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16. Abstract

This study evaluated two half-cell mapping methods for nondestructive evaluation of epoxy-coated rebar (ECR) in concrete: the semi-fixed bi-electrode and the moving bi-electrode methods. These methods were expected to provide early detection of corrosion-related damage and ensure adequate time for repair. The techniques were evaluated by comparing the half-cell measurements using the two half-cell mapping techniques and measurements using the standard half-cell technique.

The study found that in concrete specimens the response of both bi-electrode techniques was similar to that of the standard half-cell technique. Each technique was sensitive enough to distinguish between ponded and unponded regions along the Type I test beams. Although additional research is required to determine exactly how sensitive either bi-electrode technique is for assessing corrosion of ECR in concrete, it is clear that the use of any nondestructive tool for condition surveys of bridge decks would benefit VDOT and Virginia.

The author recommends that the Type I test beams used in this study continue to be ponded until corrosion is initiated to aid in understanding the benefit of using the two bi-electrode methods during the various stages of corrosion. In addition, the Virginia Department of Transportation's Structure & Bridge Division should identify two structures that are beginning to show signs of corrosion, one bridge with ECR and the other with bare bar, to be used in a field study to determine if either bi-electrode method would benefit VDOT as a condition survey tool.

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FINAL REPORT

NONDESTRUCTIVE EVALUATION OF EPOXY-COATED REINFORCING BARS IN CONCRETE USING BI-ELECTRODE HALF-CELL POTENTIAL TECHNIQUES

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INTRODUCTION

In the late 1970s, the transportation sector began using epoxy-coated rebar (ECR) as a replacement for bare steel bars to mitigate corrosion in highway bridge decks. Then, in the Florida Keys in 1986, after only 5 to 7 years of service, corrosion became evident on bridges where ECR was used as the reinforcing steel.[1] Since then, the use of ECR in bridge decks has increased, as has the number of publications debating its ability to provide long-term corrosion protection.[1-4]

Regardless of the outcome of the debate, it is indisputable that the use of ECR has significantly increased since the late 1970s and that the decks are continuing to age. Therefore, an inspection method similar to the standard half-cell potential method (ASTM C876) would seem to be a valuable condition survey tool for many ECR bridge decks.   As shown in Figure 1, this simple technique can easily be applied in the field to determine the probability of corrosion.[5] Unfortunately, this method will not work with ECR because ASTM C876 requires a direct connection to the entire reinforcing steel network, which is not possible with ECR.[6] However, work by others has shown that a two half-cell mapping technique has worked favorably with bare steel bars.[7-10] It is conceivable that this or a similar technique may be applicable in the inspection of bridge decks constructed with ECR.
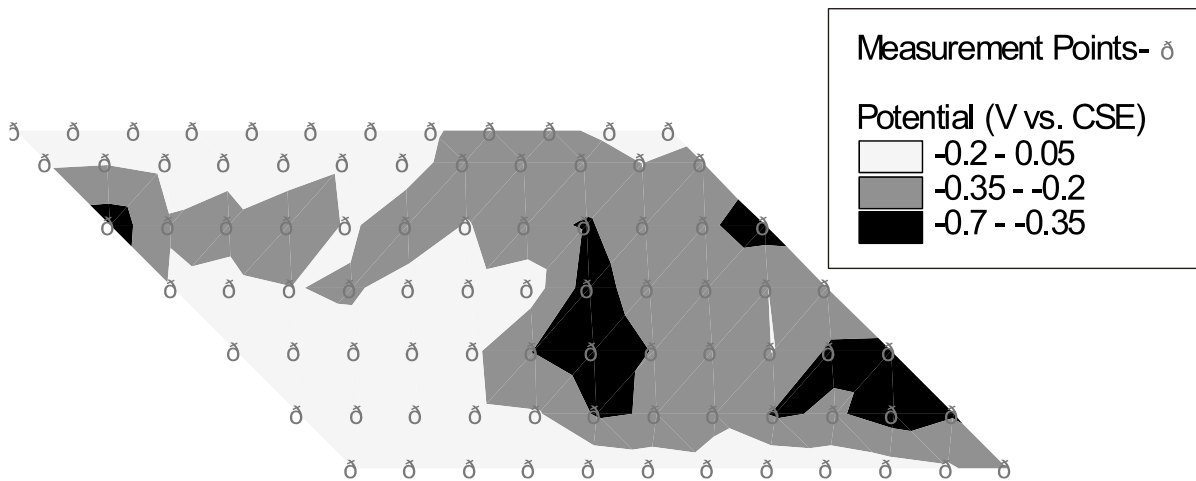

Figure 1.   Half-Cell Measurements from Bridge Deck Reinforced with Mild Steel. The points measured can be plotted as a contour plot to provide a "picture" of the structure's condition.

PURPOSE AND SCOPE

The objective of this study was to determine if bridges reinforced with epoxy-coated bars could be evaluated for corrosion potential using an inexpensive nondestructive technique. To accomplish this goal, two bi-electrode techniques were evaluated using laboratory specimens.

METHODS

Overview

Two tasks were performed to determine if it is possible for commercially available techniques to be adapted for nondestructive evaluation of concrete bridge decks reinforced with epoxy-coated bars:

1. *A half-cell study of a single bar embedded in a sand was conducted.* This task included embedding ECR in sand (one specimen containing a damaged bar and the other an undamaged bar), ponding the specimens with a saturated sodium chloride (NaCl) solution, and monitoring the specimens. To accomplish this task, testing included monitoring for changes in the potential along the bar using the standard half-cell, semi-fixed bi-electrode, or moving bi-electrode technique.

2. *A half-cell study of Type I test beams was conducted.* This task included casting concrete slabs; ponding them with a saturated NaCl solution; and monitoring for differences in the slabs cast with undamaged ECR, damaged ECR, or carbon steel rebar. To accomplish this task, testing included monitoring for changes in the potential along the bar using the standard half-cell, semi-fixed bi-electrode or moving bi-electrode technique. The regional temperature was recorded because the specimens were located outside.

Epoxy-Coated Rebar Specimens Embedded in Sand

Embedding a single No.5 ECR bar in sand provided a means of comparing two test bar conditions (damaged versus undamaged coating) using different half-cell measurement techniques. To embed the bars, two wooden boxes were constructed and lined with plastic, as illustrated in Figure 2. In each box, a single piece of ECR was placed. To simulate an abraded surface, the coating on the "damaged" ECR bar was removed at 48 in, which was located at the bar midpoint. (This damaged region can be more clearly seen in Figure 6, which shows the onset of corrosion in the damaged region following exposure to a neutral NaCl solution.) The bars were then placed in the box, the box was filled with sand, and the sand compacted. A 2.0-in depth of cover above the ECR was created by scraping off the excess sand so that the surface of the sand was flush with the top edge of the box. The sand was kept moist (determined through visual observation) by applying water periodically and keeping wooden boxes covered with plastic. Throughout the testing phase, the pH was neutral.
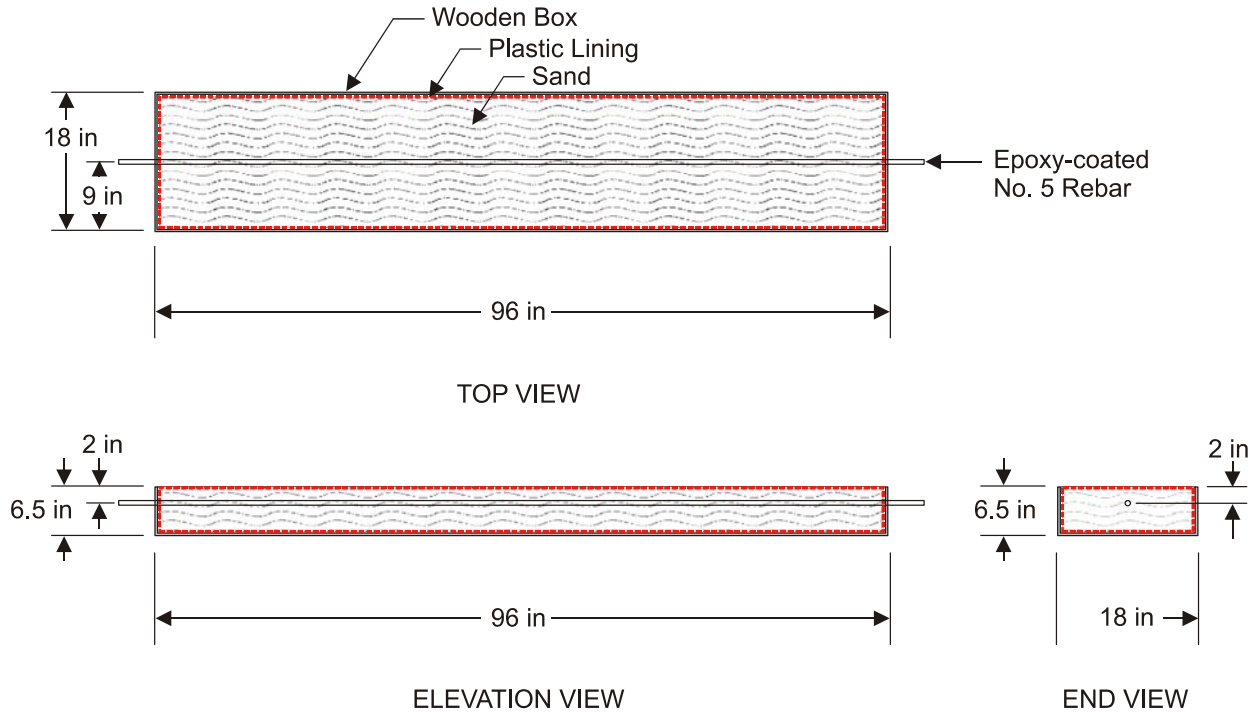
Figure 2. Specimen for Sand Study

Type I Concrete Beams

These test beams provided a means of comparing three test bar conditions (damaged, undamaged, and uncoated coating) using three nondestructive half-cell techniques. In addition, set locations over the bar were ponded with a saturated NaCl solution; the location were 12, 36, 60, and 84 in from the end of each beam. The ponding cycle was 1 week ponded, 1 week dry.

The reinforcing steel used in these specimens was a Grade 60, No. 5 bar. For the coated specimens, the epoxy coating complied with the requirements in ASTM A775.[11] The concrete mix design for the study is given in Table 1, and a description of the Type I test beams is given in Table 2. An illustration of a test beam is shown in Figure 3. In Figure 4, one of the damaged regions prior to corrosion is shown.

Table 1. Mix Design

Materials	Quantity/yd^3
Cement, lb (Lehigh Type I/II)	635
Stone, lb^a	1809
Sand, lb	1165
Water, gal	34.3

^{a}Granite stone No. 57 (3/4 in) 100% passing 1-in.

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Table 2. Description of Type I Concrete Test Slabs

Chloride Exposure Method	Width x Length	Cover Thickness	Test Bar (damage location measured from end, in)	Slabs Tested
Ponding	18.0 in x 96.0 in	2.0 in	ECR (No Damage)	1
Ponding	18.0 in x 96.0 in	2.0 in	ECR (12, 36, 60 and 84)	2
Ponding	18.0 in x 96.0 in	2.0 in	Bare Steel Bar	1

TOP VIEW
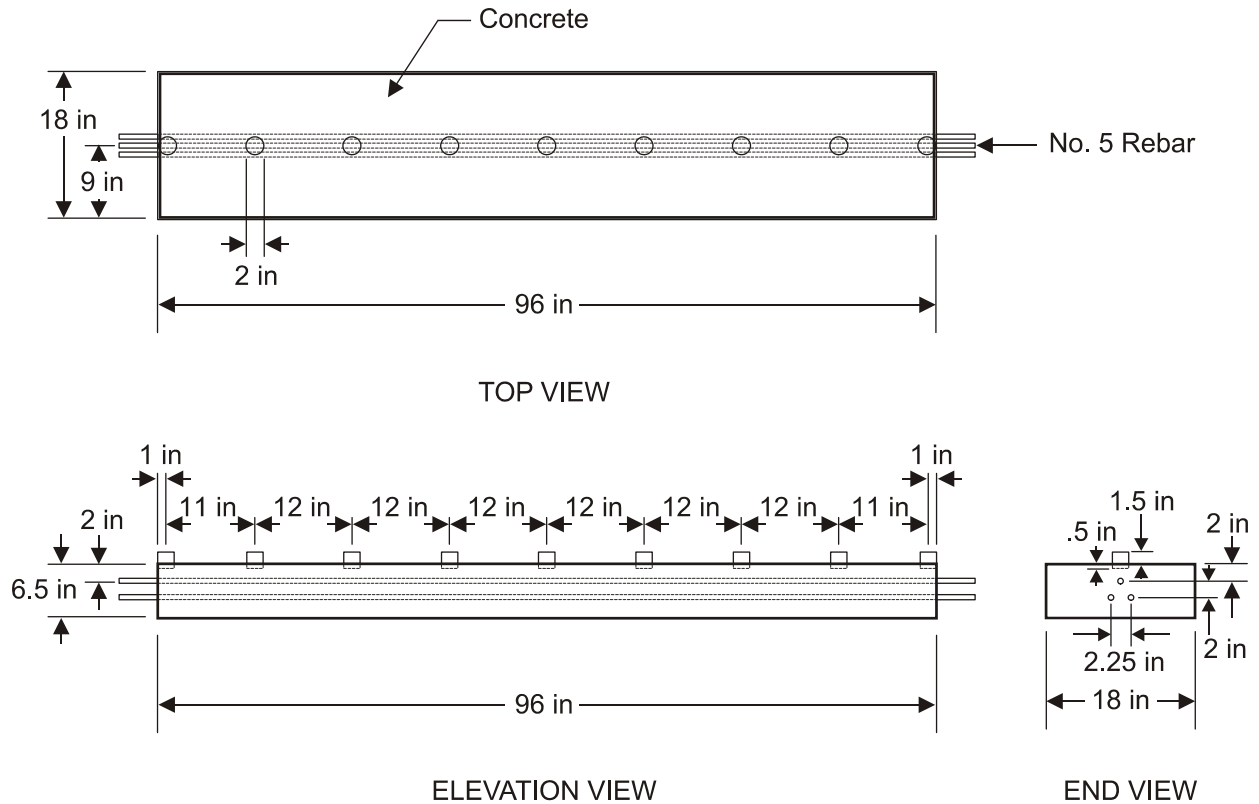
ELEVATION VIEW   END VIEW
Figure 3. Type I Concrete Test Beam

Figure 4. No. 5 Epoxy-Coated Bar Damaged Prior to Placement in Type I Concrete Test Beam. The black marking along the bar but below the damaged coating is from a permanent marker and is not part of the coating damage.

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Half-Cell Techniques

Three methods were used to measure the potential along a single steel bar: standard half-cell, semi-fixed bi-electrode, and moving bi-electrode techniques. ASTM C876 provided guidance when these measurements were performed except where deviations from the standard were required. Modifications during this study included the following:

- While the standard half-cell measurements were made, only the bar being measured was directly connected to the test lead.

- Silver/silver chloride (Ag/AgCl) half-cells were used when measurements were made on the Type I beams.

- During the semi-fixed bi-electrode and moving bi-electrode measurements, electrical contact was not made directly with the rebar.

- While the semi-fixed bi-electrode measurements were made, one half-cell remained stationary above the rebar while the other half-cell was moved along the length of the bar.

- When the moving bi-electrode measurements were made, the distance between the two half-cells remained constant.

Figure 5 illustrates the half-cell arrangement along the bar, and Table 3 summarizes the test methods used during this portion of the study.

To minimize confusion as to which type of half-cell was used for a set of measurements, the label on each axis in each figure indicates if the voltage was measured using a saturated
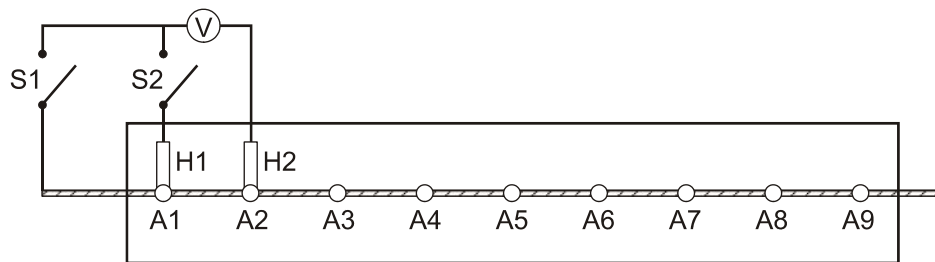
Figure 5. Top View Illustration of Half-Cell Arrangement Along Bar

Table 3. Description of the Three Methods Used to Evaluate ECR Embedded in Concrete

Method	Switch 1 (S1)	Switch 2 (S2)	Half-Cell 1 (H1)	Half-Cell 2 (H2)
Standard Half-Cell Method (ASTM C876)	Closed	Open	Nonfunctional	Functional (Measures A1 – A9)
Semi-Fixed Bi-Electrode Method	Open	Closed	Functional (Remains at A1)	Functional (Measures A2 – A9)
Moving Bi-Electrode Method	Open	Closed	Functional (Measures A1 – A8)	Functional (Measures A2 – A9)

copper/copper sulfate electrode (CSE) or a 0.6 M Cl⁻ silver/silver chloride electrode (Ag/AgCl/ 0.6 M Cl⁻ (seawater)). It is important to recognize, therefore, that since different electrodes were used for the embedded sand versus the concrete beam study, the different reference electrodes will naturally have a voltage difference between dissimilar types of reference cells, which is shown in ASTM G3.[12] This difference is significant, however, only when directly measuring the voltage difference between the steel and the reference half-cell, unlike measurements made using the bi-electrode techniques (measurements of differences between equivalent types of half-cells). ASTM G3 provides conversion factors for these two electrodes and other reference electrodes.[12]

After the embedded sand and Type I beam studies were completed, calculations using values from the standard half-cell measurements were used to evaluate the ability of the semi-fixed and moving bi-electrode methods to provide accurate data. For the semi-fixed case, this was done by calculating the difference between the standard half-cell measurements at T1 and all other test points. For the moving bi-electrode technique, the difference between each pair of adjacent standard half-cell values was determined. Then, for a given set of test points and test date, the calculated values were compared to the appropriate measured values.

RESULTS AND DISCUSSION

Study of Single Bar Embedded in Sand

Figure 6 shows the damage along the epoxy-coated bar after exposure to saltwater. In Figures 7 through 9, it is clear that the significant difference between the damaged and undamaged bars evident in Figure 7 is not observed in Figure 8 or 9. In these two figures, only a slight difference is seen, and considering the data error possible, the difference in these measured values is not significant between the damaged and undamaged bars using either the semi-fixed (Figure 8) or moving (Figure 9) bi-electrode techniques.

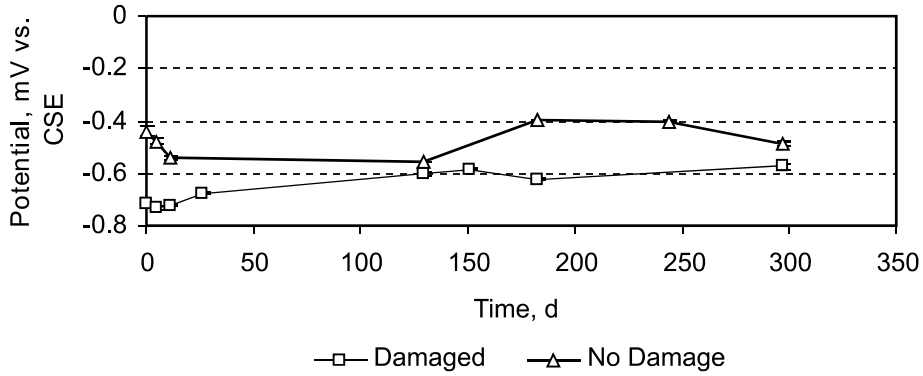**Figure 6. Damaged Region Along Epoxy-Coated Rebar**

Figure 7. Average Standard Half-Cell Measurement in Neutral Humid Environment
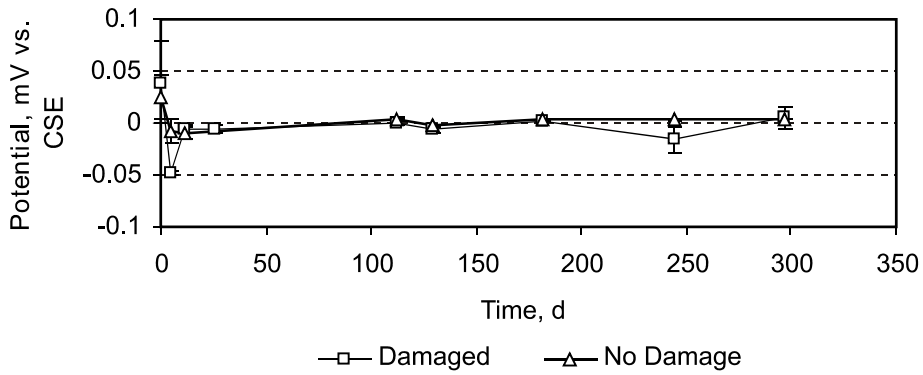

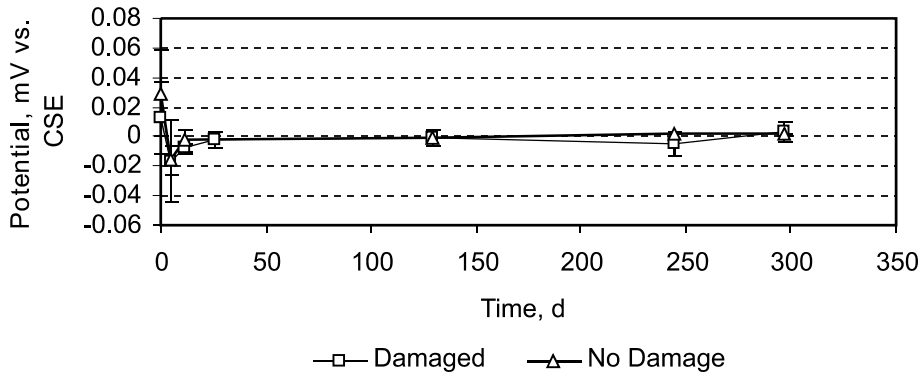**Figure 8. Average Semi-Fixed Bi-Electrode Measurements in Neutral Humid Environment**


Figure 9. Average Moving Bi-Electrode Measurement in Neutral Humid Environment

After the potential measurements over time were reviewed, a comparison was made between the measured semi-fixed bi-electrode measurements and the calculated values based on the standard half-cell measurements for undamaged and damaged ECR. As is shown in Figures 10 and 11, the undamaged case demonstrates a weak correlation between the standard method and the semi-fixed method, but the case with the damaged ECR shows no correlation between the calculated and measured values. Similarly, a comparison between the measured moving double half-cell measurements and calculated values, again based on the standard half-cell measurements, does not indicate a strong correlation. This can be seen in Figures 12 and 13.

7
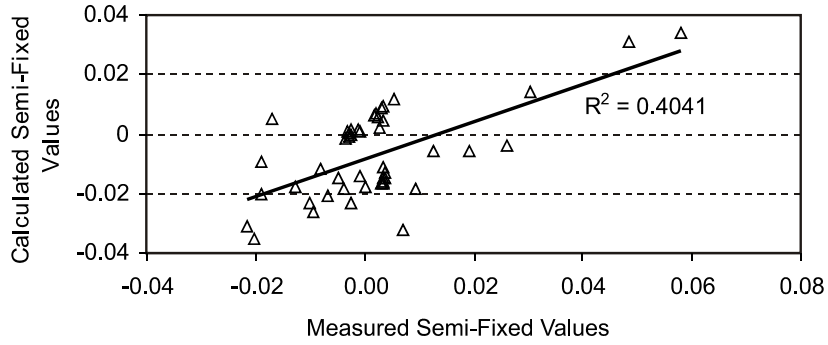
Figure 10. Calculated vs. Measured Semi-Fixed Bi-Electrode Values for Undamaged ECR in Neutral Humid Environment
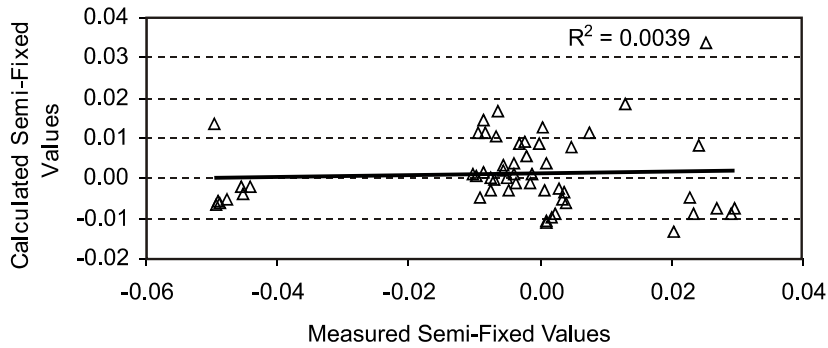
Figure 11. Calculated vs. Measured Semi-Fixed Bi-Electrode Values for Damaged ECR in Neutral Humid Environment
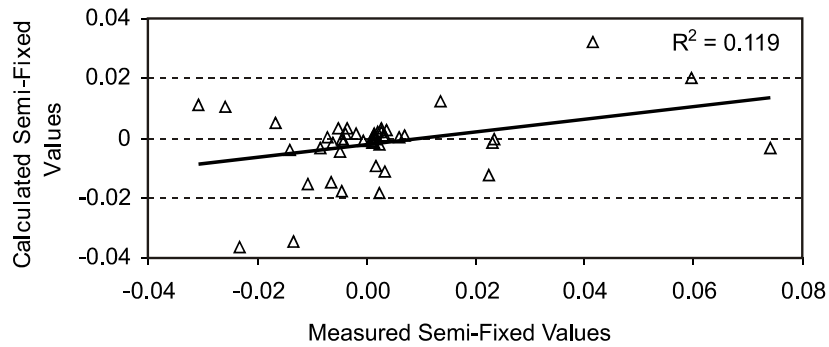
Figure 12. Calculated vs. Measured Moving Bi-Electrode Values for Undamaged ECR in Neutral Humid Environment
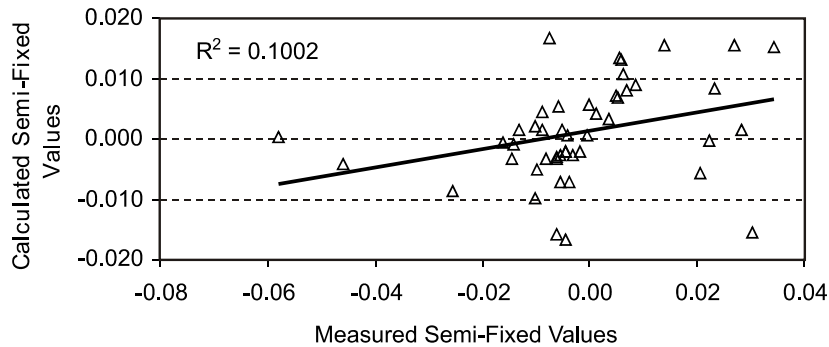
Figure 13. Calculated vs. Measured Moving Bi-Electrode Values for Damaged ECR in Neutral Humid Environment

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It was clear from the correlation plots that half-cell measurements of ECR in a neutral humid environment at most demonstrated a weak correlation. This is consistent with what is seen in Figures 7 through 9. However, it is important to emphasize that this test environment (ECR embedded in sand) is a different electrochemical test situation than is a bridge deck (ECR embedded in concrete). Research has shown that steel and epoxy respond differently when subjected to a chlorinated neutral environment as opposed to a chlorinated alkaline environment or chloride-contaminated cement paste, and it has also noted that care must be taken when interpreting results from bi-electrode techniques.[4, 13-15]

It was anticipated that embedding ECR in sand would provide a means of easily accessing the test areas while addressing any unforeseen difficulties that might arise with the different half-cell techniques. Ultimately, though, it was known that the true comparison between the different half-cell techniques would need to be done using ECR and bare steel rebar embedded in concrete.

Half-Cell Study on Type I Specimens

Regional Temperature

The temperature where the outdoor laboratory study was performed is known for seasonal changes, and these changes can influence the values measured using half-cells. Figure 14 shows the change in temperature recorded during this study for the region; these data were gathered from the National Climatic Data Center (NCDC), Monticello Station. This weather station is approximately 4 miles from the outside specimen test site.
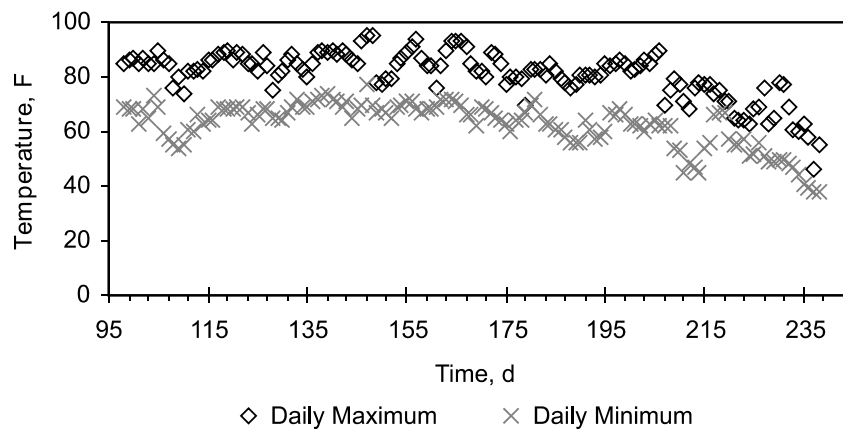

◇ Daily Maximum   ✕ Daily Minimum

Figure 14. Average Regional Air Temperature

**Measurements using Different Half-Cell Techniques on Type I Specimens**

The three half-cell techniques provided interesting results, depending on how the results were plotted. Figures 15 through 17 are plots of the average measurement over time. In all three plots, on average, each bar type exhibited some fluctuations in potential but generally maintained a constant slope. In Figures 16 and 17, the overall trend of the slope is negative, whereas in Figure 15, except for the undamaged ECR, the slope is closer to zero. After these three figures are reviewed, it might be assumed that none of the bars is undergoing any kind of change.
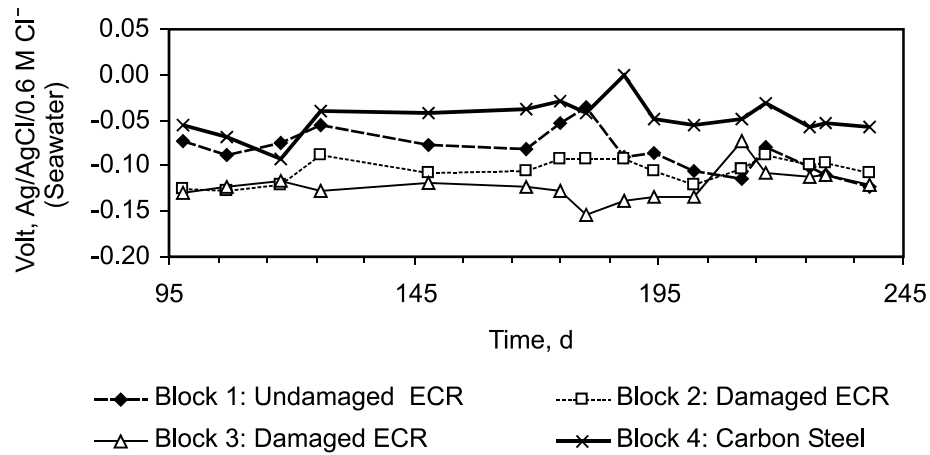
Figure 15. Average Half-Cell Measurement Using Standard Method
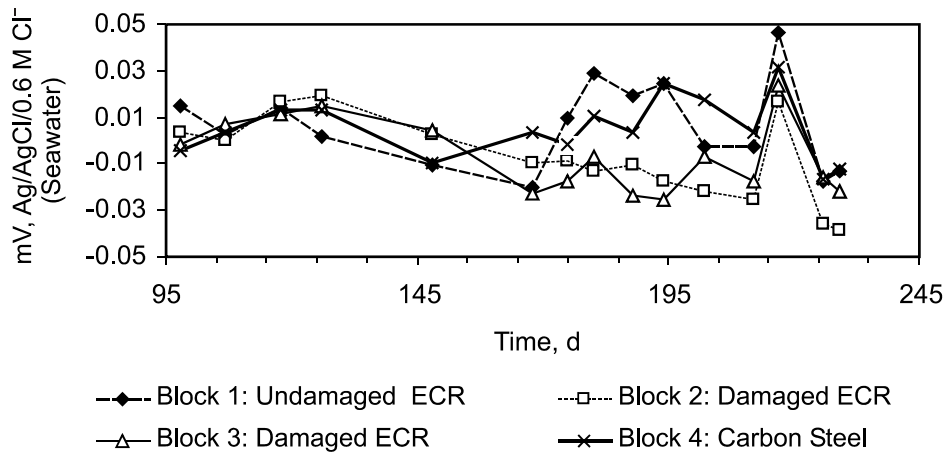
Figure 16. Average Half-Cell Measurement Using Semi-Fixed Bi-Electrode Method
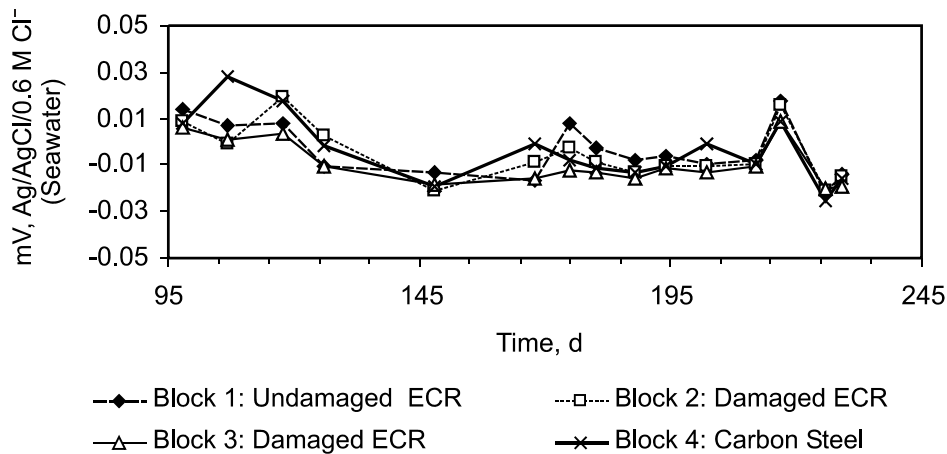
Figure 17. Average Half-Cell Measurement Using Moving Bi-Electrode Method

Although it might appear in Figures 15 through 17 that very little change is occurring within the concrete, Figures 18 through 26 reveal a very different picture. In these figures, the plots show the response of each test spot along the beam. Each spot was either ponded or not and was situated above a damaged epoxy coating, an undamaged epoxy coating, or an uncoated steel surface. It is clear that during the warmer months (shown in Figure 14) there was a separation in potential between each group of plotted measurements. The average precipitation increases during the warmer months, which could influence the moisture condition of these test beams. However, as the season changed and temperatures become colder, the data began to overlap again. It is interesting that these trends are observed in each plot and are not dependent on the half-cell method used.

A second interesting observation in Figures 18 through 26 is the influence of ponding. Again, independent of the half-cell measurement used, the introduction of ponded and unponded regions along the test beam produced a distinct separation in the measured values. This separation was observed with all of the test beams, regardless of the coating condition of the steel. This is consistent with the article by Gu et al., which indicated that not only does the steel surface influence the bi-electrode potential, but theoretically, the resistance of the concrete can also be a factor.[14]
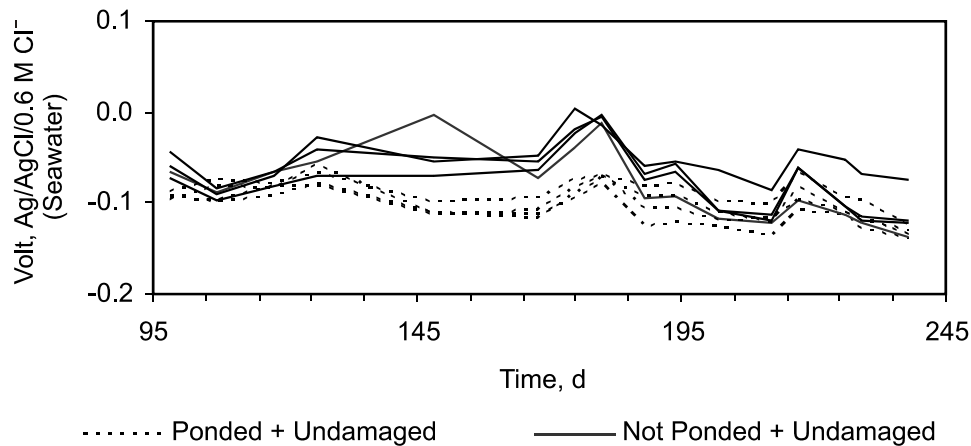

······ Ponded + Undamaged   ——— Not Ponded + Undamaged

Figure 18. Standard Half-Cell Measurement of Undamaged ECR Embedded in Concrete

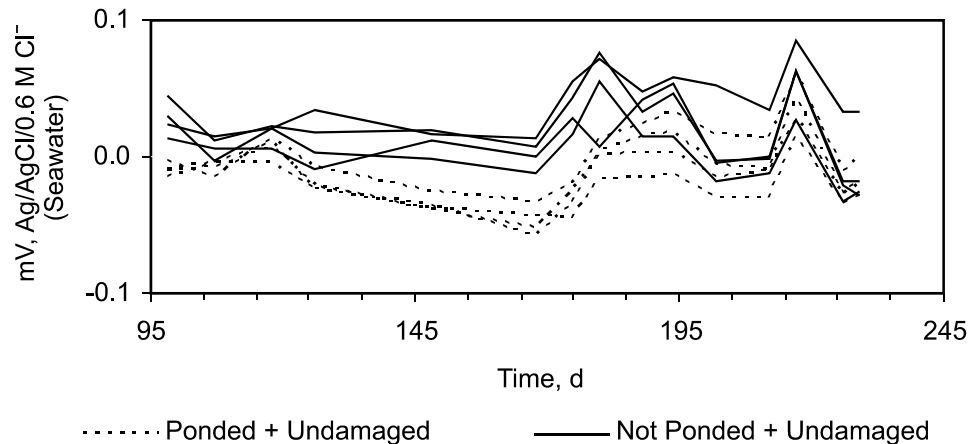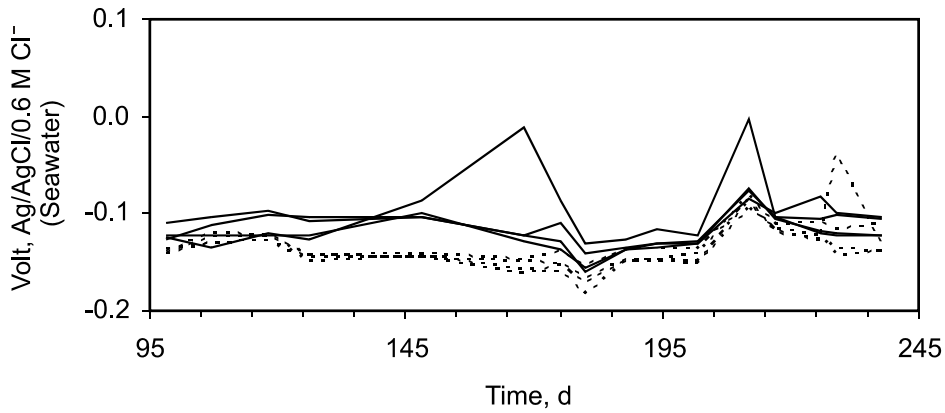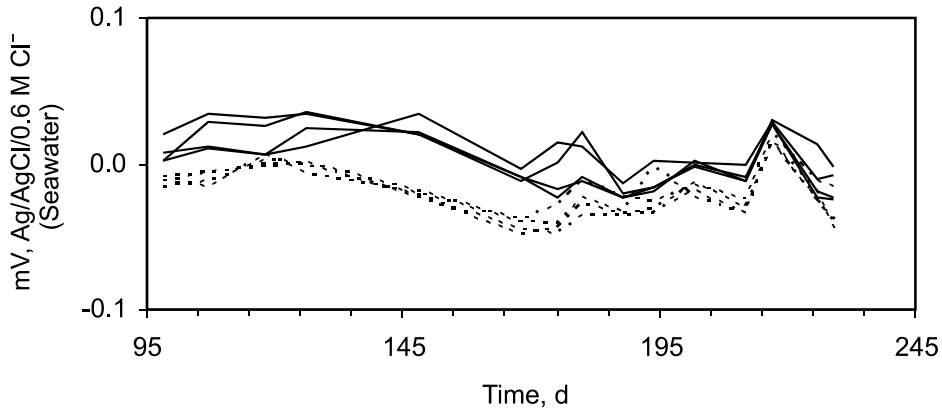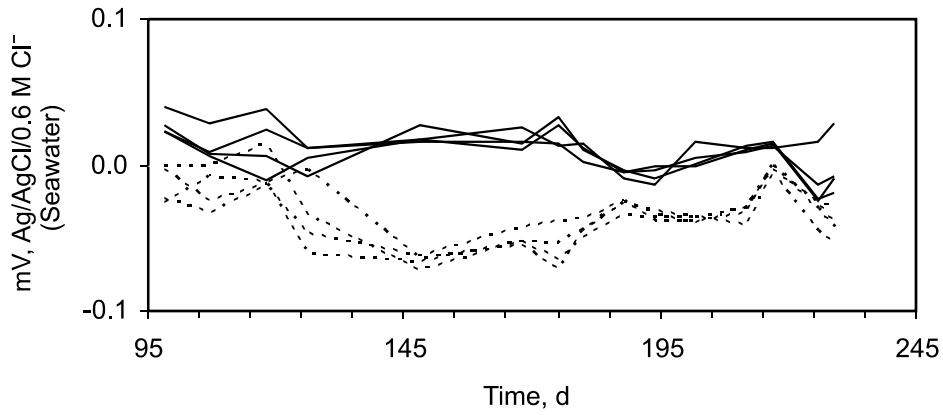······ Ponded + Undamaged   ——— Not Ponded + Undamaged
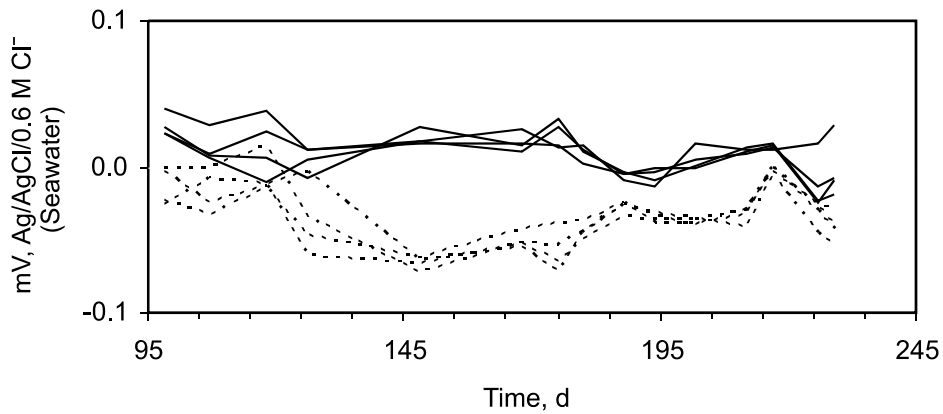
Figure 19. Semi-Fixed Bi-Electrode Measurement of Undamaged ECR Embedded in Concrete

11
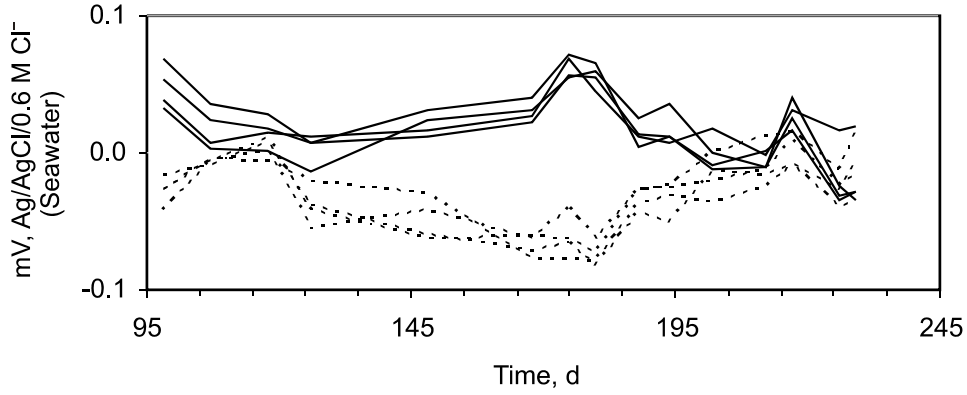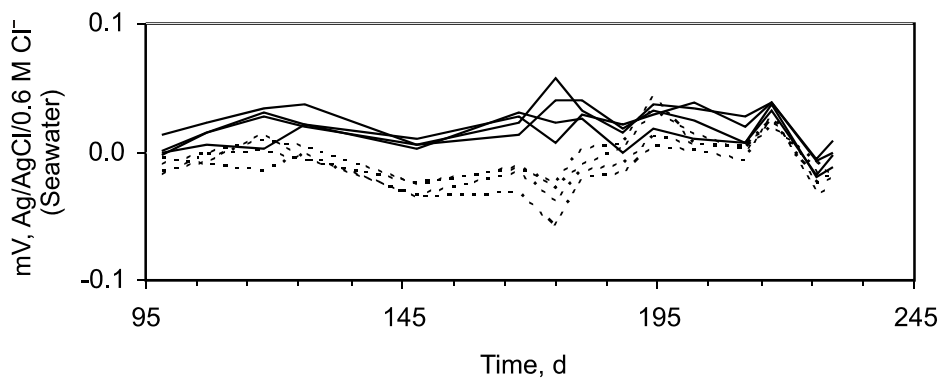
Figure 20. Moving Bi-Electrode Measurement of Undamaged ECR Embedded in Concrete

Figure 21. Example of Standard Half-Cell Measurement of Damaged ECR Embedded in Concrete

Figure 22. Example of Semi-Fixed Bi-Electrode Measurement of Damaged ECR Embedded in Concrete

Figure 23. Example of Moving Bi-Electrode Measurement of Damaged ECR Embedded in Concrete

Figure 24. Standard Half-Cell Measurement of Bare Steel Rebar Embedded in Concrete

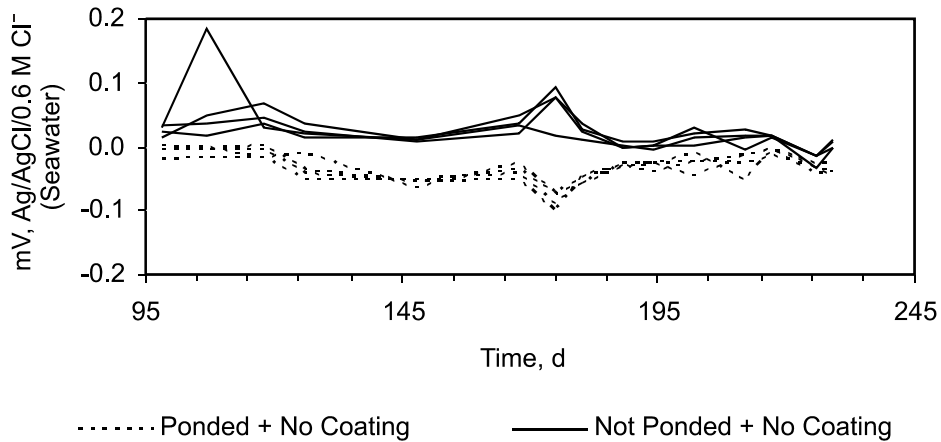**Figure 25. Semi-Fixed Bi-Electrode Measurement of Bare Steel Rebar Embedded in Concrete**

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Figure 26. Moving Bi-Electrode Measurement of Bare Steel Rebar Embedded in Concrete

The correlation plots between the calculated and measured half-cell values for the Type I test beams are shown in Figures 27 through 32. Other researchers have indicated that the use of a bi-electrode technique on a bare steel bar can provide a better understanding of the condition of the steel and can be used as a condition survey tool.[7-10] For comparison purposes, therefore, measurements using the two bi-electrode techniques on embedded steel became the standard upon which the measurements were judged.

Upon reviewing Figures 27 through 29, the semi-fixed bi-electrode case, a stronger linear correlation was observed for ECR embedded in concrete as opposed to embedded bare steel. Next, upon examining Figures 30 through 32, the moving bi-electrode method, a slightly higher correlation value was determined for the bare steel bar verses the damaged ECR. However, it is important to note that when compared to the semi-fixed bi-electrode method that on average the moving bi-electrode method demonstrated a stronger correlation to the calculated values that were based on the standard method.
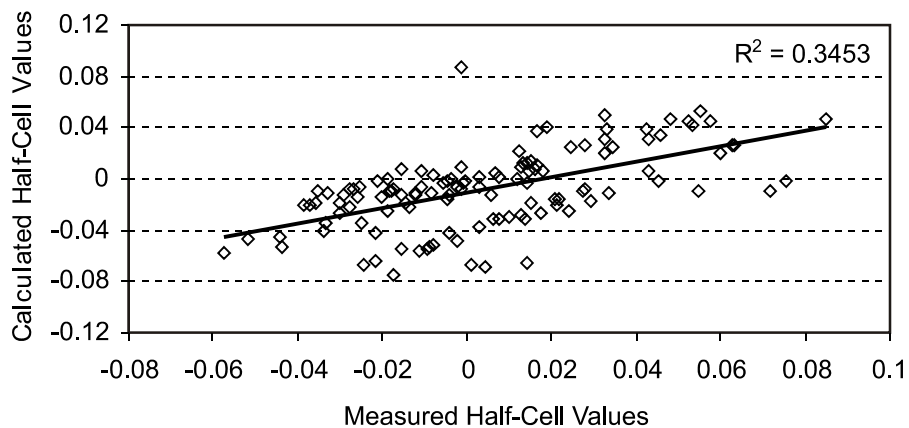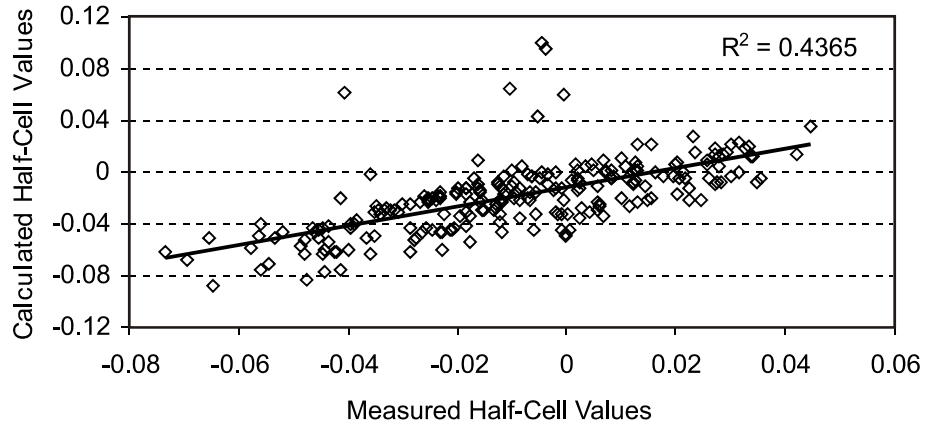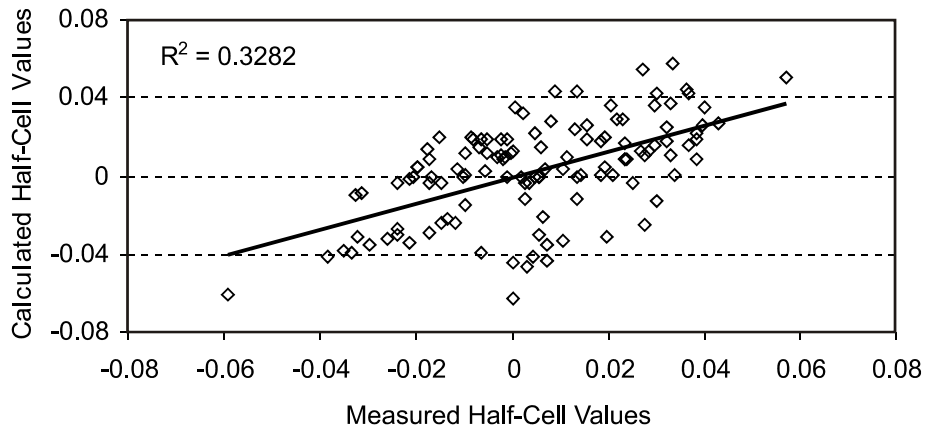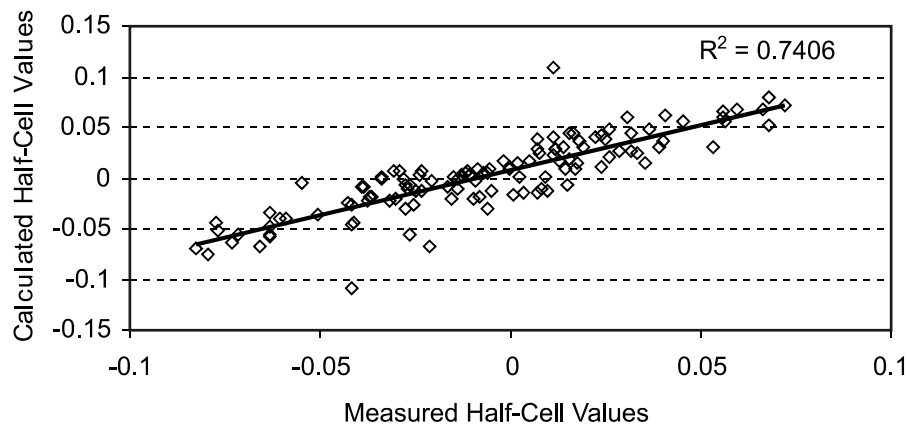

Figure 27. Calculated vs. Measured Semi-Fixed Bi-Electrode Values for Undamaged ECR Embedded in Concrete

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Figure 28. Calculated vs. Measured Semi-Fixed Bi-Electrode Values for Damaged ECR Embedded in Concrete

Figure 29. Calculated vs. Measured Semi-Fixed Bi-Electrode Values for Bare Steel Rebar Embedded in Concrete

Figure 30. Calculated vs. Measured Moving Bi-Electrode Values for Undamaged ECR Embedded in Concrete
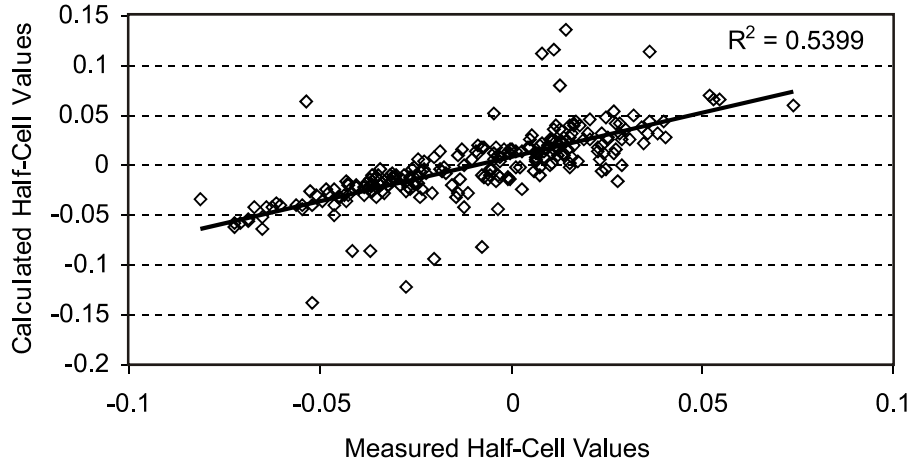
Figure 31. Calculated vs. Measured Moving Bi-Electrode Values for Damaged ECR Embedded in Concrete
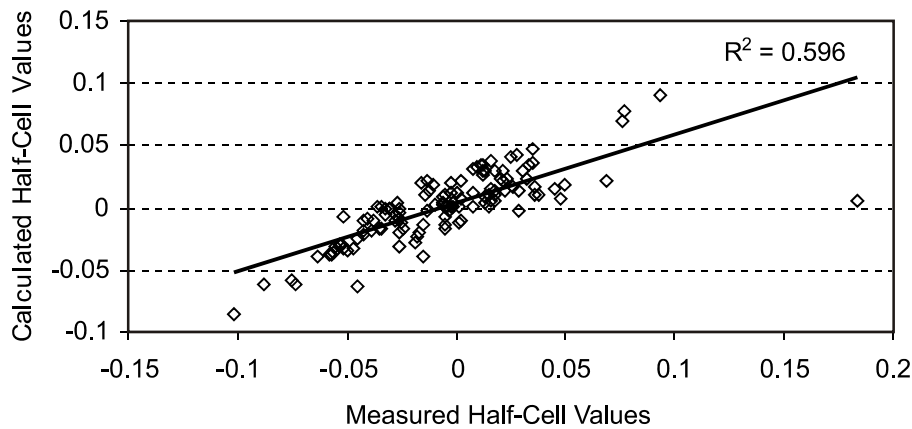

Figure 32. Calculated vs. Measured Moving Bi-Electrode Values for Bare Steel Rebar Embedded in Concrete

A summary of these observations and the criteria used to evaluate the bi-electrode techniques are provided in Table 4. Based on the criteria listed, the semi-fixed bi-electrode method performed better than did the moving bi-electrode method. It is important to note, however, that the moving bi-electrode method correlated reasonably well with the calculated values based on measurements using the standard half-cell method.

Table 4. Comparison Among Three Half-Cell Techniques

Technique	Consistent Over Time	Influence of Different Test Conditions Identified	R^2 Value Greater Than That for Bare Steel Bar in Concrete
Standard Half-Cell Method	Yes	Yes	N/A
Semi-Fixed Bi-Electrode Method	Yes	Yes	Yes
Moving Bi-Electrode Method	Yes	Yes	No

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Although this research has shown a reasonable correlation among the three methods, the Type I test beams (shown in Figure 33) are not displaying any signs of corrosion. This is expected since they are less than 1 year old. However, it is anticipated that as the magnitude of the anodic and cathodic potentials continues to grow, the techniques will correlate reasonably well with the standard half-cell method. Further, because these techniques are providing early indications of differences along the test beams, the semi-fixed bi-electrode method, and possibly the moving bi-electrode method, could prove valuable as a condition survey tool for bridge decks reinforced with ECR.

Figure 33. Type I Test Beams at 1 Year

CONCLUSIONS

1. The response to the semi-fixed and moving bi-electrode techniques was similar to the response to the standard half-cell technique, demonstrating the ability to show a difference between ponded and unponded regions along the Type I test beams.

2. On average, the moving bi-electrode technique showed a stronger correlation than the semi-fixed electrode technique to calculated values based on measurements using the standard half-cell method

3. When compared to measurements of bare steel rebar embedded in concrete, the semi-fixed electrode measurements of ECR were more strongly correlated with the calculated values based on measurements using the standard half-cell method.

RECOMMENDATIONS

1. *The Virginia Transportation Research Council Materials Team should continue to pond Type I test beams, initiate corrosion and evaluate the benefit of using the two bi-electrode methods during the various stages of corrosion.*

2. *VDOT's Structure & Bridge Division should identify two structures that are beginning to show signs of corrosion, one bridge with ECR and the other with bare bar, for use in a field study to determine if either bi-electrode method would benefit VDOT as a condition survey tool.*

ACKNOWLEDGMENTS

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