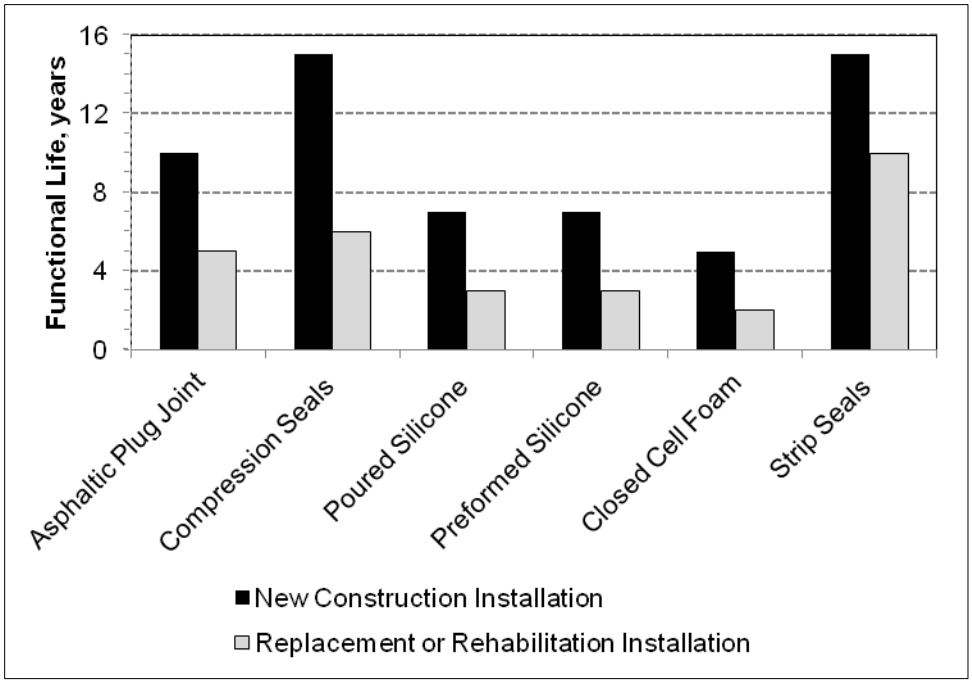

Figure 5. Comparative Results From the Northeast Bridge Preservation Partnership Study on the Functional Life of Bridge Joints. Based on data from Milner and Shenton (2015).

Concrete Sealant

Concrete sealants are used to provide a barrier that restricts the contamination of concrete by chlorides. VDOT's Materials Division maintains a list available to the public that indicates the products that are approved for use on VDOT structures (VDOT, 2015b). The approved concrete sealants are listed under "Hydraulic Cement and Concrete Sealants, Stains, and Coatings" in this list.

Although NACE International's (NACE) *Standard Practice SP0107-2007, Electrochemical Realkalization and Chloride Extraction for Reinforced Concrete,* discusses

applying ECE to reinforced concrete (NACE, 2007a), it does not mention sealing the concrete after applying ECE. NACE's *Electrochemical Chloride Extraction from Steel Reinforced Concrete—A State of the Art Report*, however, does discuss different post-treatment options, which include sealers (NACE, 2001). This is important to highlight since on the Virginia bridges discussed in this report, the 5th Street Extended Bridge and the solely ECE–treated I-95 bridge, a sealant was used after ECE treatment.

Cathodic Protection

CP systems are designed to reduce the corrosion rate in a structure. Currently, VDOT does not usually design, install, or perform maintenance on CP systems that are incorporated into its structures but instead uses private consultants and contractors to perform this work.

Although CP systems are usually specifically designed for a given structure, NACE has provided guidance that can be used by transportation agencies and consultants as they design CP systems. These NACE reports and standard practices that support CP design, installation, and maintenance for reinforced concrete structures include the following:

- *Standard Practice SP0187-2008: Design Considerations for Corrosion Control of Reinforcing Steel in Concrete* (NACE, 2008)
- *Standard Practice SP0290-2007: Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures* (NACE, 2007b)
- *Standard Practice SP0408-2014: Cathodic Protection of Reinforcing Steel in Buried or Submerged Concrete Structures* (NACE, 2014)
- *State-of-the-Art Report: Criteria for Cathodic Protection of Prestressed Concrete Structures* (NACE, 2002)
- *Sacrificial Cathodic Protection of Reinforced Concrete Elements—A State-of-the-Art Report* (NACE, 2005).

Sharp and Brown (2007) also evaluated the use of CP systems on VDOT bridges. These systems included impressed current CP and GACP, which were both designed to mitigate corrosion in Virginia bridges. The findings of Sharp and Brown guided VDOT's decision-making process in selecting appropriate interventions for the I-95 bridges.

Burlington Bay Skyway

In 1989, the first ECE project in North American began on the Burlington Bay Skyway in Burlington, Ontario, Canada. This bridge has been evaluated several times by Ontario's Ministry of Transportation in an effort to understand the effectiveness of ECE in the field. It is important to note that prior to treatment, a new bridge deck was constructed in 1988, so leaking joints that supplied salt to this area were eliminated (Manning and Pianca, 1990). A sealer was not used in order to simplify the interpretation of the results and the determination of any additional service

life because of the ECE treatment (Manning and Pianca, 1990). Therefore, this work demonstrated the influence of ECE on the additional service life that would result from halting corrosion and eliminating exposure to salt in this region.

Prior to the ECE project, 92% of the half-cell readings in the area to be treated were in the range that ASTM C876 (ASTM, 2009) specifies as having an uncertain level of corrosion activity (-200 to -350 mV vs. CSE), and 8% of the readings were in the range that indicated a high probability of active corrosion (greater than -350 mV vs. CSE) (ASTM, 2009; Pianca et al., 2003). At this point in time, there were no readings indicating a low probability of corrosion (less than -200 mV vs. CSE) (ASTM, 2009; Pianca et al., 2003).

Thirteen months after the western face of the bridge element was treated, 1% of the half-cell readings in the treated area were in the uncertain corrosion activity range and 99% were in the low probability of corrosion range. The readings, shown in Figure 6, provide a strong indication that the ECE treatment had successfully passivated the reinforcing steel (Pianca et al., 2003).

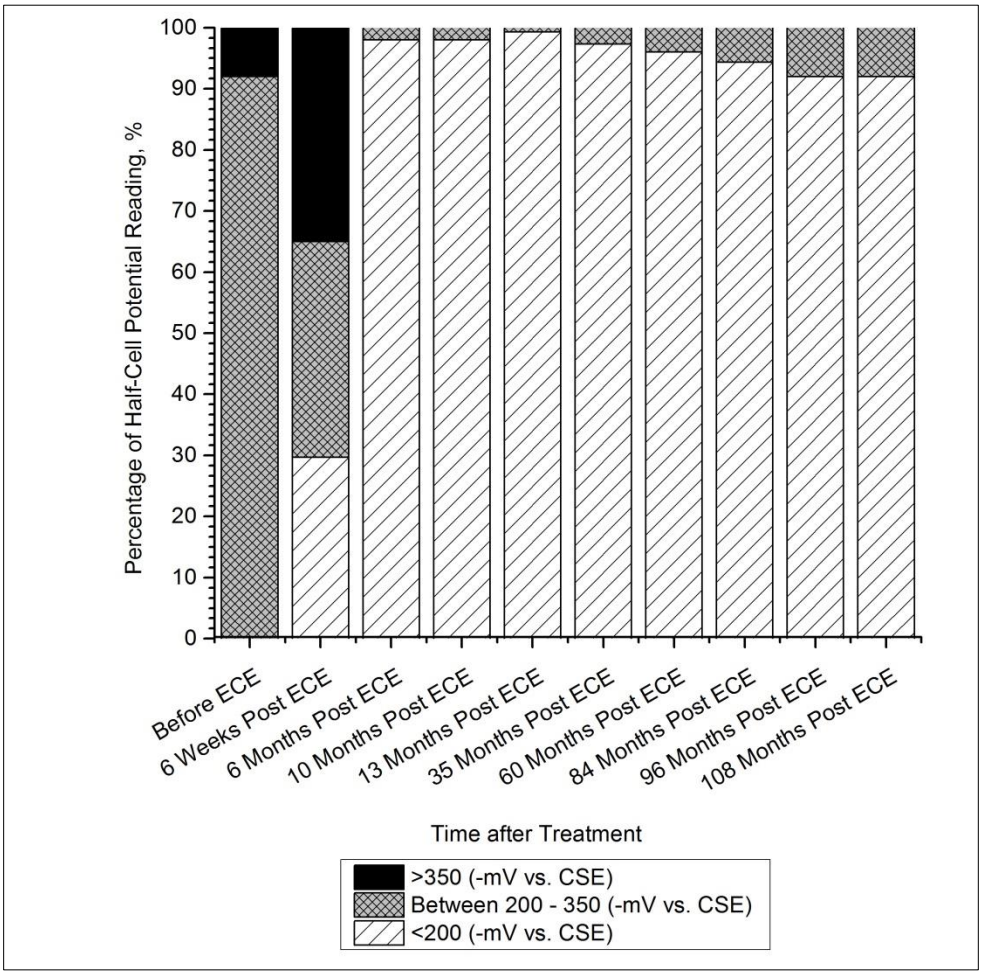

Figure 6. Percent Change in Average Half-cell Reading Over Time for 1989 ECE-Treated Substructure Faces on Burlington Bay Skyway. Based on data from Pianca et al. (2003). ECE = electrochemical chloride extraction.

The readings were repeated periodically over the subsequent 108 months and were found to be fairly constant for this bridge element for the next 9 years after treatment, which can be seen in Figure 6 (Pianca et al., 2003). The last set of data was reported for the ninth year after treatment, at which time 8% of the readings was in the uncertain corrosion activity range and 92% were in the low probability of corrosion range (Pianca et al., 2003). Pianca et al. (2003) concluded that "significant long-term passivation of the reinforcement can be achieved by ECE."

Evaluation of 5th Street Extended Bridge

ECE Treatment

Overview

The 5th Street Extended Bridge is an ideal structure for a comparative evaluation because the western piers and caps are isolated from the eastern piers and caps. This was discussed by Clemeña and Jackson (1996a), who also described the method used to treat the bridge and the initial data after treatment. It is important to highlight that ECE was performed on the western portion of the structure while the eastern portion was left untreated so that it could be used as the control case for this study. In addition, a water-based silane sealer was applied to the piers of the ECE-treated portion of the structure after ECE treatment (Clemeña and Jackson, 1996a).

Finally, although a VDOT special provision specification was written for this 1995 project, it is important to mention that since the completion of this demonstration project, additional documents have become available that can provide more up-to-date guidance in this area. This would include NACE Standard Practice SP0107-2007 (NACE, 2007a) mentioned previously. In addition, the VDOT special provision used during ECE treatment starting in September 2010 on 2 of 11 structures that were part of the I-95 Richmond Bridge Restorations in Richmond, Virginia, is more current and is provided in the Appendix. It builds on earlier ECE work, including the 1995 5th Street Extended Bridge demonstration project.

Previous Inspection Reports

A review of the VDOT inspection reports from 2006 to 2013 with regard to the 5th Street Extended Bridge revealed two pieces of critical information: failing deck expansion joints and additional substructure spalling. The comments in the reports document the failing and details about the condition of the substructure and the location of regions of damage. After this inspection, maintenance was performed, and the 2013 inspection indicated that condition states improved after completion of repairs.

The 2006 report noted the following: "Heavy build up of dirt in armor joint on top. Crack in armor joint adjacent to top of sidewalk 6" in length. Pour seal in median is snagging with random areas of deterioration thru-out" (VDOT, unpublished data, 2006). An example of the observed condition is shown in Figure 7.

Figure 7. Photograph From VDOT Inspection Report. The report stated: "Note heavy deterioration of joint seal & spalling along the edges of longitudinal joint in median" (VDOT, unpublished data, 2006).

The 2008 report noted the following: “leaking and damage joints” and “joints are leaking over piers, abutments and median” (VDOT, unpublished data, 2008). The 2010 and 2012 reports continued to support these assertions: “All joints are leaking over piers and abutments including the median seal” (VDOT, unpublished data, 2010; 2012). All of this information indicates that since at least 2008, the piers have not benefited from having a deck with working joints to provide protection from the elements.

The substructure in 2012 was considered to be in satisfactory condition and was assigned a condition rating of 6, which was the same rating as in 2008 and 2010 (VDOT, unpublished data, 2008; 2010; 2012). With the 2006, 2008, 2010, and 2012 data, the total amount of delaminated or spalled areas on the column or cap were plotted to allow a better understanding of the change in condition of these bridge elements with time (Figure 8). It is clear that the cap exhibited the greater degree of damage when compared to the column. This could be because the cap protects the underlying column from moisture leaking down on the cap through the damaged joints.

Not all of the inspection reports provide detailed information to determine precisely where delamination or spalling was found during the inspection. The 2012 inspection report, however, provided ample information to determine if the repair area was in the treated or untreated area. Therefore, this report was used to evaluate how well the treatment was working after 18 years of exposure. Clearly, the untreated areas showed a greater quantity of damage when compared to the treated regions (Figure 9). Even if the transition region (the damaged area of the piers where the break between columns occurs that separate the treated and untreated cap regions) is added to the damaged area on the treated side of the structure, the untreated damage area is still larger. Overall, comparing the damage in treated and untreated areas, the untreated area exhibited more than 5 times the damage of the ECE-treated and sealed area.

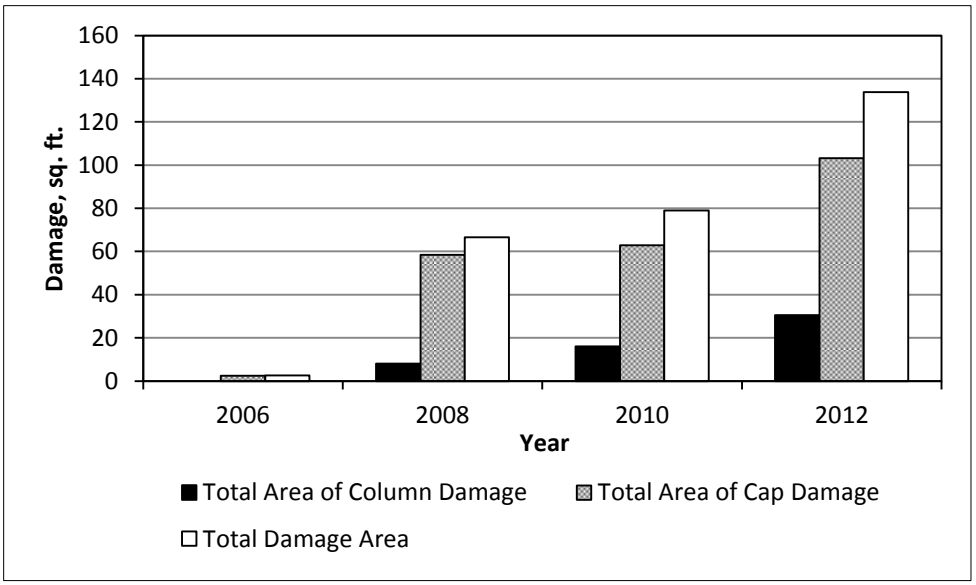

Figure 8. Column and Cap Reported Concrete Damage With Time for 5th Street Extended Bridge

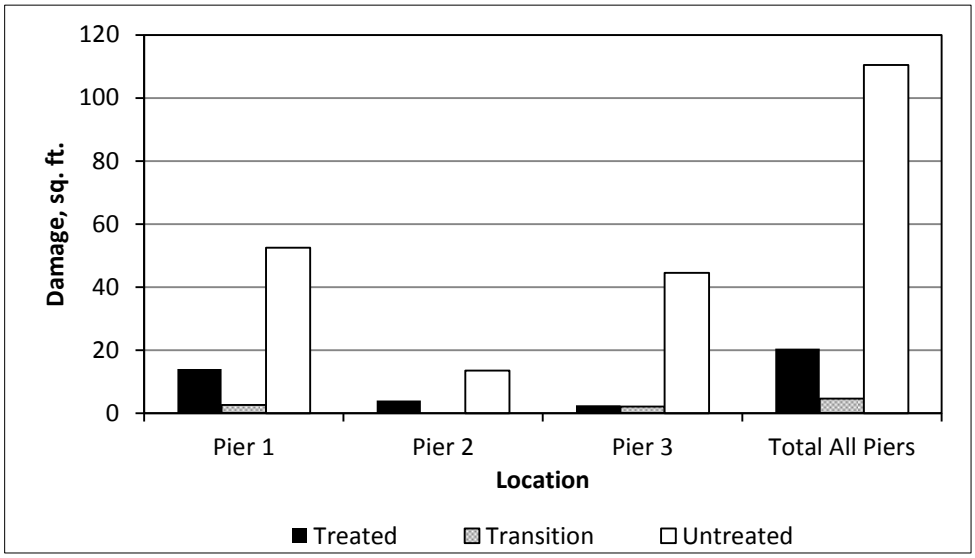

Figure 9. Comparison in Performance for Each Pier and General Performance for All Piers Combined Based on 2012 Evaluation Results for 5th Street Extended Bridge

Current Evaluation

The evaluation of the columns and cap of the 5th Street Extended Bridge was performed over two consecutive days. On October 7, 2014, the Pier 2 columns and cap were evaluated. On October 8, 2014, the Pier 1 columns and cap were evaluated. On both days, rain had fallen the night before and it was evident that leaking bridge joints still allowed the water to fall onto the pier caps and run down the columns. This was mentioned in the 2013 inspection report: "All joints are leaking over piers and abutments including the median seal" (VDOT, unpublished data, 2013).

Visual Observations

In general, the treated portion of the substructure looked better than the untreated (control) section. It was clear that joints were leaking, as indicated in the latest inspection report. Leaking joints comprise a tremendous cost to VDOT because of damage to other elements, which is why this is one of the areas that VDOT has focused on to reduce maintenance costs.

More moisture was observed on the eastern caps and column as a result of the rain the night prior to the assessment. The condition of the piers and some of the leaking moisture can be seen in Figures 10 through 14.

Figure 10. Portion of Pier 1 Under 5th Street Extended Bridge That Was ECE Treated and Silane Sealed. ECE = electrochemical chloride extraction.

Figure 11. Untreated Side of Pier 1 Under 5th Street Extended Bridge

Figure 12. Pier 2 Under 5th Street Extended Bridge Showing Moisture Attributable to Leaking Joint Above Treated Cap and Columns

Figure 13. Pier 2 Under 5th Street Extended Bridge That Shows Some Moisture on Untreated Cap Also Exhibiting Some Delaminations That Have Been Repaired

Figure 14. Pier 3 Columns Under 5th Street Extended Bridge: Left 3 columns treated with ECE and sealed; 4 right columns served as control (untreated and not sealed). ECE = electrochemical chloride extraction.

Chloride Concentrations

On Pier 2, which is located between the eastbound and westbound lanes of traffic, a higher concentration of chlorides was found for the untreated columns than for the treated columns. This can be seen in Figure 15, which shows that for both the interior and exterior of the untreated columns, the surface and subsequent sample depths had higher chloride concentrations than Column 1, which was treated. This would be expected if ECE and the sealing of the surface were effective, since the ECE treatment would have lowered the concentration of chlorides and the sealing of the piers would have restricted new chlorides from entering the concrete.

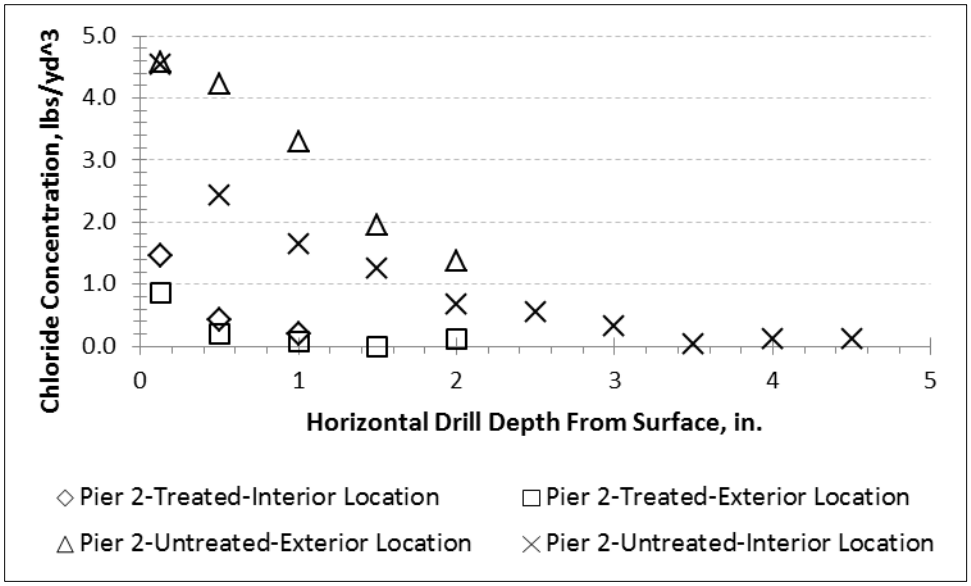

Figure 15. Pier 2 of 5th Street Extended Bridge Showing Chloride Concentrations in Treated and Untreated Columns After 19 Years. Figure 4 shows interior location, indicated by "I," and exterior location, indicated by "E," of the pier.

Delaminated Areas and Soundness of Repairs

Soundings of Pier 1 and Pier 3 indicated that patches and the surrounding area were sound. Therefore, no additional damage, including any damage associated with the halo effect, has been detected since the last set of repairs.

Resistivity

Resistivity measurements were made in Pier Cap 2 in old and new concrete areas in regions that were treated and control (untreated). The control concrete showed a wider range of resistivity values, as seen in Figure 16, and also higher resistivity values. However, it is important to mention that fewer measurements were made in the treated region of Pier 2. In addition, since additional moisture was observed on the eastern, treated half of the caps, lower resistivity values would be expected. This is because additional moisture in the concrete provides a solvent for ionic substances to dissolve in, allowing for a more conductive (less resistive) pathway in the concrete, which would be reflected in the resistivity data gathered. Moreover, if additional moisture is diffusing into the concrete, this would also be an indication that the concrete sealer is no longer restricting the flow of moisture into the concrete. If moisture and salt are able to diffuse into the concrete, this will increase the chance of initiating corrosion of the reinforcing steel.

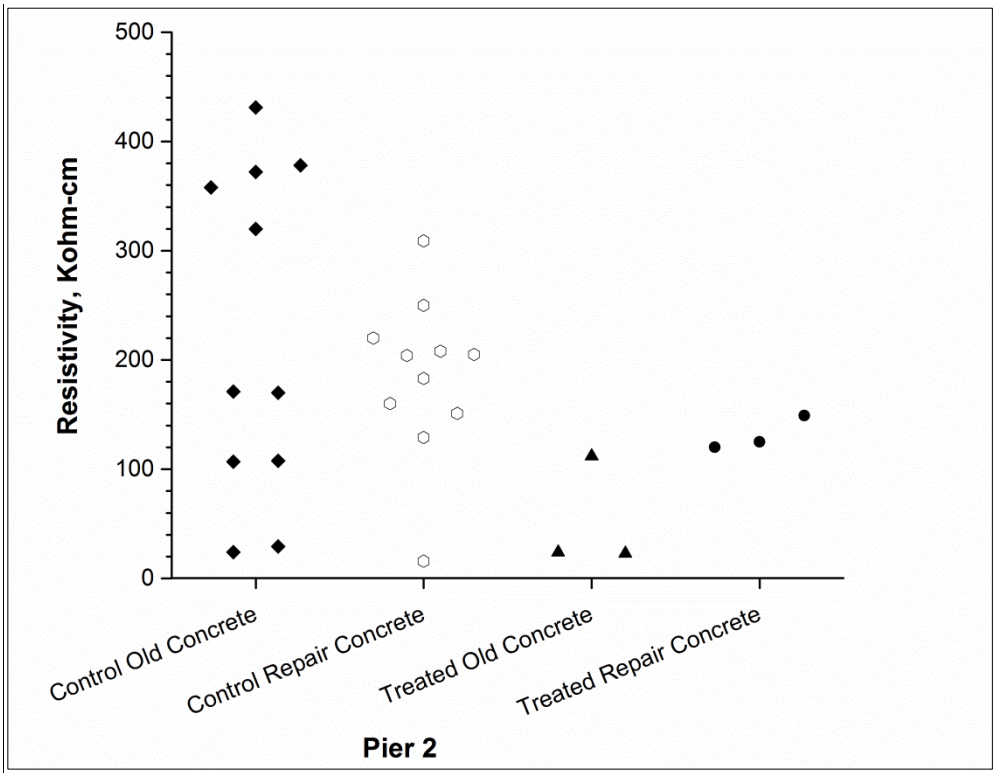

Figure 16. Resistivity Measurements on Cap of Pier 2 of 5th Street Extended Bridge

Since the resistivity of the concrete influences the corrosion susceptibility of embedded reinforcing steel, some have associated the range in resistivity to the likely corrosion rate. For example, Broomfield (2007) indicated a low corrosion rate for resistivity values greater than 20 Kohm-cm; A low to moderate corrosion rate for values ranging from 10 to 20 Kohm-cm; a high corrosion rate for values ranging from 5 to 10 Kohm-cm; and very high corrosion rates for values less than 5 Kohm-cm. Therefore, based on this ranking, the majority of resistivity measurements that were made 1 year after the repair of the damaged concrete areas were in the low corrosion rate range. There are several values that would rank in the low to moderate corrosion rate range, but these lower values could also be attributable to the proximity of reinforcing steel, which would increase the conductivity in the area.

Half-cell Potentials

Evaluations of the pier cap ends on the treated and untreated sides of the bridge indicated a lower probability of corrosion in the treated region as compared to the untreated region of the piers. Figure 17 shows the half-cell potential measurements, which indicate that the three control (untreated) caps were exhibiting a more negative electrochemical half-cell potential.

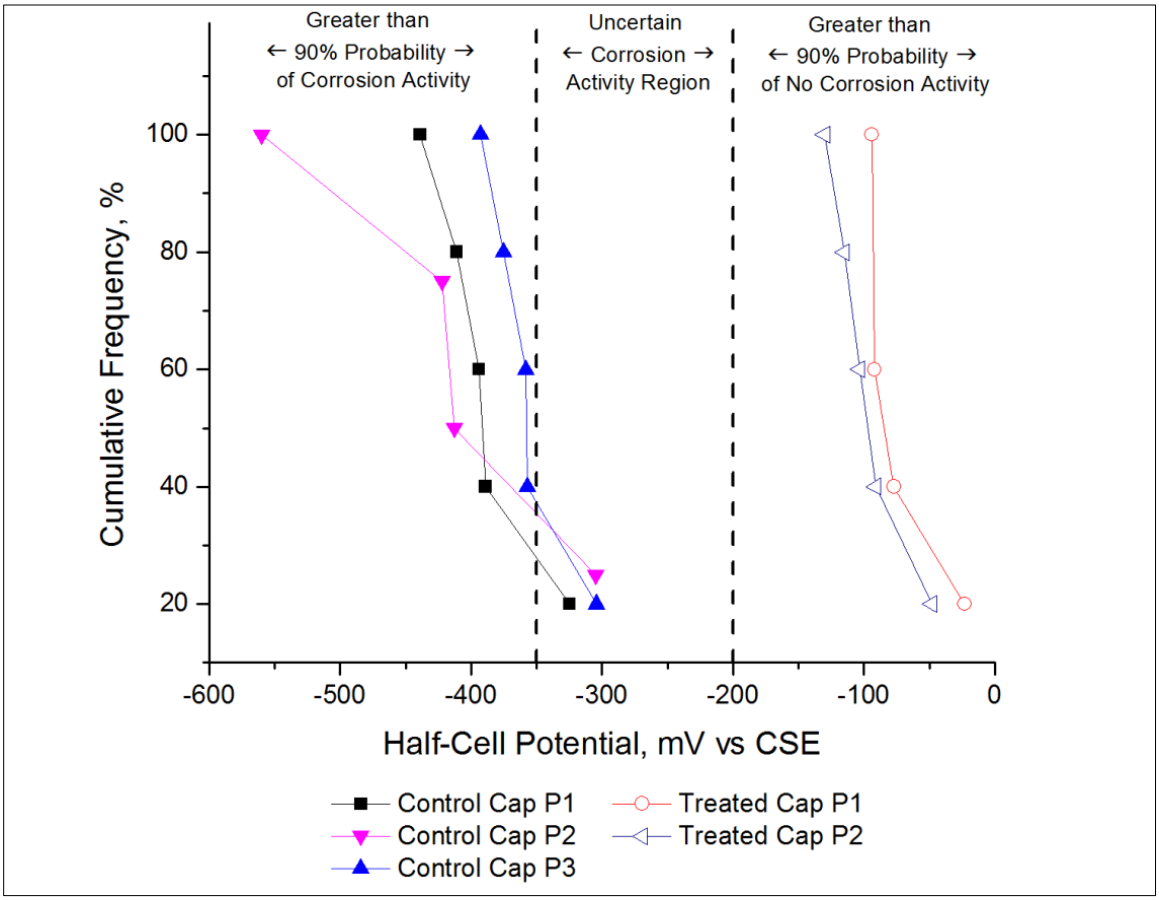

Figure 17. Half-cell Potential Measurements for Treated and Untreated Pier Cap Ends of 5th Street Extended Bridge

Concrete Depth of Cover

The depth of cover measurements were made on the columns that supported each pier cap. These measurements, shown in Figure 18, indicated some variability in the depth of cover from pier to pier and within a set of columns on a given pier. The mean depth of cover varied between 3.0 and 3.5 in, with the Pier 2 treated and control columns having the least variation in cover depth. The minimum depth of cover was 2.0 in, and the maximum was 4.6 in.

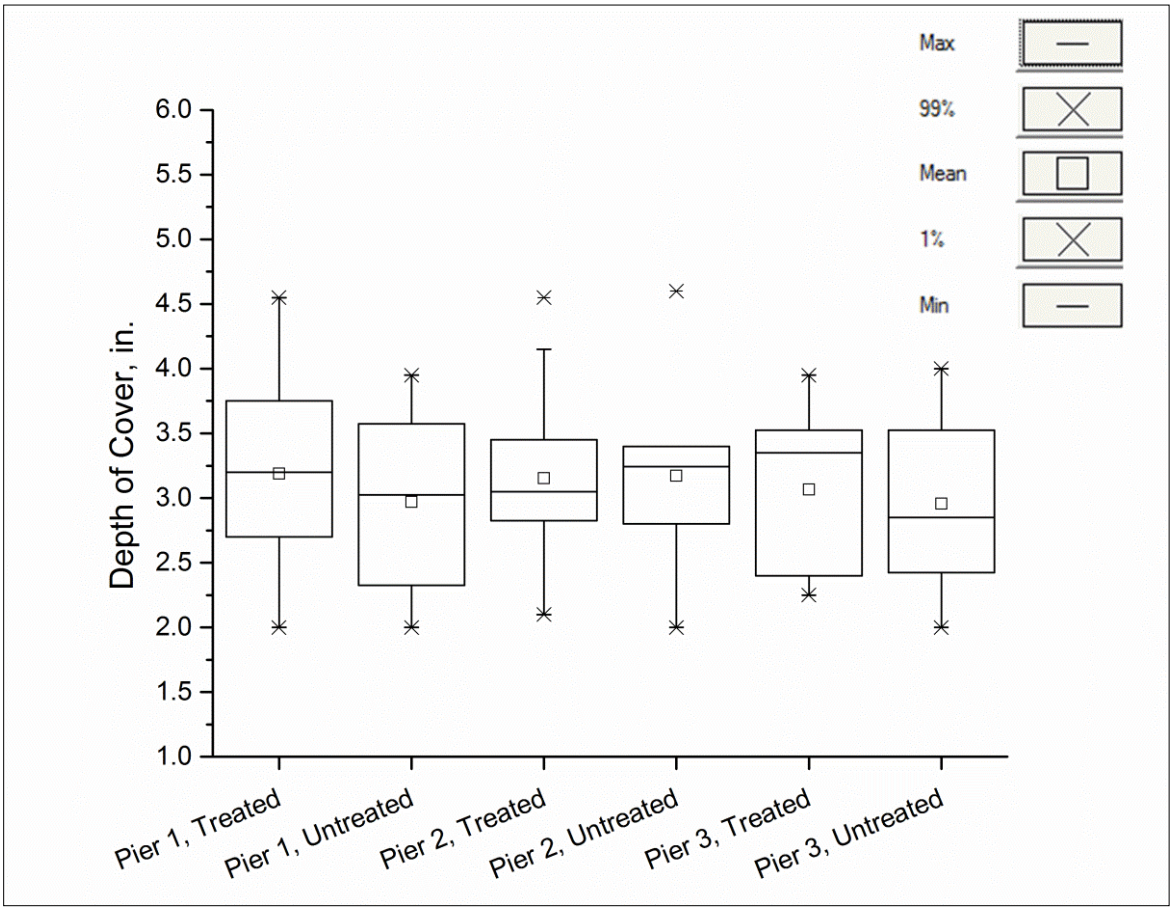

Figure 18. Depth of Cover Measurements on Piers of 5th Street Extended Bridge

Evaluation of I-95 Bridges

Overview

Originally when the work was proposed, all 11 bridges were to have concrete repair followed by the application of ECE and the installation of a CP system. This recommendation was challenged by VDOT and a letter was written by the corrosion services consultant in response to a request made by VDOT to revise the corrosion mitigation approach used for the substructures. The consultant's repair method for the 11 bridges is shown in Figure 19, and VDOT responded with the proposed decision flowchart shown in Figure 20.

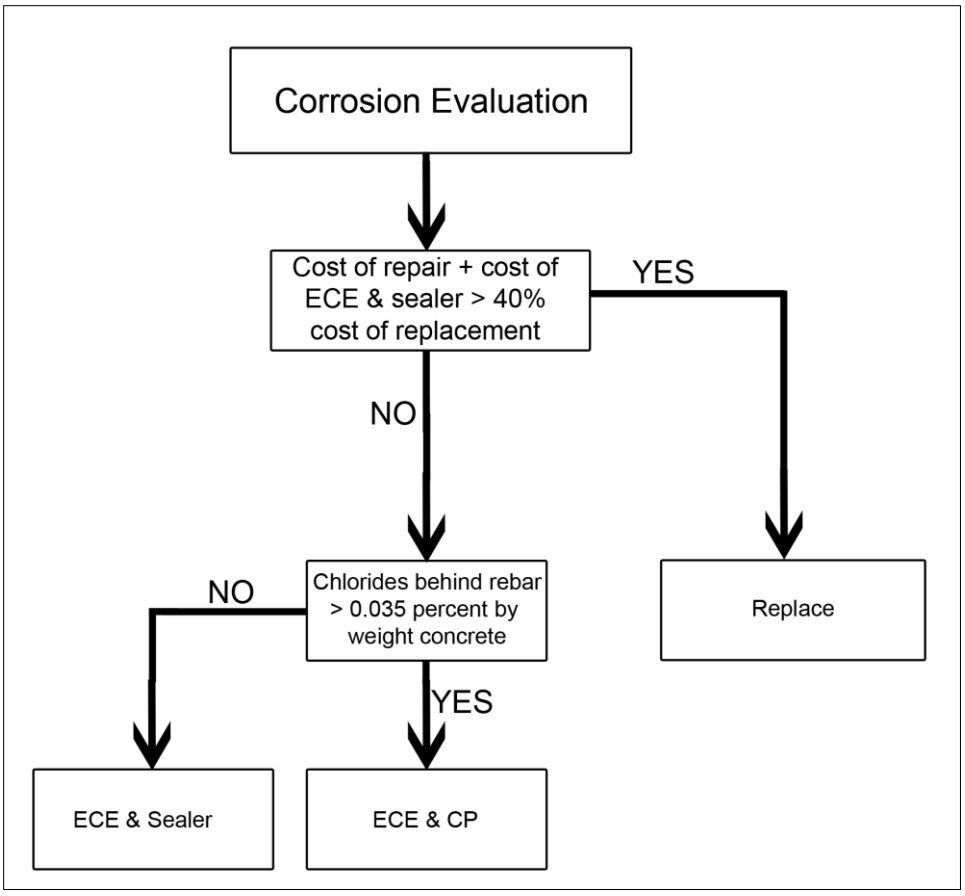

Figure 19. Repair Method Proposed by Corrosion Services Consultant for the Eleven I-95 Bridges in Richmond, Virginia

The difference between the two methods revolves around the critical chloride concentration limit. The corrosion consultant uses a lower and more traditional value of 0.035% by weight of concrete, and VDOT recommends a higher value of 0.080% by weight of concrete. This difference was influenced by the range of chloride threshold values that are reported in the literature. Glass and Buenfeld (1997) summarized the values reported in various studies; various studies reported a threshold range from 0.17% to 2.2% by weight of cement for field structures. With the same assumptions as Glass and Buenfeld (1997), i.e., a cement content of 590 lb/yd^3 and a concrete weight of 3,879 lb/yd^3, the reported threshold value would range from 0.026% to 0.33% by weight of concrete. This reported difference can most likely be attributed to variability in the service conditions, concrete, and even reinforcing steel (Glass and Buenfeld, 1997; Li and Sagues, 2001; Stratfull et al., 1975).

In this same letter, the consultant also recommended the use of arc-sprayed zinc with humectant routinely applied during the winter months to keep the CP system active to ensure it remained functional and corrosion of the reinforcing steel was mitigated. However, it was recognized that this would create a challenge for VDOT because VDOT would have to commit to performing this routine maintenance on these structures.

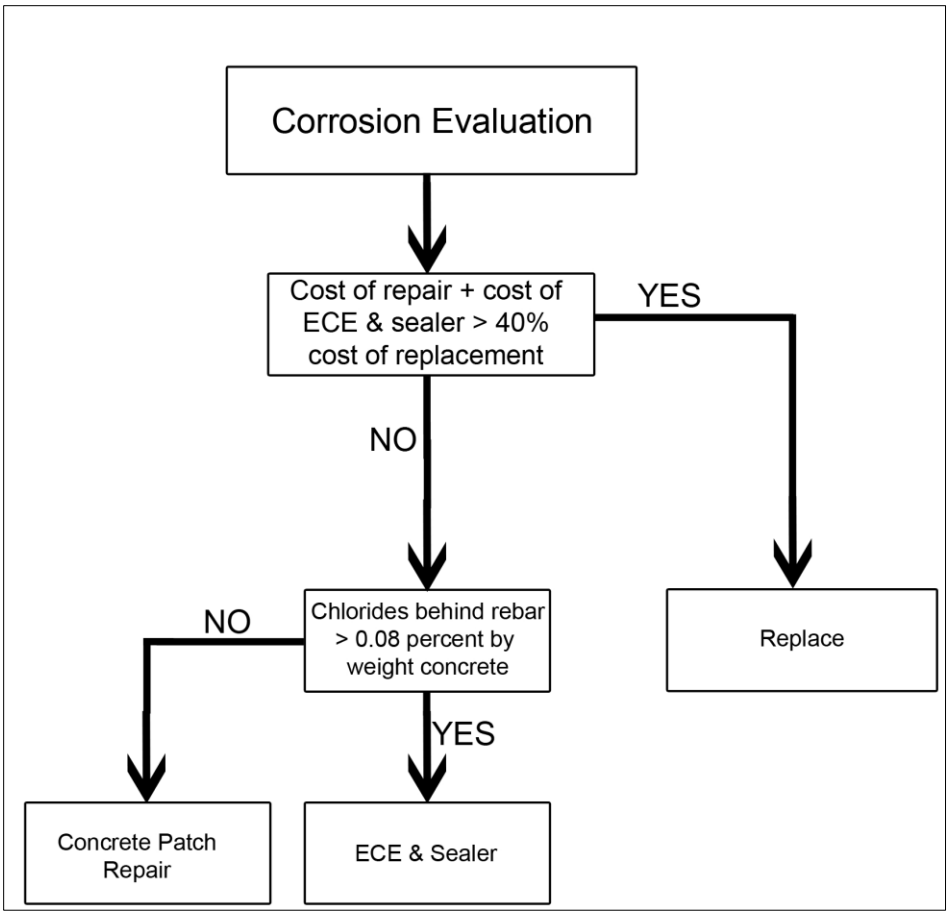

Figure 20. Repair Method Recommended by VDOT for the Eleven I-95 Bridges in Richmond, Virginia

The consultant recognized that for the CP system to be maintenance free, the CP system selected would need to be an arc-sprayed aluminum-zinc-indium (Al-Zn-In) galvanic anode, with which VDOT had research experience (Clemeña and Jackson, 1999). This is because unlike the arc-sprayed zinc system, the composition of the Al-Zn-In anode makes it self-activating, so a humectant is not required. In addition, according to the anode supplier, the Al-Zn-In anode offered other benefits over the sprayed zinc anode. The life expectancy according to Virmani and Clemeña (1998) is at least 15 years, with other reports indicating a potentially longer service life (Clemeña and Jackson, 1999; Funahashi and Young, 1998). Virmani and Clemeña (1998) also determined that the Al-Zn-In anode exhibited higher current output and exhibited similar adhesion behavior as compared to a zinc anode.

It was also decided that since neither arc-sprayed zinc nor Al-Zn-In had been sprayed on concrete that had undergone ECE, only 1 of the 11 structures should be restored using both ECE and CP. This was done first to address concerns of potential adhesion problems between the ECE-treated concrete and the arc-sprayed metal anode and second to enable later investigators to distinguish the effects of the ECE and the arc-sprayed metal. First, if adhesion had been a problem, this could have resulted in increased project costs and project delays. Second, a lack of information was available with regard to how the beneficial life of each of the two processes would combine for the resulting beneficial life. Therefore, it was decided to perform both ECE

and CP on one bridge, the I-95 bridge over Hermitage Road, and only ECE on a second bridge, the I-95 bridge over Overbrook Road.

After the necessary contract documents were completed, the project was advertised and bids were submitted. One of the bids was selected, and the work was initiated in September 2010. Table 1 lists all 11 structures, their functions, and the type of corrosion mitigation treatment each received.

As indicated in Table 1, either CP or ECE was used on selected bridges. The CP protection system was a galvanic system that uses an arc-spray applied Al-Zn-In anode. For this project, the Al-Zn-In anode material cost was \$6/ft^2 and the installation using the arc spray process ranged from \$18/ft^2 to 20/ft^2 for a total applied cost of \$24/ft^2 to \$26/ft^2. Project specifications required the indium concentration to be 0.2%. On the bridge that crosses over Hermitage Road, both ECE and CP were used. This novel approach was proposed as a means to extend the service life beyond that gained by only ECE (Overbrook Road) or only CP (other 9 bridges listed in Table 1). The associated anode costs varied slightly from those originally used to estimate the most cost-effective bridge restoration method. The original CP repair cost numbers, as well as other estimated repair costs, are provided in Table 2. These numbers were used to determine whether the cost of repair and remediation was a more acceptable option as compared to the cost of replacement of the damaged member. It was determined that if the cost of repair was greater than 40% of the cost of replacement, it would be more cost-effective to replace the member.

Table 1. The Eleven I-95 Bridges in the VDOT Project

Name	Description	Year Built	Superstructure Replacement Dates	Substructure Mitigation Technique
Upham Brook (Northbound)	Bridge crosses over Upham Brook Waterway	1962	Nov. 2013- June 2014	CP
Upham Brook (Southbound)	Bridge crosses over Upham Brook Waterway	1962	Nov. 2013-June 2014	CP
Laburnum Avenue	Bridge crosses over Laburnum Avenue	1958	Oct. 2011-April 2012	CP
Westwood Avenue	Bridge Crosses over Westwood Avenue	1958	Southbound June 2012 Northbound Oct. 2012	CP
I-95 South Ramp to Boulevard	Ramp connects I-95 to Boulevard	1958	Southbound May 2012 Northbound Sept. 2012	CP
Boulevard	Bridge crosses over Boulevard	1958	Southbound June 2012 Northbound Aug. 2012	CP
Hermitage Road	Bridge crosses over Hermitage Road	1958	Southbound July 2012 Northbound Sept. 2012	ECE and CP
Robin Hood Road	Bridge crosses over Robin Hood Road	1958	Southbound Nov. 2012 Northbound April 2013	CP
Sherwood Avenue	Bridge crosses over Sherwood Avenue	1958	Southbound Nov. 2012 Northbound April 2013	CP
Overbrook Road	Bridge crosses over Overbrook Road	1958	March 2013	ECE
Lombardy Street	Bridge crosses over Lombardy Street and the CSX Railroad	1958	May-Oct.2013	CP

Source: VDOT (2015a).
CP = cathodic protection; ECE = electrochemical chloride extraction.

Table 2. Estimated Repair Cost for I-95 Bridge Replacement for Damaged Member

Description	Amount, $	Unit
Concrete repair	900	yd^3
ECE treatment	30	ft^2
CP	16	ft^2
Graffiti-resistant sealant	2	ft^2
Pier cap replacement	4,630	ft
Column replacements (in conjunction with pier cap replacements)	1,135	yd^3

ECE = electrochemical chloride extraction; CP = cathodic protection.

It is also important to highlight that in each case, a new deck was placed on the older substructure. This was beneficial in that it should contribute to a longer post-treatment service life because a significant number of the expansion joints were eliminated. Unfortunately, many of the bridges still have a significant number of deck joints, many of which began to leak within 1 year from project completion. As discussed previously, once these joints leak, additional moisture, sometimes salt laden, is able to reach the bridge caps and piers. If the joints are not repaired in time, corrosion can initiate and damage the concrete, and repairs again will be required.

Bridge Over Hermitage Road

Of the two I-95 ECE-treated bridges, the bridge over Hermitage Road was treated first, with treatment starting on Abutment A in October 2011. However, before ECE could be performed, delaminated concrete had to be removed. A total of 2,501 ft^2 of concrete was removed and replaced with shotcrete. An itemized list of the demolition and shotcrete quantities is provided in Table 3.

After removal of any damaged or delaminated concrete, repairs were made with high-quality shotcrete. Since a highly resistive shotcrete was used, these repair areas were not used in the calculation of the ECE treatment area.

To prepare each pier for ECE, as discussed in earlier work by Clemeña and Jackson (1996a), a conductive layer was created against the exterior of the concrete by embedding a steel anode mat in a layer of spray cellulose and then wrapping the pier in plastic, as shown in Figure 21. A solution of calcium hydroxide was circulated around the piers and caps to ensure the electrolyte remained alkaline throughout the treatment.

During ECE treatment, the abutments and three piers were divided into 90 sub-zones. According to the specification for the I-95 project, the minimum amount of charge passed during ECE before treatment would be considered acceptable, and therefore terminated, was 84 A-hr/ft^2 (900 A-hr/m^2). Figures 22 through 26 show the average amount of charge passed for the abutments and piers, as well as the numerous sub-zones.

Table 3. Quantity of Concrete Removed From I-95 Bridge Over Hermitage Road Prior to ECE

Location	Demolition and Shotcrete Quantity, Sf
Abutment A	143
Top of Abutment A	0
Pier 1, West Side, North Face	113
Pier 1, West Side, South Face	65
Pier 1, Middle West Side, North Face	85
Pier 1, Middle West Side, South Face	35
Pier 1, Middle East Side, North Face	81
Pier 1, Middle East Side, South Face	114
Pier 1, East Side, North Face	65
Pier 1, East Side, South Face	52
Top of Pier Cap	30
Pier 2, West Side, North Face	182
Pier 2, West Side, South Face	98
Pier 2, Middle West Side, North Face	88
Pier 2, Middle West Side, South Face	74
Pier 2, Middle East Side, North Face	121
Pier 2, Middle East Side, South Face	50
Pier 2, East Side, North Face	111
Pier 2, East Side, South Face	57
Top of Pier Cap	26
Pier 3, West Side, North Face	75
Pier 3, West Side, South Face	49
Pier 3, Middle West Side, North Face	97
Pier 3, Middle West Side, South Face	67
Pier 3, Middle East Side, North Face	158
Pier 3, Middle East Side, South Face	54
Pier 3, East Side, North Face	130
Pier 3, East Side, South Face	28
Top of Pier Cap	69
Abutment B	182
Top of Abutment B	2
Total	2,501

ECE = electrochemical chloride extraction.

It is clear from these figures that although on average the abutments and piers received the minimum treatment required, there was some variability, as not all of the sub-zones met the 84 A-hr/ft^2 requirement. The lower current density in these sub-zones became an issue since treatment times were starting to become excessive, and in some cases ECE treatment had reached approximately 3 months. To rectify this issue, it was decided to measure the chloride concentration at the level of the reinforcing bar and terminate ECE in selected cases if the chloride concentration was determined to be less than 330 ppm. Therefore, in Figures 22 through 26, in cases where the sub-zones did not meet the 84 A-hr/ft^2 requirements, ECE was terminated only when the chloride concentration at the reinforcing bar was below 330 ppm (assuming a concrete density of 3,879 lb/yd^3, 330 ppm equals a chloride concentration of 1.28 lb/yd^{3}of concrete).

Figure 21. ECE on I-95 Bridge Piers. To ensure better control and an even current distribution during ECE treatment, the electrical systems are divided into smaller areas (sub-zones) on each substructure element. These sub-zones are being monitored during treatment and electric measurements recorded by a qualified technician. ECE = electrochemical chloride extraction.

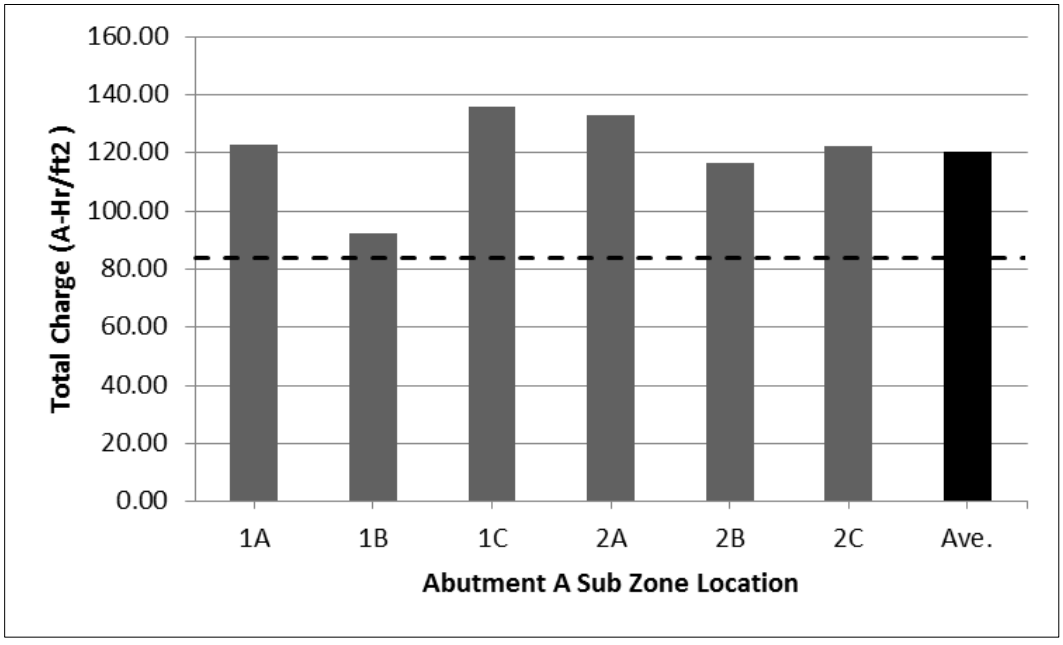

Figure 22. Total Charge Passed During ECE Treatment on Abutment A of I-95 Bridge Over Hermitage Road. ECE = electrochemical chloride extraction.

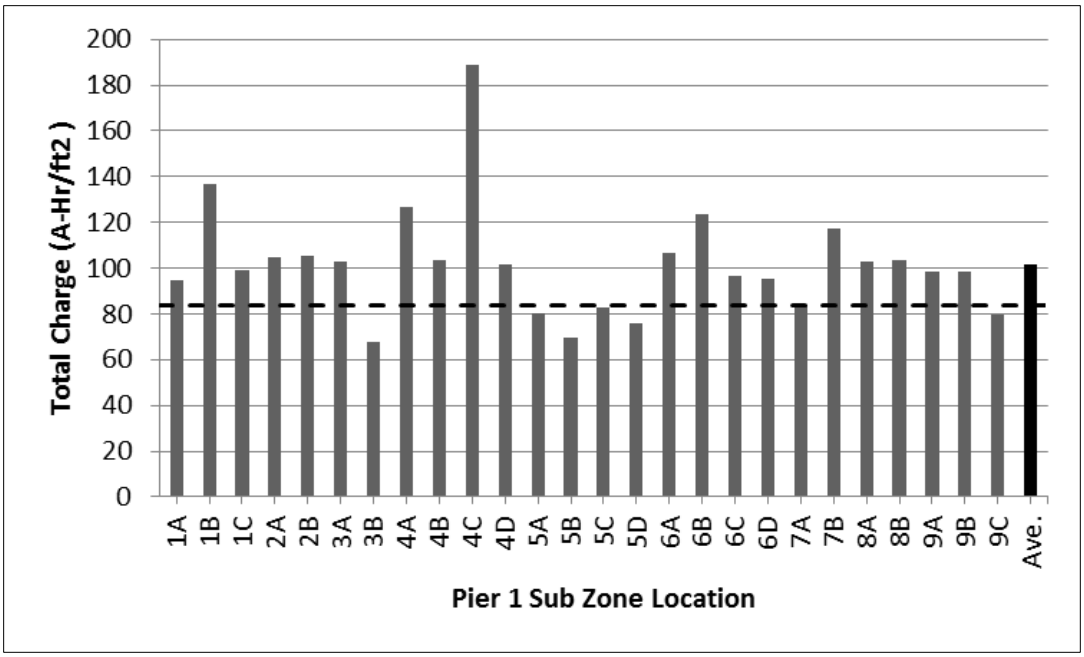

Figure 23. Total Charge Passed During ECE Treatment on Pier 1 of I-95 Bridge Over Hermitage Road. Sub-zones that did not meet the criteria for charge did meet the chloride level requirement. ECE = electrochemical chloride extraction.

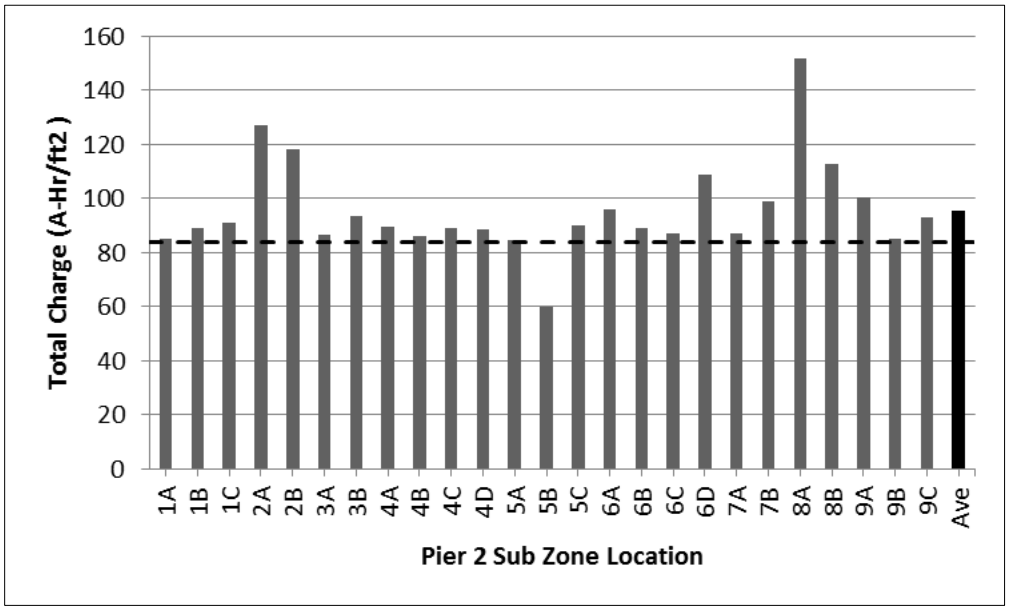

Figure 24. Total Charge Passed During ECE Treatment on Pier 2 of I-95 Bridge Over Hermitage Road. Sub-zones that did not meet the criteria for charge did meet the chloride level requirement. ECE = electrochemical chloride extraction.

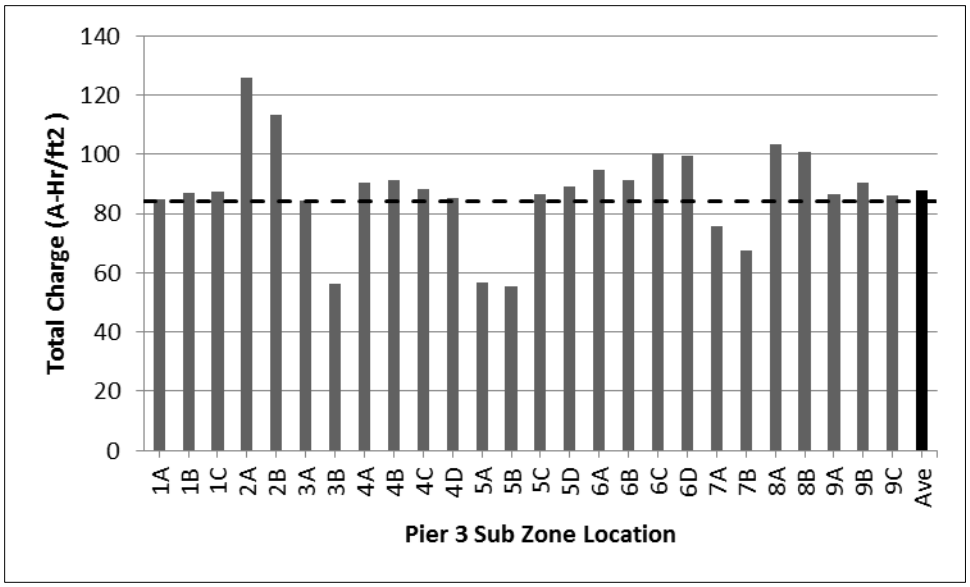

Figure 25. Total Charge Passed During ECE Treatment in Selected Sub-zone Areas on Pier 3 of I-95 Bridge Over Hermitage Road. A partial data set was made available by the contractor. Sub-zones that did not meet the criteria for charge did meet the chloride level requirement. ECE = electrochemical chloride extraction.

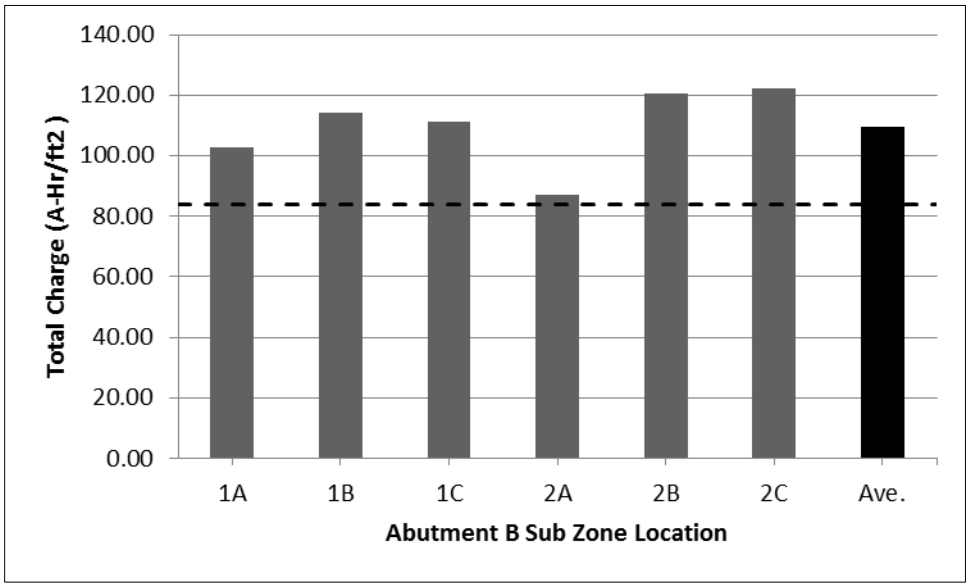

Figure 26. Total Charge Passed During ECE Treatment on Abutment B of I-95 Bridge Over Hermitage Road. ECE = electrochemical chloride extraction.

After ECE was completed, the Al-Zn-In anode wire (Figure 27) was applied to the concrete surface using the arc spray process (Figure 28), which converts the wire to a tightly adherent metallic coating on the concrete surface (Figure 29). This metallic coating on the surface of the concrete will be slowly consumed, intentionally, as it keeps the underlying steel from corroding. Since the anode is on the outside of the concrete, one benefit of this type of CP system is that if additional Al-Zn-In anode material is needed in the future to replace the consumed anode material, the arc spray process can be used again to add more anode material to the concrete surface.

Figure 27. Al-Zn-In Anode Wire on Spool. This wire will be fed through a specially designed gun that will result in the molten metal striking and adhering to the surface being coated.

Figure 28. Photograph Taken in December 2011 Showing Arc Spraying of I-95 Bridge Abutment Along Hermitage Road. Molten Al-Zn-In is being applied to the surface of a reinforced concrete element by the arc spray process. Photograph courtesy of VDOT Public Affairs.

Figure 29. Metallized Reinforced Concrete Surface of I-95 Bridge Substructure Where Test Dolly Was Removed. The removal of the dolly was part of an adhesion test to evaluate the bond between the metallized layer and the concrete substrate.

The equipment used to apply the Al-Zn-In anode material is designed to create an arc at the wire tip, which results in the solid wire becoming a liquid. While the wire is in a liquid state, dry compressed air is used to direct the liquid metal, in the form of a spray, onto the concrete surface as shown in Figure 28. Since the Al-Zn-In anode material is sprayed onto the concrete, the surface of the concrete must be properly prepared to ensure it remains in place while performing its function. This was one of the concerns with applying the Al-Zn-In anode material after ECE; there were no documented trials indicating if there would be issues. As of this writing, the Al-Zn-In anode material placed on the substructure along Hermitage Road has remained in place after ECE and there is no observable debonding.

More than 3 years after the superstructure was replaced, the bridge site was revisited and the conditions of the substructure and the underside of the deck (Figures 30 and 31) were visually assessed. Numerous rain and snow events had occurred since the superstructure replacement. The bottom of the deck along the closure pours and joints appeared to be protecting the underlying substructure, as shown Figure 32. Prior to the repair, cracking and spalling were evident (Figures 33 and 34); however, the spalled concrete was removed and replaced with shotcrete and the cracks were sealed. The closest column on the left in Figure 35 is the same column shown in Figure 33, but the photograph in Figure 35 was taken after all repair work was completed.

Figure 30. Underside of I-95 Bridge Over Hermitage Road Showing Beams, Diaphragms, and Joints After Superstructure Replacement Was Completed

Figure 31. Underside of I-95 Bridge Over Hermitage Road Showing Post-Tensioning Termination Points After Superstructure Replacement Was Completed. No leaking joints were observed.

Figure 32. Abutment Under I-95 Bridge Over Hermitage Road After Superstructure Replacement Completed

Figure 33. Corrosion Damage Resulting in Spalling of Column Supporting I-95 Bridge Over Hermitage Road Before Repair

Figure 34. Rust Stains From Water Dripping Onto Caps and Corrosion Damage on Underside of Cap Supporting I-95 Bridge Over Hermitage Road Before Repair. Tight cracks can also be seen on the underside of the cap on the right. Photograph courtesy of VDOT Public Affairs.

Figure 35. I-95 Bridge Over Hermitage Road After Repairs Completed

Figure 36 provides a closer view of the concrete surface showing how the Al-Zn-In anode coating forms to the surface and appears similar in color to uncoated concrete. Surface preparation, as with other types of coatings, is very important to ensure the coating will adhere to the surface and will be able to perform its required function. Figure 28 shows the coating being applied to the abutment in December 2011. The apparent integrity of the coating 4 years after the application is an indication that the surface preparation using abrasive blasting was adequate and that Al-Zn-In anode coating can be applied to a surface after ECE. However, the current condition does not allow prediction of the expected beneficial life provided by the combination of these two corrosion mitigation techniques: ECE and GACP.

The substructure cracks in the concrete, which were also evident in the concrete before repair (Figure 34), appeared to have a mineral deposit in them after all the repairs were completed (Figure 37). It has been documented that the passage of a current through concrete can cause the deposition of minerals in cracks. Clemeña and McGeehan (1993) indicated that electrochemical methods can be used to seal cracks in a marine environment, and Sharp et al. (2002) documented that mineral deposits form on the surface and in the pores during ECE. Although these deposits might not completely seal the concrete, it is likely that they further restrict the opening by forming a mineral deposit in the opening. If this restricts the movement of moisture and salt into these rehabilitated structures, it should increase the beneficial life of this treatment by constricting the open pathways to the reinforcing steel.

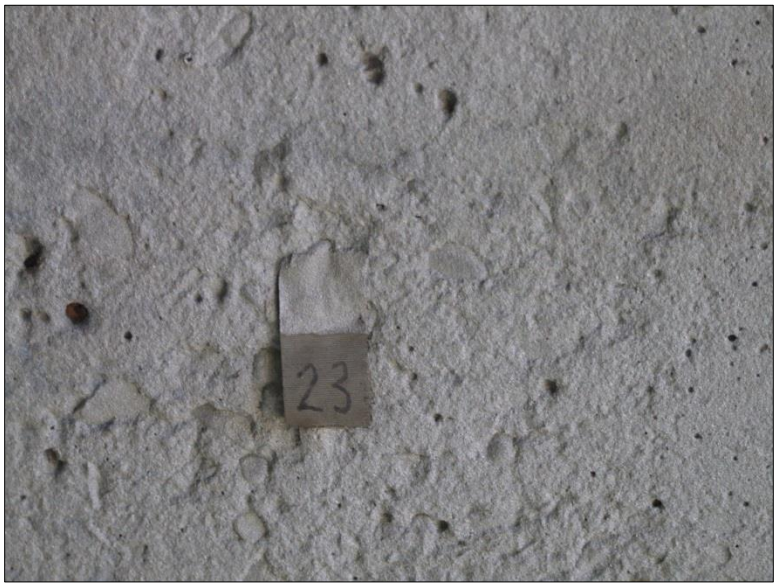

Figure 36. I-95 Bridge Over Hermitage Road Concrete Surface Substructure Element After Application of Al-Zn-In Coating for GACP. GACP = galvanic anode cathodic protection.

Figure 37. Previously Existing Crack in Concrete Exhibits Mineral Deposit, Possibly Forming During ECE Treatment of I-95 Bridge Over Hermitage Road. ECE = electrochemical chloride extraction.

Overall, the piers and abutment of the I-95 bridge over Hermitage Road appear to be in good condition. A reasonable recommendation would be that every 5 years from the date of treatment, the reinforced concrete should be evaluated to determine the condition of the GACP system and if corrosion has started to initiate in these reinforced concrete elements. This will increase the likelihood that if corrosion initiates again, it will be detected before it becomes apparent through cracking and spalling of the concrete.

To evaluate the condition of the GACP system that was installed after ECE, monitoring zones were incorporated into the GACP system at selected locations. In these areas, the anode can be isolated from the reinforcing bar so that the condition of the GACP system can be assessed.

Bridge Over Overbrook Road

Unlike the I-95 bridge substructure over Hermitage Road, the I-95 bridge substructure over Overbook Road received only ECE to mitigate the ongoing corrosion of the reinforcing steel. The substructure prior to mitigation work (Figure 38) exhibited sound concrete in many areas. This is important if ECE is going to be considered since ECE will not strengthen the existing concrete. Rather, it halts the corrosion reaction that is taking place. Therefore, it is important to use ECE in situations where a sufficient amount of sound concrete will remain after any delaminated concrete has been replaced and cracks have been repaired prior to ECE.

Figure 38. Underside of I-95 Bridge Over Overbrook Road Before Superstructure Replacement and Corrosion Mitigation Work Began. Photograph courtesy of VDOT Public Affairs.

During ECE treatment, the abutments and three piers were divided into 40 sub-zones. According to the VDOT specification for the I-95 project, the minimum charge passed during ECE before treatment would be considered acceptable, and therefore terminated, was 84 A-hr/ft^2 (900 A-hr/m^2). Figures 39 through 42 show the average charge passed for the abutments and piers, as well as the numerous sub-zones. On Pier 1, ECE was interrupted several times, but not for more than 7 days in any instance, to allow for the installation of the precast concrete units (decks) and because of vandalism and power supply issues.

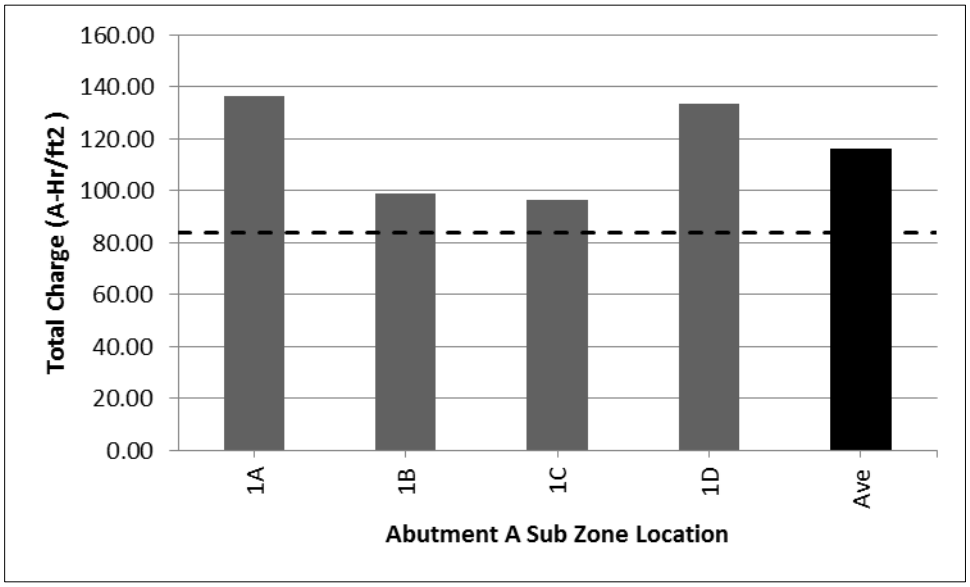

Figure 39. Total Charge Passed During ECE Treatment on Abutment A Under I-95 Bridge Over Overbrook Road. ECE = electrochemical chloride extraction.

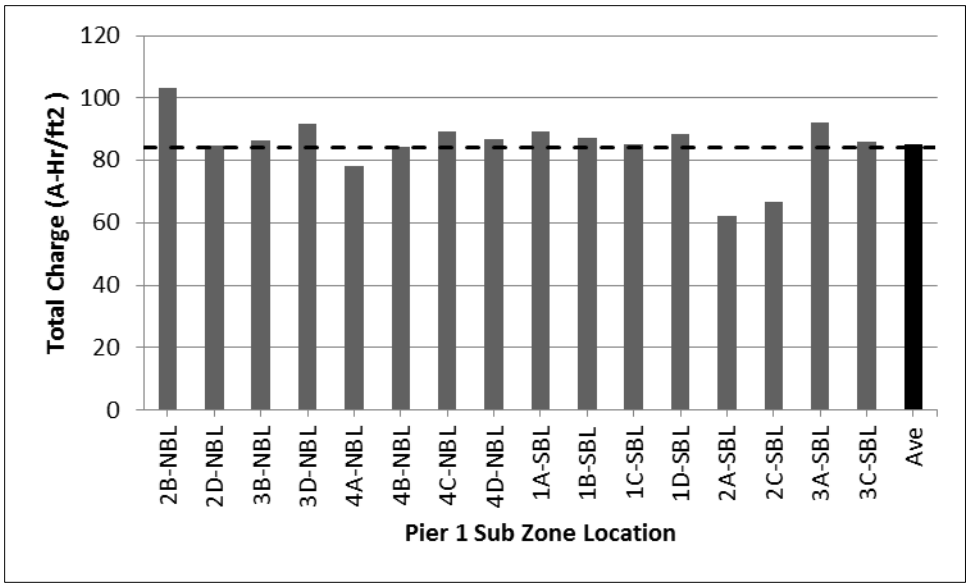

Figure 40. Total Charge Passed During ECE Treatment on Pier 1 Under I-95 Bridge Over Overbrook Road. Sub-zones that did not meet the criteria for charge did meet the chloride level requirement. ECE = electrochemical chloride extraction.

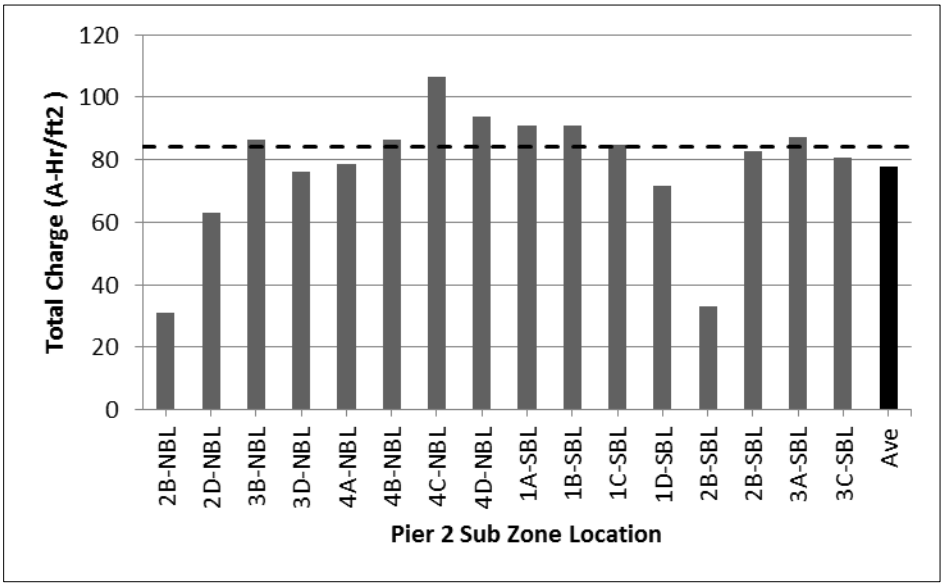

Figure 41. Total Charge Passed During ECE Treatment on Pier 2 Under I-95 Bridge Over Overbrook Road. Sub-zones that did not meet the criteria for charge did meet the chloride level requirement. ECE = electrochemical chloride extraction.

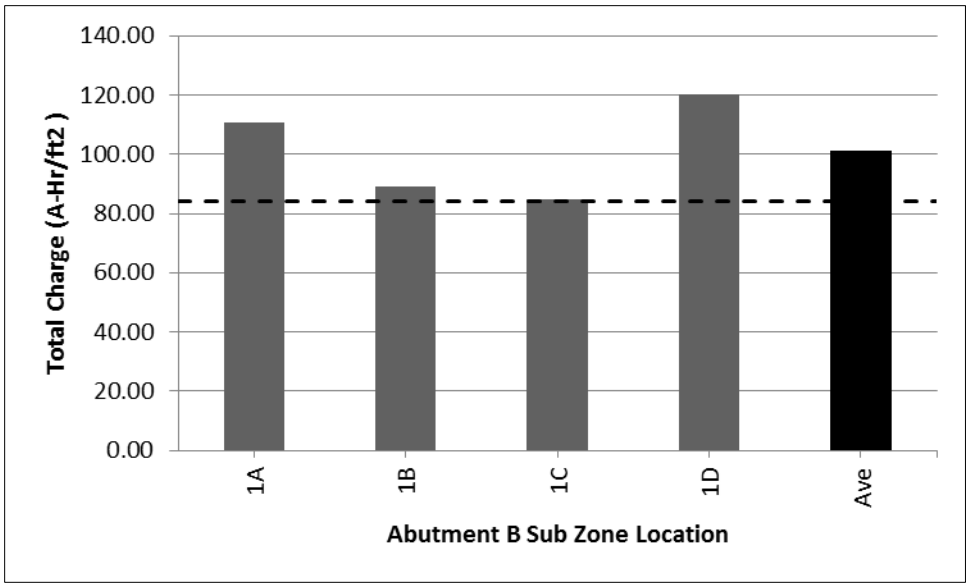

Figure 42. Total Charge Passed During ECE Treatment on Abutment B Under I-95 Bridge Over Overbrook Road. ECE = electrochemical chloride extraction.

As with the Hermitage Road substructure, some of the ECE treatment times exceeded the projected times; some sub-zones were treated for approximately 7 months. Again, samples of concrete were gathered and the chloride concentration was determined. As with the Hermitage Road substructure, in cases where the sub-zones did not meet the 84 A-hr/ft^2 requirements, the contractor was permitted to terminate ECE once the chloride concentration at the reinforcing bar was measured to be below 330 ppm. In some of these sub-zones, the chlorides at the depth of the reinforcing steel were around 20 ppm when tested in accordance with AASHTO T 260-97, Procedure A.

After ECE, a graffiti-resistant sealer was required on this structure. It was proposed by VDOT to use the non-sacrificial sealer and anti-graffiti coating to restrict the intrusion of additional chlorides into the concrete. PermaKote was selected from the VDOT approved products list for this application.

Although the superstructure replacement greatly improved the appearance of the deck and beams during construction (Figures 38 and 43), similar improvements to the appearance of the substructure were not apparent. Close inspection (Figure 44) revealed that cracks in the concrete exhibited a mineral deposit, similar to those on the bridge over Hermitage Road (Figure 37). These deposits probably formed in the cracks during the ECE treatment. This was a relatively small feature when compared to the overall substructure, so it was not obvious. However, connections to the steel that were used during ECE were not cut in a manner that would have left them recessed and patched with concrete. Instead they were allowed to project out from the concrete surface (Figure 45), which was unsightly. Future ECE specifications should require the contractor to leave the wire embedded at an acceptable depth below the concrete surface and patch the area with a highly resistive cementitious repair material.

Overall, the piers and abutment of the I-95 bridge over Overbrook Road appeared to be in good condition. A reasonable recommendation would be that the reinforced concrete be

evaluated every 5 years from the date of treatment using electrochemical testing, such as the half-cell potential method, in conjunction with a delamination survey and chloride analysis of the concrete. This should be done to capture routinely the condition of the reinforced concrete and to determine if corrosion has started to initiate in these reinforced concrete elements. This would increase the likelihood that if corrosion initiated again, it would most likely be detected as the corrosion began, i.e., before it became apparent through cracking and spalling of the concrete.

Figure 43. I-95 Bridge Over Overbrook Road Showing Underside After Completion of Project

Figure 44. I-95 Bridge Over Overbrook Road Showing Mineral Deposit on Column After ECE. ECE = electrochemical chloride extraction.

Figure 45. I-95 Bridge Over Overbrook Road Showing Connection Protruding After Completion of ECE Corrosion Mitigation Work. ECE = electrochemical chloride extraction.

Potential Benefit of Combining Repair Technologies

In this report, the repair techniques discussed can be categorized into one of two groups based on how they influence corrosion rates: (1) barrier techniques or (2) electrochemical mitigation techniques. The barrier techniques limit reactants from reaching the steel and initiating corrosion. These include properly functioning joint materials or concrete surface sealers such as silane, methacrylate, or epoxy. Both limit the ability of chloride either to reach or penetrate the concrete and diffuse to the embedded steel. Electrochemical mitigation techniques, e.g., ECE and CP, impede the electrochemical reaction at the surface of the steel so that the corrosion rate is decreased and is no longer detrimental.

It is reasonable to presume that electrochemical mitigation techniques when employed in conjunction with a reduction in the exposure to chloride-laden water will increase service life. For example, performing ECE on the substructure while simultaneously repairing or eliminating leaking joints should mitigate the existing corrosion while also reducing the ingress of additional salt and water that would re-initiate corrosion over time. The literature indicated that the repair of leaking joins will last 2 to 10 years, depending on how the joint is constructed. Nine years after treatment of the substructure on the Burlington Bay Skyway Bridge, which also benefited from repair of the deck joint prior to ECE, an average of only 8% of the readings were in the uncertain corrosion activity range. This result indicated that ECE provided additional service life to the Burlington Bay Skyway Bridge substructure that exceeded the 9 years that were documented. This is supported by the additional service life after ECE was performed on the 5th Street Extended Bridge, which also benefited from the application of a silane sealer to the substructure that restricted chloride movement even with leaking bridge joints. Therefore, a projected service life extension is expected based on the observations of the Burlington Bay Skyway and the 5th Street Extended Bridge, and it is also reasonable to assert that performing

measures to restrict the reintroduction of chloride into the concrete will further extend the service life of a structure.

Moreover, a second assertion, increasing service life by combining electrochemical techniques, has also been suggested by some consultants, as in the case of the I-95 bridges project, which combined several electrochemical corrosion mitigation techniques to increase service life beyond what a single technique would provide. Therefore, the reported additional service life with the use of Al-Zn-In as part of a GACP system is 15 to 20 years, or ECE with a sealer can reasonably add 15 to 20 years of additional service life for the substructure. However, this second assertion is more difficult to quantify for two reasons: (1) it is not clear how the beneficial life of each electrochemical mitigation technique combines to increase the total service life, and (2) ECE is a relatively new method with reinforced concrete structures, so historic data are limited. In addition, there are sometimes questions with regard to the feasibility of combining two mitigation techniques, especially on large projects when historical documentation does not exist for trial studies or smaller projects.

As discussed previously, there were concerns with metallizing numerous bridge substructures along I-95 after ECE treatment when there was no record of it ever being attempted. Problems with adhesion between the Al-Zn-In galvanic anode and the concrete after ECE, however, were not detected. Quality control testing during the metallizing operation on the substructure of the I-95 bridge over Hermitage Road indicated that the coating was bonding. Visual inspection of the substructure 4 years later further confirmed that the coating can be applied to a surface after ECE.

A Pessimistic Model of Combined Benefits

The most pessimistic set of assumptions is as follows:

1. that each treatment individually is an effective defense against corrosion for as long as it continues to function

2. that no treatment prolongs the functional life of any of the other treatments

3. that corrosion is mitigated as long as at least one of these treatments continues to function and corrosion begins when the last treatment ceases to function.

Under these assumptions, the minimum and maximum duration before the onset of corrosion would be described by the following equations.

min[duration of A+B+C] = min[min(duration of A), min(duration of B), min(duration of C)]

max[duration of A+B+C] = max[max(duration of A), max(duration of B), max(duration of C)].

These assumptions amount to saying that there are *no* additive benefits. The duration of the effective impact of any number of treatments would be simply the duration of the one treatment that lasts the longest.

These assumptions are unrealistically conservative for a couple of identifiable reasons. First, the assumption that any one treatment is an absolutely effective barrier from the completion of its application until the end of its useful life is unrealistic. Each of the treatments, even with the most expert application, exhibits a certain amount of spatial lack of uniformity from one spot to another, and the rate of degradation is somewhat uneven from one spot to another. A second treatment is almost certain to provide a useful "second line of defense" somewhere. Second, the assumption that no treatment affects the functional life of any other treatment is unrealistic. Available evidence, and understanding of the mechanisms at work, suggests that one treatment can affect the rate of degradation of another treatment. For this reason, too, a combination of two treatments is likely to have a longer effective life than either treatment would have by itself.

A More Realistic (But Still Conservative) Estimate of Combined Benefits

A more realistic estimate of the compound benefit of multiple treatments—albeit a more complicated estimate—may be made by considering (1) the extent to which each treatment's effectiveness diminishes with time and (2) the impact that one treatment can have on the rate at which the effectiveness of another treatment diminishes.

Joint Repair Plus Any Treatment to the Substructure

Deck joints fail by cracking and thereby becoming more permeable to water, which also transports salt. Degradation of (deck) joint function is probably primarily a function of construction quality and environmental exposure. No second treatment applied to the substructure can be expected to augment the life of a joint repair, as the joints block passage of water and chlorides to the substructure for as long as they function; however, a joint repair can be expected to prolong the effective life of any substructure treatment.

For the 2 to 10 years that a deck joint repair may be expected to hold up, it is possible that a concrete surface sealer will deteriorate more slowly than it otherwise would, that the impact of an ECE may scarcely begin at all, and that an anodic coating will deteriorate more slowly than it otherwise would. The service life impact of joint repair and the service life impact of ECE could be completely additive: the "clock" on the benefits of the ECE treatment may scarcely begin to run until the "clock" on the benefits of the joint repair has run out. Therefore, this would lead to a beneficial life of 2 to 10 years (joint repair) + 9 to 15 (plus) years (ECE) = 11 to 25 (plus) years of bridge life extension.

Concrete Surface Sealer Plus ECE

The surface sealer (presumably) fails by becoming permeable as a result of wear or tear. For as long as it lasts, a surface sealer that coats all surfaces of the concrete substructure (except perhaps the underside) could largely block the moisture and chlorides that otherwise would

gradually reverse the effect of the ECE treatment. The service life impact of a surface sealer and the impact of ECE would be similar to the previously discussed joint repair plus any treatment to the substructure, so it would be expected generally to be additive.

As degradation of a concrete surface sealer—although probably in good part environmental—depends also on water passing through the deck; the addition of a deck joint repair as a third treatment may prolong the effective life of a substructure surface sealer plus ECE.

GACP Plus ECE

The use of GACP after ECE is the only restoration technique that directly alters the corrosion rate by altering the embedded steel itself. The additional service life that results from simultaneously increasing alkalinity and decreasing chloride concentrations at the steel (ECE) plus immediately polarizing the steel and reducing the propensity for corrosion (GACP) will probably be longer than that predicted by the minimum as a result of some benefit provided by combining the techniques. ECE and GACP are likely to reinforce each other mutually. One can view ECE as "turning back the clock" on the conditions that promote corrosion, whereas GACP "slows the clock down" for as long as the anode is functioning; therefore, GACP prolongs the benefits of ECE. This can be more easily explained by first reviewing how the combination of techniques might influence the movement of ions via the Nernst-Planck equation and then second by reviewing how CP influences the corrosion rate.

First, the Nernst-Planck equation (Eq. 1) relates the mass transfer (ion movement) in solution to the mechanism for movement, which are diffusion (response to chemical potential gradient), migration (response to electric field gradient), and/or convection (response to solution displacement). Several researchers, such as Andrade et al. (1995), have discussed the application of Eq. 1 and the movement of chloride ions in concrete.

$$\underbrace{J(x)}_{\text{Movement}} = \underbrace{-D_j \frac{\partial C_j(x)}{\partial x}}_{\text{Diffusion}} \underbrace{- \frac{z_j F}{RT} D_j C_j \frac{\partial E(x)}{\partial x}}_{\text{Migration}} \underbrace{+ C_j V(x)}_{\text{Convection}} \qquad \text{[Eq. 1]}$$

Although it was outside the scope of this study to model the effect of combining mitigation techniques to increase the beneficial life of the repair, it is clear that altering both the diffusional and migrational components in the Nernst-Planck equation, assuming convection is not a factor, affects the movement of a species. It has been demonstrated that after ECE on a structure, the structure remains polarized for a period of time after the ECE treatment stops, which can be seen for the Burlington Bay Skyway in Figure 6. In addition, during ECE, the alkalinity adjacent to the steel is increased as a result of the reduction of water to hydroxide. As a consequence, since corrosion requires the aggressive ions, chloride in this case, to move through the concrete to the surface of the steel in order to initiate corrosion, restricting the ion movement will influence the time to corrosion. Therefore, it is possible that by continuing to polarize the steel negatively using GACP, which is known to reduce the corrosion rate of the steel, after ECE treatment, a much longer service life extension could be realized as long as the

galvanic anode remained active. From the Nernst-Planck equation, it can be concluded that by applying CP to a reinforced structure after ECE, a polarization effect, although smaller than during ECE, will remain and so in addition to the diffusional component given in the Nernst-Planck equation a migrational component will need to be accounted for in the evaluation of the movement of chloride ions in a structure.

Second, with regard to how the corrosion rate of the reinforced structure is influenced by CP, as discussed earlier, ECE "turns back the clock" on the conditions that promote corrosion whereas GACP "slows the clock down" for as long as the anode is functioning. Whereas ECE will have reduced the chloride ions in the concrete and increased the alkalinity adjacent to the reinforcing steel, thus reducing the corrosion rate of the steel, the GACP system will slowly consume the anode while it creates a cathodic current that further slows the dissolution of the steel in the concrete; therefore, GACP prolongs the benefits of ECE. This interaction implies that the service life impact of ECE and GACP will be at least partly additive, possibly fully so.

With several restoration techniques used, it is anticipated that additional monitoring of the I-95 bridges over Hermitage Road and over Overbrook Road will provide a comparison as to how much longer a GACP system when used after ECE treatment can extend the service life beyond that of ECE treatment alone. Further, by repairing leaking joints and applying a new coating of Al-Zn-In in the future, an even greater extension of service life can be obtained.

CONCLUSIONS

- *Based on the ECE treatment of the substructure of the 5th Street Extended Bridge, additional years of service life are possible for reinforced concrete that is properly treated with the use of ECE and a post-treatment sealer.*

- *Elimination or improvement of existing deck joints should be considered when ECE will be applied to substructure elements to extend the service life after ECE.*

- *The ECE process is often terminated when the "passed charge" exceeds an established threshold, but difficulties in the field might result in unforeseen construction delays as a result of the attempt to meet this criterion. Future contracts should establish that the chloride concentration at the level of the reinforcing bar can be used to set an alternative criterion in case treatments are lasting excessively long.*

- *Combining electrochemical techniques, such as CP and ECE, is feasible and could theoretically provide additional life beyond that provided by the use of one of these techniques alone.*

- *The I-95 bridges over Hermitage Road and over Overbrook Road will provide a comparison with regard to how much longer a galvanic anode can extend the service life beyond that of the ECE treatment. In addition, other installations can be used to compare the service life with GACP and ECE.*

- *All ECE connections to the steel should be completely removed or embedded after completion of the treatment and a highly resistive cementitious repair material should be used to patch any holes.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division, in order to comply with a request by the FHWA, will work with the Virginia Transportation Research Council (VTRC) to continue to monitor the I-95 bridges, in particular those over Hermitage Road and Overbrook Road, to determine the benefit of combining electrochemical corrosion mitigation techniques such as GACP and ECE and to compare the performance of both techniques.*

2. *VDOT's Structure and Bridge Division should include ECE as an option for repair when extending the service life of existing structures. As part of the repair, a post-treatment sealer and joint elimination or improvements should be required.*

3. *VDOT's Structure and Bridge Division should require that all ECE connections to the steel be completely removed or embedded after completion of the treatment and that a highly resistive cementitious repair material be used to patch any holes.*

BENEFITS AND IMPLEMENTATION

Benefits

The benefit of monitoring the I-95 bridges, in particular those over Hermitage Road and Overbrook Road, to determine the benefit of combining electrochemical corrosion mitigation techniques such as GACP and ECE and to compare the performance of both techniques is that it will provide VDOT's Structure and Bridge Division with an understanding of when this approach is reasonable.

The benefit of including ECE as an option for repair when extending the service life of existing structures is that it will provide VDOT's Structure and Bridge Division with the ability to reduce the amount of concrete repair work required, which could reduce the repair time needed in certain cases. Another benefit generated by this study is the assertion that as part of the ECE repair, a post-treatment sealer and joint elimination or improvements should be required, which will increase the beneficial life of the ECE repair.

There are two benefits of requiring that all ECE connections to the steel be completely removed or embedded after completion of the treatment and a that highly resistive cementitious repair material be used to patch any holes. First, this will improve the aesthetics of the repair while eliminating unnecessary protrusions from the patch. Second, these connections when left unsealed can provide a pathway for moisture and salt that links directly to the steel.

Implementation

VDOT's Structure and Bridge Division, through its special provisions for corrosion mitigation services on the I-95 bridges (for example, the Appendix), has agreed with a request by the FHWA to continue to monitor the I-95 bridges. This will allow a comparison of how much GACP can extend service life beyond that of ECE treatment alone. VTRC research staff will assist in this effort.

ACKNOWLEDGMENTS

The author expresses his sincere gratitude to Linda Evans, William Ordel, Ali Akbar Sohanghpurwala, Siva Venugopalan, David Whitmore, and Jun Zhu. The author also acknowledges the assistance of the staffs of VDOT's Central Office, VDOT's Culpeper District, VDOT's Richmond District, and VTRC's Concrete Laboratory. The author further thanks the members of the technical review panel for this project: James Gillespie, Jose Gomez, Rodolfo Maruri, Adam Matteo, Rex Pearce, and Michael Sprinkel.

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APPENDIX

VDOT SPECIAL PROVISION FOR ECE ON I-95 BRIDGES

ORDER NO.: D28
CONTRACT ID. NO.: C00018944C02

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
ELECTROCHEMICAL CHLORIDE EXTRACTION

April 12, 2010

I. Description

This item relates to the Electrochemical Chloride Extraction (ECE) treatment of pier caps, columns, and abutments of structures in this Contract. The purpose of the ECE treatment is to extract chlorides from the concrete and protect the structure from corrosion related damage. ECE is a treatment process that takes about 60 days per zone. It is a non-destructive treatment that does not alter the final appearance of the structure. ECE stops corrosion by migrating chlorides away from the embedded reinforcement and by increasing the alkalinity of the concrete around the embedded reinforcement.

The proposed ECE treatment shall be performed per this special provision. This special provision presents specifications for the installation and operation of Electrochemical Chloride Extraction (ECE) systems for vertical, overhead, and chloride contaminated concrete surfaces. This special provision details the requirements for preparing, testing (prior to ECE), supplying, installing, energizing, testing (after ECE), and preparing a report for ECE treatments. Any alternative or equivalent materials, equipment, or methods proposed for use on this project shall be approved by the Engineer before being used on the project.

This is a patented process. It is the Contractor's responsibility to work within the agreement with the patent holder. All associated costs incurred when using this process/product including licensing and/or royalty fees shall be included in the bid price for this item.

II. Materials

Materials and equipments shall be designed, manufactured, and tested in accordance with applicable requirements from latest editions of the following codes and standards:

- National Electrical Manufacturers' Association (NEMA)
- American Society for Testing and Materials (ASTM)
- National Electric Code (NEC)
- American National Standards Institute (ANSI)

The materials and equipment to be used in this project will be subject to a corrosive atmosphere, to an ambient temperature of -22 ºF (-30ºC) to 122 ºF (50ºC), and to very high relative humidity.

a) Anode System Materials

Anode material shall be #4 gage welded wire steel mesh.

b) Epoxy for Coating Welded Connections, Exposed metal, and Exposed Copper wire

The epoxy material shall be a non-conductive 100 percent solid, moisture, and chemical resistant two-part epoxy. The epoxy shall initially cure in 20 minutes at 70 ºF (21ºC) and cure to an ultimate compressive strength of 9000 psi (62 Mpa) in 24 hours at 70 ºF (21ºC).

c) Junction Boxes

The junction boxes shall be installed on the structure to facilitate testing of all anode and structure negative connections. The junction boxes shall be weatherable plastic or fiberglass, with a nonmetallic cover. The junction boxes shall also have minimum dimensions of 8" (203 mm) high by 8" (203 mm) wide by 4" (102 mm) deep. The junction boxes shall be secured to the concrete surface using at least four plastic mechanical fasteners. There shall be at least one junction box per individual zone.

d) Electrical Condu t and Related Hardware

The conduits for cables and wires used in the ECE tre tment shall be polyvinyl chloride (PVC). The fittings (i.e. couplers, reducers, etc.) and attachment hardware (i.e. clamps, fasteners, etc.) shall be 100% plastic. Each length of the conduit shall bear the UL label. PVC conduits shall conform to NEMA standard publications No. TC2. Conduit fittings shall meet NEMA TC3. Solvent cement for attaching fittings to the conduit shall be supplied or recommended by the conduit manufacturer. The conduits and fittings shall not be affected by exposure to sunlight and the pH of the ECE environment.

e) Electrical Outlet

The Contractor shall provide all necessary outlets for ECE treatment including rectifiers, motor for the timed irrigation system, lighting, and other outlets related to ECE work. The Contractor shall also provide one 110V, 20A electrical outlet (at every substructure slated for ECE) to the Engineer, when required, for use before and during ECE treatment.

f) Wires and Cables

The wires used for system negative connections shall be black #6 AWG THHN. The anode wires for anode subzones shall be red #10 AWG THHN. If there are no anode subzones within a zone, the anode wire from the junction box to that zone shall be #6 AWG THHN. The wires from the junction boxes to the rectifier circuit shall be black #4/4 SO for both system negatives and the anode.

g) Licenses & Permits

The Contractor is responsible to obtain all necessary licenses and/or permits to drop a power pole at the site. Each zone of the ECE rectifier shall be limited to a max. of 40V.

h) Electrolyte for the ECE Treatment

The electrolyte for the ECE treatment shall be potable water. The Contractor is responsible to obtain all necessary licenses and/or permits to tap into the City fire hydrants. The Contractor shall install all necessary fittings (acceptable to the City water department) to tap into the fire hydrant. The Contractor shall take all necessary precautions to prevent the electrolyte from freezing.

III. Procedures

Submittals

The Contractor shall submit for approval three sets of design drawings and catalog cuts of all the materials to be used on this project. Prior to installation, the Contractor shall survey the concrete surface and submit the survey report with his statement of suitability of the surface for ECE installation.

Removal of Delaminated Concrete

The Contractor shall identify and mark on the concrete surface all of the delaminated areas using water based spray paint. Any replacement reinforcement, if required, shall be black bar and tied directly to the existing reinforcement to ensure electrical continuity. The Contractor shall remove concrete from all spalled and delaminated areas to a depth of at least 1” (25 mm) below the top layer of reinforcing steel. All areas where concrete was removed shall be formed to the original concrete surface. Spalled and delaminated areas shall be patched with a concrete material having an electrical resistivity of less than 5,905 ohm-in (15,000 ohm-cm). Avoid high resistivity mortars, patching materials, and bonding agents that have electrical resistivities over 5,905 ohm-in (15,000 ohm-cm). Standard Portland cement concrete is an acceptable patching material (Type B patching according to Virginia Department of Transportation). Concrete patching material shall not contain fly ash or slag. Concrete with fly ash, slag, or other materials will increase resistivity of the patch and CP will not work well.

Pre-Installation Test ng for Baseline Data

The Contractor shall clean the surface by pressure washing or light sand blasting. The Engineer shall identify the two most anodic locations in each zone via half-cell potential survey. Half-cell potential readings shall be taken at every one-foot interval. At the most anodic locations, additional readings shall be taken around that location to identify the most anodic spot. All half-cell readings shall be summarized in table form, along with the two most anodic locations for chloride sampling, and submitted to the Engineer for approval.

The Engineer will collect concrete powder samples from most anodic locations. It is important that concrete powder samples for chlorides be collected within 1/4" (6 mm) of the reinforcing steel. The exact location of the reinforcing steel shall be located with a cover meter, pachometer, or other suitable rebar locating device. Powder samples shall be collected adjacent to the intersection of two reinforcing steel components. Concrete powder samples shall be collected by the Engineer at two depths: at the surface (1/4" to 3/4" or 6 mm to 19 mm) and at the rebar (1" or 25 mm to top of rebar).

Samples shall immediately be placed into sealed airtight bags or other suitable containers. Samples should then be clearly marked with the contract name, date, sample location, and sample depth. All chloride samples shall be sent to a laboratory for testing.

The Engineer shall prepare an accurate sketch of chloride hole locations. The Contractor shall patch all chloride holes with a VDOT approved mortar mix.

Concrete Surface Preparation

The Contractor shall identify and seal all cracks that are wider than 1/32" (0.8 mm) prior to ECE treatment. The cracks shall be repaired by injecting VDOT approved epoxy material. Sealing of cracks is not included in ECE work. Concrete shall be identified and removed from all spalled and delaminated areas at least 1" (25 mm) below the reinforcing steel. All areas where concrete was removed shall be formed to the original surface.

The Contractor shall use light sand blasting to remove all dust, debris, rust stains, laitance, grease, and all other contaminants that may interfere with adhesion of the Cellulose Fiber. The sand blasting shall not remove excessive amounts of cement paste and expose aggregates, which may interfere with the adhesion of sprayed Al-Zn-In anode.

Survey of Repaired Concrete Surface

The Contractor shall locate all areas of insufficient cover (i.e., less than 3/8" or 9 mm) over the reinforcing steel by means of a cover meter/pachometer survey and selective chip-outs. If this area/length is less than 3" (76 mm), it shall be epoxied. If this area/length is 3" (76 mm) or more, the concrete shall be removed and replaced with VDOT's type B patching material until the cover is at least 0.4" (10 mm). The patch material shall not contain fly ash, slag or other additives that increase the resistivity of the patch material.

The Contractor shall survey the concrete surface at the end of all concrete repair work to ensure that there is no delaminated concrete left in place. The Contractor shall submit all relevant findings to the Engineer and include locations and sizes of delaminations, if any, present on the structure. If no delaminations are found, the inspector shall state as such and submit a letter to the Engineer.

The Engineer shall survey the repaired concrete surface just prior to ECE treatment (i.e. within 3 months) to ensure that there is no new delaminated concrete. The Engineer shall document findings with locations and sizes of delaminations, if any, present on the structure. If no delaminations are found, the Engineer shall state as. such.

Enclosures for Debr s
The Contractor shall provide appropriate enclosures to collect ll debris during concrete removal, sandblasting, and power washing type operations. No debris shall be allowed to fall into the water below. The Engineer may stop work at any time if the enclosures to trap the debris and fines are not provided to the satisfaction of the Engineer. The Contractor shall immediately correct this situation to the satisfaction of the Engineer at no additional cost to the Department. The Engineer's decision is final and binding.

Electrical Connection to the Reinforcing Steel
Each ECE zone shall have two distinct system negative connections. The Contractor shall use black #6 AWG THHN for system negative wires from the junction box to the reinforcing steel. The wires shall be of sufficient length to reach the junction box without any splicing. The Engineer shall verify the electrical continuity of all system negative connections prior to coating the welding. This can be accomplished by testing electrical continuity between one end of the system negative wire and the reinforcing steel to which the system negative wire is attached. Any connection that fails the electrical continuity test shall be replaced by the Contractor at no additional cost to the Department. All wiring shall be routed to the appropriate junction box.

Welding of system negative wires to the reinforcing steel shall be accomplished by a commercially available exothermic weld kit. The exothermic weld kit shall include a mold and powder charge of suitable size for the wire and reinforcing steel. The reinforcing steel shall be thoroughly cleaned before welding. The weld and the wire shall be cleaned of all oil and grease with a solvent and a clean cloth. The mold shall rest on the reinforcing steel and securely hold the wire in place. When ignited, the charge in the mold shall burn and result in a mechanically secure and electrically conductive weld of the wire to the reinforcing steel. The Contractor shall test the integrity of the finished weld for mechanical strength by tapping it with a hammer. All failed welds shall be replaced by the Contractor at no additional cost to the Department.

Electrical Connection to the Anode
Each sub zone shall have two distinct anode connections. The Contractor shall use red #10 AWG THHN for wires from the junction box to anode subzones. The wires shall be of sufficient length to reach the junction box without any splicing. If a particular zone does not have any subzones, the anode wire from the junction box to that zone shall be #6 AWG THHN. The Contractor shall verify the integrity of anode wire connections. The data shall be recorded and submitted to the Engineer. Any connection that fails the electrical continuity test shall be replaced by the Contractor at no additional cost to the Department. All wiring shall be routed to the appropriate junction box.

Coating Welded Connections
The finished weld shall be cleaned of any slag. The weld and exposed copper of the wire shall be coated with two coats of the epoxy mentioned in this special provision. The second coat of epoxy shall be applied only after the first coat has completely cured. The epoxy shall be allowed to cure 100% prior to patching.

Electrical Continuity of Reinforcing Steel
The purpose of this test is to ensure that all the embedded reinforcing steel/metal in the structure is continuous. If the embedded reinforcing steel is not continuous, it may be subjected to corrosion during ECE treatment.

The Contractor shall check for electrical continuity of reinforcing steel at a minimum of 5 locations per zone (with at least three per sub zone) and between all exposed rebars (during the concrete repair stage) using the DC millivolt technique. The continuity test points shall be distributed uniformly throughout each zone. Testing shall be performed during the delamination/repair stage to avoid unwanted excavations to expose the rebars for testing purposes. Test equipment for this procedure consists of a standard digital voltmeter, test leads, and wire reel. Continuity between two metallic elements is considered to exist if the DC millivolt between the two is not greater than 1mV, the DC resistance is not greater than 1ohm, and the difference in DC ohms measured in forward and reverse is not greater than 1ohm. The readings shall be obtained using a digital multimeter with at least 10-mega ohms internal resistance and shall be calibrated within six months of testing. The multimeter shall have a resolution of 0.1mV in the lowest DC Volts scale and 0.1ohm in the lowest DC ohms scale.

All metals (including existing electrical surface mounted conduits and junction boxes) that are identified as discontinuous shall be made electrically continuous by the Contractor by bonding the metal to the reinforcing steel (with one #10 AWG wire with THHN insulation) using the thermite welding procedure.

The Contractor shall prepare and submit drawings that detail the continuity test points. The drawing, along with the continuity data, shall be submitted to the Engineer for approval.

Labeling of Wires
All wires (i.e. system negatives and anode wires from each sub zone) shall be labeled clearly at the junction box. All wires from the junction box to the rectifier shall also be labeled clearly both at the junction box and at the rectifier. The Engineer shall verify all labeling and termination.

Routing Wires
All wire connections are temporary in nature in the ECE process (i.e. may stay in place only as long as required for ECE treatment). However, these wires carry large amounts of current and operate up to 40VDC. Wires from the anode and steel to the junction box shall be installed such that safety of the public is ensured. The wires shall also be protected from being vandalized. The wires from the anode and reinforcing steel to the junction box shall be routed through a PVC conduit. The wires from the junction box to the rectifier shall also be routed through a PVC conduit. The PVC conduit shall be attached to the concrete surface using plastic clamps and anchors.

Anode Application
The concrete surface shall be cleaned by light sandblasting and/or pressure washing prior to installing the #4 gage steel anode mesh. Wooden spacers, 1” x 2” (25 mm x 51 mm), shall be attached to the concrete surface using plastic anchors. Distance between spacers shall not exceed 4ft. (1220 mm). The anode shall be laid out as shown in the construction plans. The anode shall be securely fastened to the concrete surface via plastic anchors in order to prevent any electrical short with rebar or other metals in the structure. Anode mesh shall be placed at least 6” (152 mm) away from all exposed metals. When necessary, the anode shall be cut/bent to accommodate installation requirements.

The anode mesh panels shall be placed one against the other. No spacing is necessary between two adjacent anode mesh panels. All anode mesh panels shall be made continuous to adjoining anode mesh panel(s) in at least two distinct locations. The anode mesh shall extend 1” (25 mm) below soil/ground level.

The concrete surface to be treated is divided into isolated anode zones. Each anode zone is then further divided into anode sub zones. The spacing between anode sub zones shall not exceed 3” (76 mm). The spacing between anode zones shall not exceed 6” (152 mm). The anode zones and sub zones are spaced apart to ensure electrical isolation from one another.

All bearing pads 6” (152 mm) or taller shall receive ECE tre tment on all sides except the top. The anode mesh on the side of the bearing pad shall be made electrically continuous with the anode mesh on the top of the pier cap or other nearest sub zone (at least two connections per pad).

Test Window
Provide a 2” (51 mm) circular knock out (prior to spraying the Cellulose Fiber) to access the concrete surface for testing. The knock out shall be centered on the space between steel wires in the anode mesh. There shall be at least two knock out windows per zone. The locations of the test windows shall be marked in the field by Engineer

Inspection of ECE Installation
The installed anode system, its electrical connection, power cables, rectifier grounding, and other connections shall be inspected by the Engineer prior to starting the ECE process. Cable insulation shall be checked for any cuts and nicks occurred during installation. Any damaged insulation shall be repaired using a generous amount of an appropriate insulation material (i.e. heat shrink tubes followed by electrical taping), or by making new joints, all of which shall be provided at no additional cost to the Department. The integrity of the cables throughout the ECE treatment process is the responsibility of the Contractor. The Contractor shall repair/replace all cable that has lost its integrity before or during ECE treatment at no additional cost to the Department.

Electrolyte Media
The Electrolyte Media shall be sprayed Cellulose Fiber. The Cellulose Fiber shall be sprayed to encapsulate the welded steel mesh anode. The Cellulose Fiber material shall provide high moisture retention and shall be easily applied to awkward and uneven surfaces. The Cellulose Fiber and the electrolyte shall be delivered through separate hoses, then mixed at a nozzle and sprayed directly onto the concrete surface. The Fiber-electrolyte mixture shall be applied only after the anode is securely installed. The Fiber-electrolyte layer shall be approximately 2" (51 mm) thick. The welded steel mesh anode shall have at least 1” (25 mm) Cellulose Fiber on either side.

Wetting of Electrolyte Media
The Electrolyte Media must be kept wet at all times. The Contractor shall set up an automatic, timed irrigation system to ensure that all surfaces stay continuously wetted throughout the ECE treatment period. The treatment areas shall be tightly wrapped in plastic to minimize moisture loss due to evaporation. The Contractor shall take precautions to prevent external water from entering the wrapped Electrolyte Media. Without this precaution, a loss of adhesion of the Cellulose Fiber may result, leading to loss of the ECE treatment process for this section.

Placement of Rectifiers
Suitable and safe locations for placement of rectifiers shall be chosen to provide minimal disturbance. If any locations are outside of the Contractor’s trailer, they shall be enclosed behind a secured chain link fence. The Contractor shall ensure that the rectifiers are properly protected from vandalism. Any damage to the rectifier shall be corrected promptly by the Contractor at no additional cost to the Department. The chassis of the rectifiers shall be grounded in accordance with relevant NEC codes and standards. All AC power cables shall be installed in accordance with relevant NEC and local codes and standards.

System Operation and Maintenance

1. System Start Up
   Circuit Verification - Prior to energizing, all circuits shall be tested to ensure that all cables are wired correctly and labeled properly. The Contractor shall coordinate with the Engineer at least one week prior to starting ECE treatment.

2. Energizing
   Energization shall be performed in the presence of the Engineer. Each circuit shall be energized in steps of 1% of full current up to 5%, then in steps of 5% of full current up to 20%, then in steps of 20% of full current up to 100%. The current and voltage of each circuit shall be recorded at each step. The current to each anode sub zone shall be recorded as well. The polarity of the reinforcing steel and the anode shall be recorded using a digital voltmeter and a half-cell. The energizing shall be discontinued immediately if there is any discrepancy in the measured polarity. Any discrepancy in the polarity shall be immediately investigated and corrected by the Contractor at no additional cost to the Department.

3. Setting current output.
   The initial current for the ECE treatment shall generally be between 0.1A/ft^2 (1.1 A/m^2) to 0.2A/ft^2 (2.1 A/m^2) but shall not exceed 0.35 A/ft^2 (4.0 A/m^2) at any time. The total current can be adjusted by decreasing or increasing the applied voltage. During the treatment, the current output shall be measured individually on each anode cable. If the results indicate an unexpected current distribution, the Contractor shall immediately inspect and take appropriate remedial action at no additional cost to the Department.

4. Monitoring of System Operation
   During the treatment, the operation of the system shall be verified by the Engineer at least once a day, and the following shall be recorded: (i) structure name (ii) substructure number/name under ECE (iii) date and time, (iv) current (to each zone and sub zone as appropriate), (v) voltage (to each zone), and (vi) calculation of total ampere-hours passed for each zone.

   The operating parameters (i.e. rectifier circuit voltage, current, and current to individual sub zones) of each circuit shall be recorded two times a day until the values stabilize. Subsequently, these parameters shall be recorded once a day. All operating parameters shall be recorded and submitted to the Engineer.

   Any problems that develop during the ECE process shall be identified, recorded, corrected, and reported. Visual inspection of cable connections, cable insulation, anode condition, and wetting of the Electrolyte Media shall be conducted regularly and recorded by the Contractor. Any interruption in the operation shall be recorded and reported to the Engineer immediately.

   In addition to regular inspection, determination of the chloride content in the concrete adjacent to the steel (per AASHTO T 260 Method A or as approved by the Engineer) shall be carried out at predetermined locations by the Engineer. The concrete samples for chloride evaluation shall be taken at locations within 1/4" (6.4 mm) of the baseline chloride locations. All chloride samples shall be obtained by the Engineer and be sent to the laboratory for testing. The Engineer shall test the samples for chloride levels and calculate percentage reductions in chloride concentration before and after ECE treatment.

   Remedial Work - During the treatment, remedial work shall be conducted whenever any inspection indicates the system is not performing properly. This remedial work shall include, but not necessarily be limited to, the following: (i) repair or replacement of defective components of the system and (ii) modification to correct any electrical short circuits or to prevent stray currents. The materials and workmanship for remedial works shall be in accordance with standard concrete repair practices except when otherwise agreed.

Terminating the ECE Treatment

The ECE treatment shall be performed until a total charge of 84 Ampere-hours/ft^2 (900 Ampere-hours/m^2) is achieved. It may not be possible to achieve a total charge of 84Ampere-hours/ft^2 at all times. In such cases, the Contractor shall inform the Engineer and obtain the approval of the Engineer prior to terminating the ECE treatment. The Engineer's decision is final and binding. The expected treatment period is approximately 60 days. It is possible that treatment, on occasion, may take more than 60 days. The Contractor shall take this into account in planning and scheduling all work.

Dismantling and Disposing the ECE System

After completion of the ECE treatment, the Contractor shall obtain the approval of the Engineer prior to turning off the ECE treatment. The Contractor shall remove all electrical cables, conduits, hangers, and power supplies from the site. The anode, Electrolyte Media and wooden battens or dams (if used) shall also be removed from the site or be disposed in accordance with all applicable federal and local disposal and safety regulations. The system negatives from the reinforcing steel (terminated at the junction boxes) and the junction boxes shall be left in place. The Engineer shall test to ensure that the system negatives were not damaged during the dismantling process. The Contractor shall repair/replace any damaged system negatives at no additional cost to the Department.

Surface Cleaning and Patching of the Concrete after ECE Treatment

The surface of all treated concrete shall be either pressure washed using clean, potable water or using light abrasive blasting. There shall be no rust stains on the concrete surface. The entire treated structure shall then be inspected; the occurrence, location, and extent of any physical damage or changes to the concrete shall be noted. Any defects in the concrete shall then be repaired. This concrete repair is a part of the ECE process.

Sealing the Treated Concrete Surface

Typically, the surface of all ECE treated concrete shall be sealed with a penetrating sealer to prevent further intrusion of chlorides. For substructure of I-95 Bridge over Overbrook Road, seal all the ECE treated surface soon after the completion of ECE treatment (i.e. within 30 days). The site shall be clean at the end of ECE treatment. Since the sacrificial CP system will be installed on substructures of I-95 Bridge over Hermitage Road, no surface sealant is required after the ECE treatment. The Contractor shall apply this sealer only after the Engineer approves and accepts the ECE treatment. The sealer shall be graffiti resistant. The following graffiti resistant sealer is in VDOT's approved list:

Prmakote – This is a non-sacrificial sealer. It is water based and breathable. It is manufactured by Visual Pollution Technologies, Inc. (480) 657-9183. The Contractor shall provide a catalog cut sheet and the MSDS for this sealer along with other submittals prior to commencing any work.

Providing Access to the Structure

The Contractor shall provide safe access to the Engineer at no additional cost to the Department. Such access shall be provided in a timely manner so that the Engineer can perform testing and evaluations called for in this Special Provision. The Engineer shall coordinate his need for access with the Contractor.

Final Report
After completion of the work, the Engineer (with input and data obtained from the Contractor, where appropriate) shall prepare a final report as defined below. The final report shall include the following:

- Project name and location.
- Reinforcing steel continuity testing performed on the structure and locations of all continuity bondings.
- Surface preparation performed before treatment.
- Description of the ECE installation and procedure used.
- Materials used and the manufacturer's data sheets.
- Description of test locations and test procedures.
- Current and voltage readings during treatment.
- All test results including pre and post treatment chloride levels.
- Pre and post treatment corrosion potential survey data.
- Locations and repair of all damage to concrete arising from ECE treatment.
- Discussion of results, including consideration of all local anomalies or variations in results.
- Statement on the effectiveness of the treatment.

Corrosion Engineering Services
The Contractor shall employ the services of a CP Specialist for overseeing the ECE process. The Contractor shall submit the qualifications of the CP specialist and Corrosion Technician (within thirty days after notice to proceed) for Engineer's review and approval.

CP Specialist: The CP Specialist shall be a registered Professional Engineer (registered in Virginia) or a National Association of Corrosion Engineers (NACE) certified Cathodic Protection (CP) specialist. The CP Specialist (either the Professional Engineer registered in Virginia or the NACE certified Cathodic Protection specialist) shall have at least 8 years of experience in corrosion control investigation and evaluation, corrosion control system design and installation, inspection and energizing of Cathodic Protection systems/ECE for steel reinforced concrete structures exposed to atmosphere. The CP Specialist shall also be directly responsible for all corrosion engineering services on this project. The CP Specialist shall perform pre-energizing testing (including verifying and confirming anode sub zone layout drawing, wiring, labeling, and proper connection and termination at the rectifier) and ECE energizing.

Corrosion Technician (CT): The Corrosion Technician shall be a National Association of Corrosion Engineers (NACE) certified Corrosion Technician (CT). The CT shall assist the Contractor's CP specialist in accomplishing field inspections by performing delamination surveys, half-cell potential surveys, electrical continuity, and anode to reinforcement isolation testing. The CT shall have at least two years of experience in performing the testing and inspection services required on this project.

Consultant Services: The Department has retained a corrosion Consultant to perform the following:

- Submittals: Review all submittals related to the ECE treatment process for compliance with all project specifications. This shall include as built drawings prepared by the Contractor. Written communication detailing all conclusions and recommendations for each submittal shall be provided to the Engineer.

- Continuity Testing: Electrical continuity testing between two metallic elements shall be tested to ensure electrical continuity. Testing shall be performed between all system negative leads, all anode wires from each sub zone, and between all exposed rebars during concrete repair. Any connection or rebar found to be electrically discontinuous should be made continuous by the Contractor at no additional cost to the Department. Any connections formerly found to be continuous, but made discontinuous by the Contractor during the repair and rehabilitation process, shall be repaired by the Contractor per the method provided in the specifications at no additional cost to the Department. A final decision as to the event which caused the discontinuity shall be determined by the Engineer.

- Anode to Reinforcing Isolation Testing: The electrical isolation between the reinforcing steel and the steel anode mesh shall be checked prior to energizing. All data shall be recorded and submitted to the Engineer. Any electrical short identified shall be eliminated by the Contractor using methods approved by the Engineer. The elimination of electrical shorts shall be performed at no additional cost to the Department.

- Check for Labeling: The Consultant shall check and confirm proper installation of all components including labeling of wires. All identified defects shall be immediately corrected by the Contractor at no additional cost to the Department.

- Chloride sampling before the ECE Treatment: The Consultant will extract concrete powder samples (for baseline data prior to ECE) from locations decided based on half-cell potential survey data prior to ECE treatment.

- Chloride sampling after ECE Treatment: The Consultant will extract concrete powder samples at locations adjacent to the baseline sampling. Chloride samples shall immediately be placed into sealed airtight bags or other suitable containers. They should then be clearly marked with the contract name, date, location of the sample, depth from which the sample was removed, cover depth of the reinforcing steel at that location, and lateral distance to the nearest reinforcing bar. The Consultant will test or arrange to get these samples tested per AASHTO T260 Method A or as approved by the Engineer. The chloride content before and after ECE treatment will be compared, and the results will be summarized in table form and presented to the Engineer. The Consultant will also provide conclusions and recommendations along with chloride testing results.

- ECE Energization: The Consultant will be present at the site while the Contractor performs the following:

  a. Record the static potentials at the most anodic locations in each sub zone.
  b. Measure the AC resistance between the anode and the reinforcing steel.
  c. Measure the concrete temperature.
  d. Obtain rectifier output data including currents to individual sub zones.
  e. Calculate the Ampere-hours of charge applied to each sub zone and submit a signed copy to the Engineer.
  f. The Consultant will perform steps “d” and “e” once a day until the ECE process is terminated.

- Documentation: The results of electrical testing, half cell potential survey, chloride testing before and after treatment, rectifier output data, current to each anode sub zones, total charge applied to each zone, and other relevant information shall become a part of the final report. The final report will also include analysis of all test data, a table listing the total charge applied to each zone, conclusions, and recommendations.

IV. Measurement and Payment

ECE Treatment: The items for ECE treatment process shall be measured and paid on a lump sum basis. The lump sum price shall include any and all patent or royalty costs, all materials, engineering, surface preparation, sealant application, continuity bonding, welding, conduits, wires, equipment, tools, and labor for completion of this item.

Payment will be made under:

Pay Item	**Pay Unit**
ECE Treatment (Structure no.)	Lump Sum per Structure