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Evaluation of Reinforcement Corrosion in Repaired Concrete Bridge Slabs—A Case Study

S. Qian,^{†*} D. Cusson,^{*} and N. Chagnon^{*}

ABSTRACT

Results of a study of reinforcement corrosion in four repaired concrete slab sections taken from an old bridge are presented, as well as results measured on electrochemical cells. Significant evidence is provided to help the inspection engineer to interpret the corrosion survey data taking into account the specifics of the environmental conditions that prevailed during the survey. The measurements comprised half-cell potential, linear polarization, and concrete resistivity, which are known to be sensitive to the ambient environment, especially to oxygen and water in concrete. Some semi-destructive tests, including chloride concentration, chloride permeability, and carbonation depth, were also carried out to assist the analysis and to support the results of the nondestructive corrosion testing techniques. The concrete cover of the slab samples was later removed to assess the actual state of corrosion of the reinforcement and to compare it to the corrosion predicted from the corrosion surveys. This study shows that each corrosion measurement technique has its specific advantages and limitations. Better prediction of corrosion can be obtained by analyzing the data collected from various evaluation methods with careful consideration for the effects of environmental conditions.

KEY WORDS: concrete bridges, current density, electrical resistivity, half-cell potential, reinforcing steel

INTRODUCTION

A large number of highway bridges are made of reinforced concrete and have shown serious deterioration as a result of reinforcement corrosion, particularly those bridges more than 20 years old.¹ Extensive bridge deterioration can affect safety and serviceability, and may result in loss of life or injury, traffic disruption, and high users' costs.

Corrosion-induced deterioration of concrete bridges is caused by the breakdown of the passive film on the steel reinforcement as a result of chloride attack or carbonation. When the concentration of chloride ions in concrete exceeds the chloride corrosion threshold, the passive film breaks down and localized corrosion initiates. Chloride attack is the main cause of bridge corrosion, particularly in Canada and the northern U.S., where bridges suffer from the heavy use of deicing salts. When embedded steel corrodes, the resulting voluminous corrosion products induce internal stresses in the concrete surrounding the reinforcement. The tensile stresses eventually exceed the concrete tensile strength, leading to cracking and spalling of the concrete cover.

There are many techniques or devices available to investigate corrosion in reinforced concrete. However, there is no single technique that will adequately inform the engineer about the quantity and rate of corrosion or damage growth in the structure.² The bridge inspector will have to gather information from different corrosion evaluation techniques to get an accurate assessment of the state of corrosion-induced damage in the concrete structure.

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Since the early 1980s, the half-cell potential measurement method for identifying corrosion on reinforcing steel bars in concrete has been widely used because of its simplicity and cost effectiveness.³⁻⁴ This method allows evaluation of the probability of corrosion activity through the measurement of the potential difference between a standard portable reference electrode and the reinforcing steel. However, it is unable to determine the corrosion rate or the degree of corrosion that has occurred. The data analysis guidelines described in ASTM C876-99 provide general principles for the evaluation of corrosion probability of reinforcing steel in concrete structures. A large discrepancy between the condition assessment based on the ASTM guidelines and the actual condition has been observed in many bridges when they were about to undergo repair.⁵ It is known that the ASTM guidelines do not indicate precisely how to deal with factors such as oxygen and chloride concentrations, or temperature and moisture content in the interpretation of the half-cell potential data. For instance, studies on European bridge decks, where waterproofing membranes are used or where deicing salts are applied less frequently, have resulted in different interpretation guidelines.⁶

Measuring concrete electrical resistivity is relatively simple. Several studies have shown that the measured resistivity values are closely related to the actual corrosion rates in the structure.⁷⁻⁸ However, changes in the moisture and salt contents affect the resistivity measured at the concrete surface and therefore complicates evaluation of the corrosion rate.

The electrochemical technique for quantitative assessment of the corrosion rate in concrete is the polarization resistance method. Measurements can be done using permanently embedded reference and counter electrodes^{4,9} or external electrodes placed on the concrete surface.¹⁰ There are several difficulties associated with this technique:

- The electrochemical current at the fixed potential should be constant during the entire polarization time.

- The polarized surface area should be known.¹¹

- The current distribution should be uniform.

- The effect of high electrical resistance of concrete should be eliminated.

These conditions are often difficult to achieve. Moreover, this technique measures only the instantaneous corrosion rates of the reinforcement; it does not necessarily reflect the long-term corrosion rate, which can fluctuate or change significantly in a very short time¹² due to changes in temperature, oxygen content, and moisture content. It has been reported¹³ that in the case of localized pitting, corrosion rates can be 5 to 10 times larger than regular corrosion rates.

This article presents an examination of the key factors affecting the corrosion process and corrosion

assessment under specific conditions, with the objective of providing additional experience and evidence for an improved and more reliable prediction of the corrosion activity of reinforcing steel in concrete slabs by using nondestructive corrosion measurements.

RESEARCH SIGNIFICANCE

Many bridge owners or their consultants rely only on a single, nondestructive evaluation technique, most often the half-cell potential survey to assess the corrosion condition of their concrete bridges. Often, it is found during demolition that the extent of corrosion damage is different from that predicted by the survey. This, of course, results in additional unplanned costs for the bridge owner and possibly longer construction delays for the users.

Recent studies¹ reported that half-cell potential data, under some circumstances (such as different concrete moisture contents, temperature, and oxygen and chloride concentrations), can be misinterpreted and therefore lead to wrong or inadequate conclusions. It is more appropriate to use a combination of three or more corrosion evaluation techniques to assess the corrosion state in concrete structures.¹⁴

The assessment of corrosion has also become more challenging as a result of the rising popularity of new concrete and repair technologies such as dense material overlays, concrete sealers, corrosion inhibitors, and other chemical admixtures. Information on corrosion assessment in heavily repaired concrete structures (with large concrete cover >75 mm) is not generally available. More research is needed to improve understanding of the complex electrochemical effects induced by repair materials on the existing substrate concrete.

Significant evidence is given in this paper to help the inspection engineer to interpret the corrosion survey data depending on the specifics of the environmental conditions that prevailed during the survey. For instance, a shift in the half-cell potential toward more negative values by 500 mV was found possible on a corroded steel electrode in the electrochemical cell when oxygen concentration was depleted. A similar potential shift of 200 mV was also measured on a steel electrode embedded in a concrete sample.

EXPERIMENTAL PROCEDURES

Concrete Slab Samples

The highway bridge selected for the study was the Old Perley Bridge, located in Hawkesbury, Ontario, Canada. The bridge, owned by Public Works and Government Services Canada (PWGSC), was built in 1931 and had been repaired extensively between 1974 and 1998 (Figure 1). The bridge deck consisted of simply supported reinforced concrete

FIGURE 1. View of the concrete bridge deck showing the severe state of repair.

slabs on steel girders. Four concrete slab sections (Slabs 1 through 4 in Figure 2) were cut and transported to National Research Council Canada (NRC) labs for testing (Figure 3). Each slab sample was ~3,150 mm long (in the traffic direction), 1,150 mm wide, and 280 mm thick, and had a concrete cover of ~140 mm to the top reinforcement. The top reinforcement layer in each slab section was composed of five 15-mm-diameter longitudinal bars, spaced at 230 mm, and six 12-mm transverse bars, spaced at 450 mm (Figure 4). The thickness of the repair concrete overlay varied between 50 mm and 90 mm, depending on the location on the slab sections.

Internal relative humidity and temperature (RH/T) were measured by 16 embedded sensors connected to an automated data logging system. In each slab section, four sensors were installed at the center of each quarter of the slab at the top reinforcement level. The sensors were inserted in drilled holes from the bottom slab surface as shown in Figure 4.

Following the electrochemical measurements, cores were taken from the cover of the slabs to determine its material properties. Compressive strength, pull-off strength, and chloride ion permeability were measured according to ASTM C39M99, D4541-95e1, and 1202-97, respectively. Carbonation depth was tested using a phenolphthalein pH indicator solution. Chloride content was determined by the potentiometric titration of chloride with silver nitrate as described in ASTM C114-00. This last test was carried out on 50-mm-diameter cores at 5-mm-depth increments from the top surface down to the rebar level in each slab.

Conditioning of the Slab Samples for Corrosion Testing

Three sets of corrosion measurements were carried out using the same procedure on the four slabs between June 1999 and December 1999. To simulate environmental conditions in the laboratory, to which

FIGURE 2. Location of slab samples on Span 18 before demolition.

FIGURE 3. Laboratory setup of Test Slabs 1 through 4.

a bridge slab is exposed during service, identical water conditioning was imposed on the four slabs between sets of measurements. Figure 3 illustrates the water dams built on each slab. They consisted of rigid polystyrene strips that were bonded on the perimeter of the top slab surface with construction adhesive.

The first set of measurements was made in June 1999, 2 months after receiving the samples, which were left drying in the lab (50% RH, 23°C). Afterward, the four slab samples were covered with 50 mm of tap water for 2 months and the water was removed on September 1, 1999. The slab samples

FIGURE 4. Locations of half-cell potential measurements and RH/T sensors.

were then left drying in the lab for 1 week before a second set of corrosion measurements was performed. Following these measurements, the four samples were subjected to identical biweekly wet/dry cycles for a 2-month period. The third set of corrosion measurement was then performed in December 1999, 48 h after removal of water.

In each set of measurements, the half-cell potential was taken first, followed by the concrete resistivity and the corrosion rate. The locations of the half-cell potential and corrosion rate measurements were chosen to evaluate the condition of the rebars in both directions (Symbol "x" in Figure 4). The concrete resistivity measurements were located over the longitudinal rebars only. All electrochemical measurements were performed on the concrete surface directly over the rebars halfway between the intersections of longitudinal and transverse rebars.

Electrochemical Measurements on the Slab Samples

A saturated copper/copper sulfate reference electrode (CSE) and a multimeter with an input impedance $>1,000 \text{ M}\Omega$ were used to measure the half-cell potential on the slab samples following the procedure provided in ASTM C876-99. The CSE electrodes were regularly compared with other reference electrodes to ensure their stability.

Corrosion rate measurements were made using Sensor A of the GECOR6[†] unit.¹⁵ The unit uses an external guard ring to confine the applied electrical current to a known rebar area.¹⁶⁻¹⁷

[†] Trade name.

Resistivity measurements were made using Sensor B of the corrosion rate measurement unit. This unit applies a pulse signal and measures the IR drop between the reference electrode and the bar, allowing the polarization potential at the sensor and the rebar surface to be eliminated. Each measurement was an average of two or three readings.

Visual Inspection and Rating of Reinforcement Corrosion

After completion of the corrosion measurements on the slabs, the concrete cover on the top layer of the reinforcement was removed with a jackhammer to expose the top reinforcement for visual inspection to evaluate and confirm the predictions based on the previously conducted nondestructive corrosion measurements. The state of the reinforcing bars was then carefully rated at every location where corrosion measurements were taken. Three corrosion levels were identified, as shown in Figure 5. Level 1 is for a bar with no visible rust products on the surface, which is probably still in a passive condition. Level 2 is for a bar with a little rust at the surface. Level 3 is for a bar on which a thick rust product has built up. It is important to mention that the corrosion rating was only based on the actual state of corrosion visible on the top surface of the first layer of reinforcement. Pitting corrosion, for instance, was not taken into account since it is often not easily observed by the naked eye.

Measurements in an Electrochemical Cell

To provide new evidence and to support the data collected on the slab samples, additional experiments

were also carried out in an electrochemical cell using two identical steel electrodes but under different surface conditions: passivated and corroded. The electrode potentials with nitrogen (N_2) or oxygen (O_2) bubbling were measured and recorded by a potentiostat connected to a computer. Samples of carbon steel reinforcing bars were machined to 8 mm in diameter and embedded in epoxy resin to ensure a reproducible and well-defined surface area. The working surfaces of the electrodes had a final polish using no. 600 silicon carbide (SiC) papers. The electrodes were then immersed in an electrochemical cell containing a saturated calcium hydroxide [$Ca(OH)_2$] solution with a pH of 12.6. Before immersion in the electrochemical cell, the corroded electrode surface was created by exposure to humid air until a thin layer of brown corrosion product formed on the steel surface. The cells were deaerated and oxygenated by bubbling high-purity N_2 or O_2 gas through the solution.

Measurements on a Concrete Prism in the Laboratory

Half-cell potential measurements were also done in the laboratory on a concrete prism (540 by 140 by 120 mm) made from type-10 Portland cement with a water:cement:sand:aggregate ratio of 0.4:1:2:3 by weight. The 28-day strength was 30 MPa. A partially-corroded 15-mm-diameter rebar was located along the longitudinal axis of the prism with a minimum 50-mm concrete cover. The prism contained 1% calcium chloride ($CaCl_2$) by weight of cement.

Before the test, the concrete prism was fully immersed in tap water for 16 h. The sides of the prism were sealed using plastic sheets with only the top side exposed to air for water evaporation. A copper/copper sulfate ($Cu/CuSO_4$) reference electrode and a potentiostat were used for the measurements, and the half-cell potential values were continuously recorded on a digital oscilloscope. This test was carried out in a room at 50% RH and 23°C.

RESULTS AND DISCUSSION

Initial Conditions of the Concrete Slabs

Tests on cores indicated that the concretes in the substrate and repair layers had relatively high compressive strengths (45 MPa to 51 MPa for the old concrete and 48 MPa to 65 MPa for the repair concrete). However, the pull-off strengths of the concrete samples varied from 0 MPa to 3.2 MPa and all failures occurred at the interface of the substrate and the repair layer, which indicates that the interface was the weakest element of the slabs. A visual inspection indicated no concrete spalling at the top surface of the slab. There were a few horizontal cracks between the substrate and the new overlay, as observed from the cut sides.

FIGURE 5. Rebar samples representing the three levels of corrosion observed in the survey.

The measured chloride ion penetrability in the repair layer was low, as the count of electrical charges that passed through the cores after 6 h was between 1,315 Coulomb and 1,922 Coulomb for the test slabs. The chloride content at the rebar level, however, was far above the chloride threshold value (0.02 wt% of concrete)¹⁶ in some areas despite the low chloride ion penetrability of the patch layer. The reason is that a deep enough layer of salt-contaminated concrete had not been removed before the repair layer was installed in the field. A small carbonation depth was measured at the surface of the slab cores (<2 mm), which was due to the relatively young age (a few years) of the repair patches that covered the concrete deck slabs.

The RH at the top reinforcement level was found to be relatively high during the monitoring period (from June to December 1999) with values >91% in Slab 1 and >95% in Slabs 2, 3, and 4. The RH at the top reinforcement level increased by only 1% to 2% due to water conditioning over the entire monitoring period. This is attributable to a thick concrete cover and a relatively high density of the repair material.

Since the RH at the rebar level hardly changed during the water conditioning period, the effect of the conditioning on the half-cell potential and the corrosion current measurements was found to be insignificant. Therefore, only one set of results (June 1999) for the measurements of half-cell potential and corrosion rates is presented in this paper.

Half-Cell Potential of the Reinforcement

A large number of closely spaced half-cell potentials were taken on the four slabs. The potentials are plotted in the form of an equipotential contour map in Figure 6. The results of the visual corrosion inspection and the ratings of the corrosion state after removal of the concrete cover are plotted in Figure 7 for the same four slabs.

FIGURE 6. Equipotential contour plots measured on the four slabs (June). The potentials are in mV_{CSE} .

FIGURE 7. State of rebar corrosion in Slabs 1 through 4 rated according to the visual inspection conducted after removal of the concrete cover. Level 1—no visible rust; Level 2—thin layer of rust on steel; Level 3—thick layer of rust on steel.

The relative variations of the half-cell potential values are found to be consistent with the visual inspection results. In Slab 2, the top and bottom edges have more negative potential values than the rest of the slab. The visual inspection shows more corrosion on these areas. The middle-left side of Slab 3 and the top half of Slab 4, which have the most negative potential values (Figure 6), also have the worst corrosion condition, as rated in Figure 7.

The results of the half-cell potential measurements show that most potentials on Slabs 1, 3, and 4 are more negative than -350 mV. According to the ASTM C876-99 guidelines, these slabs should have a high probability of corrosion activity. However, Slabs

1 and 2 were found on average to be in good condition and almost a third of Slab 3 and of Slab 4 were also in a relatively good condition on the basis of the visual corrosion inspection (Figure 7). A careful examination of the results in Figures 6 and 7 suggests that the threshold value should be -450 mV for these four particular slabs, instead of -350 mV as suggested by the guidelines (90% probability of corrosion). With the new threshold value, the half-cell potential prediction of the corrosion correlates with the actual condition of the four slabs.

It is demonstrated that the interpretation of half-cell potential results, based on the ASTM C876 guidelines, is not adequate for these slabs, probably

a result of the particular structural and environmental conditions involved (mainly the thick concrete cover), which are not taken into account in the guidelines. As noted in the ASTM standard, the interpretation of the half-cell potentials under conditions where concrete is saturated with water or where the chloride concentration is high, and under many other conditions, requires modifications based on the knowledge of the particular corrosion conditions. However, no information is given as to how much change there should be under these specific conditions.

Effect of Oxygen Concentration on Half-Cell Potential

Figure 8 shows the continuous half-cell potential monitoring curve of a rebar in a concrete prism with a 50-mm concrete cover that has been immersed in tap water for 16 h. The half-cell potential was close to $-0.65 V_{CSE}$ for approximately 2,000 min, then it gradually shifted to $-0.45 V_{CSE}$ as the concrete cover became dryer. This demonstrates clearly that a water-saturated concrete can lead to a significant half-cell potential shift toward more negative values.¹⁹⁻²⁰ It took almost 2 days for the water to evaporate to the condition under which the half-cell potential could shift back to its original value (before being immersed in the tap water).

Effects of oxygen concentration and anodic reaction rate on half-cell potentials can also be demonstrated by the potential curves (Figure 9) obtained from experiments carried out in an electrochemical cell. The half-cell potentials were $-0.443 V_{CSE}$ and $-0.760 V_{CSE}$ for the passivated and the corroded electrodes, respectively, when oxygen was purged by bubbling N_2 through the solution ($0 < t < 70$ min in Figure 9). The potentials shifted to $-0.21 V_{CSE}$ and $0.22 V_{CSE}$ by bubbling oxygen through the solution ($t = 360$ min). The potentials then shifted back close to their original values by bubbling N_2 through the solution again. The potential shift was more significant at the corroded steel surface than on the passivated surface. The right-hand side of Figure 9 shows the potentials on the corroded electrode after the addition of 3.5% sodium chloride (NaCl). The potentials shifted to more negative values under all three conditions (to $-0.5 V_{CSE}$ under O_2 bubbling, $-0.69 V_{CSE}$ when the cell was opened to air, and $-0.79 V_{CSE}$ under N_2 bubbling).

Figure 10 explains how oxygen concentration and anodic reaction rate can affect the electrode potentials. Under air access conditions, the cathodic (oxygen reduction, Line AA') and anodic (metal dissolution, Line CC') partial reaction rates are electrically equivalent at the corrosion potential, E_1 . The corresponding corrosion current, I_1 , provides an electrical representation of the common rates of the anodic and cathodic partial reactions at this potential.²¹

FIGURE 8. Time variation of half-cell potential measured on a rebar embedded in a concrete prism after being immersed in tap water for 16 h.

FIGURE 9. Half-cell potential measured on passivated and corroded rebar electrodes in an electrochemical cell with N_2 or O_2 bubbling.

FIGURE 10. Polarization diagram showing the corrosion potential and current when the cathodic process is under mass-transfer control.

FIGURE 11. Cumulative frequency distribution of half-cell potential measured on the four slabs (June).

FIGURE 12. Cumulative frequency distribution of half-cell potential calculated for the three levels of corrosion (June).

If the concrete cover is saturated by water, oxygen is not freely available at the metal surface because O_2 has to dissolve into and diffuse through water to reach the metal surface. The cathodic reduction rate is controlled by the rate of arrival of O_2 at the metal surface and is significantly reduced. The cathodic reaction rate then changes from Line AA' to Line BB'. The cathodic and anodic reaction rates will have a new equivalent at the corrosion potential, E_2 , and the corresponding corrosion current, I_2 . Because of the diminution in oxygen concentration, the corrosion potential will change from E_1 to the more negative value, E_2 .

When the anodic metal dissolution rate increases with the addition of NaCl, the line CC' shifts to the right-hand side (dashed line). The cathodic and an-

odic reaction rates are thus equivalent at the corrosion potential, E_1 , under air access condition and E_2 , under O_2 diminished condition. The corrosion potential decreases by increasing the rate of the metal dissolution.

The four slab samples tested in this study had a concrete cover of 140 mm to the top reinforcement. The RH at the surface of the concrete might have changed with the ambient conditions, but the RH at the reinforcement level was always very high during the test period (>91% in Slab 1 and 95% in Slabs 2, 3, and 4). Under these RH conditions, most pores in the concrete are saturated with water and the transfer of O_2 through the concrete pores to the reinforcement takes place almost entirely through liquid-phase diffusion. Therefore, the concentration of oxygen at the metal surface was reduced and the corrosion potentials shifted toward more negative values, leading to incorrect predictions if ASTM guidelines were used directly.

The distribution of cumulative frequencies of half-cell potential values, calculated for the four slabs, are plotted in Figure 11. It is shown clearly that the half-cell potentials in Slabs 1 and 2 were less negative than the potentials in Slabs 3 and 4, indicating that the corrosion condition is more severe in Slabs 3 and 4 than in Slabs 1 and 2. This is consistent with the corrosion ratings from the visual inspections (Figure 7).

Figure 12 shows the cumulative frequency distribution of half-cell potentials at various corrosion levels on the four slabs. One can see that, for noncorroded rebars (Level 1), 80% of the potential values were distributed over a less negative range (-295 mV to -425 mV) with a median value of -365 mV. For corroded rebars (Level 3), 80% of the potential values were distributed over a more negative range (-355 mV to -525 mV) with a median value of -450 mV. It should be noted that a small percentage of the potential values could still be very negative even though the rebar is noncorroded. Similarly, a small percentage of the potential values could be very positive for a corroded rebar. It shows that considering only individual measurements or single measurement locations can result in an inadequate assessment of corrosion. A statistical analysis based on a relatively large number of measurements can provide a much more reliable prediction of rebar corrosion.

Corrosion Rate of the Reinforcement

The corrosion rates measured at various locations on the slabs based on the linear polarization method are shown in Figure 13. The corrosion rates in Slabs 1 and 2 correspond to the category of low corrosion rate ($<0.5 \mu A/cm^2$). The corrosion rates obtained for Slabs 3 and 4 were larger and varied significantly at different locations, indicating that corro-

sion on these slabs was quite active. This agrees very well with the results of the visual inspection.

In the less corroded areas of Slabs 3 and 4, some metal surfaces were very likely under the passive/active transition condition or under localized (pitting) corrosion. Although this state of corrosion was very difficult to identify in the visual inspection, the measured currents provided an indication of the presence of the pitting corrosion.²² In the severely corroded areas of Slabs 3 and 4, the corrosion rate probably depended on the availability of oxygen or was affected by the buildup of corrosion products.

In chloride-contaminated concrete, corrosion often starts as pitting corrosion. The corrosion current can be at first very high; however, with time the current could change depending on the activity of the cell, the buildup of corrosion products on the steel surface, and the availability of oxygen. Because of the natural fluctuation of the corrosion rate, it was found more reliable to use the corrosion rate to locate the active areas on the slabs instead of evaluating the overall loss of material or predicting the presence of badly corroded bars.

Relation between Corrosion Potential and Corrosion Current

Figure 14 is the plot of corrosion potential, E_{corr} , vs the logarithm of the corrosion rate, I_{corr} , determined by the linear polarization method on all four slabs. Although the potential is seen to decrease (toward more negative values) with an increase in the corrosion rate, the correlation between E_{corr} and $\log I_{\text{corr}}$ is quite poor. Feliú, et al., also reported a similar finding.²³ The poor correlation is probably caused by current fluctuations at the corrosion active areas and shifts in potential as a result of a change in the oxygen concentration at the surface of the reinforcing steel.

In the analysis, the consideration of both the half-cell potential values and the corrosion rate measurements provided a reliable evaluation of reinforcement corrosion in the slabs. To demonstrate this point, two specific examples from this study are given as follows:

—On Slabs 1 and 2, the half-cell potentials with readings more negative than -350 mV should not be interpreted as an indication of a high probability of corrosion, because the corrosion rates were low and stable. In this case, the shift in half-cell potential readings toward more negative values should be attributed to a low oxygen concentration (or a high concrete RH).

—On Slabs 3 and 4, the potential readings, which were generally more negative than -450 mV, should be interpreted as an indication of a high probability of corrosion. Taking into consideration the high corrosion rates measured and their significant fluctuations from one location to another, the

FIGURE 13. Corrosion rate measured on: (a) Slabs 1 and 2 and (b) Slabs 3 and 4.

FIGURE 14. Half-cell potential vs corrosion rate for the four concrete slabs.

FIGURE 15. Cumulative frequency distributions of concrete resistivity for the four slabs at different times.

prediction of active corrosion can be made with confidence in this case.

Electrical Resistivity of the Concrete Cover

Resistivity measurements were used in conjunction with a half-cell potential survey to obtain valuable information for the interpretation of the electrode potential made under the same conditions. Since readings of electrical resistivity fluctuate with the measurement location (different size and distribution of aggregates), a statistical analysis relying on a relatively large number of representative measurements had to be used.

It is also important to note that the corrosion rate measurement unit was also designed to measure the resistivity in a concrete cover that has a normal thickness based on the given current distribution. When the thickness of the concrete cover is significantly larger (as in this case), the condition of the top layer of concrete has a larger influence on the resistivity measurement than the condition of the concrete layer at the reinforcement level.

The cumulative frequency distribution of resistivity values measured on the four slabs in June 1999, September 1999, and December 1999 are plotted in Figure 15. The results show that the resistivity measured in June has the largest value while the resistivity obtained in September has the smallest. This is because the moisture content in the top concrete layer was lowest in June and highest in September. (The measurements carried out in June were conducted after 2 months of dry conditions; the September measurements were performed after 2 months of continuous wet conditions, while the measurements in December were done after 2 months of biweekly wet/dry cycles.) Since the water conditioning significantly changed the moisture content of the concrete near the top surface, its effect on the resistivity measurements was quite significant.

FIGURE 16. Cumulative frequency distributions of concrete resistivity for the three levels of corrosion obtained on the four slabs: (a) June, (b) September, and (c) December.

Figure 16 presents the cumulative frequency distribution of electrical resistivity at various locations on reinforcing bars having different levels of corrosion as rated by the visual inspection after concrete cover removal. For the data obtained in June (Figure 16[a]), it was found that differences in resistivity between corrosion levels were quite small due to the contribution of the high resistivity of the top layer of concrete. Larger differences in resistivity can be clearly observed in the results obtained in September (Figure 16[b]) and especially in December (Figure 16[c]). In these two sets of measurements, the concrete resistivity was not dominated by the top layer of

concrete since it had been thoroughly wetted, thus the resistivity in the top part of the concrete cover was reduced. Therefore, the resistivity in the concrete layer near the reinforcement level had a relatively larger contribution in the resistivity measurements. In these surveys, the most corroded bars (Level 3) were located in the areas where the concrete resistivity was low, while the less corroded bars (Level 1) were found in areas having high concrete resistivity.

Chloride Content in the Concrete Cover

Figure 17 presents the average profile of the chloride ion content measured on cores from the top surface down to the reinforcement level in each slab. The acid-soluble chloride ion content ranged from 0.1 wt% to 0.6 wt% of concrete (except for the value of 0.02% measured on Slab 4 at the depth of 133 mm). This is because the repair layer was thicker on Slab 4 than on the other slabs, and it took longer for the chloride ions to diffuse through the thick, dense repair layer. Regardless of the slab number, or the depth at which measurements were made, the chloride content exceeded the 0.02% threshold limit¹⁸ over which concrete is considered to be significantly contaminated by chloride ions. In each slab, the chloride content reached a maximum value at a depth of 10 mm from the top surface and decreased to lower concentrations (but still excessive) toward the reinforcement level in the old concrete. Slightly lower chloride contents were found at the surface than at the 10-mm depth as a result of the effect of rain washing out chloride ions at the slab surface.

Slabs 3 and 4 had much larger chloride ion contents than Slabs 1 and 2 in the repair layer. This may be related to the original location of the slabs on the bridge where the deicing salts had a higher concentration and likelihood of remaining there longer. This is consistent with the results of the electrochemical measurements and the visual inspection, which indicated a higher probability of corrosion in Slabs 3 and 4.

CONCLUSIONS

- ❖ The results of the study of the reinforcement corrosion in four repaired concrete slab sections extracted from an old bridge are presented in this paper. Adequate evaluation of the state of reinforcement corrosion in concrete bridge slabs by nondestructive testing methods is complex. It requires extensive experience and simultaneous consideration of several interrelated factors, such as corrosion potential, corrosion rate, concrete resistivity, chloride ion content, structure design, and environmental conditions.
- ❖ Good correlation was found between the relative variation of half-cell potential measured on the slabs and the actual corrosion condition of the slab rein-

FIGURE 17. Chloride content measured on 50-mm-diameter cores cut from the slabs.

forcement (determined after removal of the entire concrete cover).

- ❖ The ASTM C876 guidelines did not adequately predict the level of reinforcement corrosion observed in the concrete slabs. This was mainly attributed to particular conditions not accounted for in the guidelines, such as the presence of a thick concrete cover (140 mm) and high moisture content (>90% RH).
- ❖ A threshold value for the corrosion potential of -450 mV (90% probability of corrosion) was found to better predict the state of reinforcement corrosion in these particular slabs.
- ❖ It was demonstrated that oxygen depletion in the concrete cover (caused by high moisture content) can shift the half-cell potential toward more negative values by 100 mV, and even by 200 mV in severe cases.
- ❖ Good correlation was found between the corrosion rates measured on the slabs and their observed corrosion condition. Slabs with mild reinforcement corrosion had low, stable corrosion rates (<0.5 $\mu\text{A}/\text{cm}^2$). On the other hand, the slabs with severe corrosion had much larger rates with significant fluctuation between measurement locations, which is considered a good indication of intense, active corrosion.
- ❖ The measurement of the electrical resistivity with the corrosion rate measurement unit may have a limitation for use on slabs with very thick concrete cover, where the measured value is dominated by the resistivity of the top layer of the concrete cover. Thorough pre-wetting of the concrete surface can reduce the influence of the top layer.
- ❖ This study confirms that the simultaneous use of the half-cell potential method and other types of measurements such as corrosion rates and electrical resistivity can provide reliable evaluation and prediction of reinforcement corrosion in concrete. Direct visual inspection of reinforcing steel in some typical areas, by taking cores or removing a small section of the concrete cover, is recommended to verify the prediction accuracy.

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New Member Named to *CORROSION* Editorial Board

Rudolph G. Buchheit has been named to the *CORROSION* Editorial Board.

The appointment was made by the NACE International Publications Administrative Committee.

Dr. Rudolph G. Buchheit is Associate Professor in the Department of Materials Science and Engineering and Associate Director at Fontana Corrosion Center at The Ohio State University. He received his Ph.D. and M.S. in Materials Science from the

University of Virginia. His B.S. in Engineering Science was completed at Loyola College in Baltimore, Maryland.

He has been involved in and has contributed to more than 130 technical publications, patents and patent disclosures, books, and book chapters. Dr. Buchheit is a member of NACE International, The Electrochemical Society, The Materials Research Society, and The Minerals, Metals, and Materials Society. He also serves on the editorial board for the *Journal of Materials Research*. He is a recipient of several awards, including the H.H. Uhlig Educator's Award (2002) from NACE, the Lumley Research Award (2002) from

the College of Engineering at The Ohio State University, the U.S. Department of Energy (DOE) Outstanding Accomplishment Award (1996), and the Morris Cohen Award (1993) from the Corrosion Division of The Electrochemical Society.

Dr. Buchheit's research interests include metallurgical factors in localized corrosion and environment-assisted cracking phenomena focused on aluminum alloys, environmentally acceptable and novel corrosion inhibition, novel methods for corrosion sensing, deterministic factors in pit initiation, use of empirical modeling methods for corrosion prediction, and corrosion of steel in concrete.