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HIGH PERFORMANCE CONCRETE SPECIAL TOPIC:

CORROSION MONITORING BEST PRACTICES GUIDE
SPECIAL STUDY NO. 3, CONTRACT P.O. 030107

FINAL REPORT

April 6, 2006

By A. J. Schokker and S. Mason

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Prepared for

Commonwealth of Pennsylvania
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16. Abstract

Corrosion of reinforcement in concrete remains a major safety and economic concern for highway departments of transportation. Advances have been made in high performance concrete mixture designs as well as in alternate reinforcing materials. However, the problem of identifying the extent and level of corrosion for in-service bridges remains. Multiple methods are available for potentially addressing these concerns, including half-cell potential measurements, corrosion rate measurements, resistance measurements as well as more invasive methods such as chloride penetration sampling and coring. None of these methods is effective alone in isolating the location and extent of corrosion damage reliably, and many exceptions to "standard procedure" exist for their use in typical DOT structure environments such as bridge decks. This best practices guide is intended to provide DOTs with guidelines for evaluating corrosion on existing structures. This guide has been developed based on existing literature, experience of the authors, and extensive test data collected at Penn State on a variety of concrete slab specimens.

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HIGH PERFORMANCE CONCRETE SPECIAL TOPIC:

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Introduction

Corrosion of reinforcement in concrete remains a major safety and economic concern for highway departments of transportation. Advances have been made in high performance concrete mixture designs as well as in alternate reinforcing materials. However, the problem of identifying the extent and level of corrosion for in-service bridges remains. Multiple methods are available for potentially addressing these concerns, including half-cell potential measurements, corrosion rate measurements, resistance measurements as well as more invasive methods such as chloride penetration sampling and coring. None of these methods is effective alone in isolating the location and extent of corrosion damage reliably, and many exceptions to "standard procedure" exist for their use in typical DOT structure environments such as bridge decks. This best practices guide is intended to provide DOTs with guidelines for evaluating corrosion on existing structures. This guide has been developed based on existing literature, experience of the author, and extensive test data collected at Penn State on a variety of concrete slab specimens (Smith, 2003; Mason, 2004).

Background Literature

Considerable research has been devoted to the understanding and prevention of steel corrosion in reinforced concrete structures, but far less attention has paid to how to use available corrosion evaluation methods to assess the condition and remaining service life of a structure. A basic review of the corrosion literature as it relates to corrosion monitoring is included in this section as background information.

Corrosion of Steel in Concrete

The steel found in reinforced concrete structures is protected by a thin oxide film (also known as the passive film) that forms spontaneously in the high alkaline concrete pore water. Concrete is alkaline due to microscopic pores with high concentrations of soluble calcium, sodium, and potassium oxides. When water is added to concrete, these oxides form hydroxides, creating a very alkaline condition (the concrete pore water solution typically has a pH value of about 13). The penetration of chloride ions or carbonation of the concrete decrease the alkalinity and subsequently destroy the passive film. Once this layer is broken down and oxygen and moisture reach the steel, corrosion begins (Jones, 1996).

It is important to note that corrosion in the active state does not ordinarily take place at a constant and uniform rate. Changes in environmental conditions (temperature and moisture) may accelerate or decelerate the actual rate of corrosion. Typically, both passive and corrosive areas form and coexist on the same reinforcement bar, causing what is known as a macrocell (Carino, 1999; Millard et al., 1992). This macrocell forms a short circuited, galvanic element with the corroding area as the anode and the passive area acting as the cathode. The anodic reaction is $Fe \rightarrow Fe_2+ + 2e-$. The two electrons created in the anodic reaction must be consumed elsewhere on the steel surface for electrical neutrality, which is done by the cathodic reaction. The cathodic reaction is $2e- + H_2O + ½ O_2 \rightarrow 2OH$. The flow of electrons between the anodic and cathodic areas on the steel and its counter-current flow in the concrete pore solution constitute the corrosion current. The counter flow consists of negatively-charged hydroxide ions and positively-charged ferrous ions. If the concrete's electrical resistance to these ions is high, the rate of current flow carried by the ions will be

low. Subsequently, the anodic and cathodic reactions will proceed slowly and the rate of corrosion will be low.

Passivation

Most experts will agree that, once concrete is placed, some level of corrosion of the reinforcement bar takes place immediately due to the exposure to the electrolytic condition. However, the level of corrosion depends on the amount of oxygen that is present or is able to quickly diffuse to the bar (Khan, 1991). In the absence of interfering chloride or other ions, the corrosion forms a layer of Fe_3O_4 under an outer layer of Fe_2O_3. These two layers combine to form the thin protective oxide layer that is created around the reinforcement bar that is also known as the passivation layer (Jones, 1996).

While the passivation layer forms, calcium hydroxide forms from cement hydration and contributes to the high alkaline pore water solution. The new environment that is created for the reinforcing steel stops the corrosion process and secures the passivation layer around the steel. As additional oxygen progresses through the concrete with time, the passive layer develops further, and protection against corrosion deterioration increases.

Corrosive Elements

The passive layer provides excellent protection, but can be broken down. Depassivation may occur under two specific sets of conditions within concrete: (1) reduction of the pH level due to reaction with atmospheric CO_2 (carbonation); and (2) penetration of chloride ions into the concrete pore solution around the steel. Once depassivation occurs, the steel is no longer protected and the onset of corrosion may be initiated.

It has been proven that even when the concrete pore water solution pH level remains high, chloride ions in high concentrations can still effectively destabilize the passivating film. These Cl^- ions may be introduced in the concrete mix as an admixture component (normally as $CaCl_2$) or in chloride-contaminated aggregates or mix water. Only chloride dissolved in the concrete pore solution functions to depassivate the steel, but chloride ions can diffuse into the cured concrete from external sources such as sea water or de-icing salt on concrete pavements. The content of dissolved chloride can be significantly less than the total chloride content of the concrete.

When carbon dioxide molecules penetrate into reinforced concrete, they can react with solid calcium hydroxide, C-S-H, and alkali and calcium ions in the pore solution and subsequently decrease the alkalinity of the pore solution. This reaction creates carbonates and water, which subsequently evaporates, causing carbonation shrinkage and may create microcracks that permit further carbon dioxide ingress. A carbonation front usually penetrates slowly into the concrete member to the surface of the reinforcing steel. The time it takes this front to reach its destination is a function of the depth of the cover and of the rate of diffusion of the atmospheric CO_2 into the concrete (which is very dependent on the quality of concrete). Once the carbon dioxide reaches the steel, it reacts with the iron elements to produce corrosive material (Mindess and Young, 1981).

Service Life

Service life can be illustrated by the model shown in Figure 1 (Tuutti, 1982). It is comprised of an initiation stage (time of completion to time chloride threshold is reached) and the propagation stage (after chloride threshold is reached to the end of service life). The chloride threshold is the amount of chlorides necessary to breakdown the passive film; this quantity varies for different types of concrete and there is not agreement among researchers about the value. The initiation stage is dependent on many variables, including environment, chloride exposure, cover, and concrete type. In poor or cracked concrete, the initiation stage may be quite short. The length of the propagation phase depends on the corrosion rate after the chloride threshold is reached. Corrosion rate may vary considerably depending on the resistivity of the concrete, the oxygen availability, and the environmental conditions. The end of service life is defined by the user.

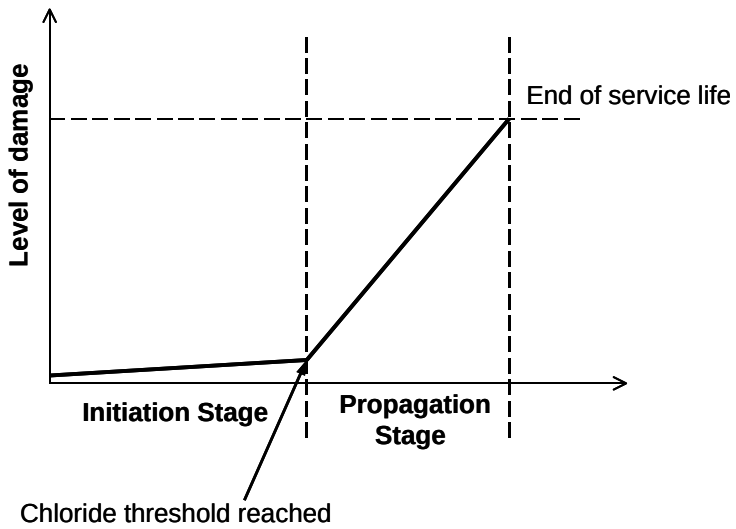

Figure 1: Service Life Model

Cracking and Corrosion

Cracking in the concrete provides a more direct route for the corrosive agents to reach the steel. Cracks may develop from several different mechanisms such as shrinkage, loading, poor construction practices, or poor material design. Although all experts agree that cracks have an effect on corrosive element ingress, there is controversy over how the presence of cracks affects corrosion.

Most experts agree that cracks do lead to a faster ingress of corrosive materials in concrete, but many disagree over the relationship between crack width and chloride ingress (Paulsson-Tralla and Silfwerbrand, 2002; Schiebl and Raupach, 1997). In very poor concrete, chlorides may penetrate through uncracked concrete relatively quickly, but with high quality concrete, chloride penetration through cracks is much more likely to initiative corrosion than penetration through uncracked concrete.

It is important to realize that surface width is not necessarily related to crack depth (Weyers et al., 2002). Additionally, cracks that run parallel to the reinforcement bar often cause more extensive damage than cracks that cross over the bar perpendicularly (Borgard et al., 1990).

Environmental Effects

Relative Humidity

Little corrosion activity typically takes place when the relative humidity is under 60% with no chloride ions present. If relative humidity increases, the corrosion rate increases up to a threshold value where it then begins to decrease again. When chloride ions are present at humidity levels below 60%, corrosion activity may still develop. Additionally, as the chloride ion content increases, the inclination of corrosion rate according to relative humidity increases (Jung et al., 2003).

Effect of Temperature on Corrosion Activity

In general, the expected life of reinforced concrete structures increases with increasing temperature in dry environments because of the temperature's effect on water condensation and evaporation equilibrium in the pore structure of concrete. Conversely, in environments with high humidity, increasing temperatures cause considerably shorter expected lives for the structure. However, although temperature obviously has an effect on the performance of reinforced concrete, it should never be taken into account without also recognizing the effects of pore saturation and chloride ion content, among other factors (Lopez et al., 1993).

Concrete Resistivity

Concrete resistivity is a geometry-independent material property that describes the ratio between applied voltage and resulting current in a unit cell (Gowers and Millard, 1999; Millard et al., 1991). For corrosion of steel reinforcement in concrete to occur, an ionic current must pass between anodic and cathodic regions of the concrete. The degree of resistivity of the concrete impacts this ionic flow and therefore affects the corrosion rate of the reinforcement. The higher the concrete resistivity, the lower the current flowing between anodic and cathodic areas will be, and therefore the lower the corrosion rate (Broomfield and Millard, 2002; Gowers and Millard, 1999).

The resistivity of concrete depends upon several factors, such as capillary pore size, pore system complexity, and moisture content (Broomfield and Millard, 2002). Additionally, the resistivity is also dependent upon the degree of pore saturation, the degree of paste hydration (curing) and the presence of dissolved salts in the aqueous paste of the concrete (Gowers and Millard, 1999). Resistivity decreases with increased pore saturation as well as with an increased number of larger diameter pores (higher water-to-cement ratio) and increases when the concrete dries out and when it carbonates (Broomfield and Millard, 2002; Millard et al., 1991).

The effect of increased chloride content due to salt ingress on resistivity is relatively small. These chlorides have little direct effect on resistivity because the hydroxyl ions from the cement dissolved in the pore water outnumber the few chloride ions (Broomfield and Millard, 2002). In general, the chloride diffusion coefficient is inversely proportional to the concrete resistivity because of the hygroscopic property of the chlorides. Within a particular structure, more permeable zones will have a comparatively lower resistivity and higher chloride penetration (Polder and Peelen, 2002). In addition to all of these factors, resistivity is also strongly influenced by cement content, admixtures, and curing regime (Broomfield and Millard, 2002).

It has been found that concrete resistivity and reinforcement corrosion rate are inversely proportional over a wide resistivity range (Lopez and Gonzalez, 1993). Within a given structure, areas with low resistivity will be associated with a relatively high corrosion rate after depassivation (Polder and Peelen, 2002).

Resistivity Measurements

The four-probe Wenner technique that was originally developed for measuring soil resistivity is most commonly used for measuring concrete resistivity. A current is applied between the two outer probes of the device and the potential difference across the two inner probes is measured. These two properties are then used to calculate the resistivity (σ) of the concrete using the following equation:

$$\sigma = 2\pi a V/I \qquad (1)$$

where a is the contact spacing in cm, V is the potential difference, and I is the current.

Preliminary resistivity tests employed a simple metal electrode that was held against the surface of a concrete specimen. This method gave repeatable results when the concrete was visibly moist, but gave unreliable results in other cases. Additionally, the resistivity measurement often varied significantly with the degree of contact pressure applied (Millard et al., 1991).

Early versions of the resistivity probes required that holes be drilled into the concrete to take measurements with four-probe tools, but modern devices do not require invasive analysis. Instead, either spring-loaded probes or probes with sponge-tips or wooden tips are employed to create and maintain electrical contact (Millard et al., 1991). Many resistivity devices require the use of a wetting contact medium for electrical contact.

In addition to the commonly-used four-probe system, a two-probe system is also available, but is less accurate (Broomfield and Millard, 2002). Unlike the four-probe system, the two-probe devices do not eliminate any effects due to surface contact resistance.

Half-Cell Potential Mapping

As a method of providing information about likelihood of corrosion activity, the potential of reinforcement bar may be measured through a half-cell device. Because the potential of a corroding reinforcement bar can differ from that of a noncorroding reinforcement bar by up to several hundred millivolts, these results can give good insight into whether corrosion

activity is present within a specimen. The potential measured by a half-cell device is not the potential at the steel surface that drives the corrosion cell, but rather the potential difference between the surface and the steel (Oh et al., 2001). The current flow that is present once both the anode and cathode develop on corroding reinforcement bar is coupled with an electric field, and the change in electric potential between the anode and cathode is continuous. The electric field is then measured at the surface of the concrete, creating equipotential lines that allow the location of corroding zones (Elsener et al., 1994).

Half-Cell Potential Measurements

To accurately measure the potential of reinforcement bars in concrete, an electrical connection to the reinforcement must be achieved. A voltmeter is then connected to the reinforcement bar, as well as to a reference electrode. In most cases, this reference electrode is in the form of a copper/copper sulfate electrode with a sponge tip. This reference electrode is then moved to various surface locations in order to determine the differing potentials over the surface.

The measured potential is influenced by several factors and can vary within a wide range. Some of the main influences on the measured potential include level of corrosion of the reinforcement, chloride content of the concrete, moisture content of the concrete, resistivity of the concrete, depth of carbonation of the concrete (pH of the concrete pore water), and oxygen content of the concrete. Additionally, several secondary influences may affect the results, but to a lesser degree. Some examples of secondary influences are temperature, concrete properties, age of the concrete, arrangement of the reinforcement, cracks and joints, areas where the reinforcement is not completely surrounded by concrete, and cover of the reinforcement. When surface potentials are taken, they are measured at a location remote from the reinforcement due to the concrete cover. As a result, the measured potentials are affected by the ohmic potential drop in the concrete (due to the concrete resistivity). The main influences on potential result in a permanent change in potential, whereas the secondary influences change the values slightly, temporarily, or locally.

The corrosion potential of the reinforcement becomes more negative with an increase in concrete chloride content at the level of the reinforcement. The chloride content itself is influenced by several factors, including type and duration of contact with chloride-containing water, concrete porosity, method of chloride transport in the concrete, and concrete moisture content. Highly resistive surface layers cause errors in results due to the fact that macrocell currents tend to avoid highly resistive concrete. Because of this, the measured potentials at the surface become more positive and may therefore give misleading results. Additionally, with increasing concrete cover, the potential values at the concrete surface over both actively corroding and passive steel become similar. Therefore, the location of small corroding areas becomes difficult to find.

The potentials of steel in concrete immersed in water or in the earth will likely be very negative due to restricted oxygen access. This oxygen depletion shifts half-cell potentials more negatively by 100-200 mV (Qian and Chagnon, 2001). In the transition region (waterline) of these structures, more negative potentials may also be measured due to

galvanic coupling with immersed rebars that may not represent the presence of corrosion (Stanish et al., 2000).

When concrete admixtures containing ions are added to concrete, the half-cell potential readings may be affected. As a result, it has been suggested that the evaluation of the corrosion activity in specimens with corrosion inhibiting systems not be based on the half-cell potential values alone. Results should be analyzed along with other corrosion activity test results. Additionally, as is the case with submerged concrete, the application of a coating on concrete may enhance the oxygen depletion in the concrete (Qian and Cusson, 2004).

Although the presence of epoxy coatings on reinforcement typically cause less negative half-cell potentials than those for bars without coatings, significant negative shifts in results may occur due to a damaged or scratched epoxy coating in some areas (Qian and Cusson, 2004).

Corrosion Rate

The corrosion rate is a function of the interfacial polarization resistance between the steel and concrete in a specimen (Millard and Broomfield, 2003). For many years, the potential and concrete resistivity was used to predict the corrosion rate of reinforcement, but the actual rate cannot be estimated by multiplying the concrete resistivity by the half-cell potential. Oxygen depletion can lead to very negative potentials (Ismail and Soleymani, 2002; Law et al., 2000) and the moisture condition of the concrete can lead to very low resistivities. These skewed results, therefore, may indicate a higher corrosion rate than is actually present.

Unlike the aforementioned method of predicting corrosion, the linear polarization resistance (LPR) measurement of corrosion rate gives a direct measurement. Past research has suggested that LPR tests be carried out along with resistivity and half-cell potential tests in order to derive direct evaluations of corrosion rate in concrete (Carino, 1999). Although this method is a huge asset for determining corrosion rates, the accuracy of results is limited by the difficulty in defining the polarized area of reinforcement.

Due to the large time constraints associated with the time it often takes steel to begin corroding in concrete, the measured corrosion rate will depend upon the delay time or sweep rate chosen during the measurement.

Corrosion Rate Measurement by the LPR Method

A common system used in linear polarization resistance tests is the three-electrode system. This method first measures the corrosion potential (E_{corr}) of a section of the working electrode (the steel reinforcement) with respect to a stable reference or auxiliary electrode. This reference electrode is typically a silver/silver chloride electrode or a copper/copper sulfate electrode. Subsequently, a small electrochemical perturbation is then applied to the working electrode and the rate of corrosion is evaluated from the response to this perturbation (Law et al., 2000; Millard et al., 1992). Current output to the auxiliary electrode is variable and often automatically controlled via a potentiostat to maintain a preset potential at the reference electrode.

Another common linear polarization resistance test is the potentiostatic linear polarization technique. This process uses an external perturbation (e.g., an externally applied current ΔI) to shift the metal potential by ΔE and measures the resulting current flow through the auxiliary electrode (a process known as polarization) (Carino, 1999; Millard et al., 1992). While the corrosion of steel in concrete is an electrochemical process and does not directly obey Ohm's Law ($V = IR$), past research has shown that Ohm's Law will be approximately true if polarization applied to the steel reinforcement does not exceed ± 30 mV (Millard et al., 2001). As shown in Figure 2, within a small range of overvoltage (± 10 to 15 mV from the free corrosion potential), a linear relationship between the metal potential (ΔE) and the applied current (ΔI) is evident.

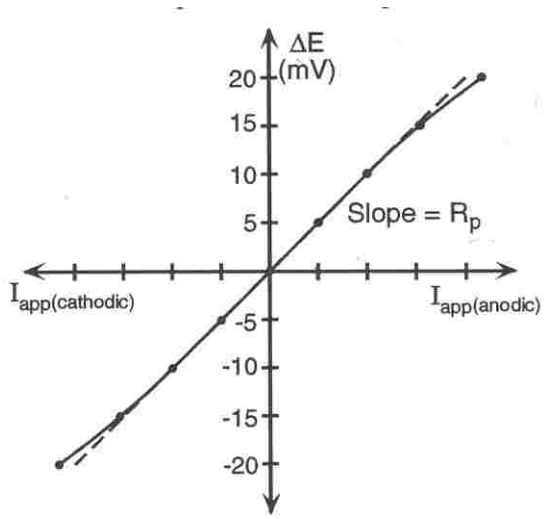

Figure 2: Applied Current Linear Polarization Curve (West et al., 1999)

The slope of this linear portion of the curve is the polarization resistance and therefore is calculated through Equation 2:

$$R_p = \frac{\Delta E}{\Delta I} \qquad (2)$$

The polarization resistance may be defined as the steady-state resistance that the metal interface presents to a change in potential. Once R_p is known, the overall corrosion current, I_{corr}, may be determined through Equation 3:

$$I_{corr} = \frac{B}{R_p} \qquad (3)$$

The value of B may be determined by measuring anodic and cathodic Tafel constants, but is often assumed to equal 26 mV for corroding steel and 52 mV for passive steel (Carino, 1999; Millard and Broomfield, 2003). As shown in the above equation, a small R_p value would correspond with a high rate of corrosion, indicating active corrosion. When the passive layer is present on the reinforcement, the R_p value would be large, and the corrosion rate would

therefore be low. Following the calculation of I_{corr}, the corrosion current density, i_{corr}, may be calculated from Equation 4:

$$i_{corr} = \frac{I_{corr}}{A} \tag{4}$$

where A is the area of the steel reinforcement.

LPR Equipment and Limitations

The simplest linear polarization resistance systems consist of a potentiostat with IR (ohmic resistance) compensation capability and a multimeter. Roughly 70-90% of the current will flow into the steel closest to the surface of the concrete (Millard and Broomfield, 2003). The influence of deeper steel layers may therefore be neglected, since only the top steel layer will be corroding in most cases.

For new structures, wires may be connected to the reinforcement or electrodes can be embedded during construction so a connection may be made at a later date. For existing structures, linear polarization electrodes may be embedded adjacent to reinforcement bars.

It is important to note that corrosion of concrete reinforcement does not always occur at a constant rate. Therefore, corrosion rate measurements taken on one occasion may not be demonstrative of the overall corrosion activity over a long period of time. During the formation of the passive film on the reinforcement, corrosion rates may be quite high. However, corrosion rates typically decrease with time due to the presence of corrosion-inhibiting systems or oxygen depletion at the metal surface (Qian and Cusson, 2004).

To properly carry out polarization resistance measurements from the current-potential relationship, several requirements must be met. For instance, to prevent the alteration of the steel interface, the perturbation must not be applied for an extended period of time. In order to avoid non-linear effects, the magnitude of the perturbation must be small, yet large enough to be measurable under field conditions. Resistance measurements may also include a portion of the resistance presented by the concrete cover; various methods may be used to offset such influences.

When measuring the linear polarization resistance away from the reinforcement bar, both the interfacial resistance (R_p) and the resistance of the concrete between the bar and the auxiliary electrode will be included in the results. This additional resistance is known as the solution resistance (R_s) and must be compensated for when calculating R_p (Millard and Broomfield, 2003). Some of the available instruments incorporate automatic compensation for the solution resistance by measuring the transient response as the perturbation current is interrupted.

Additionally, it may be possible to independently measure R_s and subtract it from the uncompensated LPR measurement through a process called IR compensation. This is achieved by applying a high frequency (100-300 Hz) current of voltage input signal between the auxiliary electrode and the reinforcement. This short-circuits the capacitative part of the

corrosion interface at the bar surface and the resistance measured will be solely due to the concrete solution resistance (Millard and Broomfield, 2003).

Limitations

The aforementioned corrosion current density equation may be used when it is assumed that the corrosion is uniform over the surface of the reinforcing bar. However, corrosion may be concentrated in small, localized anodic zones across the reinforcement as a result of pitting. The local loss of the section in these areas may be considerably greater than what is indicated by a uniform corrosion rate over the whole area of reinforcement (Millard et al., 2001). The accuracy of corrosion rate measurements will be affected by pitting on the reinforcement bar surface. Because of pitting, corrosion current is not evenly distributed along the reinforcement surface area being tested. As a result, local section loss in the pit is underestimated. Also, corrosion rates in pits are five to ten times higher than those found with general corrosion activity (Millard and Broomfield, 2003).

During the period between corrosion initiation and the first signs of concrete cracking, the pitting density increases until the smaller pits join to form a large pit. As a result of this phenomenon, the corrosion rate will rise to a maximum and subsequently drop. This process can produce enough corrosion product to cause cracking in the surrounding concrete (Millard and Broomfield, 2003). When cracks are present in concrete, conducting linear polarization resistance measurements over or next to cracks will produce misleading readings.

If steel reinforcement was previously allowed to corrode in conditions where oxygen was readily available, there may be inaccuracies in oxygen-starved conditions. Additionally, if the effects of electrochemical treatment (e.g., cathodic protection or re-alkalization) have not been allowed to diminish, large errors may result (Millard and Broomfield, 2003).

To correctly measure corrosion current density, the area of steel being assessed must be calculated. This often poses a problem when measuring reinforcement bar corrosion rate from the concrete surface, since the applied potential change may move past the area directly below the auxiliary electrode. If the polarization can be confined to a known area or if a small section of reinforcement can be electrically isolated, the density may be calculated using the aforementioned corrosion current density equation (Millard et al., 2001). One way of preventing drift of the applied potential is the employment of a large auxiliary electrode to cut down on additional perturbed area and subsequent errors. Additionally, a guard ring may be used to confine the perturbing current to a prescribed area.

The current flowing from an auxiliary electrode is unconfined and can spread laterally over an unknown, larger area of steel than is assumed. A second auxiliary guard ring electrode surrounding the inner auxiliary electrode may therefore be introduced to confine the current during linear polarization resistance measurements. Studies have shown that corrosion rates calculated from an unconfined linear polarization resistance measurement display a considerable increase over those from guard ring devices (Law et al., 2000).

Although it is helpful in confining the current, the guard-ring technique creates a series of practical disadvantages when put to use. Among these disadvantages are difficulty in using

potentiostats in field measurement, the fact that the reinforcement (working electrode) is connected to the concrete (the ground), and the chance of the equipment amplifiers picking up electrical interference from the reinforcement, which may act as antennae (Feliu et al., 1990).

When an unconfined measurement is taken over a section of non-corroding steel, the perturbation current is drawn towards the active site. As a result, the measured corrosion rate is influenced considerably by the active site. This results in a higher corrosion rate than would be measured if the perturbation current were successfully confined to the non-corroding steel with a guard ring device (Law et al., 2000).

Environmental Impacts

As is the case with any measurement process, there are certain environmental limitations associated with linear polarization resistance tests. For instance, temperature and relative humidity may have considerable effects on linear polarization resistance results. Past studies have shown that measurements above 50 ºC or 80% relative humidity should be avoided (Millard and Broomfield, 2003). However, it has also been shown that when the external relative humidity fluctuates considerably during wetting and drying cycles, the relative humidity within concrete remains invariant. Regardless of relative humidity values, polarization resistance begins to rise during extended drying cycles, indicating a reducing corrosion rate. On the other hand, during wetting phases, there is an immediate drop in R_p, which indicates an increase in the rate of corrosion (Millard et al., 2001).

Relative temperature and internal temperature also have an effect on linear polarization resistance results. Unlike relative humidity effects, the temperature inside concrete specimens has been shown to follow the external temperature fluctuations relatively closely. A study has shown that the two temperatures are typically within 2 ºC of each other. As temperature rises, there is a definite increase in the corrosion rate, but no constant trends have been gathered from past research (Millard et al., 2001). Freezing conditions also affect linear polarization resistance results, so it is advised not to carry out these tests under such conditions.

Because corrosion rate measurements are instantaneous, they will be affected by various other factors such as the internal concrete environment and measurement procedure. Therefore, rather than relying on single measurements, readings should be taken over time to understand the trends involved. When this method is to be used in the field, the variability of measurements and the influence of fluctuations in ambient environmental conditions on spot readings provide reason for concern.

Corrosion Evaluation

Numerous methods are available to aid in the evaluation of the extent of corrosion of steel reinforcement in concrete. These range from standard test methods (both destructive and non-destructive) to newly developed techniques with little performance record outside the research laboratory. This guide focuses on three specific methods (each described in detail in the previous section):

- Resistivity measurements
- Half-cell potential (HCP) measurements
- Linear polarization resistance, or LPR measurements

These methods have been chosen because they have been in use for a long period of time and are already in use (or readily available to) many departments of transportation. Each method is discussed with respect to the following specific items:

- Brief description of the method
- Equipment use and procedures
- Analysis of data from the equipment
- Environments outside the "standard" applications and unexpected results
    - Moisture effects
    - Temperature effects
    - Coatings
    - Alternate reinforcement materials
    - Prestressed reinforcement: specifics for pretensioned and post-tensioned concrete
    - Edge effects
    - Bar proximity effects
    - Concrete mix effects and cracking

The most effective evaluation of a structure comes from using these methods in combination rather than relying on a single method.

Resistivity Measurements

The resistivity of the concrete surrounding the reinforcement impacts the current flow between the anodic and cathodic regions in the concrete, and thus impacts the rate at which corrosion occurs. As resistivity increases, corrosion rate is decreased (with other variables held constant). Many probes are available commercially for measurement of resistivity in concrete. Variations include two-probe versus four-probe and probes that require surface drilling versus those that do not. The four-probe Wenner technique that was originally developed for soil resistivity measurements is one of the more common methods for measuring concrete resistivity in the field. This probe does not require invasive drilling and is more accurate than the two-probe configuration; thus it will be the focus of the discussion in this section. Figure 3 shows an example of one brand of four-probe resistance measurement equipment.

Figure 3: Corvib RESI Resistivity Meter (Proceq, 2004)

Resistivity measurements alone do not indicate whether the steel reinforcement is corroding; however, they do provide insight into the quality of concrete and the environment to which the steel is subjected. Resistivity measurements can be combined with HCP measurements to estimate a corrosion rate when the steel is depassivated (active corrosion is likely). The ranges shown in Table 1 were suggested by Broomfield and Millard (2002).

Resistivity values in excess of 100 kΩcm can be found, particularly in dry concrete. Resistivity measurements should be used in combination with half-cell potential measurements as a minimum, and preferably be used in combination with all four methods described herein as well as visual examination for spalling, cracking, corrosion product staining, and other indications of potential problems. Figures 4 and 5 show resistivity readings over time on two different concrete slabs (Mason, 2004). The slabs underwent wet-dry ponding cycles with saltwater. The effect of the moisture of the slab is clearly visible. The Figure 4 results are from a standard concrete mix with no pozzolans, while the Figure 5 results are from a ternary mix with silica fume and fly ash. Resistivity is clearly higher with the ternary mix (and fluctuations due to moisture were also greater).

Table 1: Resisivity Evaluation in the Presence of Active Corrosion

Resistivity Range (kΩcm)	*Likely Corrosion Rate*
> 20	**low**
10-20	**low to moderate**
5-10	**high**
< 5	**very high**

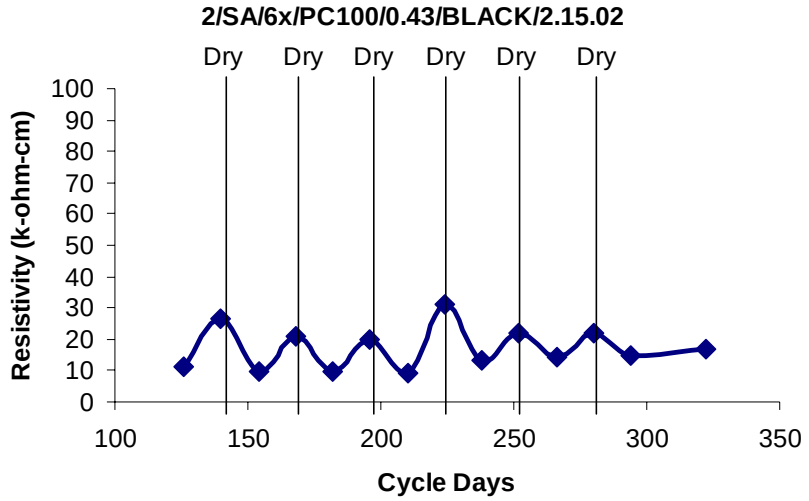

Figure 4: Example Resistivity Values (Standard Concrete, Wet-Dry Saltwater Ponding)

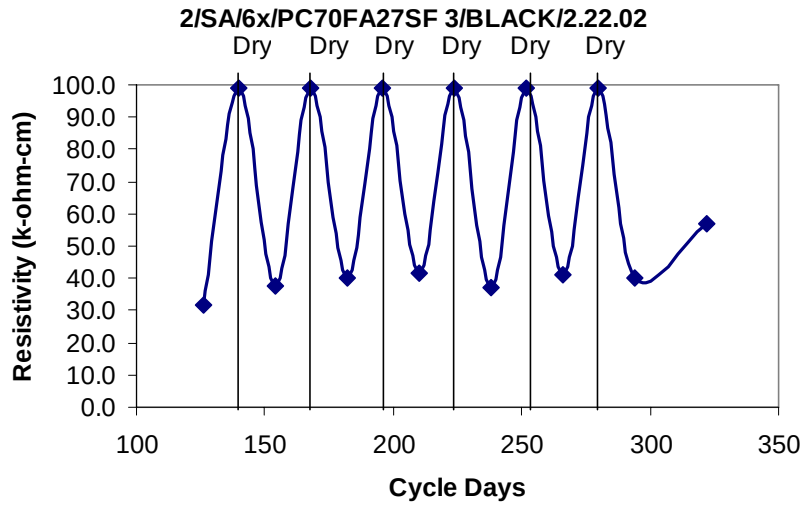

Figure 5: Example Resistivity Values (Ternary Concrete, Wet-Dry Saltwater Ponding)

Resistivity values are affected by the environment (temperature, moisture/humidity), geometry of the concrete element, inhomogeneity of the concrete, probe surface contact, presence and position of reinforcement, and epoxy coating on the reinforcement. Mason (2004) completed an extensive study with multiple concrete mixes resulting in a large database of resistivity readings. Table 2 summarizes a number of variables that were evaluated with respect to their effect on resistivity measurements. Temperature and humidity were held fairly constant in this study (slabs were indoors), so no significant effect was observed.

Table 2: Summary of Effect of Various Parameters on Resistivity Readings

Parameter	*Effect on Resistivity Readings*

Concrete age	**Long-term increase with concrete drying**
Surface moisture	**Light surface moisture needed to record accurate results in dry concrete**
Cover depth	**Decreased with increase in cover depth**
Edge effect	**Higher values near slab edges**
Bar effect	**Decreased in vicinity of reinforcement due to interaction of current flow with steel**
Epoxy-coated reinforcement	**Increased**
Cracked concrete	**Increased directly above cracks**
Probe orientation	**Related to bar effect: decreased as amount of steel in flow path increased**

Procedural Suggestions: Resistivity Measurements

- Record ambient temperature.
- Carry out tests that will be compared under as similar a set of conditions as possible.
- Consider concrete age, bar cover, bar location, bar coatings (or other types of bar material such as galvanized, stainless, or MMFX) in interpretation of results.
- Apply wetting solution to dampen surface: sponges or cloths laid over the reading area work well.
- Record crack locations (and preferably crack widths) with respect to test locations.
- Ensure that the prongs of the probe remain moist during testing to ensure good electrical contact.
- Apply steady pressure to hold the probe in place during reading.
- Allow the current flow to reach 100% (as indicated on equipment) prior to recording final reading.
- If possible, avoid taking readings directly above reinforcement; if this cannot be avoided, orient probe at a 90º angle to known reinforcement direction.
- Carry out multiple readings in a general area to check local variability.
- Carry out a grid-based survey (noting locations of all readings) of large surfaces to provide a representative contour plot that may indicate areas of variability (due to chlorides, moisture, or other conditions as described previously).

Half-Cell Potential Measurements

The half-cell potential measures the difference in potential between the concrete surface and the underlying steel. Figure 6 shows an example of one brand of HCP measurement equipment. Large wheeled systems with electrodes embedded in the wheels are also available for use in mapping large surfaces quickly. The measurement requires an electrical connection to the steel and a reference electrode that is placed on the concrete surface. The reference electrode has a sponge tip that is moistened with an electrolyte solution (dish soap in water is commonly used as a "wetting solution"). The most commonly used field reference electrode is the copper-copper sulfate electrode. The electrode is moved to different locations over the concrete surface to provide a map of the potentials in different locations. Readings indicate the HCP of the bar to which the system is attached. If there is good electrical continuity from the attached bar and the rest of the reinforcement cage of interest, then multiple connection locations are not needed. In the case of epoxy bar, electrical continuity of the entire cage is less likely, but there is typically more continuity than expected due to nicks in the coating at bar crossing locations.

HCP measurements provide an indication of whether there is likelihood of active corrosion. They do not indicate corrosion rate or metal loss. ASTM C876 gives the guidelines shown in Table 3 for interpreting HCP measurements.

Figure 6: CANIN Corrosion Analyzing Equipment (Proceq, 2004)

Table 3: HCP Interpretation Guidelines (non-submerged concrete, non-coated bar)

mV vs. CSE	*Probability of corrosion*
0 to -200	**>90% probability of no corrosion**
-200 to -350	**Uncertain corrosion activity**
More negative than -350	**>90% probability of corrosion**

An example of a half-cell potential map is shown in Figure 7 for a reinforced concrete slab with cracking and corrosion.

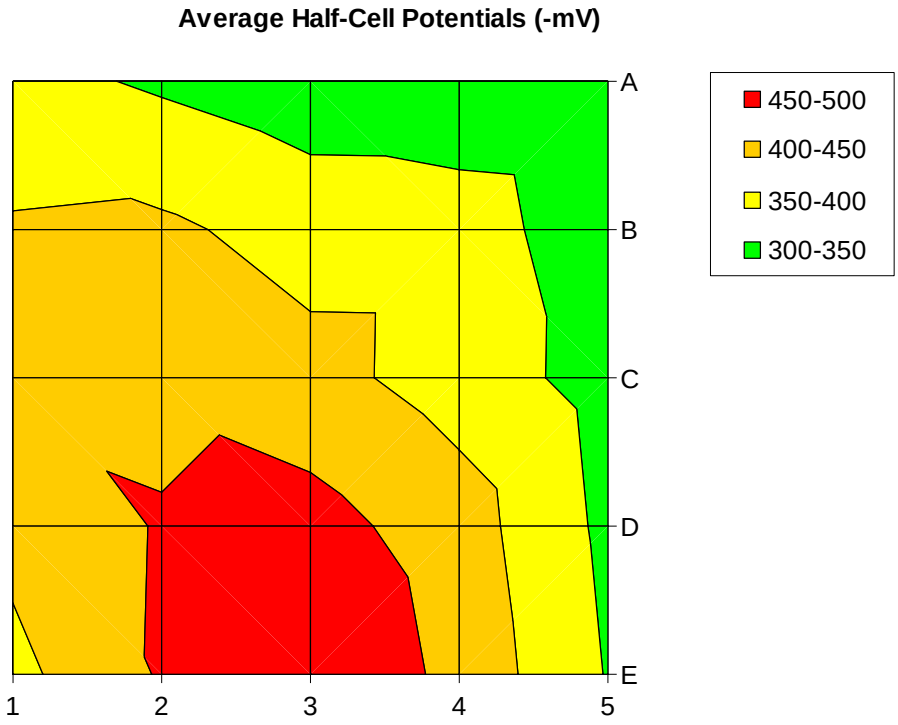

Figure 7: HCP Surface Map

As indicated in the literature review, HCP values can be affected by a large number of variables. Table 4 summarizes those variables that were evaluated with respect to their effect on HCP measurements from Mason's study (2004).

Table 4: Summary of Effect of Various Parameters on HCP Readings

Parameter	*Effect on HCP Readings*
Surface moisture	**Wetted surface necessary during readings**
Test surface location	**Localized corrosion accuracy dependent on number of surface readings**
Bar effect	**Lower (less negative) values directly above clamp location**
Epoxy-coated reinforcement	**Decreased (less negative) than equivalent condition black bar**
Cracked concrete	**Increased (more negative) to coincide with corrosion development**

Procedural Suggestions: Half-Cell Potential Measurements

- Record ambient temperature.
- Carry out tests that will be compared under as similar a set of conditions as possible.
- Consider concrete age, bar cover, bar location, bar coatings (or other types of bar material such as galvanized, stainless, or MMFX) in interpretation of results.
- Apply wetting solution to dampen surface prior to readings: sponges or cloths laid over the reading area work well.
- Record crack locations (and preferably crack widths) with respect to test locations.
- Avoid taking readings directly over the location where the connection to the reinforcement is made.
- Ensure that the sponge of the reference electrode remains moist during testing to ensure good electrical contact.
- Check for good electrical contact with the reinforcement being evaluated (beware of loose or broken wires or clips to the reinforcement in the areas between the various reading locations).
- Hold electrode in place until HCP reading stabilizes.
- Maintain the proper solution level and quality in the electrode (refer to manufacturer's instructions).
- Carry out multiple readings in a general area to check local variability.
- Carry out a grid-based survey (noting locations of all readings) of large surfaces to provide a representative contour plot that may indicate areas of likely corrosion activity.

Corrosion Rate (LPR) Measurements

The linear polarization resistance technique is a common technique for field measurement of corrosion rate. An electrical connection to the reinforcement is required and a reference electrode is used, similar to the setup for HCP measurements. A current is applied over a small range where the current versus potential relationship is linear. Full details on the process and calculations involved are given in the literature review. A guard ring is often included with the equipment to confine the current during the LPR measurements. Figure 8 shows an example of one type of LPR measurement device with a guard ring.

Figure 8: NDT James Instruments Gecor 6 Instrument (James, 2004)

LPR measurements provide an indication of the corrosion rate at a given instant under specific environmental conditions. Multiple readings over time under different conditions are much more useful than a few isolated readings. The LPR measurements take considerably longer than the resistivity and HCP measurements. These measurements can be very useful in pointing out areas of interest to focus LPR measurements. The suggested criteria from Broomfield and Millard (2004) for rate measurements are given in Table 4. As outlined in the literature review, care should be taken in interpreting corrosion rates and corresponding metal loss estimates, keeping in mind that values represent an instant in time rather than the full spectrum seen over the service life of the structure.

Table 4: Corrosion Current Criteria for Surface Applied Corrosion Rate Measurements

Corrosion Current Density ($\mu A/cm^2$)	*Metal Loss at Section (μm/year)*	*Corrosion Classification*
< 0.2	**< 2**	**very low or passive**
0.2 to 0.5	**2-6**	**low to moderate**
0.5 to 1.0	**6-12**	**moderate to high**
> 1.0	**>12**	**high**

Of all the methods described in this document, LPR field corrosion rates are the most susceptible to error in application and interpretation. Many of these issues are discussed in detail in the literature review section. Table 5 summarizes some general comments from Mason's study (2004).

Table 5: General Comments on LPR Variables

Parameter	*Effect on LPR Corrosion Rate Readings*
Surface moisture	**Ensure that sponge tip is always fully dampened prior to initiating a reading.**
Test surface location and bar effect	**Can have major influence depending on accuracy of estimate of underlying reinforcement.**
Signal confinement	**Guard ring appeared to help reduce error in final result.**
Epoxy-coated reinforcement	**Errors in measurements; skewed results due to discontinuous current flow.**
Cracked concrete	**Increased to coincide with corrosion development.**
Correlation with resistivity and HCP	**High corrosion rates did not necessarily correspond with areas of low resistivity and high HCP.**

Procedural Suggestions: Corrosion Rate (LPR) Measurements

- Record ambient temperature.
- Carry out tests that will be compared under as similar a set of conditions as possible.
- Consider concrete age, bar cover, bar location, bar coatings (or other types of bar material such as galvanized, stainless, or MMFX) in interpretation of results.
- Apply wetting solution to dampen surface prior to readings: sponges or cloths laid over the reading area work well.
- Record crack locations (and preferably crack widths) with respect to test locations.
- Ensure that the sponge of the reference electrode remains moist during testing to ensure good electrical contact.
- Check for good electrical contact with the reinforcement being evaluated (beware of loose or broken wires or clips to the reinforcement in the areas between the various reading locations).

- Hold electrode in place until HCP reading stabilizes before applying the perturbation to the reinforcement.
- Maintain the proper solution level and quality (refer to manufacturer's instructions).
- If possible, avoid areas where bars are overlapping to avoid errors in calculation of steel area; this includes accounting for any prestressing strand, metallic post-tensioning duct, or any other metal in the area.
- Use a guard ring for signal confinement; if the device indicates that confinement is not achieved, note this along with measurement.
- Carry out as many measurements as possible – areas of interest as indicated by HCP and resistivity measurements are good places to focus.

Summary

This guide is intended to aid the engineer with little previous background in corrosion evaluation. Three types of techniques that can be performed with commercially available equipment are discussed. In corrosion evaluation of a reinforced concrete structure, all three of these techniques should be used in combination with visual inspection and chloride penetration samples (in specific locations of interest). Visual inspection should include evaluation of any external evidence of underlying corrosion, including: rust staining, cracking, spalling, and other signs of distress. Resistivity and half-cell potential measurements can be used first to target specific areas of concern. Corrosion rate measurements are time consuming and can then be focused in specific areas with spot checks in other areas. No one method alone should be relied upon to determine the structure condition. In instances where the measurements point to a potential problem, limited destructive evaluation may be necessary to determine the extent of true metal loss and the resulting effect on service life.

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