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Field Evaluation of Reinforced Concrete Repairs Using Hydrodemolition, Galvanic Cathodic Protection, or Impressed Current Cathodic Protection

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Abstract:

For the Virginia Department of Transportation (VDOT), substructure repairs are costly, and the durability is a concern. Current conventional concrete removal methods commonly use chipping hammers and shotcrete or self-consolidating concrete (SCC), plus discrete galvanic point (DGP) anodes, for such repairs. The types of concrete VDOT uses in these repairs are resistant to chloride ion infiltration because of low permeability, which their high-resistivity values indicate. When DGP anodes are used in patch repairs, lower resistivity concretes with higher permeability are recommended to facilitate ionic current flow.

To facilitate the placement, aesthetics, and longevity of these types of repairs, SCCs were introduced. For longevity, two approaches were explored. One approach was large-area concrete removal through hydrodemolition and placing SCC. The other approach was to leave some of the chloride-contaminated areas in their current condition and apply a cathodic protection (CP) system for the whole element.

Researchers anticipated that these modifications would provide VDOT with comparisons against the current practice of using shotcrete or SCC, chipping hammers, and DGP anodes. In general, low-permeability SCC replaced inferior quality concrete in areas where it was removed. The only exception was that a lower resistivity concrete was used to ensure better current flow where ribbon anodes were placed. The following lists the four substructure rehabilitation techniques investigated based on the two aforementioned approaches.

1. Hydrodemolition to remove delaminated concrete and replace it with SCC.
2. Conventional removal of delaminated concrete, replacement with SCC designed for CP, and the installation of a CP system on each structure. The CP systems included two different impressed current CP systems and one galvanic current CP system. Each CP system required a remote monitoring unit that could be observed at the district, central office, and Virginia Transportation Research Council (VTRC), plus technical support.
3. Conventional removal of delaminated concrete, placement of precast anodes in the perimeter of the removed concrete, and replacement of the removed concrete with SCC.
4. Conventional removal of delaminated concrete, placement of precast anodes in the perimeter of the removed concrete, and replacement of the removed concrete with routinely used shotcrete.

All repairs and tasks were completed successfully. This report includes a parallel effort that is documented in a technical assistance report. This work showed that DGP anodes have limited benefits because they protect a limited area around the perimeter. Furthermore, this protection lasts only a few years because the areas farther away from the patch continue to deteriorate and soon require new repairs. It is recommended VDOT consider using large-area deteriorated concrete removal by hydrodemolition rather than small-area patches without any DGP anodes, or install a CP system for the whole element if some of the chloride-contaminated concrete remains.

Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.

FINAL REPORT

FIELD EVALUATION OF REINFORCED CONCRETE REPAIRS USING HYDRODEMOLITION, GALVANIC CATHODIC PROTECTION, OR IMPRESSED CURRENT CATHODIC PROTECTION

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

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ABSTRACT

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INTRODUCTION

VDOT has numerous steel reinforced concrete structures that require repairs because of corrosion. This can occur in pier caps and columns due to the historic use of highly permeable concrete and carbon steel rebar, as well as construction deficiencies that have sometimes resulted in concrete with insufficient cover depth, making the bridge element penetrable and vulnerable to corrosion. This approach results in corrosion-related spalling and loss of steel cross section. The historic uses of these susceptible materials and the adverse conditions these reinforced elements are routinely subjected to have led to costly repairs. These repairs are currently performed using conventional concrete removal (chipping hammers) and shotcrete or self-consolidating concrete (SCC) plus discrete galvanic point (DGP) anodes.

The types of concrete VDOT uses in these repairs are denoted as low-permeability concretes. Because permeability is the ability of a given concrete to permit liquids to pass through it, a low-permeability material would be more durable because it resists the infiltration of chloride ions that can lead to steel reinforcement corrosion (ACI, 2018). The measured resistivity of these same VDOT concretes would be high, which indicates that the concrete material's ability to conduct an electrical charge is restricted, because resistivity is inversely related to the conductivity of a material (ASTM, 2020). Therefore, when focusing on the movement of ions through concrete, restricting the ions' motion would be indicated as either high resistivity or low permeability. Therefore, this report uses two terms: (1) permeability when discussing concrete durability, and (2) resistivity when discussing ionic current flow in concrete, which occurs when using cathodic protection (CP) to mitigate corrosion.

It is also important to recognize that in some cases when an ionic material, like the corrosion inhibitor calcium nitrite, is added to a VDOT repair concrete, measurements will initially indicate a low resistivity value. However, limited work during an earlier study showed that the initial low resistivity value measured increases with time as the concrete ages. Thus, the initial low-permeability, low-resistivity concrete repair material becomes a low-permeability, high-resistivity concrete repair.

When VDOT repairs these elements (caps and columns), the deteriorated and delaminated concrete is removed and conventional VDOT A3 (3,000 psi) concrete or shotcrete that exhibits low permeability is then placed in the repair area. During this process, although the clearly damaged concrete is often removed, the adjacent concrete that is chloride contaminated but not showing visual damage will remain in place and is predisposed to initiating corrosion again soon. The amount of concrete that can be removed is limited. The VDOT *Road and Bridge Specifications,* section 412, limited the removal of concrete in the tension zone of a cap to be less than 30% of the span between adjacent columns at any one time. In the pier column, concrete in less than 30% of the height of the column and less than 30% of the diameter of the column could be removed at any one time. In addition, no more than 50% of the columns could be under repair at any given time.

When chloride-contaminated concrete remains in place, especially if it is adjacent to the steel reinforcement, this original concrete will have a different chloride content and pH level compared with repair materials, and it can lead to ring corrosion. Ring corrosion occurs because of differences between the original concrete and the repair materials where the reinforcement adjacent to the repaired area becomes an anode, and the reinforcement inside the new chloride-free, high pH patch becomes the cathode. Therefore, when ring corrosion occurs, what initially is a quality repair will slowly start to spall concrete around the repair area, and the corrosion damage continues to grow. This result requires consecutive repairs adjacent to the initial repairs. To address this issue, all the chloride-contaminated concrete must be removed from around the steel or some form of CP is required.

One promising technique for large-area concrete removal is hydrodemolition. It is widely used in bridge decks and is being adapted for substructure use. Hydrodemolition is effective for fast concrete removal operations. It can remove either vary large or whole surface areas of contaminated substructure concrete to depths below the reinforcing steel, eliminating the concern of future ring corrosion. Assuming the extent of concrete removal for structural concerns would not be a limiting factor, hydrodemolition could enable a more durable repair option.

Cathodically protecting the steel is another option that can mitigate corrosion of the steel reinforcement when performed properly. The galvanic cathodic protection (GCP) approach uses a metal, often zinc for reinforced concrete applications, which will preferentially corrode when it comes in electrical contact with steel, thus protecting the steel area that receives sufficient electrical charge that flows through the concrete to polarize the steel surface. However, once the zinc is consumed or passivates, the steel starts to corrode. With this type of corrosion, a mitigation solution depends on the amount of zinc and the ability to keep it activated. Figure 1 shows an example of the galvanic anodes VDOT uses for a column patch repair. Although this approach is simple to perform, these smaller DGP anodes have a limited amount of zinc, which limits the repair life. Therefore, the extension of service life is short. It would require more frequent repairs and replacement of the anodes, which is difficult because the DGP anodes are embedded in the repair concrete for longer protection. Furthermore, the DGP anodes require the repair concrete have a resistivity value low enough to ensure sufficient charge flow between the anode and cathode to protect the steel. Often, the resistive value for DGP anodes is less than what is measured for commonly used VDOT concrete repair materials because of adding supplementary cementing materials to ensure concretes with low permeability.

(a)

(b)

Figure 1. Placement of Anodes in Shotcrete Repair Area: (a) Column with DPG anodes (red arrow) tied to steel prior to shotcrete repair and (b) after shotcrete hardens and exhibits shrinkage cracks (blue arrow) that were emphasized on the column using yellow crayon. The cracks widths marked in yellow are less than 0.01 inch (Brown and Sharp, 2005).

It is important to recognize a couple of key differences between GCP and impressed current cathodic protection (ICCP). One of the differences is that with GCP, the potential is set by the voltage difference between the active metal, like zinc, and the reinforcing steel that is being protected, so the current output cannot be adjusted. With the ICCP system, however, the potential between the anode and the metal being protected is set by the rectifier and can be adjusted during the service life as needed, which is one of the benefits of ICCP over GCP. ICCP can exceed the service life limitations of some GCP systems and can protect wider areas than only a limited area surrounding the repair when DGP anodes are used. For example, ICCP can be used if limited concrete removal is required due to structural concerns, because it can be designed and more readily adjusted to directly suppress the corrosion reaction. Finally, although ICCP and GCP differ, both can be monitored using remote monitoring technology.

Suitable concrete repair materials are also important for durable repairs. For a material to be suitable, it must meet the job requirements dictated by the application and VDOT specifications. The specification might include properties like strength, shrinkage, alkalinity, and permeability, or even qualities related to aesthetics or consolidation. The contractor has flexibility within the specification limits and can use in-house mixtures or prepackaged materials. When VDOT A3 concrete was used for the repairs, a thicker protruding section was placed to facilitate placement and ensure enough cover. Therefore, the resulting repaired area often did not match the geometry of the existing element and is not aesthetically pleasing. In addition, the consolidation and the quality of the patch are of concern. When shotcrete is selected as the repair material, concrete is projected under velocity to the surface without the need for formwork. This operation requires special equipment and an experienced operator to ensure proper placement, which makes it a specialized and costly repair system. Moreover, field experience of shotcrete repairs indicates variable performance for this type of repair, such as the cracks in the finished repair product (Figure 1b). Finally, in both VDOT A3 concrete and shotcrete repair systems, bonding of the repair material to the existing concrete is another concern and requires proper surface preparation of the existing concrete through removal of deteriorated concrete—a roughened surface that is saturated surface dry during the placement.

Recently, a highly flowable and high-quality SCC was introduced that can be used in place of the A3 concrete and the shotcrete, avoiding the shortcomings of those materials. SCC has been used in Japan and Europe advantageously since the early 1990s (Okamura and Ouchi, 1999). VDOT has demonstrated the ability to leverage the benefits of SCC and has successfully used it in substructure repairs since 2010 (Ozyildirim and Sharp, 2017). It easily fills the congested spaces between the reinforcement and the formwork under its own mass, and without any additional consolidation energy. SCC generally has low water-cementitious materials ratios for stability, because at high water cement (w/cm) ratios, segregation is of concern in concretes with high flowability. Self-consolidation and low w/cm improve the quality of concrete by enhancing the strength and reducing the permeability, which can enhance the repair life by minimizing the intrusion of chlorides that initiate corrosion. Other advantages of SCC include smooth surfaces, which can eliminate additional labor to finish the surface of concrete elements, and a faster rate of concrete placement because consolidation, good bond, and improved safety with limited or no vibration is not needed. The high flow rate, low w/cm of SCC and no need for mechanical vibration enable the repair to match the geometry of the existing concrete and provide a high-quality repair material.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the feasibility of incorporating two large scale repair methods, hydrodemolition or impressed current cathodic protection, in substructure repairs of pier caps and columns. Where concrete was removed, low-permeability SCC was placed. The only exception was that where ribbon anodes for CP were placed, a lower resistivity SCC was placed to ensure current flow.

Repairs were performed on five bridges which included two bridges with conventional shotcrete repairs. All these bridges are over I-64 in the Richmond District of Virginia. Long-term performance of the repaired areas will be assessed in future surveys. In addition, two nearby structures using shotcrete repairs—the Route 621 Bridge and Route 622 Bridge—were monitored for comparison with the systems of this study that used SCC.

METHODOLOGY

The following repairs were conducted:

1. Remove deteriorated concrete and clean exposed steel by hydrodemolition. Then, put SCC in place. Hydrodemolition has been shown to remove poor-quality concrete effectively from a large area, on both horizontal and vertical surfaces, and SCC can be placed on narrow vertical-formed surfaces as well. However, in this study, concretes in

small areas were removed by hydrodemolition mainly because of restrictions on the amount of concrete removal and the typical decision making based on cracks, spalls, and delaminations. Areas exhibiting incipient distress were missed.

2. Remove concrete in delaminated areas by using chipping hammers (standard removal practice). Place SCC and install ICCP to extend the service life of a reinforced concrete element using a properly maintained rectifier with a remote monitoring unit (RMU).

3. Remove concrete in delaminated areas using chipping hammers. Place SCC and apply arc-spray zinc (ICCP) to the whole surface (patch and surrounding) of one pier and arc-spray aluminum indium zinc (GCP) to the whole surface of another pier. Monitor both systems using RMU.

4. In selected locations on the same structures where hydrodemolition and CP were not used because of access or convenience, repairs were performed using the conventional method. This method was accomplished by removing concrete in delaminated areas with chipping hammers and placing anodes in the inside perimeter of the patch (normal procedure). Then place SCC. This repair method is used as the control.

The concrete removal, the installation of anodes, the placement of the concretes, and the initial data transmission were monitored. Before starting the repairs, the condition of the substructure elements was determined using chloride testing, soundings for delaminations, half-cell potentials for corrosion activity, and visual surveys for cracks and spalled concretes. The VDOT *Manual of Structure and Bridge Division,* Part 2, Chapter 32—"Maintenance and Repair"—defines the chloride threshold as 2 lbs/yd^3, which is the chloride ion concentration where steel corrosion can begin to occur. The half-cell potential measurements were performed using a 16 x 16-inch grid pattern in accordance with ASTM C876-15.

This investigation used either low- or high-permeability concretes. High-permeability concretes were developed and tested in the laboratory. However, the contractor chose to use prepackaged material for convenience. VDOT routinely uses hydrodemolition of bridge decks for overlay placements. However, it is the first application of hydrodemolition for vertical surfaces. The equipment, the application of hydrodemolition, and the installations of different protective systems are explained in this section along with the laboratory and field concretes.

This application was also VDOT's first using GCP and ICCP with remote monitoring. To monitor the performance of the CP systems, VDOT installed a cellular data transmission system powered by solar energy panels, enabling transmission of CP data to several distant locations. With the CP options, the project provided guidance on the personnel qualifications required for the VDOT or outside technical support. Installation was monitored and initial data were collected both before and during construction for future assessment of the performance.

RESULTS AND DISCUSSION

This section discusses laboratory concretes and explains observations of field installation. The condition assessment prior to starting the field repairs is also provided.

Laboratory Concretes with High Permeability

Before the contractor selected a mixed design, two batches of SCC were prepared in the laboratory to achieve high permeability suitable for the anode locations (Table 1). This method showed that high-permeability concretes that meet the other VDOT requirements could be produced. To ensure high permeability, a supplementary cementitious material was not included. VDOT concretes use supplementary cementitious materials for low permeability and improved chemical resistance. Coarse aggregate was a siliceous crushed rock and the fine aggregate siliceous natural sand. The nominal maximum size of the coarse aggregate was 3/8-inch for the thin repair thickness.

Table 1. Mixture Proportions for the High-Permeability Self-Consolidating Concrete in lb/yd^3

Material	B1	B2
Type I/II Cement	658	682
Water	322	286
Coarse Aggregate (#8)	1416	1454
Fine Aggregate	1416	1454
Water Cement	0.49	0.42

The fresh and hardened concrete properties including the resistivity measurements are summarized in Table 2. In the fresh state, concretes were tested for slump flow, flow rate and stability (ASTM C 1611), and air content (ASTM C 173). The compressive strength was determined in accordance with ASTM C39 using 4 x 8-inch specimens and the permeability (ASTM C1202) was determined with 4 x 2-inch specimens. Resistivity measurements were made following the procedures described in American Association of State Highway and Transportation Officials (AASHTO) T 358-17. The resistivity values were less than the 15 kohm-cm recommended for the anode locations. However, the incredibly low resistivities obtained in the first 2 months increased to levels close to the limiting recommended value within 2 years. When anodes are used, low resistivities less than 15 kohm-cm are sought to ensure the current flow to protect the reinforcement. The low-permeability concretes exhibit high resistivity, which resists the transport of fluids and the current flow.

Table 2. Fresh and Hardened Concrete Properties of High-Permeability Self-Consolidating Concrete

Property	B1	B2
Slump Flow (in.)	23	26
Air Content (%)	6.5	6.0
28-Day Compressive Strength (psi)	3280	3490
28-Day Resistivity (KΩ cm)	2.94	3.41
56-Day Resistivity (KΩ cm)	3.41	4.00
2-Year Resistivity (KΩ cm)	14.64	12.89

Field Concretes

In the field applications, the contractor chose to use prepackaged materials for convenience and uniformity. The manufacturer of the contractor's prepackaged material indicated a resistivity value of 8.2 kohm-cm at 28 days, based on AASHTO T 358-17. This value is slightly higher than what was observed with the laboratory mixtures. However, it is less than the 15 kohm-cm value discussed previously. For areas that use CP or anodes, a high-permeability prepackaged material was used to allow the current flow that is generated by the CP system. In areas that do not use CP or anodes, a low-permeability material (a regular prepackaged SCC) was placed to resist current flow to slow the corrosion activity.

The 28-day compressive strengths of prepackaged SCC material samples used in areas with and without anodes during placement, and the concretes from the test panels for the shotcrete applications, are shown in Table 3. All strength values were high for the application that required a minimum compressive strength of 3,000 psi at 28 days. The high-permeability SCC had lower strengths than the low-permeability SCC, and the shotcrete exhibited the lowest and highest compressive strength, ranging from 6,100 to 8,300 psi, thus indicating the high variability of this product. Shotcrete quality is dependent on the ability of the operator.
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Table 3. Compressive Strengths at 28 Days

Location	Compressive Strength (psi)
SCC (#1)	7,030
SCC (#2)	7,640
SCC with Anode (#1)	6,420
SCC with Anode (#2)	6,540
Shotcrete Test Panel (#1)	7,500
Shotcrete Test Panel (#2)	8,300
Shotcrete Test Panel (#3)	6,100

SCC = self-consolidating concrete.

Field Investigations

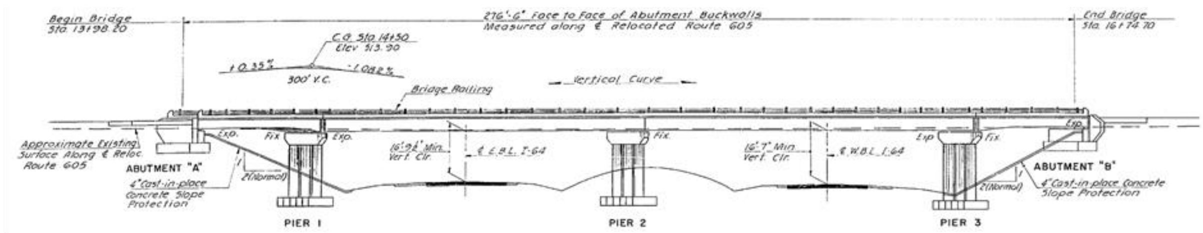
In September 2020, VDOT advertised a contract for the repair of five structures along the I-64 corridor in the Richmond District. The repaired substructures all supported bridges that cross I-64, as provided in Table 4. The Route 621 Bridge was designated to be the control structure because it received conventional repair.

Table 4. Bridges Selected and Repair Types

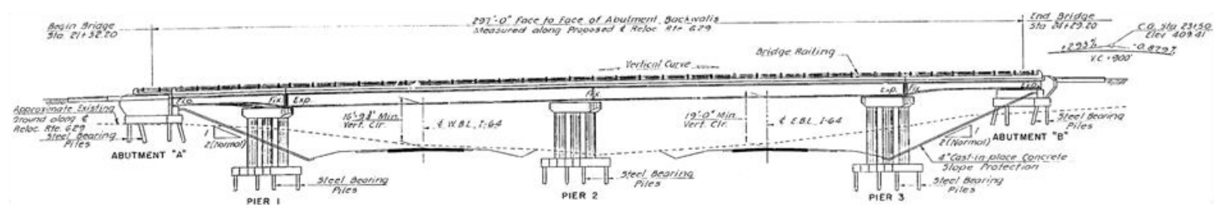
Route	County	VA St. No	Federal St. ID	Year Built	Condition Assessment, Yes/No	Research-Related Repair Used
605	Goochland	6098	8608	1968	Yes, Prior to Remediation Work	Hydrodemolition
629	Goochland	6100	8644	1969	Yes, Prior to Remediation Work	ICCP with RMU
522	Goochland	1026	11450	1968	Yes, During Remediation Work	ICCP and GCP with RMU
621	Goochland	6084	8633	1967	Yes, After Remediation Work	Conventional Shotcrete Repair
622	Goochland	6085	8635	1967	No	Conventional Shotcrete Repair

GCP = galvanic cathodic protection; ICCP = impressed current cathodic protection; RMU = remote monitoring unit.

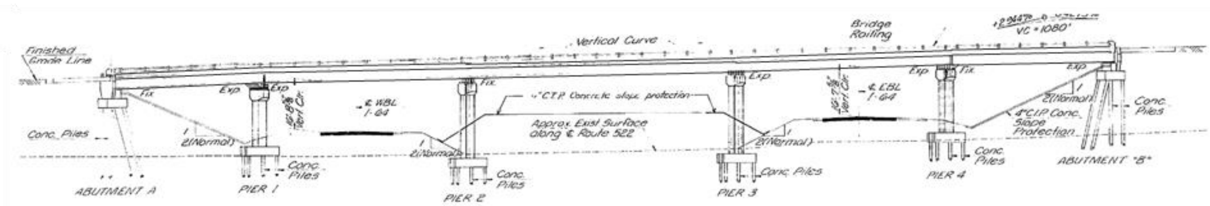
The bridge elements selected for testing were all adjacent to the travel lane of the east or westbound lanes of I-64. They were selected because of the high salt exposure due to salt spray from vehicles and leaking joints allowing salt water to reach the pier caps and columns. Figure 2 shows the five bridges.



Route 605



Route 629



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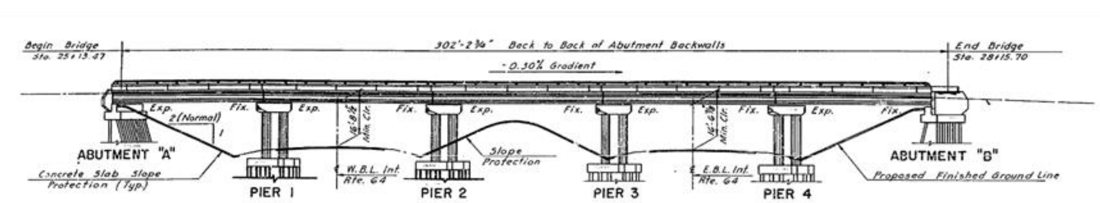
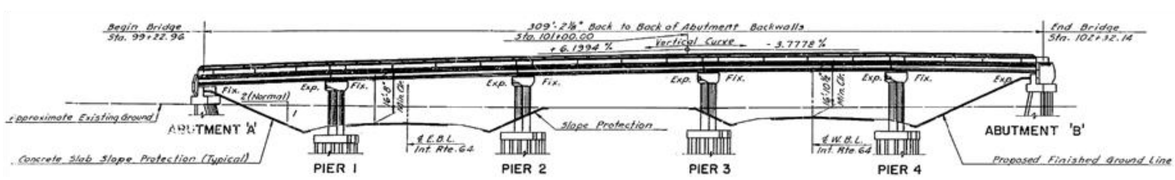


Route 621



Route 622

Figure 2. Elevation Views of the Five Structures Repaired along the I-64 Corridor in the Richmond District

As repair work began, the condition of most of the structures were evaluated, which is also indicated in Table 4. Unfortunately, some of the condition assessment work trailed the demolition and remediation work, so concrete removal and installation of formwork made it impossible to assess parts of the structure. The results of this work are provided in the following sections.

Condition Assessment of the Route 605 Bridge

The visual survey of the Route 605 Bridge was conducted on Piers 1 and 3 prior to demolition and remediation work. Corrosion of the reinforcing steel was present in the caps and columns on Piers 1 and 3. Corrosion of the reinforcement resulted in staining, concrete spalling, and steel section loss, with typical examples shown in Figures 3 and 4.

Figure 3. Corrosion on Pier 1 of the Route 605 Bridge

Figure 4. Corrosion on Pier 3 of the Route 605 Bridge, as Indicated by the Red Arrows

The chloride ion testing showed several elevated chloride concentrations in these structures, which is consistent with the visual observations. For the Route 605 Bridge, Piers 1 and 3, the percentage of samples equal to or greater than 2 lbs/yd^3 is 100% at a 1-inch depth, 90% at a 2-inch depth, and 40% at a 4-inch depth. These values demonstrate the importance of concrete cover. If the formwork placement reduces the cover over the steel, these values demonstrate how the steel would be subjected to higher chloride concentrations because cover is reduced, which is also true for samples found in both the repair and non-repair areas (Table 5).

Table 5. Chloride Concentration in Concrete Elements for Piers 1 and 3 of the Route 605 Bridge

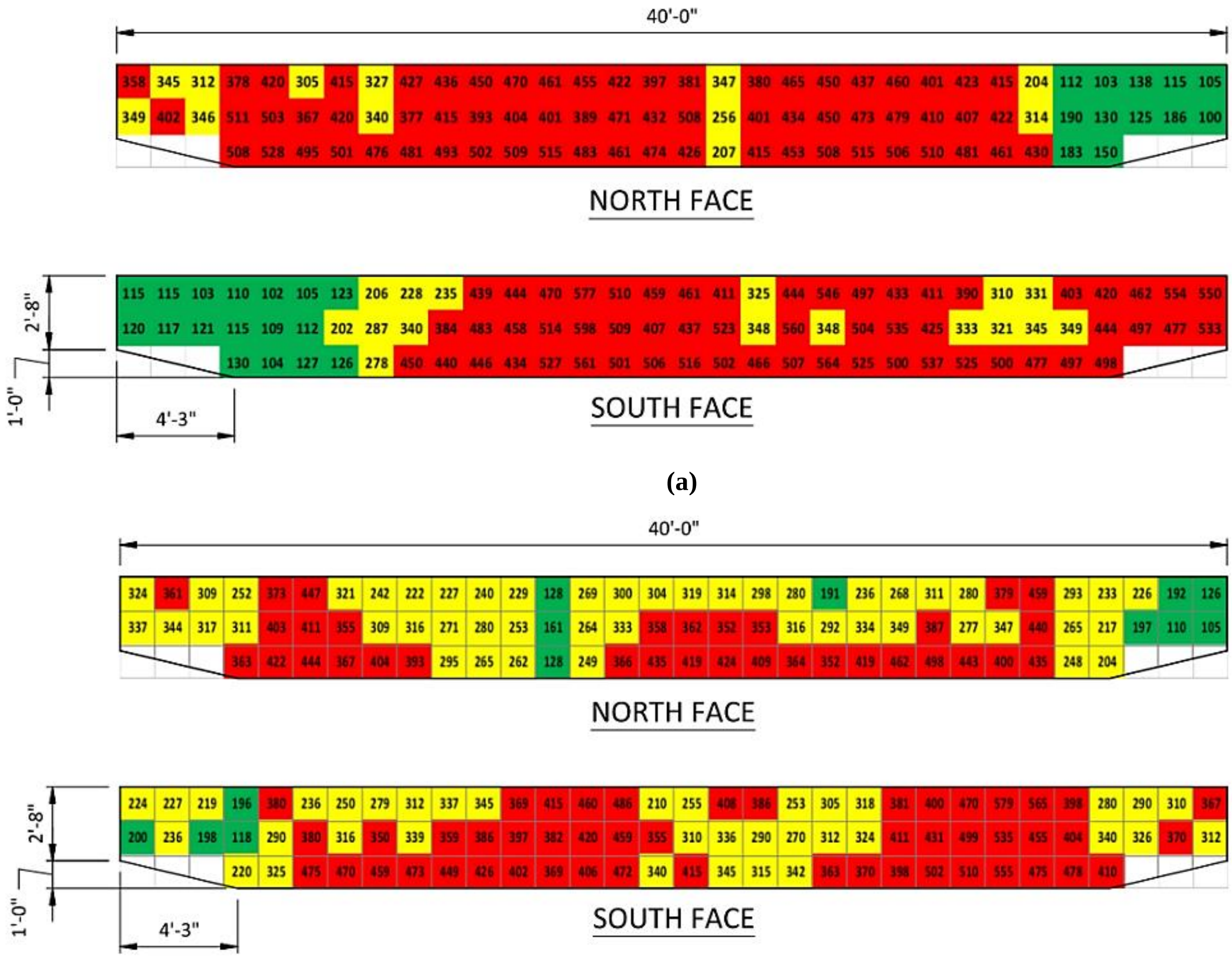
Pier No.	Support Member	Concrete Condition	Core No.	Sample Depth, in.	Chlorides, lbs. per yd^3	% Weight of Cement
1	Column	Repair	1	1	4.0	0.61
				2	2.9	0.45
				4	2.6	0.40
1	Column	No repair	2	1	3.1	0.47
				2	3.0	0.46
				4	0.3	0.04
1	Cap	Repair	3	1	13.4	2.0
				2	5.7	0.86
				4	1.8	0.28
1	Cap	No repair	4	1	5.4	0.82
				2	3.5	0.53
				4	3.4	0.52
3	Column	Repair	1	1	5.8	0.88
				2	4.1	0.63
				4	3.7	0.57
3	Column	No repair	2	1	3.8	0.57
				2	1.9	0.29
				4	0.9	0.09
3	Column	Repair	4	1	6.7	1.01
				2	6.0	0.91
				4	3.1	0.47
3	Column	No repair	3	1	4.3	0.65
				2	4.1	0.62
				4	1.4	0.21
3	Cap	Repair	5	1	16.9	2.60
				2	14.5	2.20
				4	12.5	1.90
3	Cap	No repair	6	1	5.2	0.79
				2	2.1	0.31
				4	1.5	0.23

Half-cell potential testing was performed on caps and columns of Piers 1 and 3 (Figures 5 and 6). The half-cell measurements indicated that corrosion is occurring in a sizable portion of the structure as shown in Table 6 and observed in Figures 5 and 6. A half-cell range more positive than –0.20 V versus the copper sulfate electrode (CSE) indicates a low probability of corrosion activity and is shown in green; between –0.20 to –0.35 V versus CSE indicates that corrosion activity is uncertain and is shown in yellow; more negative than –0.35 V versus CSE indicates a high probability of corrosion activity occurring and is shown in red. The chloride and half-cell measurements also indicate that little exterior concrete is worth saving based on the measurements made because a high percentage of the half-cell measurements indicate a high probability of corrosion.

Table 6. Distribution of the Half-Cell Reading in Piers 1 and 3 of the Route 605 Bridge

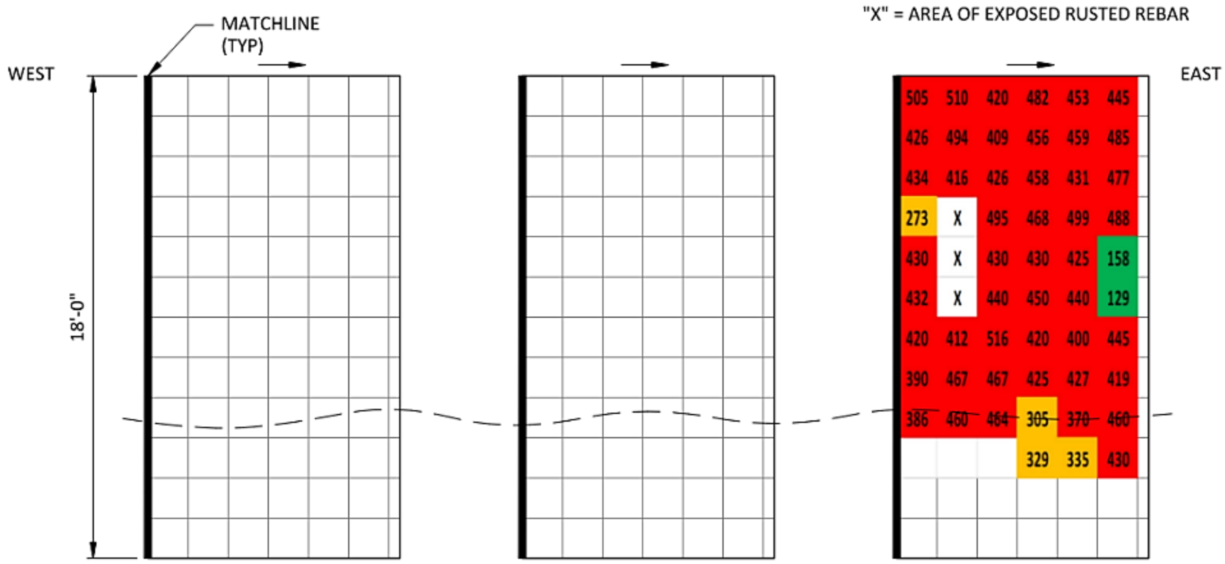
Half-Cell Range	Percent of Total for Columns, %	Percent of Total for Caps%
More Positive than –0.20 V CSE	9	11
–0.20 to –0.35 V CSE	19	32
More Negative than –0.35 V CSE	72	57

CSE = copper sulfate electrode.

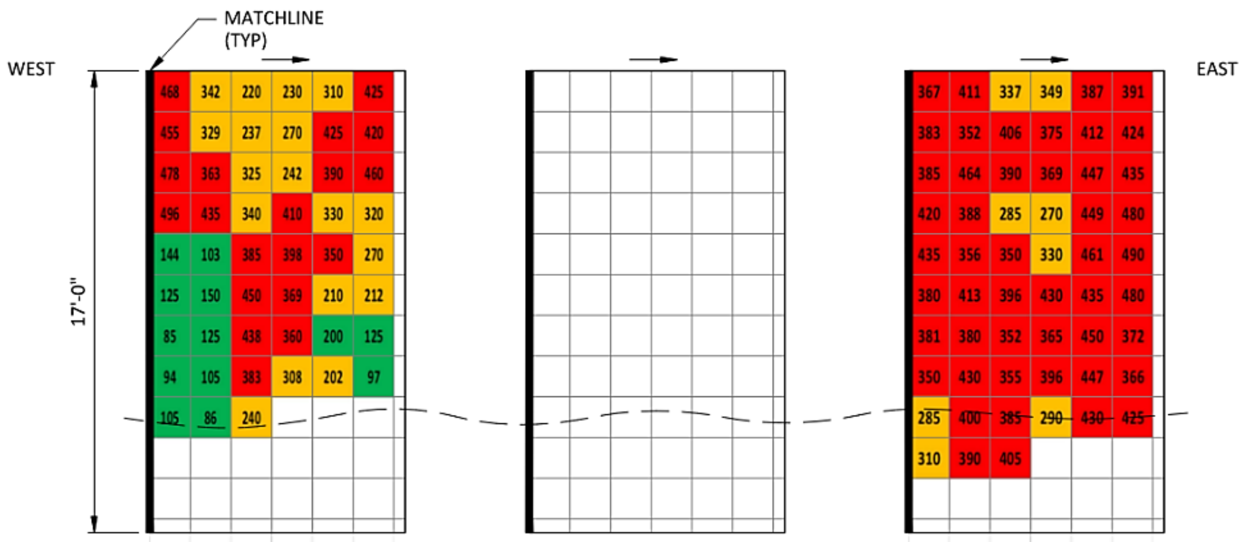


(b)

Figure 5. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a High Probability of Corrosion on the (a) Pier 1 and (b) Pier 3 Caps of the Route 605 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 605, 2021).



(a)



(b)

Figure 6. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a High Probability of Corrosion on the (a) Pier 1 and (b) Pier 3 Columns of the Route 605 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value. Dashed line indicates approximate ground-level location (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 605, 2021).

Condition Assessment of the Route 629 Bridge

The visual survey of the Route 629 Bridge was conducted on Piers 1 and 3 prior to demolition and remediation work. Corrosion of the reinforcing steel was present in the Pier 1 and Pier 3 caps and columns. Corrosion of the reinforcement resulted in staining, concrete spalling, and steel section loss, with typical examples shown in Figures 7 and 8.

(a) **(b)**

Figure 7. (a) Arrow Pointing to the Corroded Reinforcement on Pier 1 of the Route 629 Bridge; (b) Arrow Pointing to the Cracked and Delaminated Area

Figure 8. Corrosion on Pier 3 of the Route 629 Bridge, as Indicated by the Red Arrows

The chloride ion testing showed several elevated chloride concentrations in these structures, which is consistent with the visual observations. For the Route 629 Bridge, Piers 1 and 3, the percentage of samples equal to or greater than 2 lbs/yd^3 is 100% at a 1-inch depth, 43% at a 2-inch depth, and 29% at a 4-inch depth. Like the Route 605 Bridge, if the formwork placement reduces the concrete cover over the steel, the steel is then subjected to higher chloride concentrations, which is true for samples found in both the repair and non-repair areas (Table 7).

Table 7. Chloride Concentration in Concrete Elements for Piers 1 and 3 of the Route 629 Bridge

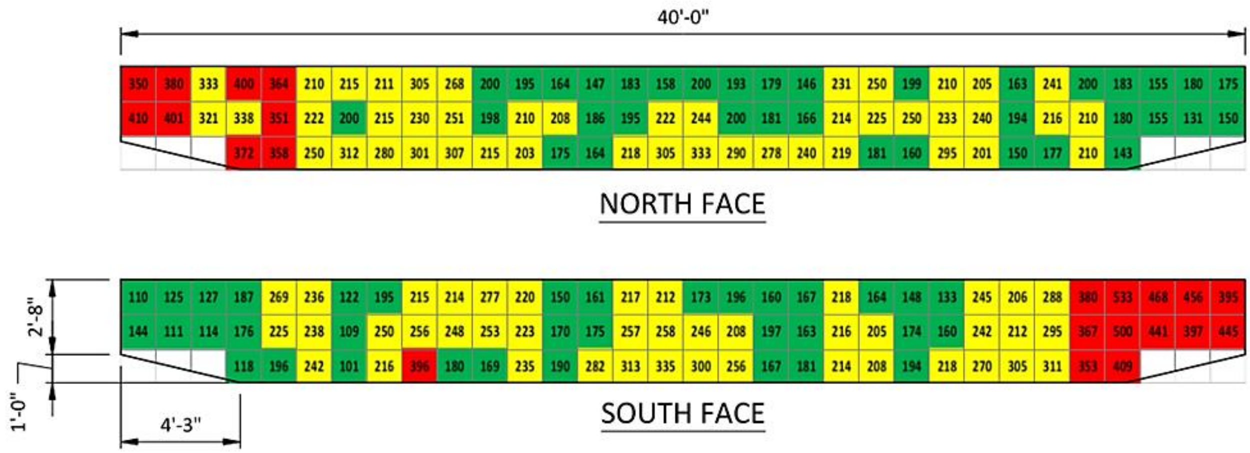
Pier No.	Support Member	Concrete Condition	Core No.	Sample Depth, in.	Chlorides, lbs. per yd^3	% Weight of Cement
1	Column	Repair	4	1	4.7	0.71
				2	2.9	0.44
				4	2.2	0.34
1	Column	No repair	3	1	5.5	0.83
				2	1.8	0.28
				4	0.1	0.01
1	Cap	Repair	1	1	20.1	3.10
				2	7.0	1.07
				4	4.6	0.69
1	Cap	No repair	2	1	1.4	0.21
				2	0.7	0.11
				4	0.1	0.01
3	Column	Repair	2	1	12.9	2.0
				2	2.6	0.4
				4	1.1	0.17
3	Column	No repair	1	1	2.9	0.44
				2	2.6	0.40
				4	2.1	0.32
3	Cap	Repair	3	1	3.8	0.58
				2	2.3	0.34
				4	1.9	0.28
3	Cap	No repair	4	1	3.5	0.54
				2	1.7	0.26
				4	0.9	0.14

Half-cell potential testing was performed on caps and columns of Piers 1 and 3 (Figures 9 and 10). The areas selected for measurements were those areas that were scheduled for the most repair. The half-cell measurements indicated that corrosion is either uncertain or occurring in a substantial portion of the structure as shown in Table 8 and Figures 9 and 10. Comparing Tables 8 and 6, the repair areas of the Route 605 Bridge have a higher probability of corrosion compared with the Route 629 Bridge.

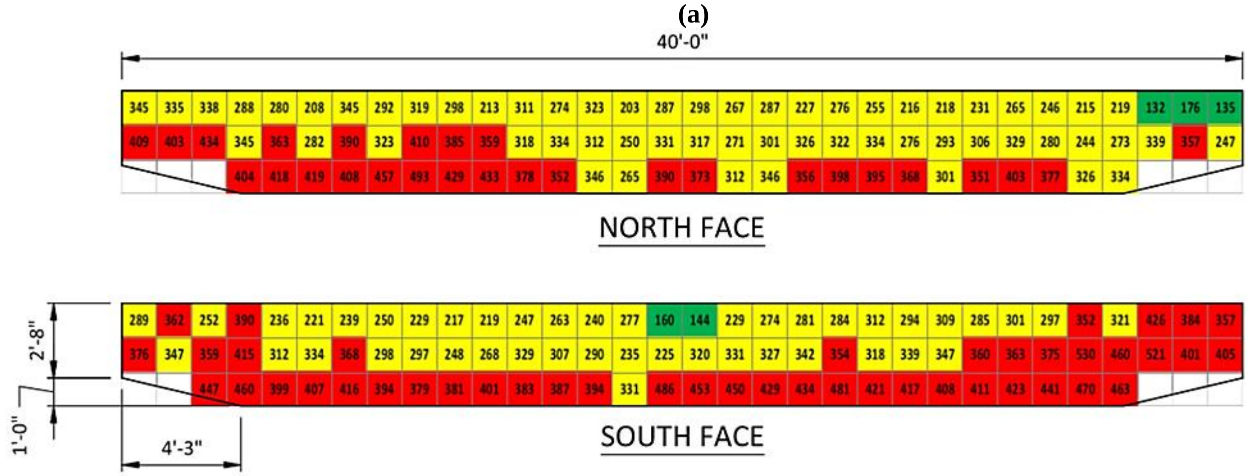
Table 8. Distribution of the Half-Cell Reading in Piers 1 and 3 of the Route 629 Bridge

Half-Cell Range	Percent of Total for Columns, %	Percent of Total for Caps, %
More Positive than –0.20 V CSE	18	21
–0.20 to –0.35 V CSE	65	53
More Negative than –0.35 V CSE	17	26

CSE = copper sulfate electrode.

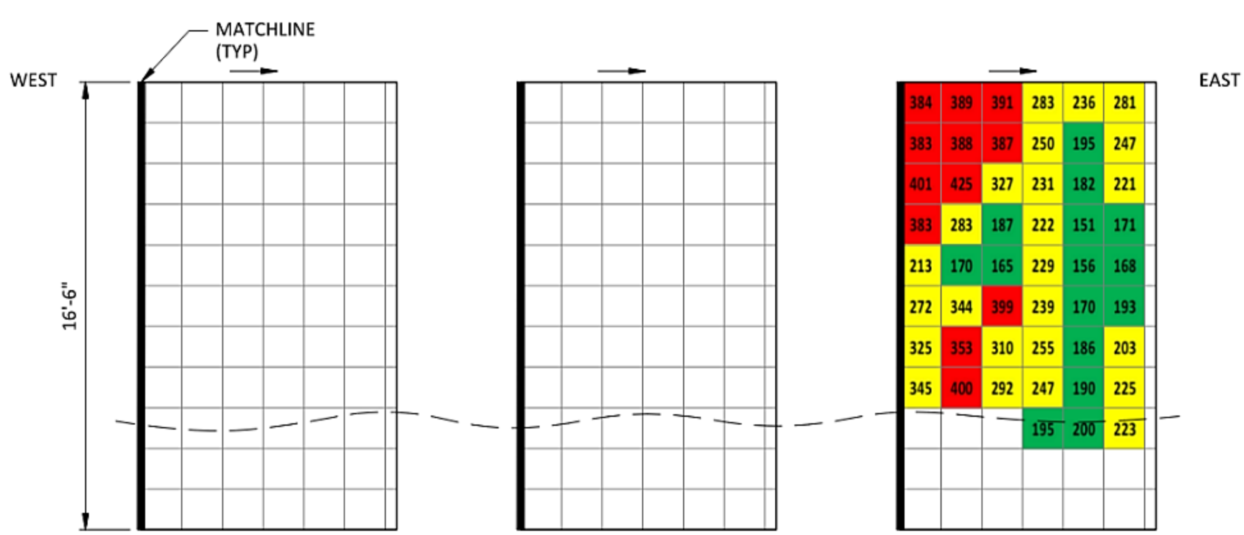


(a)

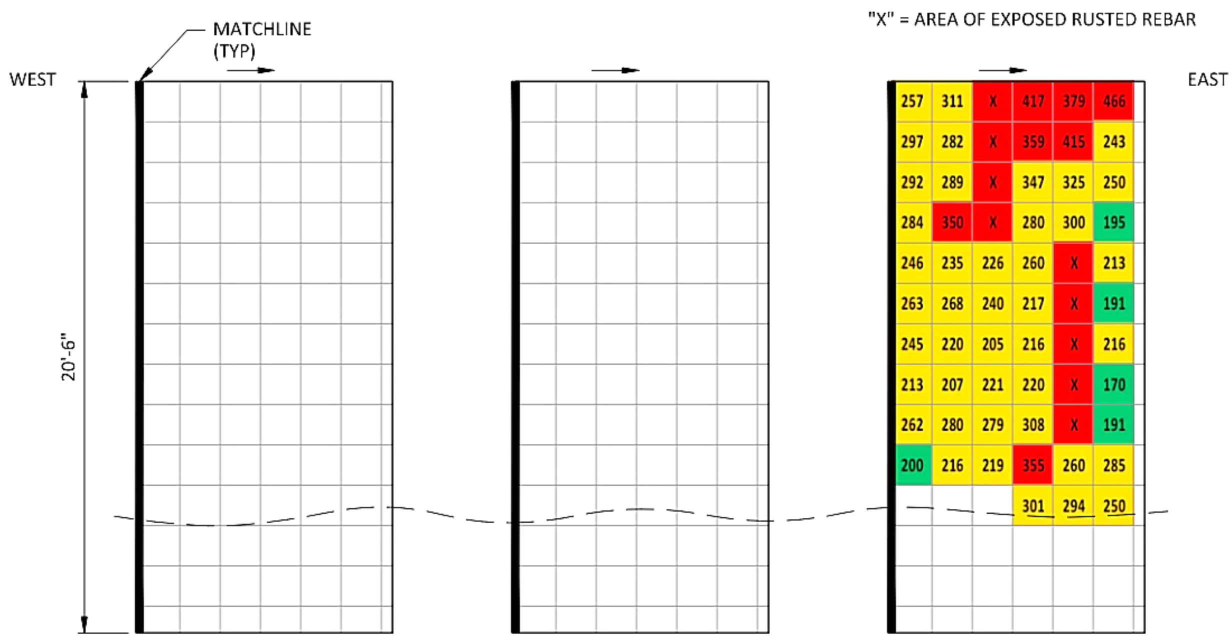


(b)

Figure 9. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show the Probability of Corrosion on the (a) Pier 1 and (b) Pier 3 Caps of the Route 629 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 629, 2021).



(a)



(b)

Figure 10. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show the Probability of Corrosion on the (a) Pier 1 and (b) Pier 3 Columns of the Route 629 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value. Dashed line indicates approximate ground level location (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 629, 2021).

Condition Assessment of the Route 522 Bridge

The visual survey of the Route 522 Bridge was conducted on Piers 1 and 4. Prior to starting the condition assessment, it was clear that the contractor had completed the remediation work on Pier 1, and Pier 4 was undergoing remediation. Corrosion of the reinforcing steel was present in the Pier 1 and Pier 4 caps and columns. Corrosion of the reinforcement resulted in staining, concrete spalling, and steel section loss, with typical examples in Figures 11 and 12.

(a) (b)

Figure 11. (a) Remediation of Pier 1 of the Route 522 Bridge; (b) Magnified View with Red Arrow Showing the Crack in an Unrepaired Area

Figure 12. Corrosion Related Damage on Pier 4 of the Route 522 Bridge, as Indicated by the Red Arrows. The picture on the left shows where concrete was removed for the contactor to make repairs.

The chloride ion testing showed several elevated chloride concentrations in these structures, which is consistent with the visual observations. For the Route 522 Bridge, Piers 1 and 3, the percentage of samples equal to or greater than 2 lbs/yd^3 is 100% at a 1-inch depth, 100% at a 2-inch depth, and 38% at a 4-inch depth. Like the other bridges, if the original formwork placement reduces the concrete cover over the steel, the steel is then subjected to higher chloride concentrations than might be expected, which is true for samples found in both the repair and non-repair areas (Table 9).

Table 9. Chloride Concentration in Concrete Elements for Piers 1 and 4 of the Route 522 Bridge

Pier No.	Support Member	Concrete Condition	Core No.	Sample Depth, in.	Chlorides, lbs. per yd^3	% Weight of Cement
1	Column	No repair	1	1	6.6	1.00
				2	6.4	1.00
				4	0.1	0.01
1	Column	No repair	2	1	7.0	1.06
				2	3.9	0.6
				4	0.3	0.04
1	Cap	No repair	3	1	9.6	1.46
				2	6.9	1.05
				4	7.0	1.07
1	Cap	No repair	4	1	4.1	0.62
				2	2.5	0.38
				4	1.9	0.30
4	Column	Repair	1	1	10.8	1.65
				2	4.8	0.73
				4	0.8	0.12
4	Column	No repair	2	1	10.8	1.64
				2	2.9	0.40
				4	1.2	0.18
4	Cap	Repair	4	1	17.3	2.62
				2	8.7	1.33
				4	2.2	0.33
4	Cap	No repair	3	1	7.0	1.07

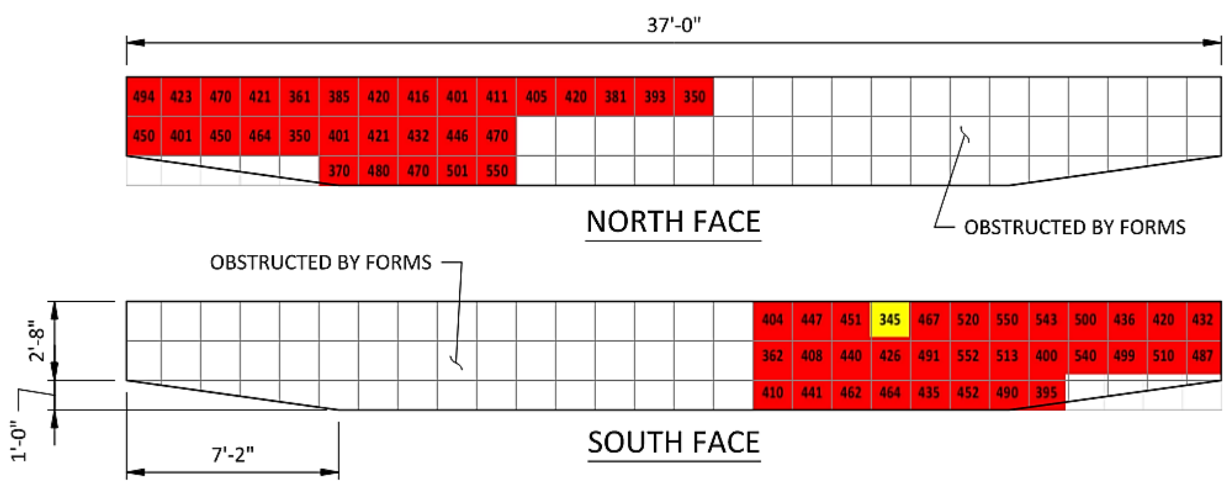
Pier No.	Support Member	Concrete Condition	Core No.	Sample Depth, in.	Chlorides, lbs. per yd^3	% Weight of Cement
				2	5.2	0.79
				4	2.3	0.30

Half-cell potential testing was performed on caps and columns of Piers 1 and 4 (Figures 13 and 14). The areas selected for measurements were those areas that were scheduled for the most repair. The half-cell measurements indicated that corrosion is either uncertain or occurring in a sizable portion of the structure as Table 10 and Figures 13 and 14 show. Comparing Table 10 with Tables 6 or 8, the repair areas of the Route 522 Bridge have a higher probability of corrosion compared with the Route 629 Bridge, but it is more like the Route 605 Bridge. However, as mentioned previously, the contractor completed the remediation work on Pier 1 and Pier 4 was undergoing remediation at the time of the condition assessment of the Route 522 Bridge.

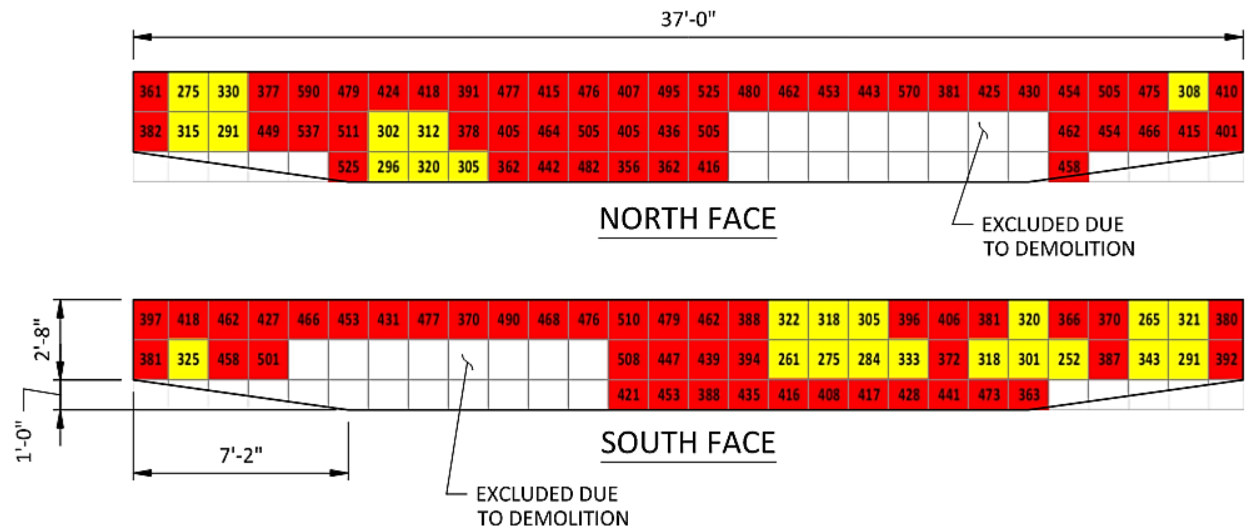
Table 10. Distribution of the Half-Cell Reading in Piers 1 and 4 of the Route 522 Bridge

Half-Cell Range	Percent of Total for Columns, %	Percent of Total for Caps, %
More Positive than –0.20 V CSE	14	0
–0.20 to –0.35 V CSE	36	15
More Negative than –0.35 V CSE	50	85

CSE = copper sulfate electrode.

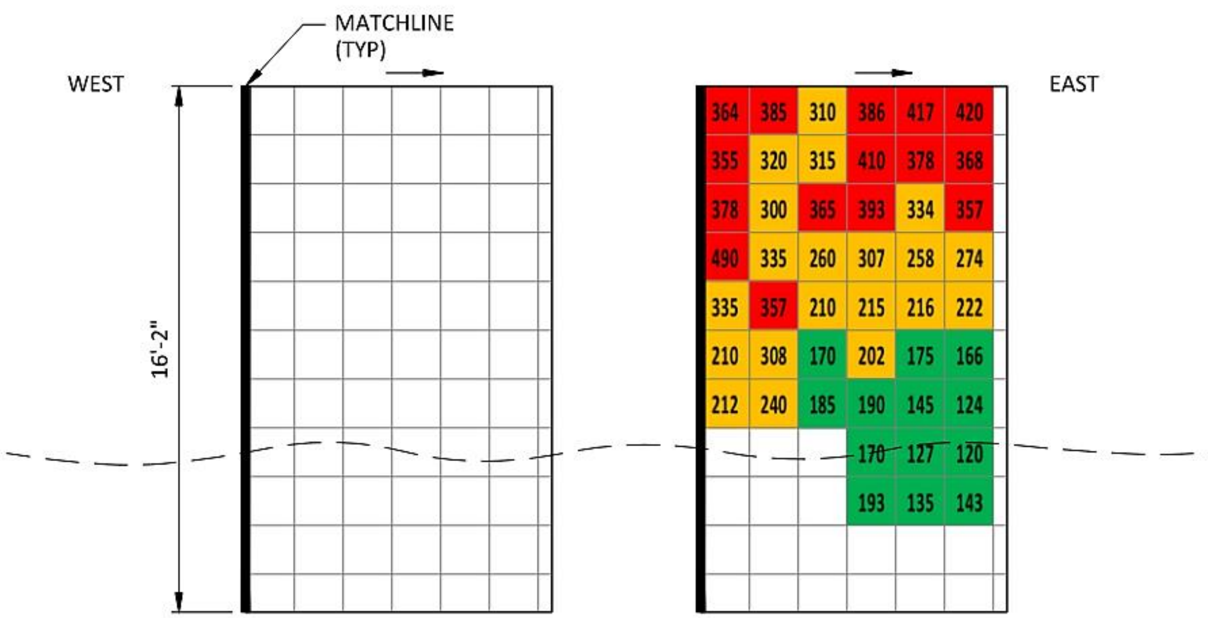


(a)

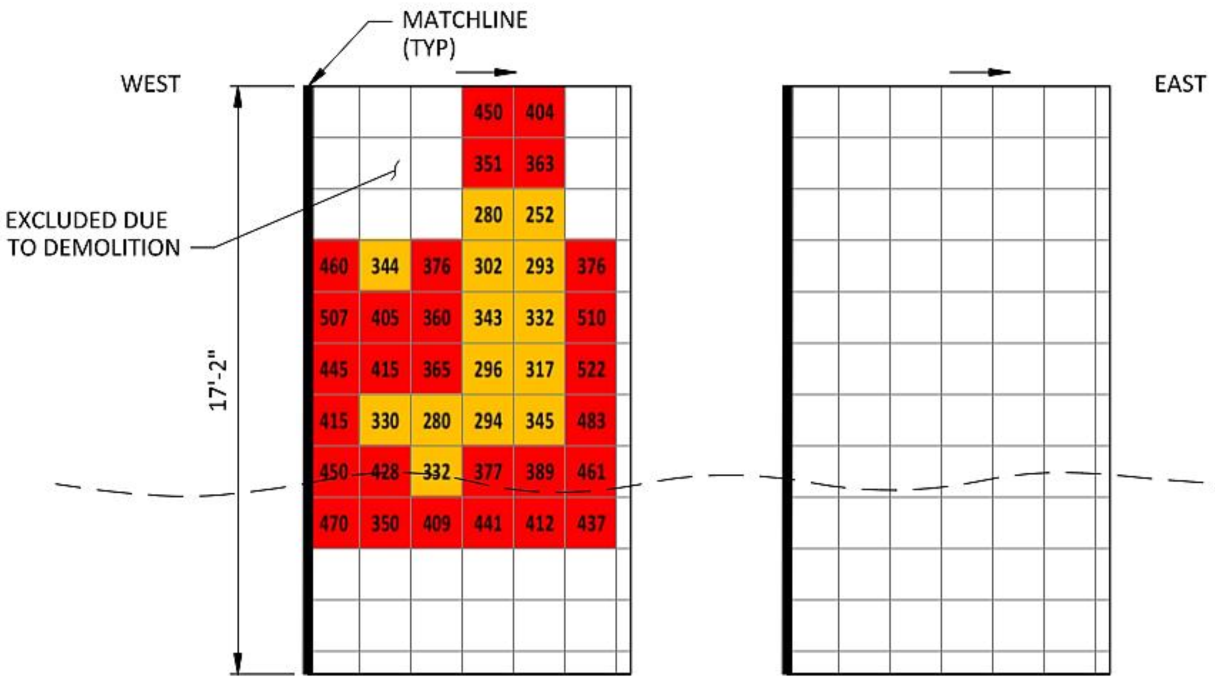


(b)

Figure 13. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a Probability of Corrosion on the (a) Pier 1 and (b) Pier 4 Caps of the Route 522 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 522, 2021).



(a)



(b)

Figure 14. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a Probability of Corrosion on the (a) Pier 1 and (b) Pier 4 Columns of the Route 522 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value. The dashed line indicates approximate ground level location (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 522, 2021).

Condition Assessment of the Route 621 Bridge

The visual survey of the Route 621 Bridge was conducted on Piers 1 and 4. Prior to starting the condition assessment, it was clear that the contractor had completed the remediation work on both Pier 1 and Pier 4. Typical examples of the condition of the structure are shown in Figures 15 and 16.

Figure 15. Condition after Remediation of Pier 1 of the Route 621 Bridge before Applying Epoxy Coating

Figure 16. Condition after Remediation of Pier 4 of the Route 621 Bridge before Applying Epoxy Coating

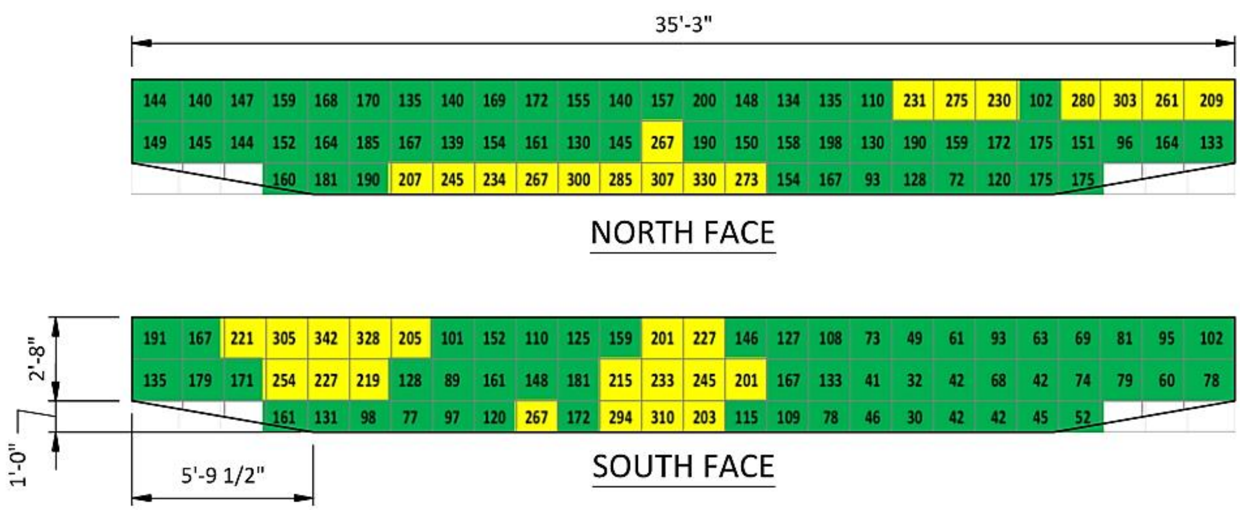
The chloride ion testing was performed on samples extracted from unrepaired areas. For the Route 621 Bridge, Piers 1 and 4, the percentage of samples equal to or greater than 2 lbs/yd^3 is 13% at a 1-inch depth, 13% at a 2-inch depth, and 0% at a 4-inch depth.

Half-cell potential testing was performed on caps and columns of Piers 1 and 4 (Figures 17 and 18). The areas selected for measurements were those areas that were scheduled for the most repair. The half-cell measurements indicated that corrosion is either uncertain or occurring in a small but localized area of the structure as shown in Table 11 and Figure 17.

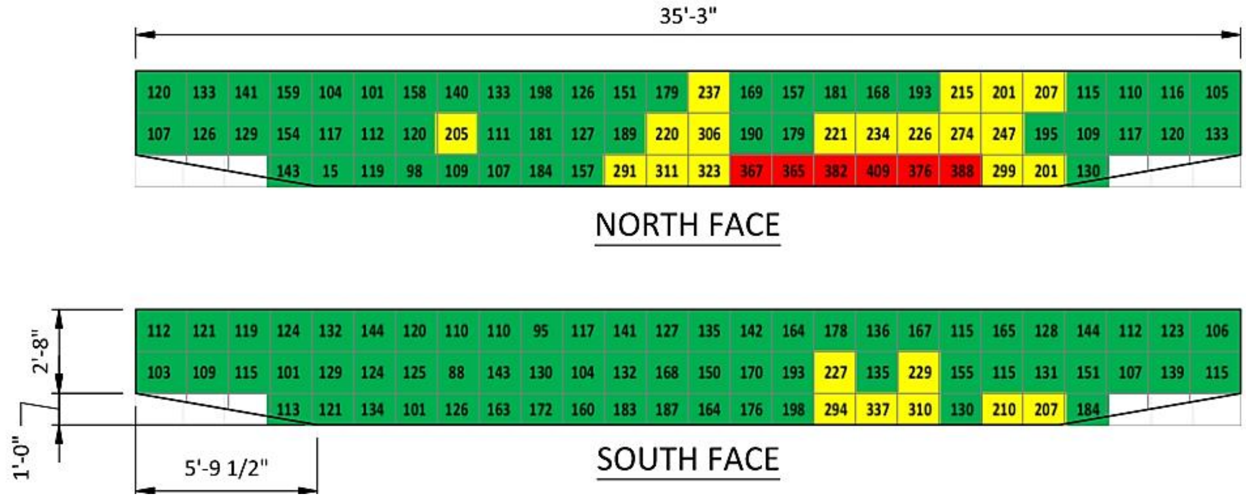
Table 11. Distribution of the Half-Cell Reading in Piers 1 and 4 of the Route 621 Bridge

Half-Cell Range	Percent of Total for Columns, %	Percent of Total for Caps, %
More Positive than –0.20 V CSE	100	77
–0.20 to –0.35 V CSE	0	21
More Negative than –0.35 V CSE	0	2

CSE = copper sulfate electrode.

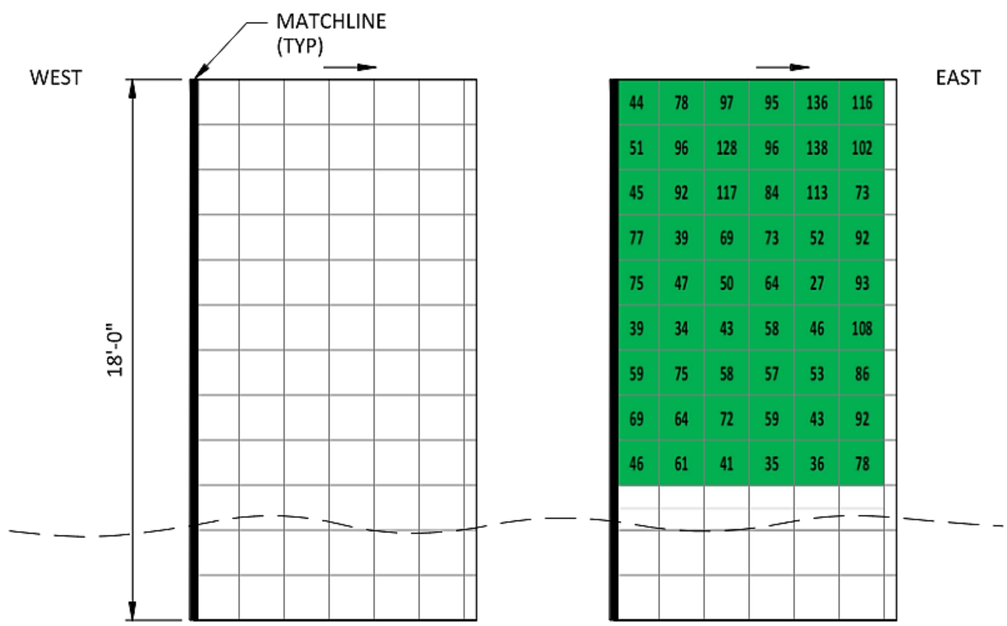


(a)

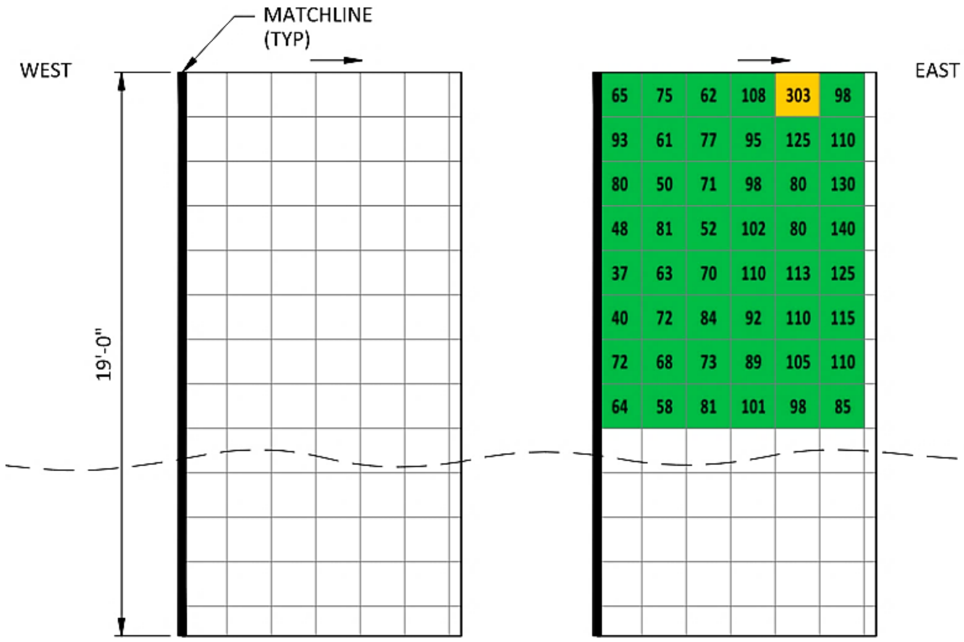


(b)

Figure 17. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a Probability of Corrosion on the (a) Pier 1 and (b) Pier 4 Caps of the Route 621 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 621, 2021).



(a)



(b)

Figure 18. Half-Cell Measurements Using a 16-x-16-Inch Grid Pattern Show a Probability of Corrosion on the (a) Pier 1 and (b) Pier 4 Columns of the Route 621 Bridge. Numbers in each square are the magnitude of the half-cell measurement but are reported as positive values instead of the measured negative value. The dashed line indicates approximate ground level location (VDOT Contracted I-64 Bridge Substructure Studies Project, Route 621, 2021).

Route 605 Bridge Chipping Hammer or Hydrodemolition Removal of Concrete and Repair

Deteriorated concrete was removed by the standard method using chipping hammers or by hydrodemolition meeting the removal requirements of VDOT.

Prior to beginning the work, hydrodemolition equipment arrived on site and was calibrated (Figure 19). Hydrodemolition was performed on Route 605 structure Pier 1, span B (Figure 20), and Pier 3, span C. The water jet nozzle was lifted using a specially fabricated frame so that it was kept tight to the vertical concrete surface (Figure 21). Hydrodemolition was effective in removal of concrete in large flat areas. However, it was limited by how much concrete could be removed and the presence of deteriorated concrete in isolated areas. Concrete was removed at different depths because of the variability in the quality. With the available equipment, it was difficult to reach behind the reinforcement and the tight areas such as the underside of the cap, requiring additional chipping after hydrodemolition, as Figures 19–21 explain in more detail.

Figure 19. Hydrodemolition Equipment is Parked on top of the Closed Bridge. Photo shows hydrodemolition truck and two tank trailers, one for fresh water and the other one for wastewater from the hydrodemolition.

Figure 20. Pier 1 Cap Where Hydrodemolition Will Be Performed

Figure 21. Frame for Supporting Hydrodemolition Equipment

During hydrodemolition, three variables control the penetration depth: (1) pressure, (2) rate of travel, and (3) number of passes over a given area. The head in the frame moves vertically and then horizontally. For this work, pressure was kept constant at 34,000 psi, and rate of travel and number of passes were changed to control the depth of penetration. Initially, 7 inches were removed (3.5 inches from behind rebar) when the rate of travel was 20 ft/min with 2 passes, each pass was a vertical movement up and down. The time to perform this operation was approximately 1 minute. The number of passes and the rate of travel was calibrated to remove 1 inch behind the reinforcing bar. The concretes showed high variability necessitating trials in a 12 square-foot area to ensure 1 inch behind the bar is removed. The debris generated was captured and the water was separated from the solid waste (Figure 22). The wastewater was pumped into storage tanks (Figure 19) and the solid waste was discarded.

Figure 22. Debris Generated after Using Hydrodemolition to Remove Concrete Is Captured. The wash water was pumped to the truck and the solid pieces discarded.

It was also difficult to get a smooth vertical cut at the edges of the Route 605 Bridge over I-64 (column along westbound lane shown in Figure 23). The water jet of the hydrodemolition unit provided direct water pressure, which left concrete behind the reinforcement and required manual removal. The high water pressure and the heterogeneous nature of concrete did prevented a sharp edge, leaving feather edges instead. The edge was saw cut about 3/4-inch to eliminate feather edging. The concrete along the perimeter was removed with hammers after the saw cut. In subsequent projects, improvements to vertical edge were achieved by placing straps around the perimeter (Figure 23). It is also possible that with new equipment and the lance, the operator can have smooth vertical faces to avoid feather edging without the straps. After completing hydrodemolition, the area must be pressure washed to remove the remaining cement slurry (Figure 24).

(a) (b) (c)

Figure 23. Comparison of the I-64 Hydrodemolition and a Later Repair. Photo (a) shows how equipment used on I-64 project did not provide a sharp edge (red arrow), and it was not able to remove concrete behind the reinforcing steel (blue arrow). More recent repair work in the Salem District (b) used straps along edges of the patch to help define a clean edge, and (c) the use of a lance allows for removal of concrete from behind the reinforcement because the lance can be tilted.

Figure 24. Rout 605 Bridge over I-64 (Pier Cap along Eastbound Lane). Concrete removed from the end of a pier cap using hydrodemolition. The area must be pressure washed to remove the cement slurry left after hydrodemolition.

Low-permeability SCC concrete was placed in formwork (Figure 25). The soundness of these repairs was determined by tapping them with a hammer. Most SCC repairs had smooth surfaces; however, some blemishes were noticeable (Figure 26). The contractor ground the surface blemishes so the repair was aesthetically pleasing.

Figure 25. Route 605 Bridge over I-64 (Columns and Pier Cap along Westbound Lane). After the removal of forms, the area was tapped with hammer to determine if the repairs were sound.

Figure 26. Route 605 Bridge over I-64 (Column and Pier Cap along Westbound Lane). Although most of the self-consolidating concrete had a smooth surface, some small surface blemishes were evident.

Installation of the Route 629 Solar ICCP System

On the Route 629 Bridge, a solar-powered ICCP system was installed to provide corrosion mitigation current to the reinforced structure (Figure 27). The embedded mixed metal oxide titanium ribbon anodes, which are titanium strips covered with a mixed metal oxide coating, are placed in a manner that ensures that current is distributed across the element.


(a)
(b)
(c)

Figure 27. Route 629 Bridge over I-64: (a) Overview of pier shows slots cut into the concrete; (b) the placement of titanium ribbon anodes (coated with a mixed metal oxide); and (c) current distributor band (blue arrow) connecting the ribbon anodes and a blue wire (orange arrow) that is connected to a silver-silver chloride reference cell installed in the concrete.

To install this system, chloride-contaminated distressed areas were first removed using hammers. A conductive concrete that enables electron flow was then placed in all repair areas receiving CP. Slots were cut into the concrete for the placement of titanium ribbon anodes (coated with a mixed metal oxide) and a stainless-steel current distributor band connecting the anodes as part of an ICCP system. After inserting the titanium ribbon anode into the slots, the slots were filled with grout, encapsulating the ribbon anode. Continuity checks were performed to ensure all steel was electrically connected, then a connection was made to the reinforcing steel, which is the part protected by this ICCP system. Finally, a silver-silver chloride reference cell was installed in the concrete. All these pieces of the ICCP system are connected to a RMU, which then transmits information to be shared within VDOT. This RMU gives VDOT the ability to monitor this system and ensure it is mitigating corrosion on the structure. Solar electricity powers the RMU and rectifiers. The “Route 629 and Route 522 Cathodic Protection Electrical Systems” section provides additional detail about RMU and how the system works.

Installation of Route 522 Solar ICCP and GCP Systems

The Route 522 Bridge is located east of the Route 629 Bridge along the I-64 corridor. This structure is unique for VDOT because it includes both a GCP system and an ICCP system, with a RMU for both systems. This bridge has four piers, with westbound traffic passing between Piers 1 and 2, and eastbound traffic passing between Piers 3 and 4. Conventional repairs were performed using SCC and galvanic anodes on Pier 1. A GCP system on Pier 3 and a solar-powered ICCP system was installed on Pier 4. Both CP systems were designed with remote monitoring using the data acquisition and control systems, which are near Pier 4. The solar-powered ICCP system on Pier 4 uses a thermally sprayed zinc coating on the concrete, which functions as the anode for the ICCP system (Figure 28).

Figure 28. Route 522 Bridge over I-64 that Had a Thermally Sprayed Zinc Coating Applied to the Concrete. It will function as the anode as part of an impressed current cathodic protection system.

Unfortunately, some of the piers on these structures are under a joint that could leak. A leaking joint was observed on the Route 522 Bridge above Pier 4 after the ICCP system had been installed. This leak damaged a portion of the zinc on the pier cap before the leaking joint was repaired.

The GCP system on Pier 3 uses a thermally sprayed aluminum-zinc-indium coating. Because arc spray is applied to the surface, the installation required the concrete to be repaired before the application.

Route 629 and Route 522 Cathodic Protection Electrical Systems

Powering the GCP and ICCP Systems and RMU

Each GCP and ICCP system is powered using solar panels (Figure 29). The five larger panels supply enough energy to provide CP current and charge the batteries, so that the system can mitigate corrosion day and night. The smaller solar panel provides power to the RMU and charges the battery for data to be collected and periodically transmitted.

Figure 29. The Five Larger Solar Panels Supply Electricity for the Cathodic Protection System and the Smaller Solar Panel Powers the Remote Monitoring Unit

Remote Monitoring Units and Data Collection

Each RMU is powered using a solar panel (Figure 29). Both RMUs are designed around Campbell Scientific products. To gather data, a CR6 data logger is connected to an AM16/32B 16- or 32-channel relay multiplexer. A CELL210 external cellular modem module transmits the collected data to VDOT using the Verizon network. It is important to note that other cellular modems are available if a different network is more suitable for a given location. Each RMU is then powered using a single SP20 20 W solar panel that is connected to the CR6 data logger. The CR6 operates as the charge controller, passing charge to a 12V DC battery to ensure the RMU is operational day and night.

After data are collected, the RMU transmits the data daily using the cellular modem. The CR6 data logger transmits the data, which are sent to a specified email address set by VDOT Structure and Bridge Division. VDOT personnel at the Central Office manually download the email to district folders in ProjectWise so the district can access the data. Because a consultant could review and monitor these types of CP systems, personnel recognized that a mechanism for sharing CP data was important. Using the ProjectWise program ensures that approved VDOT staff or consultants can access the data. With the current study, the Richmond District uses a consultant to monitor the CP system and provide monthly updates. If the RMU reports an issue, either VDOT or the consultant can troubleshoot the issue to determine the best course of action for the district, which is the current process to troubleshoot a solar panel power issue that might be addressed by adding a second panel or a larger capacity rechargeable battery.

Route 621 and Route 622 Shotcrete Repairs and Epoxy Coatings

The first control bridge, Route 621 over I-64, was repaired using dry process shotcrete (Figure 30). An epoxy coating was applied to the repaired columns and pier caps for protection from the environment and elements. The column surface is rough, and it exhibits cracks which were 1 to 2 mm wide and are highlighted with red arrows. Separation along the edges of the repair area indicated excessive shrinkage. In the areas receiving shotcrete, a prepackaged material was used.

(a) **(b)**

Figure 30. Route 621 Bridge over I-64 (Column along Eastbound Lane). The red arrows (a) indicate cracks in the repair and (b) shows a closeup of a crack being measured.

The rough surface and cracks (red arrows) are evident in the dry process shotcrete repair area of the Route 622 Bridge over I-64 (Figure 31). Areas repaired with shotcrete had rough surfaces and cracks. These bridge elements were coated with epoxy for additional protection because it covers the cracks, but the level of penetration is unknown.

Figure 31. Route 622 Bridge over I-64 (Column along Westbound Lane). Red arrows show cracks in shotcrete repair.

Benefits of Discrete Point Galvanic Anodes in Short-Term Patch Repairs

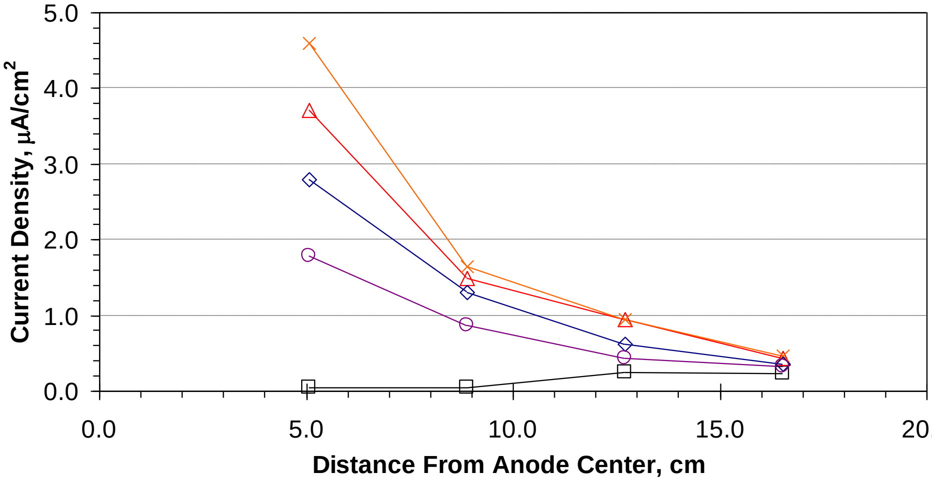
VDOT has used DGP anodes in concrete patch repairs for more than 19 years. Since then, these anodes have continued to incorporate different features in each anode to make them more effective. One anode supplier initially indicated the anodes should be installed without embedment mortar, and the manufacturer then shifted to requiring the use of embedment mortar to ensure better current distribution (Figure 32). A different anode manufacturer included a rubber strip between the anode rebar interface to insulate the rebar to ensure widespread current distribution over the reinforcement. Finally, a third anode manufacturer recommended installing the anode toward the middle of the repair area rather than the perimeter. Although differences in each brand of anode have been noticeable, all the anode designs have been engineered to be easy to incorporate into the patches. DGP anodes not only add to the repair cost because of the procurement of each anode, but they also take time to install. These anodes leave a void and use concretes with low resistivity, which is contrary to improved quality, low-permeability concretes with high resistivity used in bridge structures.

(a) (b)

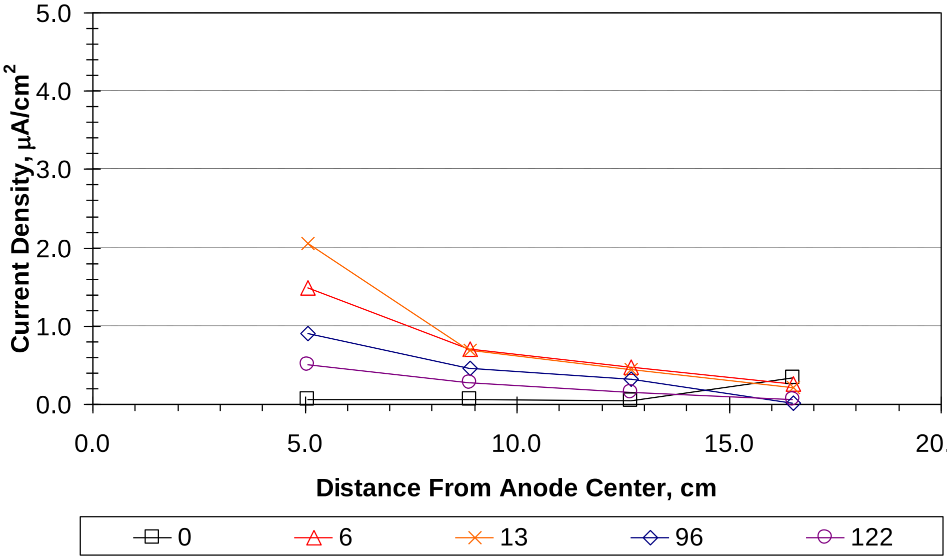
Figure 32. (a) Anode Installed along the Perimeter of the Repair without Embedment Mortar between the Original Concrete and Anode as Indicated by the Arrow; (b) Anode Installed with Embedment Mortar (top of yellow circle) to Enhance Current Flow to the Original Concrete

To better understand the benefit of using DGP anodes in substructure short-term repairs, as opposed to using long-term repair options like hydrodemolition or ICCP, VDOT Structure and Bridge personnel initiated a short technical assistance study that focused on structures which incorporate DGP anodes. This technical assistance report is provided in the supplemental materials and covers the field evaluation of DGP anodes in two SCC repairs and one shotcrete repair on substructural elements. The SCC repairs were performed in 2010 and 2013 as reported in Virginia Transportation Research Council (VTRC) Report No. 18-R9. Another structure containing DGP anodes on Route 29/Route 250 in Charlottesville was repaired by shotcrete in 2004 and reported in VTRC Report No. 05-R25.

The three substructures were repaired with and without anodes to determine the life expectancy of each. The anodes used were provided by three different companies, so the anodes had distinct differences that were reported to improve efficiency. In some areas, anodes were placed with an embedment mortar to facilitate current flow to prevent corrosion of the reinforcement in the unrepaired areas. The nondestructive testing showed that anodes with or without embedment mortar had minimal effect on the corrosion protection. The unrepaired areas next to the patches started showing distress that would inevitably need repairs. Controlled laboratory studies have also indicated that the influence of the anodes on the reinforced concrete element and the benefit of using them are sensitive to both exposure time and concrete resistivity, which directly influence the projected anode life. Work by Dugarte and Sagüés (2014) concluded that "… throwing distance in likely application scenarios may seriously degrade within a few years of operation." Similar behavior has also been observed in the VDOT elements repaired with these types of anodes in the field. For example, the current flow through the different steel bars first increases but then decreases with time (Figure 33), with most of the current going to the steel in closest proximity to the anode.



(a)



(b)

Figure 33. VTRC 05-R25 Current Density Measurements from Sacrificial Anode Sensors Placed in (a) Pier 1 and (b) Pier 12. The numbers in the legend indicate the number of days that have passed since activating the anode.

Furthermore, Trocónis de Rincón et al.'s (2008) work on concrete samples subjected to different humidity levels concluded that high concrete resistivity due to low humidity led to poorer performance of the anodes compared with concrete that has lower resistivity because of higher humidity levels, which is also consistent with what was observed in Figure 34. This observation shows that as VDOT concrete increases in resistivity as the permeability decreases with age, the current flow decreases, with most of the decrease in current occurring within the first 3 years. Conventional VDOT concrete repair materials are designed to exhibit high resistivity—at times an order of magnitude greater in the repair area compared with the unrepaired concrete—and the recent field measurements confirm it is true. The observed resistivity and current measurements also demonstrate that the sacrificial anode's current flow will be restricted by the high resistive repair material when these types of anodes are embedded in the low-permeability concretes. Use of embedment mortars did not make a noticeable difference in the performance.

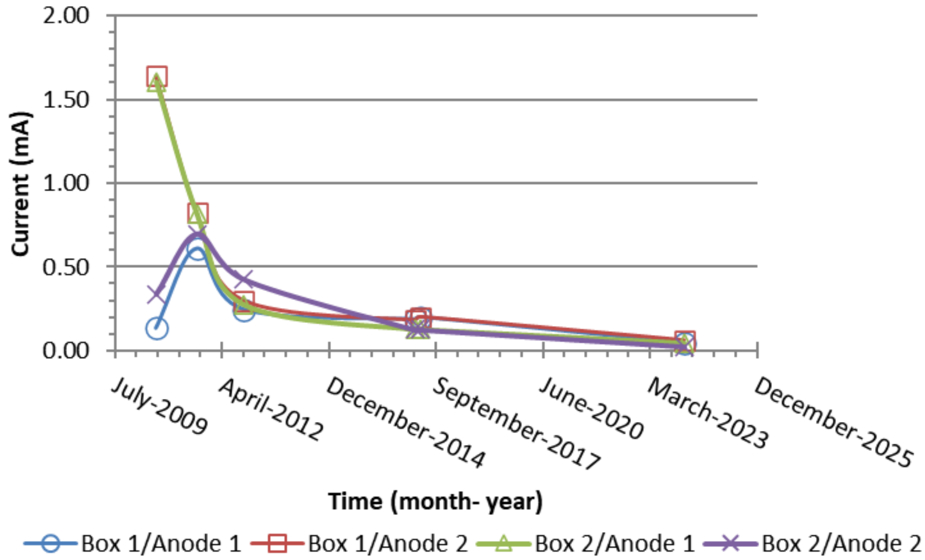


Figure 34. Measured Current Values on Route 712 Bridge

Thus, the technical assistance report concluded from field measurements of the current over time that most of the current flow occurs within 3 years of concrete placement. Field measurements also demonstrated that the distance the anode current extends from the center of the anode indicates that most of the current flows to the closest reinforcing steel bar. Both findings were not surprising because VDOT intentionally uses high resistivity concrete repair materials. The use of high resistivity concrete repair materials in patch repairs, with or without embedment mortar, limits the effectiveness of the DGP anodes. Therefore, the nearby unrepaired areas demonstrate the halo effect and show signs of corrosion-related distress within a few years of completion of the repair. Therefore, for long-term protection of the steel reinforcement, mitigating corrosion required either (1) total removal of the deteriorated concrete to below the reinforcement and replacement with a quality low-permeability concrete that naturally exhibits high resistivity, but without the DGP anodes, or (2) leave some of the deteriorated concrete in place and install an ICCP or GCP system to mitigate future corrosion on the whole element.

CONCLUSIONS

- *Hydrodemolition is effective in removing large areas of deteriorated concrete in preparation for substructure surface repairs.* However, the depth of removal can vary depending on the quality of concrete, rate of travel, number of passes, and water pressure used.

- *Low-permeability SCC patch repair without DGP anodes is the most effective option for durable repair of substructures.*

- *Removal of large concrete areas and placement of low-permeability SCC is expected to provide good performance without the need for DGP anodes.* However, the limits on the amount of concrete removal at one time are restricted by VDOT.

- *Solar-powered ICCP systems for bridge substructures using a RMU can be successfully installed, making this approach for corrosion mitigation possible.*

- *In the arc-sprayed surface, leaking joints can prematurely consume the anode material, highlighting the importance of repairing or eliminating joints prior to applying arc spray to concrete.*

- *Lower resistivity SCC without the addition of a supplementary cementitious material is available for locations where improved current distribution is needed for an ICCP system.*

- *SCC can exhibit smooth surfaces without cracks, whereas shotcrete areas often have rough surfaces and wide cracks.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should encourage the use of hydrodemolition for removal of deteriorated concrete over the traditional method of chipping.*

2. *Substructure surface repair patches should use low-permeability SCC without DGP anodes. Eliminating DGP reduces costs and facilitates repair operations.*

3. *Substructure surface repair patches should incorporate wider limits of removal than what is currently prescribed.* The current method of establishing removal limits by sounding should be expanded so that patches extend 6 to 12 inches beyond the edge of delamination, as determined by sounding. New patches should be made contiguous where they are separated by 1 foot. The final patch should be free of re-entrant corners. This change will lead to longer-lasting patches that replace concrete that has delaminated or is on the verge of delaminating, thus providing more durable patches.

4. *VDOT's Structure and Bridge Division should encourage the use of ICCP that addresses entire bridge elements with RMU and higher conductivity SCC.* The use of ICCP systems is most appropriate for bridges with substructures that have endemic chloride contamination that exceeds the threshold and when the front is at or below the depth of the reinforcing. The limited experience indicates that the repair methods of ICCP with RMU could provide repairs with acceptable long-term performance. Furthermore, the CP systems will enable less concrete removal, consistent with current specification limiting concrete removal. This repair technique allows VDOT to remove similar quantities of concrete, but the repair is expected to provide a much longer service life compared with the current repair method. ICCP is recommended in cases with an economical need to keep chloride-contaminated concrete in place but where joints should be repaired or replaced.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments section) for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This action is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

For the implementation of Recommendation 1, the VDOT Structure and Bridge Division will strongly recommend the repair of large areas of substructures using hydrodemolition and low-permeability concrete whenever it is economically viable within 2 years of the publication of this report.

For the implementation of Recommendation 2, the VDOT Structure and Bridge Division will strongly recommend the placement of low-permeability, SCC with no anodes for substructure surface repairs within 1 year of the publication of this report.

For the implementation of Recommendation 3, the VDOT Structure and Bridge Division will update the specifications for substructure surface repairs to extend the concrete removal beyond the delaminated and cracked areas and avoid re-entrant corners within 1 year of the publication of this report.

For the implementation of Recommendation 4, the VDOT Structure and Bridge Division will require ICCP with RMU for substructure repairs when chloride contamination exceeding the threshold at or below the depth of the reinforcing steel is left in place within 1 year of the publication of this report.

Benefits

The benefit of implementing Recommendation 1 is that hydrodemolition and low-permeability SCC will provide a mechanism to greatly increase the service life of the repaired element compared with conventional repairs. The current approach to repairing visibly distressed areas but leaving incipient deteriorating concrete results in adjacent areas showing distress. Therefore, complete removal eliminates frequent visits for repairs and extends the service life. This approach would be achieved through greater removal and replacement of deteriorated concrete, including behind the steel, to ensure the concrete adjacent to the steel is chloride free and of low permeability.

The benefit of implementing Recommendation 2 is that complete ICCP systems with RMU will also provide a mechanism to greatly increase the service life of the repaired element compared with conventional repairs. This benefit would be achieved through less concrete removal relative to hydrodemolition and instead mitigate corrosion electrically if salt-contaminated concrete remains adjacent to the steel.

The benefit of implementing Recommendation 3 is that by removing larger areas, the frequency of repairs will decrease.

The benefit of Recommendation 4 is that the service lives of highly contaminated bridges can be extended without the cost of replacing the bridge.

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REFERENCES

American Concrete Institute (ACI). 2018. *ACI CT-18: ACI Concrete Terminology*. Farmington Hills, MI: ACI.

ASTM. 2020. *Standard Terminology and Acronyms Relating to Corrosion.* NACE/ASTM G193. West Conshohocken, PA: ASTM International.

Brown, M.C., and Sharp, S.R. 2005. *Effectiveness of Sacrificial Anodes in High-resistivity Shotcrete Repairs.* Report No. 05-R25. Richmond, VA: Virginia Transportation Research Council.

Dugarte, M.J., and Sagüés A.A. 2014. "Sacrificial Point Anodes for Cathodic Prevention of Reinforcing Steel in Concrete Repairs—Part 2: Performance Modeling," *Corrosion* 70 (4): 414–429.

Okamura, H., and Ouchi, M. 1999. "Self-Compacting Concrete: Development, Present Use and Future." In *Self Compacting Concrete: Proceedings of the First International RILEM Symposium.* Cachan, France: RILEM.

Ozyildirim, H.C., and Sharp, S.R. 2017. *Repairs with Self-Consolidating Concrete and Galvanic Anodes to Extend Bridge Life.* Report No. 18-R9. Richmond, VA: Virginia Transportation Research Council. http://www.virginiadot.org/vtrc/main/online_reports/pdf/18-r9.pdf.

Trocónis de Rincón, O., Hernández-López, Y., de Valle-Moreno, A., Torres-Acosta, A.A., Barrios, F., Montero, P., Oidor-Salinas, P., Montero, J.R. 2008. "Environmental Influence on Point Anodes Performance in Reinforced Concrete," *Construction and Building Materials* 22 (4): 494–503.