Corrosion Assessment Fundamentals for Reinforced Concrete Structures

by Stephen Garrett, Zack Coleman, and Drew Witte

INTRODUCTION

For reinforced concrete structures, one of the most common and detrimental issues is corrosion of embedded reinforcement and associated deterioration. Fortunately, engineers and asset managers can employ corrosion assessment tools to better understand the current condition of a structure, estimate future performance, and monitor changes in condition with time. Detailed corrosion assessments with focused use of nondestructive testing (NDT) methods and material testing, coupled with service life modeling and life cycle cost analysis (LCCA), provide a holistic approach to preservation that can refine decision-making regarding maintenance, repair, and rehabilitation strategies.[1,2]

Effective use of corrosion assessment techniques can provide value in assessing a range of structure types including bridges, parking structures, building envelopes, marine structures, and buried or earth retaining elements. Like any tool, effective implementation of corrosion assessment techniques requires an understanding of functionality and limitations of the method and equipment. This article introduces some of the most common corrosion assessment methods and considerations for their implementation.

Reinforced Concrete Deterioration

Depending on the exposure environment, concrete structures can be subject to various physical and chemical deterioration mechanisms that can weaken, erode, or crack the concrete. Reinforcing steel embedded in concrete can also cause damage from corrosion. When reinforcing steel corrodes, the resulting corrosion products are less dense than the original metal and their formation generates expansive/tensile stresses in the encapsulating concrete. As corrosion progresses, tensile stresses overcome the tensile capacity of the concrete, resulting in cracking, delaminations, and spalling (Fig. 1).

Basics of Corrosion Chemistry in Reinforced Concrete

Corrosion is an electrochemical process requiring four conditions: moisture or an electrolyte for ionic connectivity; electrical connectivity; an anode; and a cathode. The latter two are electrically connected metal surfaces with differing electrochemical potentials, which in reinforced concrete can occur in the same rebar or between different rebar that are otherwise electrochemically connected (Fig. 2). At the anode, metallic iron oxidizes to produce positive iron ions and free electrons. The electrons travel through the metallic path to the cathode, where they are consumed through the conversion of oxygen to hydroxide ions. The negatively

Corrosion rate testing of reinforced concrete

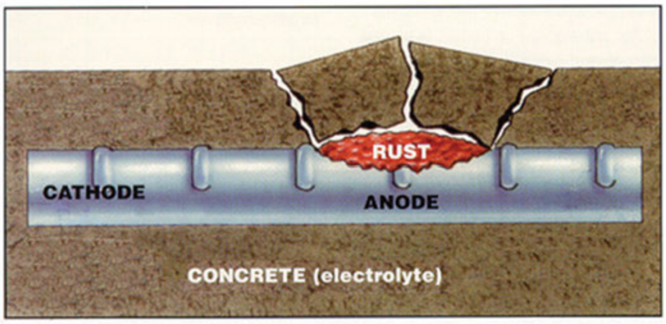

Fig. 1: Excerpt from ICRI 510.2 showing corrosion-induced cracking and spalling[3]

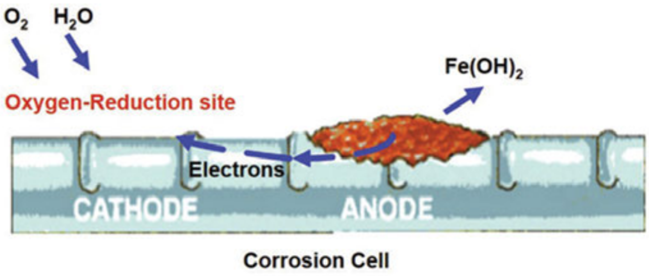

Fig. 2: Excerpt from ICRI 510.2 showing basic corrosion cell[3]

charged hydroxide ions travel through the electrolyte to the anode, where they combine with the iron ions to form the iron oxide corrosion products.

Conventional concrete has a naturally high pH (approximately 12 to 14). In this environment, the corrosion products formed from the carbon-steel corrosion process are stable, creating a "passive layer" and preventing further corrosion. However, this passive layer can be locally disrupted by chlorides or become unstable if the pH of the concrete environment is lowered below roughly 11.[4] Once steel depassivates, expansive iron oxide corrosion products form, leading to cracking and spalling (Fig. 3). A variety of methods are available to characterize the extent and rate of corrosion reactions.

VISUAL ASSESSMENT AND DELAMINATION SURVEYS

A wealth of information about the condition of a structure is obtained from visual assessment and delamination surveys. The types or patterns of surface staining, cracking, and spalling in concrete elements can inform the causes of potential distress.

Acoustic sounding methods can be used to detect delamination by identifying an audible change (dull or hollow sound) of the concrete from impacts; ASTM D4580, *Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding*, provides guidance for conducting such surveys.[5] Other forms of delamination surveys may also prove feasible, including infrared thermography techniques and ground-penetrating radar; additional discussion on these methods can be found in ICRI 210.4 *Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures*.[6]

NONDESTRUCTIVE EVALUATION—CORROSION SURVEYS

Electrochemical NDT methods can be used to evaluate the corrosion condition beyond what can be determined from visual and delamination assessments alone. The techniques are used to survey the activity, risk, and rate of corrosion in a concrete structure. Guidance on selecting and executing these methods can be found in technical documents prepared by ICRI Committee 210, ACI Committee 228, and AMPP Committee SC-12.[6,7,8] Measurements from each method should be evaluated in relation to the assessed structure to understand the effects of exposure conditions and existing distress. Several test methods are discussed in detail below.

Important considerations for conducting and interpreting corrosion results are temperature and humidity conditions. Ambient and surface temperature should be measured during testing, and the NDT methods should be employed when temperatures are above freezing. Furthermore, an understanding of seasonal changes in temperature and humidity is necessary for understanding changes in likely corrosion rates.

Fig. 3a: Example of corrosion in reinforced concrete; corrosion and spalling near drain

Fig. 3b: Corroded, embedded rebar with adjacent corrosion-induced cracking

Fig. 4: Rebar continuity verification

Considerations for Reinforcement Continuity

For the purposes of NDT, drill points are made to the rebar for grounding the equipment and for evaluating connectivity between test regions by measuring direct-current voltage and resistance (Fig. 4). Epoxy coatings can reduce connectivity which, in addition to the barrier protection, improve the corrosion resistance by electrically isolating the rebar. Alternating-current (AC) resistance has also been used in epoxy-coated reinforcement to evaluate global connectivity as a means to infer degree of electrical isolation.[9] Reinforcement continuity is also an important consideration for developing corrosion mitigation strategies (e.g., cathodic protection system design).

Corrosion Potential

The objective of half-cell corrosion potential (HCP) testing is to identify anodic and cathodic regions in the structure. HCP testing (Fig. 5) is standardized for reinforced concrete structures in ASTM C876.[10] A reference electrode comprises one "half-cell" which is placed in contact with the surface of the reinforced concrete; the anode or cathode is the other "half-cell." The potential of the structure is measured relative to the reference electrode using a voltmeter. HCP testing requires direct electrical connection to the reinforcement.

More negative (i.e., more anodic) potentials are generally associated with active corrosion while more positive (i.e., more cathodic) potentials are typically indicative of passive metals. Several methods for interpreting HCP data are summarized below.

- **Numeric Magnitude Technique.** This method entails using absolute thresholds given in ASTM C876 (-200 and -350 mV) to classify corrosion as active, passive, or uncertain. As noted in ASTM C876, these thresholds are only applicable for certain exposure conditions and structure types, such as atmospherically exposed structures with uncoated reinforcement. These thresholds are not applicable to submerged or earth-retaining structures, or structures reinforced with coated or alloyed reinforcing steel. While these ranges may be reasonable rules of thumb, they should not be used as the only interpretation criteria, since they can provide less-than-useful or false predictions of corrosion state.[11,12]

Fig. 5a: Half-cell survey method — rolling half-cell survey of bridge deck

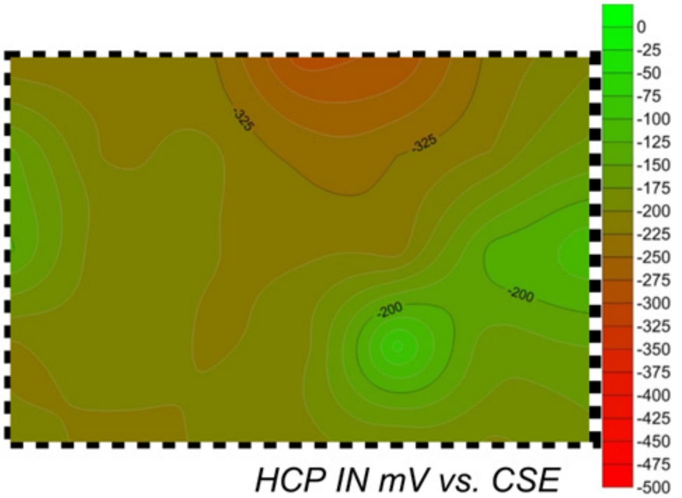

Fig. 5b: Example of contour plot showing voltage gradients and corrosion hotspots

- **Potential Difference Technique.** This technique involves identifying large spatial gradients in potential difference, which are typically indicative of localized corrosion.[10] One rule of thumb is that a change of -100 mV over one foot is indicative of corrosion, but actual conditions will likely vary for each structure, and verification of findings should be performed using other NDT methods and destructive verification.

- **Statistical Analysis.** This method entails identifying different statistical distributions of data within a full HCP dataset. Active and passive reinforcement tend to exhibit different statistical distributions; therefore, this method can be used to select a potential threshold for identifying active corrosion.[12] This threshold is tailored to the concrete component from which the data was collected, making it a more versatile method for interpreting HCP data than the Numeric Magnitude Technique, if a sufficiently large sample size can be collected.

Fig. 6: Corrosion rate measurements

Instantaneous Corrosion Rate

Measuring the instantaneous corrosion rate allows practitioners to estimate the rate of reinforcement loss. A variety of different approaches exist that correlate in-situ electrical properties to corrosion rate. Such methods commonly utilize a ground connection, a working electrode, and a reference electrode (Fig. 6). The working electrode applies a known electrical current to the concrete, and the reference electrode measures the resulting change in voltage of the reinforcement. The current and voltage are used to calculate corrosion rate. As noted by ACI Committee 228, the measured corrosion rate can vary depending on the equipment and approach employed to measure corrosion rate (e.g., potentiostatic polarization resistance or galvanostatic pulse testing).[7] Therefore, there are no standard interpretation criteria applicable for all corrosion-rate tests.

Corrosion rate measurements are not only affected by the state of the underlying reinforcement, but also temperature and environmental conditions when the test is performed. Accordingly, prior to instantaneous corrosion rate testing, HCP measurements are typically collected first to understand where reinforcement is actively corroding. It is also important to note that the measurement is referred to as "instantaneous" corrosion rate because it is the measurable rate at the specific time of testing, and the true rate will fluctuate with seasonal in temperature and humidity. Therefore, care should be taken in interpreting corrosion rate measurements.

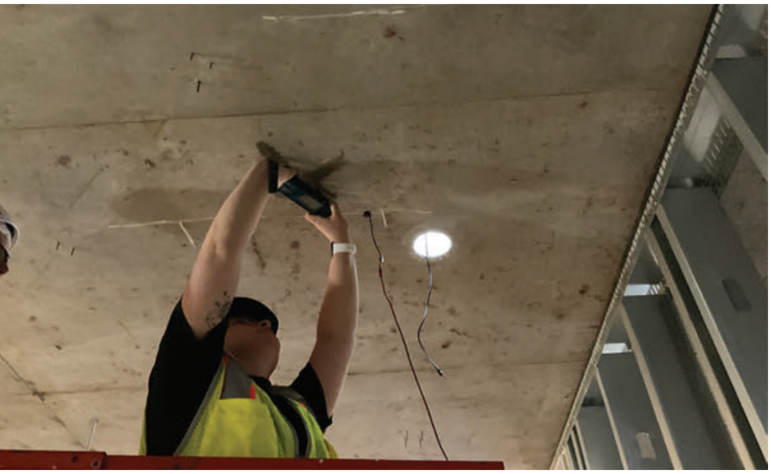

Fig. 7: Surface resistivity measurements

Electrical Surface Resistivity

Electrical resistivity is a measure of the capacity of a material to resist the flow of electrical current. In concrete structures, resistivity is empirically correlated with risk of corrosion. The corrosion current utilizes the ionic path through the concrete pore solution, and lower resistivity environments will be more conducive to promoting corrosion reactions. Among other factors, the composition of the pore solution and tortuosity of the pore network affect concrete resistivity. If corrosion is occurring (as identified through the methods described above), surface resistivity measurements can offer insight into the relative rate of corrosion at different locations in the structure.[7]

There is presently no ASTM standard for field measurements of surface resistivity. AASHTO T 358 and RILEM TC 154-EMC provide guidance for interpreting surface resistivity measurements of laboratory and field data, respectively.[13,14] The four-point Wenner test, shown in Fig. 7, is typically used in the field to measure the surface resistivity in the near surface of the concrete concrete, at a depth corresponding to roughly twice the spacing of the resistivity probes.

Fig. 8a: Carbonation Field Test—spray-applied pH indicator (phenolphthalein) at drill holes of incremental depths

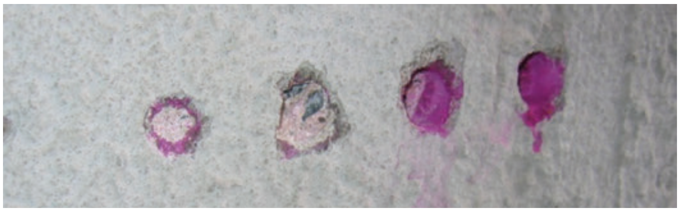

Fig. 8b: Carbonation Field Test—spray-applied pH indicator (phenolphthalein) at drill holes of incremental depths

VERIFICATION OF NDT RESULTS AND MATERIAL TESTING

While this article focuses primarily on corrosion NDT methods, some discussion on material sampling and testing is prudent. Detailed corrosion evaluations commonly include inspection openings; core sampling; corrosion product sampling; carbonation evaluation; and chloride-concentration testing.

Inspection Openings and Core Sampling

For calibration/verification purposes, it is best practice to perform some level of destructive verification for any NDT method. Inspection openings (at cores or other locations) can aid in verification of electrochemical NDT by verifying active corrosion and related delamination (Fig. 3b), measuring section loss, and sampling corrosion products for more detailed analyses. Core samples can be used for further evaluation to identify possible corrosion mechanisms.

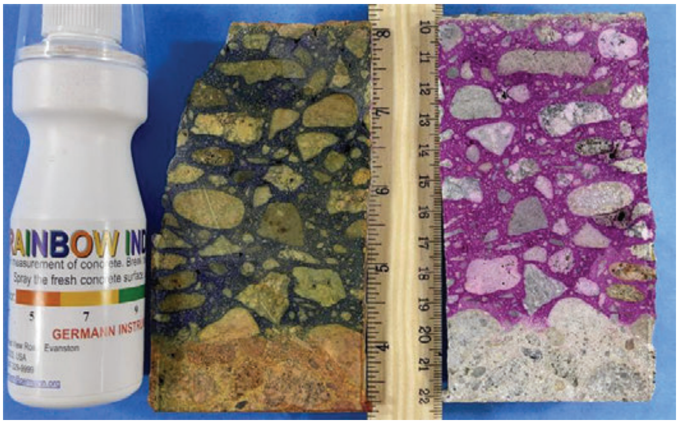

Fig. 9a: Carbonation—core treated with both phenolphthalein and rainbow indicator to show pH range through carbonation front

Fig. 9b: Carbonation—core treated with both phenolphthalein and rainbow indicator to show pH range through carbonation front

Carbonation Depth Evaluation

Carbonation causes depassivation of the steel by lowering the pH of the concrete, and this phenomenon can be measured. At drilled holes and cores, a pH indicator (phenolphthalein) can be applied to estimate the approximate carbonation front; the color change to pink occurs above a pH of 9 (Fig. 8). In reality, pH change in concrete is a continuum, and more accurate measurements can be taken on freshly fractured laboratory samples, using a variable color pH indicator (i.e., "rainbow indicator") (Fig. 9).

Chloride Concentration Evaluation

Chloride ions can accumulate and depassivate reinforcement, and while a "lower bound" concentration value (0.2 percent by weight cement) is often cited as the threshold for corrosion initiation, probabilistic distributions provide a more realistic characterization of the risk of chloride-induced corrosion.[5] The total amount of free chlorides (i.e., unbound) can be measured through laboratory testing of water-soluble chloride concentrations.[16] However, often it is more convenient to analyze the total chlorides present in a sample, including both bound and unbound chlorides, through acid-soluble testing.[17] An example of a chloride titrations setup is shown in Fig. 10.

Fig. 10: Titration of powder sample for chloride concentration evaluation

Chloride concentration evaluation is a complex topic, and in general a variety of factors need to be considered when developing test plans, including but, not limited to: depth of chloride ingress; magnitude and source of chloride exposure; aggregate size as related to core diameter and slice depth required; effect of constituents such as latex or polymers; and original contamination (i.e., "background chlorides") from admixtures or contaminated mix constituents (e.g., aggregates).

Powder samples obtained through field-drilling into the structure at incremental depths can provide a cursory screening of bulk chloride concentration. However, for more advanced analyses, core samples should be extracted, and chlorides should be measured at discrete locations through the cover concrete. Core sampling and slicing allow for greater precision in testing and interpretation of concentration profiles. Typically, core samples are sliced at important depths through the cover concrete and above the reinforcement (Fig.11, Fig. 12). Deeper slices in the concrete or substrate, away from exposure, can also be tested to identify if there is "background" or initial exposure.

Fig. 11: Core sample prepared for chloride testing

OPPORTUNITIES AND CHALLENGES

As noted by the Association for Materials Protection and Performance (AMPP), there is no one protocol for performing a corrosion assessment, due to the wide range of reinforced concrete structures.[8] Rather than using any one NDT method in isolation, corrosion assessments are most effective when they are tailored to a specific structure and when data from multiple NDT methods are leveraged. Frequently, an effective corrosion assessment requires adapting the work to the findings and conditions as they are revealed.

NDT methods for corrosion evaluation are founded on fundamental scientific principles of the electrochemical corrosion process. When properly deployed, these methods provide a wealth of information about the complex corrosion mechanisms present in reinforced concrete structures. However, to appropriately interpret the results, a thorough understanding of the corrosion process is necessary. Furthermore, as with any NDT method, verification through inspection openings and coring should be performed. The core samples can then be used to further the investigation through material testing by determining the depth of carbonation front and chloride concentration profiles.

The methods of corrosion evaluation described in this paper are specific to characterizing corrosion of embedded reinforcement. Such assessment may be only a part of a broader assessment, including evaluation of other deterioration mechanisms. The data should not be used in isolation of other findings or analyses. The implications of section loss and loss of concrete cover could have broader structural implications that may warrant actions beyond only local repairs. Corrosion evaluations contribute to a health-check of a structure, serving as a baseline for comparing actual to expected performance, and the resulting data can be used for service-life modeling and developing comprehensive structural assessment and rehabilitation programs.

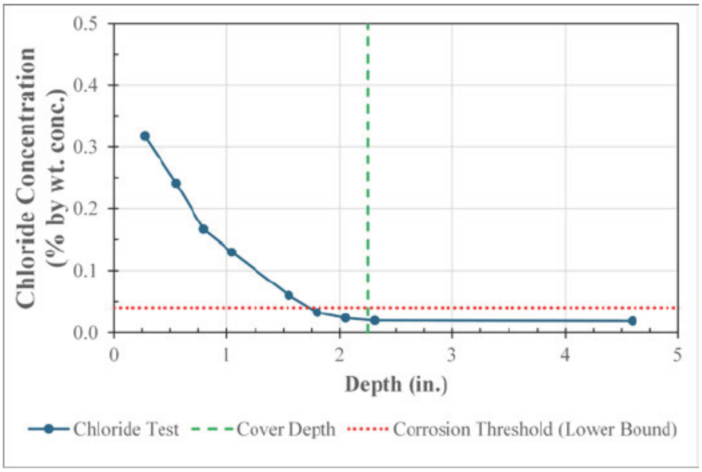

Fig. 12: Example chloride profile showing chloride ingress and negligible background contamination; depth measured from topside/exposed surface of structure. Note: corrosion threshold shown was converted to percent by weight of concrete

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Stephen Garrett is a Senior Associate at Wiss, Janney, Elstner Associates in Northbrook, Illinois. Mr. Garrett has more than a decade of experience in condition assessment and nondestructive evaluation, corrosion evaluation and mitigation, field and laboratory testing, service life and durability evaluations, and repair/rehabilitation design, particularly for reinforced concrete structures and bridges. In addition to his professional practice, Mr. Garrett is an active member of AMPP, ASNT, and ICRI. At a national level, Mr. Garrett currently serves as Chair of ICRI 160 – Life Cycle and Sustainability, Secretary of ICRI 510 – Corrosion, and an active consulting and voting member on other committees. He received his BS and MS in Civil Engineering at University of Illinois at Urbana-Champaign, is a licensed Professional Engineer in multiple states, and is a Certified Cathodic Protection Specialist (NACE CP-4).

Zachary Coleman is an Associate at Wiss, Janney, Elstner Associates in Fort Lauderdale, Florida. Dr. Coleman is experienced in assessing the material properties and structural behavior of reinforced concrete structures, in part by performing nondestructive evaluations. Dr. Coleman is also an active member of ACI, serving as the secretary for ACI 408 (Bond and Development of Steel Reinforcement) and a voting member for ACI 445F (Interface Shear). He received his BS from Lafayette College, his MS from Auburn University, and his PhD from Virginia Tech.

Drew Witte is an Associate at Wiss, Janney, Elstner Associates in Northbrook, Illinois. Mr. Witte is experienced in concrete materials testing and studying the mineralogy of cementitious materials via techniques like SEM-EDS, XRD, and Raman spectroscopy. He received his BS from Valparaiso University and his MS in Civil Engineering at the University of Illinois Urbana-Champaign. Mr. Witte is also an active member of ACI and the American Ceramic Society (ACerS).