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Effectiveness of Sacrificial Anodes in High-Resistivity Shotcrete Repairs

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Supplementary Notes

Abstract

This study investigated the use of discrete sacrificial anodes to improve the durability and extend the life of a shotcrete patch repair in a column. Three columns were used in the investigation. In two columns, anodes were placed around the perimeter of the repair area. In a third column, used as a control, anodes were not placed inside the repair area. Shotcrete was then placed in the repair areas of all three columns.

The study found that the current density level needed to improve the resistance of the steel to chloride-induced corrosion is being met. In addition, the anode current is able to reach a distance of 16 cm from the anode center, meeting the requirements for cathodic prevention within this region. A cost analysis, using the capital recovery method, indicated that repairs using shotcrete plus cathodic protection will cost less than repairs using shotcrete alone.

FINAL REPORT

EFFECTIVENESS OF SACRIFICIAL ANODES IN HIGH-RESISTIVITY SHOTCRETE REPAIRS

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Virginia Department of Transportation and
the University of Virginia)

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DISCLAIMER

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INTRODUCTION

The Virginia Department of Transportation (VDOT) employs shotcrete to repair overhead and vertical surfaces of reinforced concrete that have deteriorated, primarily because of chloride-induced corrosion. A phenomenon that affects the durability of such repairs is the "halo effect" wherein the steel within the freshly repaired area serves as a cathode to drive accelerated corrosion of reinforcement in the original concrete surrounding the repair.

One technique for corrosion mitigation in reinforced concrete structures is the use of sacrificial anodes. This technique has evolved to include designs for the rehabilitation of entire reinforced concrete structures and the protection of isolated regions (Broomfield, 2000). Further, some have indicated that the level of corrosion protection can be varied based on whether the intention is to prevent the initiation of new corrosion (corrosion prevention) or to halt ongoing corrosion in addition to preventing the initiation of new corrosion (cathodic protection) (Pedeferri, 1996; Page, 2000).

PURPOSE AND SCOPE

The purpose of this project was to provide an initial assessment of the early effectiveness of sacrificial anodes in preventing the halo effect around shotcrete repair areas containing high-resistivity concrete.

The assessment included reviewing and summarizing available information on the durability of concrete repairs, resistivity of concrete and shotcrete, and performance of sacrificial anodes in reinforced concrete repairs. The bridge selected for this study (VA No. 7-1139) is on Rt. 29/Rt. 250 in Charlottesville, Virginia, and crosses Rt. 654, which is known as Barracks Road.

METHODS

Overview

As stated previously, the evaluation included reviewing and summarizing available information on the durability of concrete repairs, resistivity of concrete and shotcrete, and performance of sacrificial anodes in reinforced concrete repairs. Based on the available information, procedures were developed to evaluate the pre-repair condition of the structure and to monitor the corrosion behavior of the anodes after repair. Field operations were coordinated with personnel in the Virginia Department of Transportation's (VDOT) Culpeper District and the contractor.

The sacrificial anodes were designed to protect an isolated region from the onset of corrosion. Therefore, the intention was to prevent corrosion by embedding zinc anodes, which were specifically designed for use in concrete, in the concrete patch repair area in the hope they would prevent the onset of corrosion in the adjacent original concrete. A diagram of this idea is shown in Figure 1, which illustrates the placement of the anodes in the shotcrete. This anode is a less noble metal and sacrificially corrodes to protect the surrounding steel reinforcement. However, the anode manufacturer stated that the anodes are less effective if the resistivity of the concrete in the repair, surrounding the anodes, is greater than 15,000 ohm-cm, which is a value that is common for quality shotcrete material (Neville, 1996).

Sacrificial anodes were placed in select locations before shotcrete repairs were made to the bridge substructure components. The subject structure was repaired under a term contract administered by the Culpeper District and was identified by the Culpeper District Bridge Engineer.

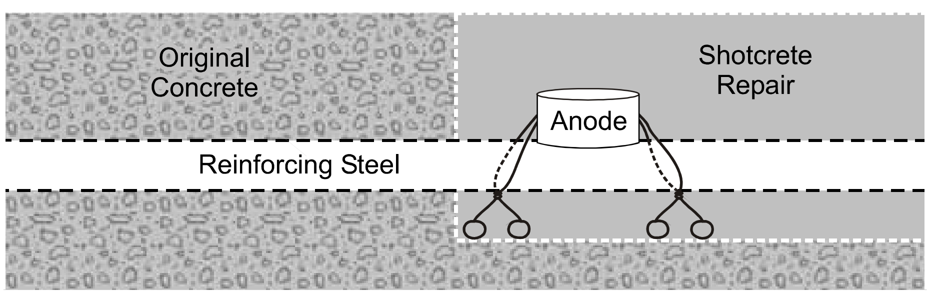


Figure 1. Diagram of Anode and Placement

Anode Placement Inside Shotcrete Repair

Corrosion-related damage to three columns of the bridge required the removal of contaminated concrete and replacement with shotcrete. Before the shotcrete was placed, the investigators determined that in two of the three columns, sacrificial anodes would be placed along the edge of the shotcrete repair, and that the third column would serve as a control reference. The two columns with embedded anodes are marked *1* and *12* in Figure 2, and the third column without anodes is marked *2*.

On May 12, 2004, shotcrete was placed in the three subject column areas. The shotcrete was allowed to cure for about 1 week before monitoring began on May 19 and 20, 2004. The shotcrete repair material was a pre-packaged mixture, identified as Gunite 7001d, by U.S. Concrete Products, LLC. Table 1 presents the mixture proportions, as reported by U.S. Concrete Products (Brennan, 2003).

The galvanic anode supplier suggested that the anodes be placed as close to the perimeter of the patch as practical and spaced no more than approximately 30 in apart. The columns were 40 in in diameter, and each contained 10 No. 10 vertical reinforcing bars. In addition, No. 3 gage wire spirals at a 6-in pitch connected the bars. The estimated ratio of steel to concrete surface areas was 0.43. Comparison of this estimate to the manufacturer's guidelines (Vector Corrosion Technologies, 2003) indicated that the anodes should be located at intervals no

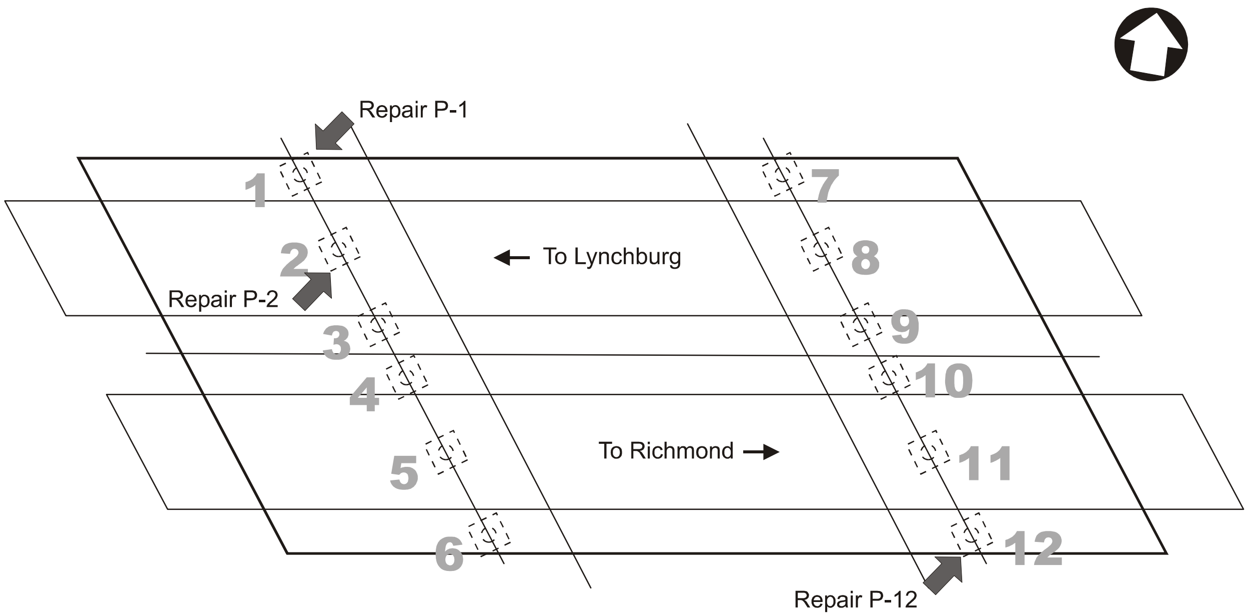


Figure 2. Sketch of Bridge Undergoing Repair

Table 1. Mix Design for Gunite 7001d

Material	% by weight
ASTM C 150 Portland Cement (Type II)	22.5
ASTM C494 Admixture	<1
ASTM C1240 Pozzolan (Silica Fume)	<2.5
ASTM C 33 Concrete Sand	74
Polypropylene Fibers	<1

greater than 24 in on center. Since potential concerns included the high resistivity of the shotcrete and uncertainties about the force to which each anode would be subjected while the shotcrete was being applied, the investigators decided that the spacing would be dictated by locations where the horizontal steel spiral reinforcement crossed the primary longitudinal reinforcement in the columns. This would provide excellent continuity between the horizontal and vertical steel components while creating strong anchor points within the repair zone for each anode. As indicated in Figure 3, anodes were placed at 12 to 24 in along the perimeter of the repair areas.

Figure 3. Placement of Anodes in Shotcrete Repair Areas

Chloride Sampling and Analysis

To characterize the level of chloride contamination of the concrete surrounding the subject repair areas, a series of chloride profiles was generated for locations adjacent to the repairs. Sampling was conducted by collecting powdered concrete material generated by horizontal drilling into the vertical surface of the subject columns. The powdered samples were collected for ranges of depth from the surface of the column inward, toward the reinforcing steel, and were tested for total (acid-soluble) chloride concentration in accordance with ASTM C 1152 (ASTM International, 2003).

Temperature and Humidity Monitoring

Temperature and humidity were recorded in conjunction with a set of corrosion measurements. Regional temperatures were monitored throughout the test period. In this region, seasonal changes in the weather influence the values measured using half-cells and the amount of chlorides to which a bridge is exposed because of the use of deicing salts during the colder months. The regional data were gathered from the National Climatic Data Center, Charlottesville 2W station. This weather station is approximately 1.8 mi from the structure.

Corrosion Monitoring

A series of tests was conducted at and near repair locations to characterize the base concrete, repair materials, and track the performance of the anodes. To ensure the same locations were tested each time, orange paint marks were made on the column. The measurement points included regions containing the original concrete and locations where repairs were made using the shotcrete, which can be seen in Figure 4. For each column, electrical potential and resistivity were measured at 10 equal horizontal intervals around the perimeter of each column at a single elevation; they reflected readings within and adjacent to shotcrete patches. Illustrations of the test locations relative to the repairs are shown in Figure 5.

Figure 4. Electrical Potential and Resistivity Test Locations After Repair

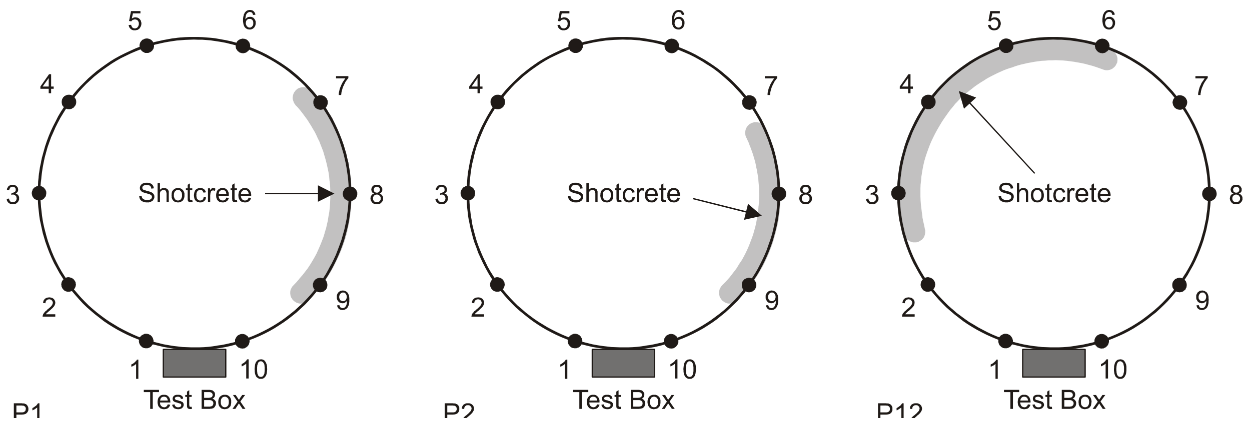


Figure 5. Electrical Test and Shotcrete Repair Locations on Each Column

Resistivity Measurements

Resistance, or more correctly impedance, was measured in accordance with the procedures described in ASTM G 57-95a (ASTM, 2001a). A Nilsson Soil Resistance Meter, Model 400, with a concrete probe in a four-pin configuration was used to make measurements at set locations around the circumference of each column. Similar to the potential measurements, the four-pin measurement points included regions containing the original concrete and locations where repairs were made using the shotcrete. This type of meter induces an AC signal between two outer pins while the voltage drop is measured between two inner pins, as illustrated in Figure 6.

The output from the resistivity meter is in units of resistance (R), and, therefore, if the pins are evenly spaced and the inner pin spacing (a) is known, the resistivity (ρ) can be calculated using [Eq. 1.

$$\rho = 2\pi a R \qquad \text{[Eq. 1]}$$

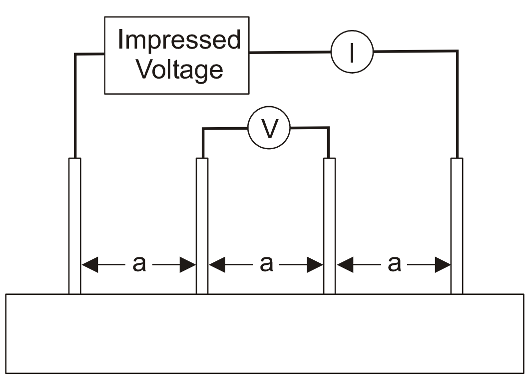


Figure 6. Four-Pin Resistivity Test Schematic

Potential Measurements

Half-cell potential measurements were made in accordance with the procedures described in ASTM C 876 (ASTM, 1999). The reference electrode selected was a copper/copper sulfate electrode (CSE), which was used to make measurements at set locations around the circumference of each column. To facilitate future monitoring, a direct electrical connection to the reinforcing steel was embedded in the repair prior to the shotcrete application.

Current Measurements

Current was measured for two reasons. First, the current flowing through the lead connecting the sacrificial anode and the reinforcing steel was measured to aid in calculating the rate of mass loss of the anode and therefore estimating the expected life. [Eq. 2 was used to calculate the mass loss of the anode.

$$W = \left(\frac{A}{nF}\right)\int I dt \qquad \text{[Eq. 2]}$$

where

W = Mass loss, g
A = Atomic weight of active species, g/mol
n = Electrons transferred per mole of active species, eq/mol
F = Faraday's constant, 96,489 C/eq
I = Current, A
t = Time, s.

Second, current was measured on four specially designed probes to determine the current density at set distances away from the probe. These probes were entirely embedded in the selected shotcrete patch areas. The probe is illustrated in Figure 7, and Figure 8 shows the probe location within a patch before shotcrete was applied.

All of the steel used to construct the sacrificial anode monitoring devices was from the same heat of steel. The reinforcing steel was a Grade 60, No. 5 bar. The chemical and physical test results for the steel, which were determined in accordance with ASTM A615 (ASTM, 2001b), are listed in Tables 2 and 3.

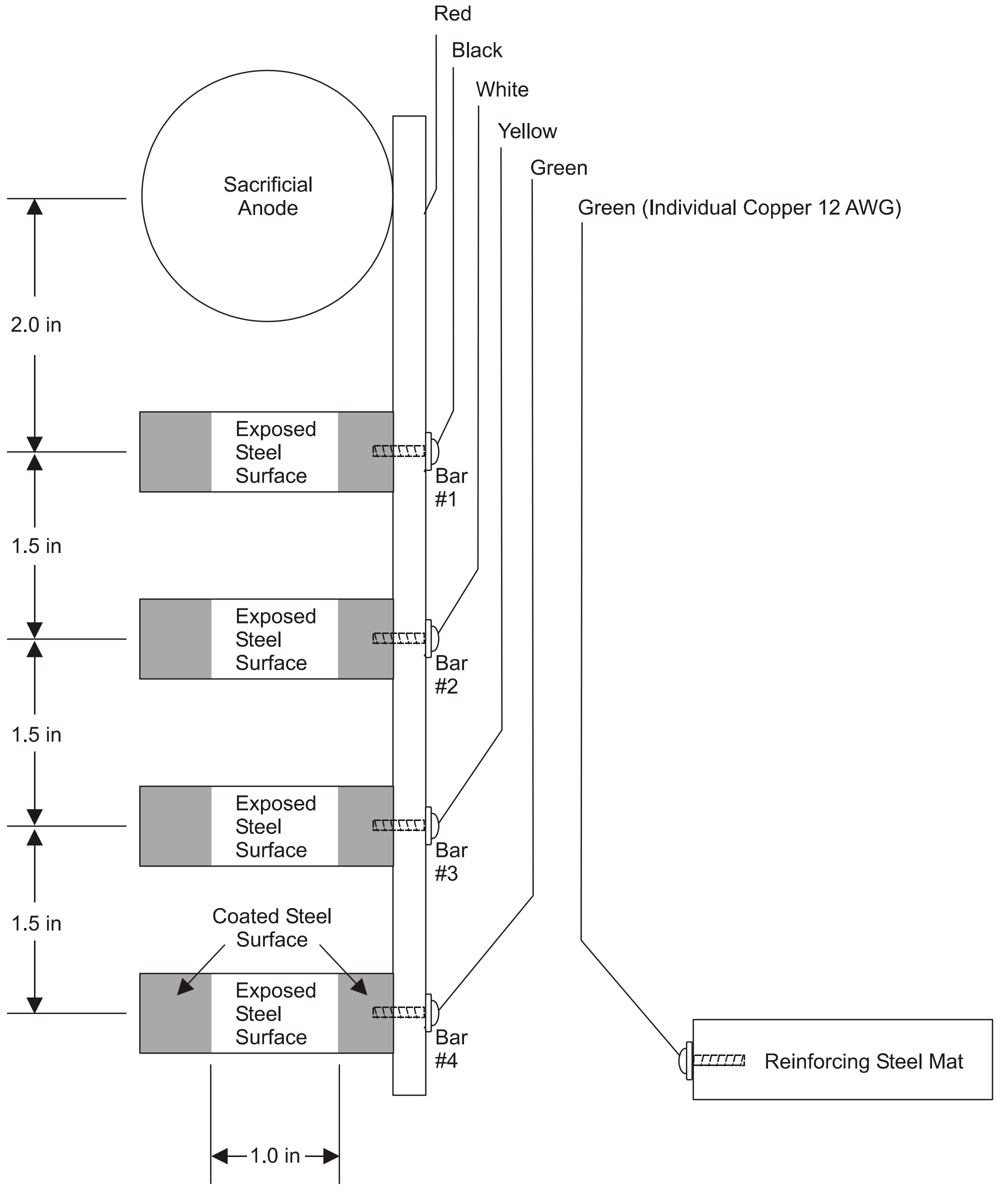


Figure 7. Sacrificial Anode Monitoring Device

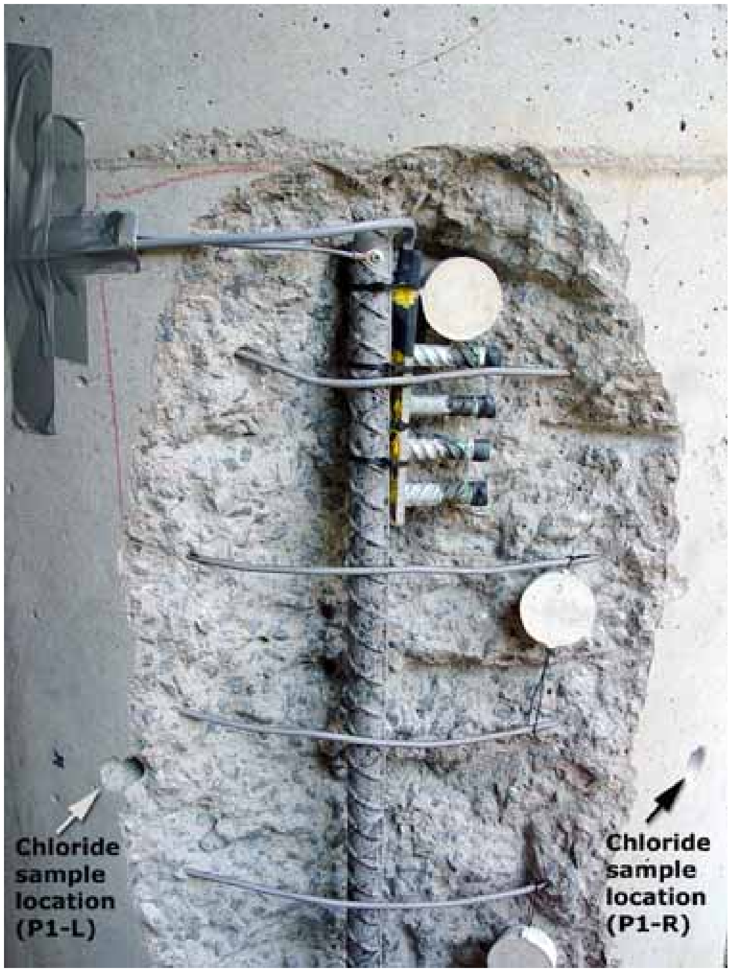


Figure 8. Sacrificial Anode Monitoring Device Placement Before Shotcrete Repair

Table 2. Chemical Composition (wt%) of Reinforcing Steel

C	Mn	P	S	V	Si	Cr	Cu	Ni	Sn	Mo
0.33	0.73	0.023	0.041	0.003	0.17	0.27	0.45	0.11	0.006	0.017

Table 3. Results of Physical Tests

Test	Reported Values
Yield point	95,700 psi (659.83 MPa)
Tensile strength	11,4100 psi (786.69 MPa)
% Elongation in 8 in	12.5
Bend	OK
Average deformation height	0.036 in (0.91 mm)
% Light/heavy	4.0 L

RESULTS

Anode Placement Inside Shotcrete Repair

The repair contractor, using pneumatic hammers, removed any loose or delaminated concrete. In areas where active corrosion had resulted in the cracking of cover concrete, the concrete material was removed to a depth of approximately one bar diameter beyond the corroded reinforcement. The repair areas were then grit-blasted to remove corrosion products and other contaminants from the reinforcing steel and the concrete. No splicing or supplementing of reinforcement was attempted.

After the repair areas were prepared, using the wires extending from the anodes, the anodes were placed with relative ease. The placement of each anode required less than 2 min each. Continuity checks indicated that the anode to steel circuit was complete and the repair region was ready for the shotcrete to be applied. As the shotcrete was applied, some of the anode pucks were observed to vacillate slightly, but each anode remained where it had been placed originally. The placement of the shotcrete repairs was monitored, as shown in Figure 9, with no noted complications.

Figure 9. Placement of Shotcrete in Column Repair Containing Galvanic Anodes

Visual Observation

A few days after shotcrete repairs were complete, electrical tests were conducted to monitor the performance of the anodes within the repair. The repairs were also visually assessed to determine any unusual activity. During the observations, the shotcrete within the largest of the repair areas, at column P12, exhibited fine cracks at regular intervals, transverse to the length of the column, with a few vertical cracks connecting between them. Figure 10 is a photograph of the column showing the cracks highlighted with lumber crayon. The pattern of the cracking relative to the dimensions of the repair suggests that the cracks were likely due to drying shrinkage of the repair material during curing. The width of all cracks was less than 0.01 in .

Figure 10. Pattern of Small-width Cracks in a Shotcrete Column Repair

Chloride Analysis

Powdered concrete samples were obtained to determine chloride concentrations in the concrete as a function of depth. These samples were obtained from three locations, two within column P1 to the left and right of the repair area, respectively, and a third from column P2. The purpose of the sampling was to compare the level of chloride exposure at each location as relates to permeability of the concrete by chloride ions and susceptibility to corrosion. The acid soluble chloride concentrations from columns P1 and P2 are presented in Table 4. These values represent the concentration in the original concrete adjacent to the repair areas prior to the shotcrete application. Figure 8 shows the chloride sampling locations for column P1.

Table 4. Chloride Concentrations

Sample	Depth (in)	Average Standard (mL)	Average Blank (mL)	Endpoint (mL)	Specimen Weight (g)	Cl^- (by wt)	Cl^- (lb Cl^-/cy)	Cl^- (kg Cl^-/m^3)
P1-R	0.50	5.1846	2.272	10.970	10.000	0.1487	5.887	3.493
	1.00	5.1846	2.272	8.209	9.500	0.1053	4.170	2.474
	1.50	5.1846	2.272	5.397	10.000	0.0520	2.058	1.221
	2.00	5.1846	2.272	3.575	10.000	0.0208	0.825	0.490
P1-L	0.50	5.1846	2.272	4.193	10.000	0.0328	1.300	0.771
	1.00	5.1846	2.272	3.836	10.000	0.0253	1.002	0.594
	1.50	5.1846	2.272	2.962	10.000	0.0104	0.410	0.243
	2.00	5.1846	2.272	2.464	10.000	0.0018	0.073	0.043
P2	0.50	5.1846	2.272	10.070	10.000	0.1333	5.278	3.131
	1.00	5.1846	2.272	8.262	10.000	0.1010	3.998	2.372
	1.50	5.1846	2.272	4.400	10.000	0.0349	1.384	0.821
	2.00	5.1846	2.272	2.480	10.000	0.0021	0.084	0.050

The driving surface chloride concentrations are represented by the respective chloride concentrations at a ½-in depth from the column surface. At shallower depths, the concentration is known to fluctuate with wetting and drying cycles, but the concentration remains stable at and below the ½-in depth. Concentrations at depths greater than ½ in are the result of chloride diffusing into the concrete. Using the profiles, the effective diffusion coefficient, D_c, of the concrete was estimated at each location. The plots in Figure 11 indicate the chloride concentration as a function of depth at the time of sampling. The plots indicate the actual measured values, accompanied by the predicted values that result from a best fit of the one-dimensional diffusion equation derived from Fick's Second Law of Diffusion:

$$C_{x,t} = C_o\left[1 - erf\left(\frac{x}{2\sqrt{D_c \cdot t}}\right)\right] \qquad \text{[Eq. 3]}$$

where

$C_{x,t}$ = chloride concentration at a depth, x, and time, t
C_o = driving surface chloride concentration
x = depth (distance of diffusion)
D_c = effective diffusion coefficient
t = cumulative time of chloride exposure
erf = mathematical error function.

The effective diffusion rates, based on the best fit, were 0.022, 0.020, and 0.017 in^2/yr for locations P1-R, P1-L, and P2, respectively. Although the diffusion coefficient values were similar, indicating a remarkable consistency in the material, the surface chloride concentration, and thus the magnitudes of the chloride concentration profiles, differed. This was due to variations in the chloride exposure from one location to the next, based primarily on exposure to salt spray from passing traffic and accumulation of salt-laden snow at the base of columns from plowing operations. In addition, proximity to leaking joints in the deck overhead can be a factor.

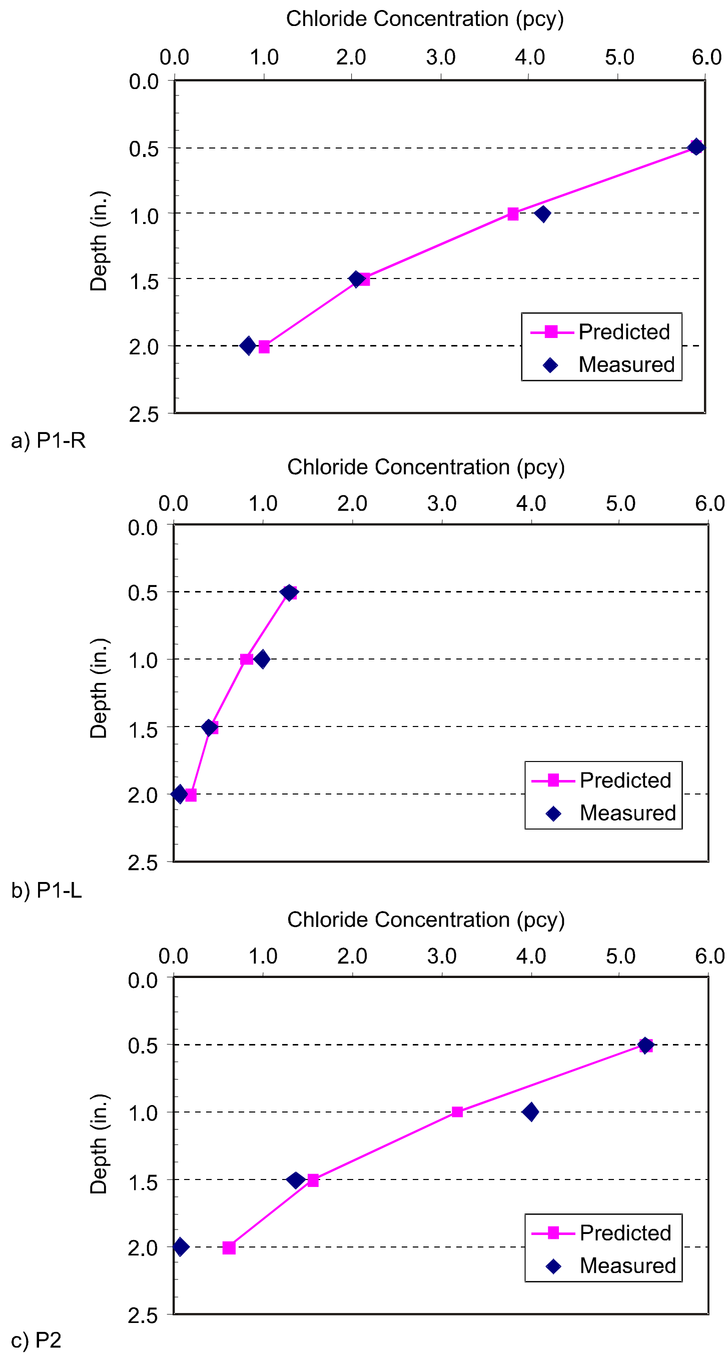


Figure 11. Chloride Concentration Profiles Adjacent to Repairs at Location P1-R, P1-L, and P2

The thickness of the concrete cover was approximated by direct observation of the original concrete removed from the delaminated column areas during rehabilitation. The thickness of the clear concrete cover ranged from 1.75 to 2.0 in. The estimated chloride concentration at a 1.75-in depth in the profiles of Figure 12 indicate there is sufficient chloride at two of the three locations tested to induce corrosion. This observation is based on a generally accepted (Stratfull et al., 1975) range of chloride concentration corrosion thresholds of 1.2 to 2.0 lb/cy for mild, uncoated steel in reinforced concrete.

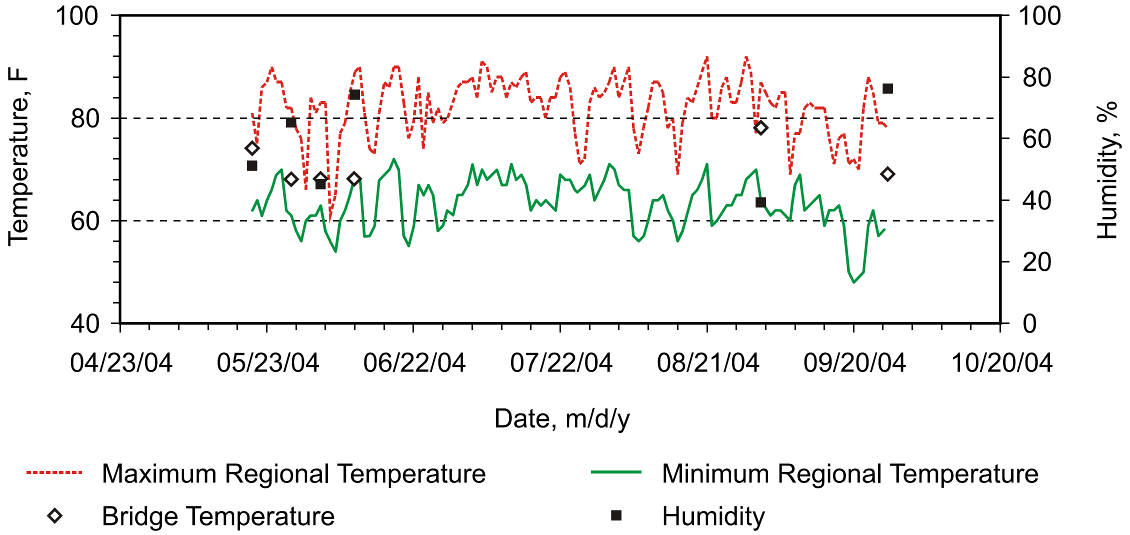


Figure 12. Temperature and Humidity Measurements

Regional Temperature and Humidity

As shown in Figure 12, the regional and measured temperatures remained constant, with a mean value of approximately 70 F, throughout the test period. However, the humidity at the bridge fluctuated between 40 and 80 percent.

Corrosion Measurements

Potential Measurements

The electrical potential measurements at different times following the repair are shown in Figures 13 and 14. The columns in Figures 13 and 15 contained sacrificial anodes, whereas the column in Figure 14 did not. In Figure 13 representing column P1, the region repaired with shotcrete is between positions 7 and 9. It is clear that steel in the repair region underwent a strong negative shift in potential, which was followed by the potential slowly becoming more positive. In addition, the region outside the repair did not show much change following the repair. Figure 14, however, shows clearly that this trend was not evident with column P2, where the shotcrete repair (position 8 to 9) did not contain sacrificial anodes. In Figure 14, the repair region was initially more negative than the original concrete, but during subsequent measurements, there was very little change in potential at the various positions around the circumference of the column. This same trend is evident in Figure 15, with the shotcrete repair being located between positions 3 and 6 for column P12. Although the negative shift in potential at the location of the anodes was to be expected, and indeed desirable, the magnitude of the change was not as large as might have been expected. One possible reason for this is that the physical locations of the half-cell readings do not necessarily correspond to points directly above the anode locations. To determine the anode locations and the maximum potential output, half-cell mapping of columns P1 and P12 will be performed in the future.

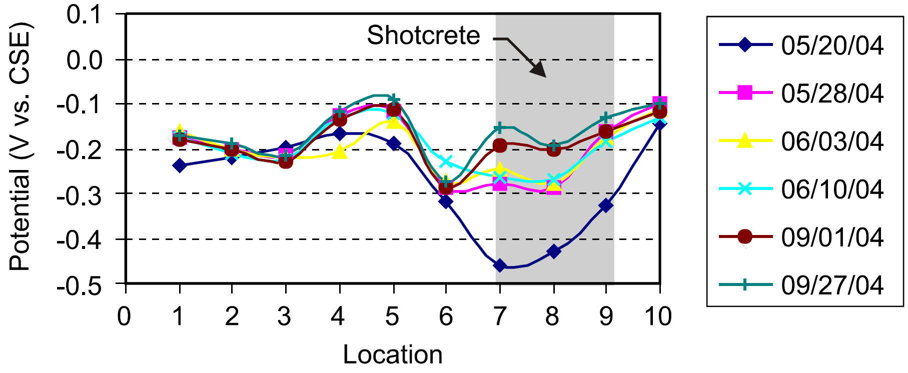


Figure 13. Half-Cell Measurements Versus Location for Column P1, Which Contains Sacrificial Anodes

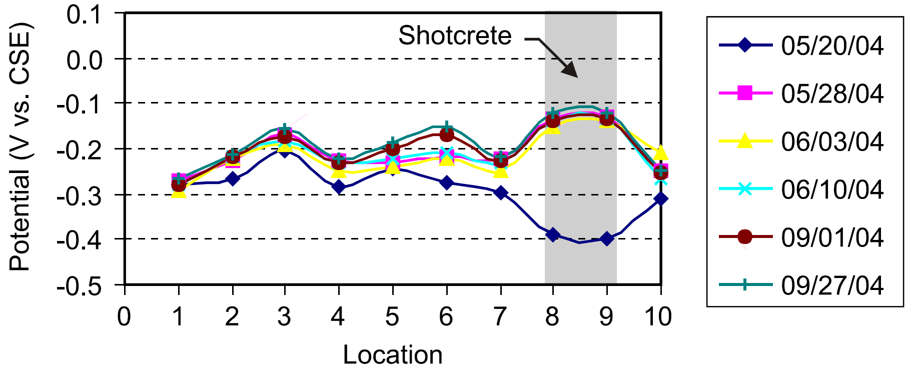


Figure 14. Half-Cell Measurements Versus Location for Column P2, Which Does Not Contain Sacrificial Anodes

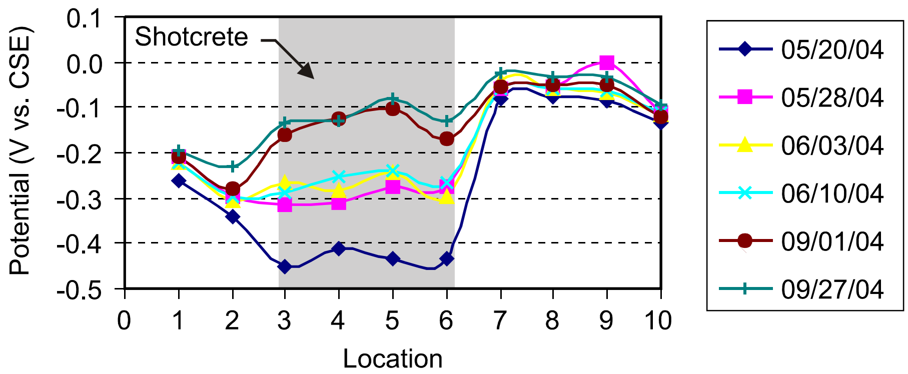


Figure 15. Half-Cell Measurements Versus Location for Column P12, Which Contains Sacrificial Anodes

Resistivity Measurements

Prior to the field evaluation, in order to answer the question of feasibility of using the anodes, resistivity was measured on a test section of shotcrete prepared by the repair contractor. Using the hand-held four-point Wenner array probe and Nilsson resistivity meter, the resistance of the concrete was measured at select locations away from internal reinforcement on the top and sides of the test slab. Comparisons were made of resistivity using the as-received finished surface resulting from the shotcrete application to measurements where the rough as-received surface was ground smooth with a diamond impregnated cup-grinder tool, and finally to a location on the side of the slab that had been saw-cut through the bulk of the repair material. In addition, after resistivity measurements were made, select locations of the test slab were cored and the cores were tested using a proposed conductivity test, which is a shortened version of the common rapid chloride permeability test in ASTM C 1202 (ASTM, 1997). From each of these tests, resistivity was calculated and compared, as shown in Table 5.

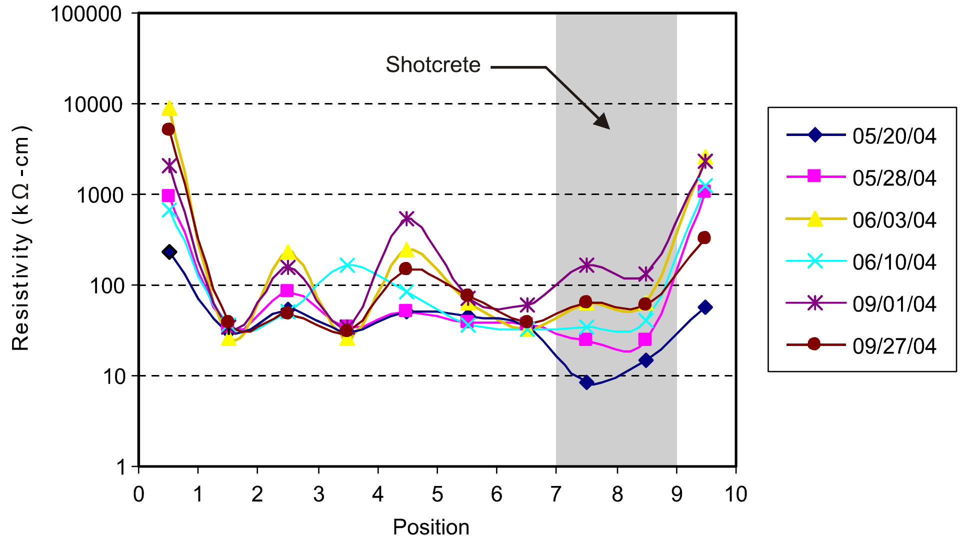
It can be seen that some measured values of resistivity for the shotcrete test slab exceeded the maximum 15,000 ohm-cm recommended by the anode manufacturer. However, many of the values were significantly lower, and on average, they were lower than this value. The condition of the surface has a significant influence on the resistivity. Since the anode current would be expected to flow in the concrete bulk, not at the surface, more confidence was placed in readings on the ground surface and on the saw-cut sides than on the as-received surface. In addition, the measurements taken at the edge of the slab were believed to be somewhat higher than would be expected for bulk concrete because of the constraint of the shallow test slab geometry on current flow. The resistivity values obtained from cores in the conductivity test were comparable and served to validate the findings of the four-point probe.

Once repairs were conducted, the resistance of the concrete was measured periodically using the hand-held four-point Wenner array probe and Nilsson resistivity meter between the locations around the columns where the electrical potential was measured.

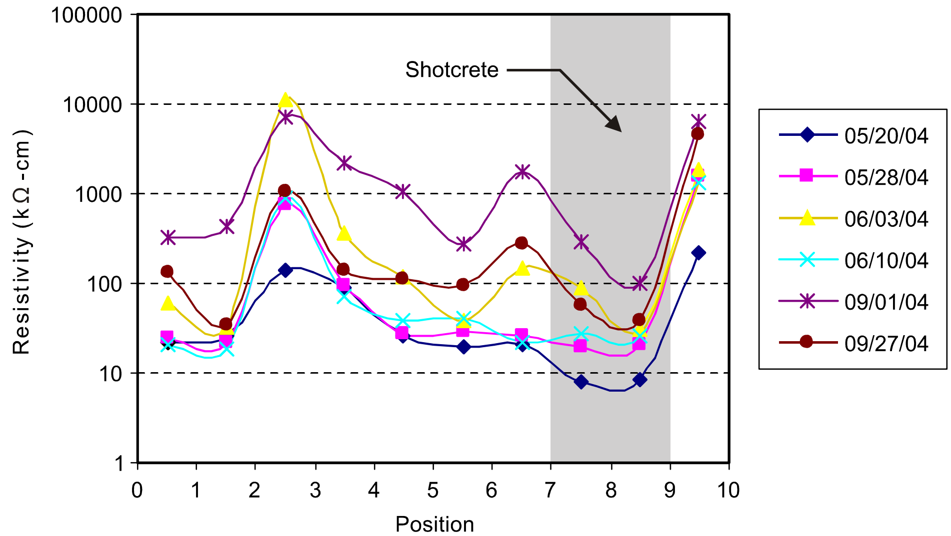
Figure 16 shows plots of the resistivity measurements around the perimeter of columns P1, P2, and P12. As would be expected, for the newly placed shotcrete, measured at locations outlined in gray, the resistivity of the material was lower overall than that of the mature base concrete. The resistivity was lowest immediately after placement of the repair material and increased over time, as resistivity would be expected to increase as free water is consumed in the cement hydration process and the hydrated cement paste becomes less permeable.

Table 5. Results of Resistivity Tests on Test Slab

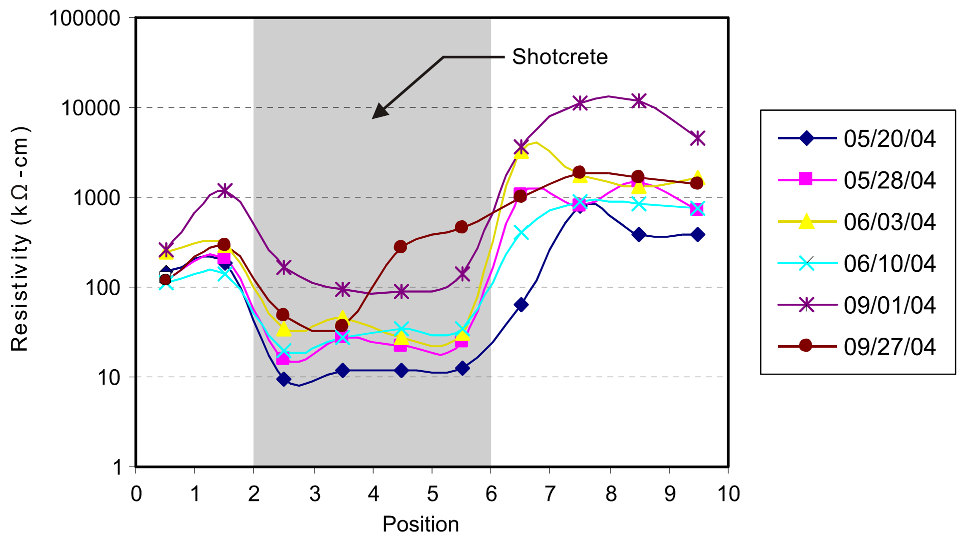
	Top As-is		**Top Ground**		**Side Saw-cut**		**Permeability**	
Location	**Impedance Ω**	**Resistivity Ω-cm**	**Impedance Ω**	**Resistivity Ω-cm**	**Impedance Ω**	**Resistivity Ω-cm**	**Current Amperes**	**Resistivity Ω-cm**
1	1,022	32,610			892	28,461	0.0500	19,159
2	409	13,060	352	11,225	402	12,821	0.0285	33,609
3	690	22,024			567	18,087	0.0420	22,799
4	517	16,491	362	11,544	364	11,624	0.0455	21,048
5	1,015	32,397			1,233	39,366	0.0415	23,077
6	1,062	33,887	497	15,853	573	18,300	0.0355	26,979
7	832	26,546			650	20,747	0.0380	25,199
Average	792	25,288	403	12,874	669	21,344	0.0401	24,553
St. Dev.	242	7,720	66	2,111	281	8,967	0.0065	4,391
CoV	33%	33%	20%	20%	45%	45%	17%	19%



Column P1



Column P2



Column P12

Figure 16. Post-repair Resistivity of Concrete Versus Location

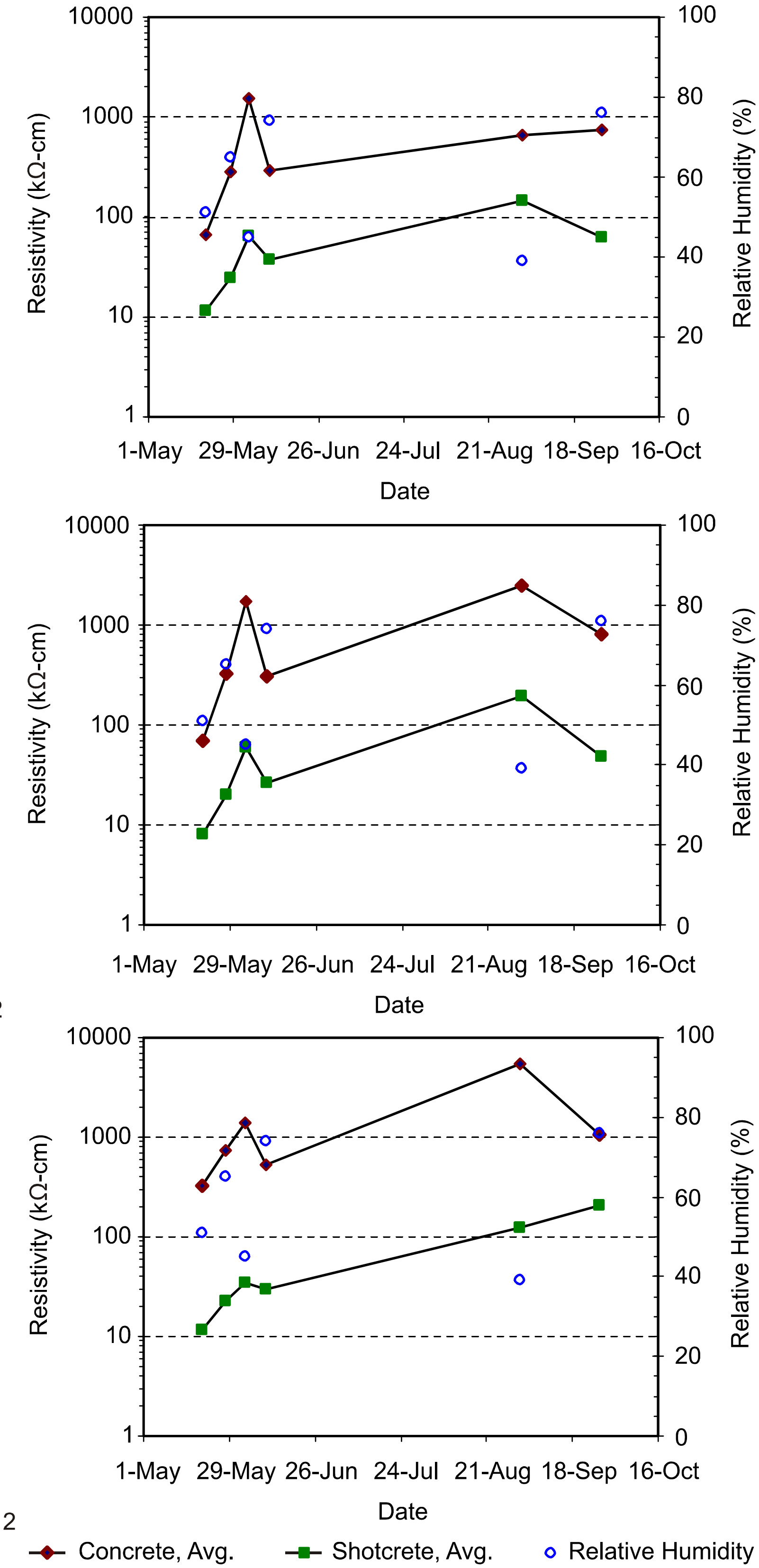
Figure 17 summarizes these same data but differentiates between the average resistivity measured within the shotcrete repairs and the resistivity of the original concrete around the remaining perimeter of the columns at the same elevation. The average resistivity for each of the two materials is shown as a function of time following the repair. It can be seen that the average resistivity in the base concrete is consistently higher than that of the new shotcrete. The resistivity of the shotcrete does appear to increase with time, indicating maturing of the cement paste. However, considerable variation is seen in both sets of data as a function of time, and this is in part accounted for by changes in the relative humidity of the bridge environment. The apparent resistivity of materials can be observed to vary inversely to changes in ambient relative humidity. Temperature may also play a role in the observed resistivity, but the effect is less pronounced.

Interestingly, within a very short time after the repairs were made, the resistivity observed at the surface of the field-applied shotcrete appeared to exceed the 15,000 ohm-cm limit recommended by the anode manufacturer. However, surface readings with the four-point probe proved to be highly variable, and the quality of the probe-concrete interface at the finished concrete surface can present a significant source of measurement error. In addition, the resistivity values, especially in the mature base concrete, are high when compared to resistivity of typical concretes. It is likely that dryness of the concrete, especially in regions of the column shielded from precipitation, contributed to these very high apparent resistivities. Therefore, further investigation was conducted using the embedded probes within the shotcrete repairs.

Current Measurements

Measurements of the current between the anode and reinforcing steel were used to estimate the amount of anode consumed during the evaluation period. By measuring the current flow between some of the anodes and the reinforcing steel, Faraday's law could be used to estimate the amount of anode consumed. Table 6 lists the exposure time for each anode and the percentage of anode consumed.

The sacrificial anode current density was also monitored as it protected isolated bars that were attached to a sacrificial anode monitoring device. The anode and bars were electrically isolated from the surrounding reinforcement during shotcrete placement and were made electrically continuous via an external junction point approximately 1 week later. Figure 18 is an example of the measurements gathered from two of four sacrificial anode sensors. Day 0 is indicative of the time at which the electrical connection was made. All of the sensors had the same current density trend with respect to distance and time. Initially, the current density was small, and then it increased during the next 2 weeks, and then began to decrease again. Therefore, the distance between the anode and steel strongly controls the magnitude of the current density. Further, for the same test date, the current density measurements in pier 1 were approximately twice the value measured in pier 12.



Column P1

Column P2

Column P12

Figure 17. Post-repair Resistivity of Concrete Versus Time

Table 6. Consumption of Anode in Columns

Anode ID	Exposure Time (day)	Anode Consumed (%)
S1C1	130	5.5
S2C1	130	4.9
S1C12	130	4.3
S2C12	130	7.3

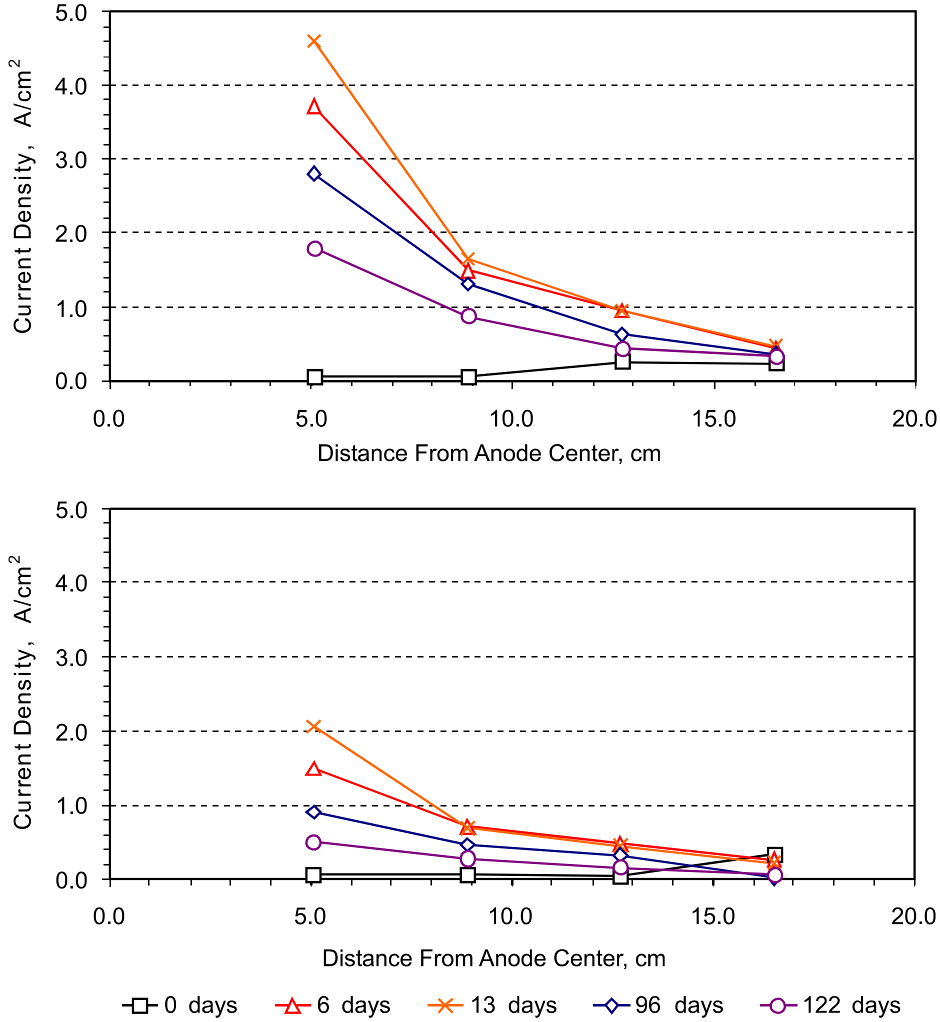


Figure 18. Current Density Measurements at Sacrificial Anode Monitoring Devices in (top) Pier 1 and (bottom) Pier 12

DISCUSSION

Half-cell potential measurements indicated that sacrificial anodes influenced the potential within the region of the shotcrete repair. A difference in response over time can be seen between the columns with anodes and the control column. In addition, this response in the shotcrete repair slowly becomes more positive as the potential difference becomes closer to the original concrete.

Current measurements indicate that anodes are being consumed, although most of the current flow occurred close to where the anode is connected to the steel. This is consistent with what would be expected from highly resistive shotcrete. After these current values are converted to current densities, based on the area of reinforcing steel, the amount of current flow per unit area reaches or even exceeds what some researchers have indicated are needed to reduce corrosion. Work by Pedeferri (1996) indicates that current densities between 0.05 and 0.2 $\mu A/cm^2$ can provide some benefit. Pedeferri indicated that within this current density range, the chloride threshold would be increased by at least one order of magnitude, whereas at higher current densities, ongoing corrosion is mitigated. Based on the measurements in piers 1 and 12 during the 4-month test period, this requirement was met at distances within 16 cm of the center of the anode.

CONCLUSIONS

- The sacrificial anodes are reaching the current density level needed to improve the resistance to chloride-induced corrosion.
- The anode current is able to reach a distance of 16 cm from the anode center and meet the requirements for cathodic prevention within this region.

RECOMMENDATIONS

1. The Virginia Transportation Research Council should continue to make routine measurements every 2 to 3 months to determine the seasonal affect temperature and humidity on corrosion rate and rate of anode consumption.
2. The Virginia Transportation Research Council should calculate life expectancy and life/cost benefit after 1 year of monitoring.
3. The Virginia Transportation Research Council should use visual evaluation and half-cell potential measurements once per year to determine if the anodes are successfully delaying the halo effect.

COSTS AND BENEFITS ASSESSMENT

Projected Anode Life

When estimating the life, it is important that the life calculation be based on data gathered during a complete calendar year. This is due to the nature of corrosion in this region, which generally undergoes high and low cycles with the seasons. In addition, it is possible that the life estimates will underestimate the life of these anodes because the measurements were gathered during the warmer months of the year, which is when corrosion rates are generally higher. Moreover, the shotcrete exhibited what will probably be its highest conductivity during a large portion of this study, which will most likely increase the rate of consumption of these anodes. However, it is also possible that not all of the anode material will be consumed if the anode passivates, which would then lead to an overestimation of the anode life.

If the anode life is determined using the fact that on average 5.5 percent of the anode is consumed in the first 130 days, these anodes can be expected to last 6.5 years. However, a linear extrapolation of the current measured from available data at days 21 and 104 (as shown in Table 7) would indicate that the current would decrease to 0 in approximately 1.4 years. The true life is likely to be closer to the former, as the current measured at 21 days is expected to be higher than over the service life of the anode. It is probable that the current will reach a lower, more or less steady state, with the influence of seasonal changes, within the latter part of the first year and remain there for the duration of the anode.

Table 7. Current Measurements at Two Times for Anode Life Calculation

Description	Current, μA @ day 21	Current, μA @ day 104
P1 Measurement Point 1	6.43E + 02	5.20E + 02
P1 Measurement Point 2	5.60E + 02	5.09E + 02
P12 Measurement Point 1	5.07E + 02	4.18E + 02
P12 Measurement Point 2	8.47E + 02	6.89E + 02
Average Value	6.39E + 02	5.34E + 02

Projected Life of Shotcrete Repairs

To determine which of the two alternatives (i.e., the use of shotcrete only or the use of shotcrete plus cathodic protection) will provide the greatest benefit to VDOT, cost analysis was performed using the capital recovery method. This method was selected because it is assumed that the two alternatives represent unequal lives and that the same repair technique will be reapplied at the end of the useful life. Table 8 lists the values used to make this calculation. Therefore, assuming the repair area is not dependent on the type of repair selected, the annual cost can be determined. In addition, it is assumed one anode could cover 2 ft^2. For these two alternatives, the annual cost is \$8.75/ft^2 and \$7.29/ft^2 for Alternative A and B, respectively. Therefore, Alternative B, i.e., shotcrete plus cathodic protection, is the best choice. VDOT

Table 8. Values for Cost Analysis

Description	Alternative A Shotcrete	Alternative B Shotcrete plus Cathodic Protection
Estimated life, yr	10	15
Initial cost, \$/ft^2	71	81
Interest rate, %	4	4
Maintenance cost, \$/yr	0	0

specifies approximately 4,333 ft^2 of shotcrete (Class A and Class B) repair each year at a cost of approximately \$71 per ft^2, for a total cost of \$307,643. Therefore, if this shotcrete is used in substructure surface repair, a 17 percent savings due to the installation of these anodes is \$51,332 annually.

ACKNOWLEDGMENTS

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