CATHODIC POLARIZATION BEHAVIOR OF ANODE AND CATHODE
ON STEEL EMBEDDED IN CONCRETE

Miki Funahashi, PE
MUI International
www.mui-int.com

ABSTRACT

The potential of steel embedded in concrete provides information relative to the thermodynamics of corrosion. However, potentials measured, using a reference electrode placed on the surface of the concrete, can contain misleading information relative to the condition of the steel. Errors can be included in the measurements due to ohmic drop and polarization of the cathodic sites resulting from corrosion (anodic) current flow. In addition, the difference in polarization characteristics of the anode and cathode, when cathodic protection is applied, can make selection of a meaningful cathodic protection criterion somewhat difficult. In this paper, measurements taken utilizing concrete specimens under laboratory conditions are presented. These measurements demonstrate the conditions which affect the selection of the appropriate cathodic protection criterion.

Keywords: Corrosion potential, cathodic protection criteria, concrete, chlorides.

INTRODUCTION

When steel is in contact with highly alkaline concrete pore water, the steel passivates and is protected from corrosion. However, when chloride ions from de-icing salt or seawater penetrate into the concrete and reach the steel surface, the passive layer is destroyed, resulting in commencement of corrosion. The
CATHODIC POLARIZATION BEHAVIOR OF ANODE AND CATHODE ON STEEL EMBEDDED IN CONCRETE

Miki Funahashi, PE
MUI International
www.mui-int.com

ABSTRACT

The potential of steel embedded in concrete provides information relative to the thermodynamics of corrosion. However, potentials measured, using a reference electrode placed on the surface of the concrete, can contain misleading information relative to the condition of the steel. Errors can be included in the measurements due to ohmic drop and polarization of the cathodic sites resulting from corrosion (anodic) current flow. In addition, the difference in polarization characteristics of the anode and cathode, when cathodic protection is applied, can make selection of a meaningful cathodic protection criterion somewhat difficult. In this paper, measurements taken utilizing concrete specimens under laboratory conditions are presented. These measurements demonstrate the conditions which affect the selection of the appropriate cathodic protection criterion.

Keywords: Corrosion potential, cathodic protection criteria, concrete, chlorides.

INTRODUCTION

When steel is in contact with highly alkaline concrete pore water, the steel passivates and is protected from corrosion. However, when chloride ions from de-icing salt or seawater penetrate into the concrete and reach the steel surface, the passive layer is destroyed, resulting in commencement of corrosion. The

Copyright
©1996 by NACE International. Requests for permission to publish this manuscript in any form, in part or in whole must be made in writing to NACE International, Conferences Division, P.O. Box 216340, Houston, Texas 77218-8340. The material presented and the views expressed in this paper are solely those of the author(s) and are not necessarily endorsed by the Association. Printed in the U.S.A.
corrosion cell involves anodic (corroding) sites on the steel surface surrounded by cathodic (non-corroding or passivating) sites.

To determine the extent of corrosion occurring on steel embedded in concrete, “half-cell” or corrosion potential measurements are commonly used. Using a portable reference electrode, the potentials of the steel are measured from the concrete surface. By measuring the potential difference between the reference electrode and the steel using a voltmeter, the corrosion activity at the reference electrode location is estimated based on the ASTM C876 standard. The potential measurement results are then typically presented using contour lines of equal potential based on the probabilities of corrosion activity. The interpretation of the potentials measured on the concrete surface can provide kinetic information if the steel is uniformly corroding. However, corrosion of the steel in concrete structures which are exposed to a chloride environment typically occurs in localized areas on the steel surface. As a result, the potentials measured on the concrete surface may include relatively large ohmic drops caused by corrosion current flowing from anodic sites to cathodic sites. In addition, corrosion current produced at the localized anodic sites polarizes the surrounding cathode sites on the steel surface.\(^1\) The ohmic drops and the polarization of the cathodic sites result in complication of the interpretation of the potential measurements. ASTM C876 states that potentials measured between -0.2 to -0.35 volt to a copper-copper sulfate reference electrode (CSE) indicate uncertain corrosion activity.

The potential of steel also provides information about the protection level of the steel from corrosion when cathodic protection is applied. A valid potential criterion for the cathodic protection of steel embedded in concrete has been discussed for many years. Various protection potentials, ranging from -0.5 to -0.7 volts (CSE), were proposed by several researches.\(^2\)\(^4\) However, the use of a potential criterion was questionable for steel embedded in concrete because the lack of potential stability of reference electrodes embedded in concrete. At present, one frequently used criterion is a 100 mV depolarization. However, the 100 mV depolarization has no theoretical justification for steel in concrete, and the validity of the 100 mV has been questioned based on the following studies:

1. Conflict in corrosion rate reduction based on anodic Tafel slope\(^5\)\(^6\)
2. Elimination of both micro and macro corrosion cells\(^7\)
3. Corrosion null probe test results\(^5\)

As a result, it has been recommended to increase the criterion to 150 mV. In addition, Sagues et. al. suggested that since polarization characteristics of corroding and passive sites on steel in concrete are different, these effects must be taken into consideration in developing cathodic protection criterion.\(^8\) In other words, when a cathodic protection current is applied to steel which is corroding in localized areas, the location of a reference electrode may provide different results on depolarization testing.

The basic criterion of cathodic protection was established by Brown and Mears.\(^9\) Cathodic protection is achieved when cathodic sites polarize to the potential of the anode. This principle can be kinetically explained using a polarization diagram, as shown in Figure 1. The anodic kinetics of the corrosion process of steel in concrete is controlled by the nature of the concrete pore water, such as pH and various ionic concentrations. When cathodic protection current (\(I_{cp}\)) is applied to the corroding steel, the corrosion current density decreases from \(I_{corr}\) to \(I_{1,corr}\) along the anodic polarization curve. The net corrosion current or corrosion rate becomes zero where the rate of anodic dissolution is exactly balanced.
by the rate of deposition at the exchange current density \( (I_{0,a}) \) or when the polarized potential of the cathode reaches the reversible potential of the anode \( (E_{0,a}) \). This theory was demonstrated by Haussman.\(^3\) He indicated that corrosion was depressed when the cathode was polarized to its critical potential. This is achieved when a sufficient amount of cathodic protection current \( (I_{cp}) \) is applied to corroding steel. For complete cessation of corrosion current by cathodic protection, the steel must be polarized to \( E_{0,a} \). The reversible potential varies according to the composition of the electrolyte, as predicted by the Nernst Equation:

\[
E_{0,a} = E^0_{0,a} + \frac{RT}{nF} \ln a_M^+ 
\]  

\(E^0_{0,a}\) is the reversible potential at standard state, \(R\) is the gas constant, \(T\) is absolute temperature, \(n\) is the valence of the metal ions in the given equilibrium electrode reaction producing the potential, \(F\) is the Faraday constant, and \(a_M^+\) is the activity of the \(Fe^{++}\) in the electrolyte. When potentials of steel embedded in concrete are measured on the concrete surface, the potentials contain ohmic drop (IR) caused by corrosion current flow. Thus, it is difficult to determine \(E_{0,a}\) of steel by measuring potentials on the concrete surface.

Utilizing the conditions that steel embedded in chloride contaminated concrete corrodes and steel embedded in chloride free concrete passivates, experiments were designed to investigate:

1. Half-cell potentials of steel with respect to distance from an anodic site under various conditions,
2. Reversible potential, \(E_{0,a}\) of steel embedded in chloride contaminated concrete,
3. Polarization behaviors of the anodic and cathodic sites with application of cathodic protection current, and
4. The validity of the 100 mV depolarization criterion based on the basic criterion of cathodic protection.

**EXPERIMENTAL PROCEDURES**

Two mild steel plates were used in this experiment. Each plate was 6 inches wide by 18 inches long by 3/16 inch thick (15.2 cm by 54 cm by 0.5 cm). A electrical wire was attached on one side of each steel plate, and the connection and the side of the steel plate was then coated with an epoxy based coating. The other side of each plate surface was prepared by sandblasting. Two holes 1/8 inch (3.17 mm) in diameter were drilled through each steel plate, as shown in Figure 2. Two plastic tubes (ID 1/16" or 1.58 mm) were inserted into the holes and were fixed inside the holes using solid epoxy. The top of the plastic tubes were flashed to the steel surface.

To create a galvanic corrosion cell, the steel surface must be divided into anodic and cathodic areas. At first, the steel plates were embedded in chloride free concrete except the 1/2-inch (1.27 cm) diameter circular areas surrounding the drilled holes. One of the steel plates was covered with 1 inch (2.54 cm) thick concrete. The other plate was covered with 2-1/2 inch (6.35 cm) concrete. After four weeks of the concrete placement, the holes in each specimen were filled with concrete mortar containing chloride.
concentrations of 1 and 5 percent by weight of cement, respectively. Conductive coating was applied on the top concrete surface except in the center area to serve as a cathodic protection anode.

The concrete blocks were stored in a chamber with 100% humidity for 30 days. The plastic tubes were then connected to clear vinyl hoses which were filled with conductive gel, and the other ends of the hoses were placed in beakers containing tap water. A silver-silver chloride reference electrode was placed in each beaker to measure the potential of the anodic site.

The specimens were exposed to the following four conditions in an environmental chamber:

1. 40°F (4.4°C) and 90% (RH) relative humidity
2. 40°F (4.4°C) and 40% RH
3. 90°F (4.4°C) and 90% RH
4. 90°F (4.4°C) and 40% RH

Each condition was maintained for 10 days. At the end of each test condition, the potential of each steel plate was measured at the anode sites and on the concrete surface at 1/2 inch (1.3 cm) intervals from the top of each anodic site along the specimen.

To study the polarization behaviors of the anodic and cathodic sites on the steel plates, cathodic protection current were applied using the galvanodynamic mode of a Gammary Corrosion Measuring System. The steel plate was polarized in small current increments with 3-minute intervals in 70 and 90 percent RH and at three different temperatures, 40°F, 70°F and 90°F (4°C, 21°C and 32°C). IR-drop free potentials of the steel plate were measured at the anodic sites and three locations on the concrete surface, which were directly above the anodic site and 1 and 2 inches (2.54 and 5.08 cm) away from the anodic site, as shown in Figure 3.

The polarization potentials and corresponding current (E-log I curves) were plotted in a semi-logarithmic graph for each condition. The magnitude of current required to achieve cathodic protection of each anodic site in a particular environment was determined from the E-log I curve obtained at the intersection of the E-log I curve obtained at the top of the anodic site and the static potential of the anodic site prior to application of cathodic protection current. To measure the magnitudes of depolarization which occurred due to the amount of cathodic protection current determined by the graphs, current was applied to the steel plate for 24 hours. At the end of the 24 hour period, depolarization testing was conducted for 4 hours at the anodic site, and at three locations on the concrete surface, which were directly above the anodic site and 1 and 2 inches (2.54 and 5.08 cm) away from the anodic site. All potentials measured in this study were converted to the Cu/CuSO₄ (CSE) reference scale.

RESULTS AND DISCUSSION

Half-cell Potentials of Steel Plates

Results of potential measurements at the anodic sites and on the concrete surfaces with respect to distance from anodic sites under various environmental conditions were studied. Figures 4(a) and 4(b) show the potentials measured over 1 and 2-1/2 inches (2.54 and 6.35 cm) concrete covers, respectively. The measurements were taken in the 90 and 40 percent RH and 90°F (32.2°C) environments, and the
anodic site was exposed to 1 percent of chloride concentration. In the 90 percent RH environment, the anodic (corrosion) current reached as far as 5 inches (12.7 cm) away from the anodic site to the surrounding cathodic sites on the steel plate. The potentials measured on the concrete ranged between -320 mV/CSE and -380 mV over the cathodic areas on the steel plate. These potentials are far more negative than those of passivating steel in concrete. It indicated that the potentials measured over the cathodic sites included ohmic drop and polarization of the cathodic sites caused by the anodic current.

The potential difference between at the anodic site and on the concrete which was directly above of the anodic site was more than 140 mv in both the 40 and 90 percent RH environments. However, the potentials measured in the 40 percent RH environment indicated that the effect of anodic current was limited to only approximately 2 inches (5.08 cm) away from the center of the anodic site.

Figures 5(a) and 5(b) show potentials measured over 1 and 2-1/2 inch (2.54 and 6.35 cm) concrete covers, respectively, in the 40 and 90 percent RH and 40° F (4.4° C) environments. The potential profiles are similar to the results shown in Figures 4(a) and 4(b). However, the potential differences between at the anodic site and on the concrete directly above the anodic site were smaller than those at 90° F. Thus, the magnitude of the anodic current appeared to be small, resulting in small polarization effect and small ohmic drop on the potentials measured over the cathodic sites near the anodic site.

Figure 6(a) shows the effect of temperature on potential measurements. The potential profiles were obtained over 1 inch (2.54 cm) concrete cover in the 90 percent RH and 40° and 90° F (4.4° and 32.2° C) environments. The anodic site was exposed to 5 percent of chloride concentration. At 40° and 90° F, the ohmic drops measured between the anodic site and on the concrete directly above the anodic site were approximately 80 mV. However, at a temperature of 90° F, potentials measured over the cathodic areas indicated greater magnitude of ohmic drop and higher polarization of the cathodic sites.

Figure 6(b) shows the potential profiles obtained on the concrete with 2-1/2 inch (6.35 cm) cover in the 40 percent RH and 40° and 90° F (4.4° and 32.2° C). The effect of temperature on ohmic drop was obviously greater at 90° F than at 40° F. However, the high resistivity caused by the low humidity limited the anodic current to reach only 3 inches (7.62 cm) away from the anodic site.

The effect of concrete cover on ohmic drop and polarization of the cathodic sites was not clear in the 90 and 40 percent RH and 90° F (32.2° C) environments, as shown in Figures 7(a) and 7(b), respectively. This may be caused by the greater effect of concrete resistivity due to the effect of humidity or temperature, resulting in the masking the effect of concrete cover.

Figures 8(a) through 8(d) show the potentials measured at the anodic sites under various environmental conditions. The potentials at the anodic sites did not show a particular pattern with respect to temperature or relative humidity. The potentials of the anodic site exposed to 1 and 5 percent of chloride concentrations ranged from -406 mV/CSE to -515 mV and from -436 mV to -563 mV, respectively. Therefore, the potential of an anodic site exposed to higher chloride concentrations appears to be more negative. These potentials can probably be considered to be or near the reversible potentials of the anode on the steel exposed to the concrete containing relatively high chloride concentrations.

**Polarization of the Anodic and Cathodic Sites**

Polarization behaviors obtained at the anodic sites and at three locations on the concrete which are directly above the anodic site and 1 and 2 inches (2.54 and 5.08 cm) away from the anodic sites, were investigated.

Figures 9 through 11 show the E-log I curves obtained in the 70 percent RH and 40°, 70° and 90° F (4.4°, 21.1°, and 32.2° C) environments, respectively. The anodic site was exposed to a 1 percent chloride concentration and covered with 2-1/2 inches (6.4 cm) of concrete. At 40° F, the cathodic polarization curves obtained at the three locations on the concrete were almost identical. The E-log I
curves obtained at the anodic site at the three temperatures showed far less polarization behavior than those on the concrete and were similar to each other. At 70° and 90° F, with increasing distance from the anodic site on the concrete, the magnitudes of polarization increased. In particular, this tendency was more remarkable at 70° F.

Figures 12 and 13 show the E-log I curves acquired at the anodic site (5 percent chloride concentration) and on the concrete with 2-1/2 inch cover. The curve in Figure 12 was obtained in the 70 percent RH and 70° F (21.1° C) environment. The curve in Figure 13 was obtained in the 90 percent RH and 90° F (32.2° C) environment. With application of various amounts of cathodic protection current, the anodic site showed little polarization. The magnitudes of polarization measured on the concrete increased with increasing distance from the anodic site. This tendency was more remarkable in the 70 percent RH and 70° F than in the 90 percent RH and 90°F.

Figure 14 shows the E-log I curves obtained at the anodic site (1 percent chloride concentration) and over 1 inch (2.54 cm) concrete cover in the 70 percent RH and 90° F (32.2° C) environment. The polarization behaviors obtained at the anodic site and on the concrete were similar to those obtained over 2-1/2 inch (6.4 cm) cover, as shown in Figure 11.

**Depolarization Tests**

Based on the results of potential measurements and polarization behaviors, the schematic equipotential diagram for corroding steel in concrete was constructed, as shown in Figure 15. When cathodic protection current is applied to the steel, the steel polarizes. With an insufficient amount of cathodic protection current, the instant-off potential on the concrete directly above the anodic site is more positive than the potential of the anodic site due to the ohmic drop caused by the existing corrosion current. When a sufficient amount of cathodic protection current is applied, the instant-off potential on the concrete above the anodic site becomes the same potential as the anodic site, resulting in elimination of the anodic site. This process is schematically shown in Figure 15(b) and 15(c).

Based on this cathodic protection principle, the minimum amount of cathodic protection current was determined from each E-log I curve (Figures 9 through 14) obtained on the concrete above the anodic site. The magnitude of cathodic protection current thus determined was applied to the steel plate in the same environmental condition under which the polarization curves were obtained. After the cathodic protection current was applied to the steel for 24 hours, depolarization testing was conducted. The depolarizing potentials were monitored for 4 hours at three locations on the concrete, which was directly above the anodic site, 1 and 2 inches away from the anodic site.

Figures 16 through 19 show the results of the depolarization tests. Figure 16 shows the magnitudes of the depolarization occurred on 2-1/2 inch (6.4 cm) concrete cover in the 70 percent RH and 40° 70° and 90° F (4.4°, 21.1° and 32.2° C) environments. The magnitude of the depolarization increased with increasing the distance from the anodic site at the three temperatures, ranging from 99 to 141 mV. The magnitudes of depolarization which occurred on the concrete directly above the anode were 99, 128 and 87 mV at 40°, 70° and 90° F, respectively. However, the magnitudes of depolarization at 1 and 2 inches (2.54 and 5.08 cm) away from the anodic site were more than 100 mV.

Figures 17 and 18 show the depolarization which occurred on the concrete with the anodic sites exposed to 1 and 5 percent of chloride concentrations in the 70 percent RH and 70° and 90°F (21.1° and 32.2° C) environments, respectively. Again, the magnitude of the depolarization increased with increasing the distance from the anodic site and appears to be smaller near the anodic site exposed to 5 percent chloride concentration. The magnitudes of depolarization which occurred on the concrete above the anodic site were 128 and 82 mV at 70° F and 87 and 53 mV at 90° F for 1 and 5 percent chloride concentration, respectively. However, the magnitudes of the depolarization were greater than 100 mV at 2 inch (5.08 cm) locations for both chloride concentrations.
Figure 19 shows the comparison of the depolarization which occurred over 1 and 2-1/2 inch concrete covers in the 70 percent RH and 90° F (32.3° C) environment. The magnitude of depolarization was greater for the 1-inch concrete cover. The magnitudes of depolarization on the concrete above the anodic site were 108 and 87 mV for 1 and 2-1/2 inch (2.54 and 6.4 cm) concrete cover, respectively. The magnitudes of depolarization at 2 inches from the anodic site were 131 and 110 mV.

CONCLUSIONS

1. In the presence of macro-cell corrosion on steel in concrete, potentials measured near the anodic sites were greatly influenced by the concrete resistivity due to ohmic drop and polarization of the cathodic sites caused by anodic (corrosion) current. As a result, potentials measured on the concrete may result in misleading interpretation of the extent of corrosion areas, particularly in high humidities and high temperatures.

2. The potentials of the anodic site exposed to 1 to 5 percent chloride concentrations appear to range from -406 mV/CSE to -563 mV. These potentials probably can be considered to be or near the reversible potentials of the anode on the corroding steel in concrete. The critical cathodic polarization (protection) potential for steel in concrete appears to be more positive than those generally presented in the past.

3. The magnitude of polarization increased with increasing distance from the macro-cell type anodic site.

4. With application of cathodic protection current, the magnitude of polarization which occurred at the anodic sites on the steel were almost negligible or far less than measured from the concrete surface.

5. In the presence of only macro-cell corrosion in concrete, if a reference electrode is located adjacent an anodic site, the 100 mV depolarization may be sufficient to achieve cathodic protection of the steel exposed to high chloride concentration (5 percent of cement). However, if the steel is exposed to a lower chloride concentration (1 percent of cement), 100 mV depolarization would be insufficient.

6. When a reference electrode is not located adjacent to an anodic site to monitor depolarization potential, 150 mV depolarization in 4 hours is probably required to achieve cathodic protection.

REFERENCES


Figure 1. Principle of cathodic protection in polarization diagram when cathodic protection current ($I_{cp}$ or $I_{cp}$) is applied to corroding steel, the corrosion current density decreases from $I_{corr}$ to $I_{1,corr}$ or $I_{o,a}$, respectively.

Figure 2. Schematic representation of the concrete specimen.
Figure 3. Schematic representation of the set-up for cathodic polarization tests.
Figure 4(a). Potentials with respect to distance from the anodic site over 1" concrete cover and the potentials at the anodic site (1% chloride concentration) in 90% and 40% relative humidity at 90 degrees F.

Figure 4(b). Potentials with respect to distance from the anodic site over 2-1/2" concrete cover and the potentials at the anodic site (1% chloride concentration) in 90% and 40% relative humidity at 90 degrees F.
Figure 5(a). Potentials with respect to distance from the anodic site over 1" concrete cover and the potentials at the anodic site (1% chloride concentration) in 90% and 40% relative humidities at 40 degrees F.

Figure 5(b). Potentials with respect to distance from the anodic site over 2-1/2" concrete cover and the potentials at the anodic site (1% chloride concentration) in 90% and 40% relative humidities at 40 degrees F.
Figure 6(a). Potentials with respect to distance from the anodic site over 1" concrete cover and the potentials at the anodic site (5% chloride concentration) in 90% relative humidity at 90 and 40 degrees F.

Figure 6(b). Potentials with respect to distance from the anodic site over 2-1/2" concrete cover and the potentials at the anodic site (5% chloride concentration) in 40% relative humidity at 90 and 40 degrees F.
Figure 7(a). Potentials with respect to distance from the anodic site over 1" and 2-1/2"
concrete cover and the potentials at the anodic site (5% chloride concentration)
in 90 % relative humidity at 90 degrees F.

Figure 7(b). Potentials with respect to distance from the anodic site over 1" and 2-1/2"
concrete cover and the potentials at the anodic site (5% chloride concentration)
in 40 % relative humidity at 90 degrees F.
Figure 9. ELog I curves obtained at the anodic site (1% chloride conc.) and over 2-1/2" concrete cover in 70% relative humidity at 40 degrees F

Figure 10. ELog I curves obtained at the anodic site (1% chloride conc.) and over 2-1/2" concrete cover in 70% relative humidity at 70 degrees F
Figure 11. ELog I curves obtained at the anodic site (1% chloride conc.) and over 2-1/2" concrete cover in 70% relative humidity at 90 degrees F

Figure 12. ELog I curves obtained at the anodic site (5% chloride conc.) and over 2-1/2" concrete cover in 70% relative humidity at 70 degrees F
Figure 13. ELog I curves obtained at the anodic site (5% chloride conc.) and over 2-1/2" concrete cover in 90% relative humidity at 90 degrees F.

Figure 14. ELog I curves obtained at the anodic site (1% chloride conc.) and over 1" concrete cover in 70% relative humidity at 90 degrees F.
Figure 15. Schematic representation of potential variation on steel and concrete surfaces with the application of various amounts of cathodic protection current.
Figure 16. Magnitudes of depolarization measured at three locations on the concrete (2-1/2" cover) with an application of cathodic protection current for the anodic site (1% chloride conc.) in 70% relative humidity.

Figure 17. Magnitudes of depolarization measured at three locations on the concrete (2-1/2" cover) with an application of cathodic protection current for the anodic site (1% chloride conc.) in 70% relative humidity at 70 degrees F.
Figure 18. Magnitudes of depolarization measured at three locations on the concrete (2-1/2" cover) with an application of cathodic protection current for the anodic site (1% chloride conc.) in 70% relative humidity at 90 degrees F.

Figure 19. Magnitudes of depolarization measured at three locations on the concrete (1" and 2-1/2" cover) with an application of cathodic protection current for the anodic site (1% chloride conc.) in 70% relative humidity at 90 degrees F.