Measuring the Corrosion Rate of Reinforcing Steel

A methodology for the non-destructive measurement of the corrosion rate of steel embedded in concrete was one of the products (SHRP 2001) that resulted from SHRP research in the concrete and structures technical area. Under contract C-101, Assessment of Physical Condition of Concrete Bridge Components, three commercially developed corrosion rate devices were evaluated. The work is reported in Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 2: Method for Measuring the Corrosion Rate of Reinforcing Steel (SHRP-S-324). Excerpts from the executive summary and technical highlights of the report are reproduced in this brief along with information about the availability of the devices as of March 1995. A draft standard test method for measuring the corrosion rate of reinforcing steel is included in Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 8: Procedure Manual and is summarized in this brief. A fourth device became available during the course of the SHRP research and has not been subjected to the same evaluation procedure as the first three. A short description of the alternate corrosion rate device is included at the end of this brief.

BACKGROUND

Corrosion-induced distress in concrete bridges is a multibillion dollar problem in many countries. Information on the corrosion rate of steel embedded in the concrete is needed to determine the present condition of concrete structures and to predict future deterioration rates. A rapid, non-destructive test method for measuring the corrosion rate would provide key information for the evaluation of structures' life-cycle costs.

Since corrosion is an electrochemical process, it is reasonable to monitor it with electrochemical techniques. Most of the electrochemical techniques for determining the rate of corrosion involve measurement of polarization resistance ($R_p$) since it is inversely proportional to the corrosion current, which in turn is directly proportional to the corrosion rate. Several implicit assumptions are involved in linking polarization resistance with corrosion rate, and in some systems there may not even exist a measurable polarization resistance. However, polarization resistance measurement has been found to generally work well with the steel-in-concrete system throughout the wide range of conditions encountered in practice.

The Strategic Highway Research Program (SHRP) was established by the United States Congress in 1987 as a five-year, $150 million research program to improve the performance and durability of highways and to make them safer for motorists and highway workers. As a follow-on program to SHRP, Congress established in the Intermodal Surface Transportation Efficiency Act of 1991 programs to implement SHRP products and to continue SHRP’s long-term pavement performance (LTTP) program. The Canadian Strategic Highway Research Program (C-SHRP) is directed at extracting the benefit of the US work for Canada.
At the time the research under SHRP contract C-101 was conducted, instrumentation for determining corrosion rates of steel in concrete was under development. Therefore, the emphasis was placed on working co-operatively with the developers of the most promising devices. Three commercially developed prototype devices were chosen based on their level of development and availability. They were provided by K.C. Clear, Inc. (3LP-NBS1), GEOCISA (Gecor 6), and Nippon Steel Corporation (CorroCatch).

The first two devices operated on the principle of linear polarization with and without current confinement, respectively. The third device was based on the principle of superimposed current pulses of high and low frequency with current confinement. The devices were used to measure the polarization resistance of reinforcing steel in concrete. The polarizing current reaches the steel rebar over an area beyond that of the counter electrode (CE) of the probe. Thus, for a proper evaluation of the corrosion rate it is important to define the polarized area of the rebar. This can be achieved by applying a guard electrode (GE) for current confinement. The GE is situated concentrically around the CE and is maintained at the same potential as the CE. As a result, the signal distribution from the CE is limited to an area not greater than the midpoint of the separation between the CE and the GE, when both the electrodes are of the same width and assuming the concrete can be treated as a homogeneous medium.

**DEVICES**

**GECOR 6**

This equipment consists of a corrosion meter and a probe. The probe uses two sensor electrodes and external CEs. The diameter of the current confinement is 140 mm. Before applying current to the system, the corrosion potential is measured with a solid silver/silver chloride reference electrode placed at the center of the probe. Any potential difference that exists between the two sensor electrodes is also determined. Current is applied from the CE in the center of the probe, changing the potential difference between the two sensor electrodes. Current is then applied from the external counter (guard) electrode until the potential difference between the two sensor electrodes returns to its original value. This procedure effectively confines the current to an area directly below the central CE, permitting calculation of the true polarization resistance. The device stores data for up to 3,500 tests in an internal RAM. The data can subsequently be downloaded to an auxiliary data-processing PC.

Developed in Spain, James Instruments in Illinois supplies the Gecor 6 device at a cost of $13,000 (USD).

**3LP-NBS1**

The 3LP-NBS1 instrument uses a three-electrode linear polarization technique. A cathodic current sweep is applied until the rebar is cathodically polarized to 12 mV. During this process, the current flow values at polarization levels of 4, 8 and 12 mV are recorded. Upon reaching the 12 mV polarization level, the system is depolarized and must return to within 2 mV of the original potential for a valid determination. The probe consists of a pencil copper/copper sulfate reference electrode and a copper mesh CE. It is not equipped with a GE. Approximately three minutes are needed to take one reading.

This device is available from RLC Instruments in Ohio for $3,000 (USD).

**CORROCATCH**

This device operates by using a galvanostatic double pulse. Two current pulses of different frequencies are superimposed. The higher frequency provides a measure of the concrete resistance (R),. The lower frequency measures the sum of concrete resistance and polarization resistance. Thus, the difference between the two provides polarization resistance (Rp), from which the corrosion current and corrosion rate can be calculated. The technique used here differs from the AC impedance technique in that it does not sweep frequencies, but uses only two. The two frequencies can be selected, or the operator may use the values incorporated in the automatic operational mode which are 1300 and 0.02 Hz. The lowest frequency that can be selected is 1 mHz, which may not be low enough to measure polarization resistance in the passive state. The probe consists of a cen-
tral silver/silver chloride reference electrode and concentric platinum CE and GE. The CE and GE are maintained at the same potential using a voltage follower.

The Nippon Steel Corporation in Japan is the supplier of Corro-Catch. The cost per unit is $25,000 (USD).

PR MONITOR

Cortest Instrument Systems in Texas supplies an alternative device for measuring the corrosion rate of steel. This device became available after the first three devices were selected for SHRP evaluation and, therefore, was not subjected to the same testing procedure. A brief description of the device is included at the end of this brief.

TECHNICAL HIGHLIGHTS

LABORATORY STUDIES

A variety of laboratory studies were carried out to answer numerous questions and to evaluate certain parameters as a necessary prelude to the development of field testing procedures. The major findings of the laboratory studies are summarized in this section.

Variations in the distribution of the concrete resistivity have a significant influence on the potential/current distribution. If the outer portion of the concrete structure has a lower resistivity compared to the remaining portion of the concrete, the system presents a more uniform signal distribution. For more accurate results, it is recommended that the concrete surface be appropriately wetted before polarization resistance measurements are made in field tests to ensure good electric contact between electrodes and concrete surface. \( R_p \) values increased after wetting because the current refracts towards the normal as it goes into a higher resistance medium. This leads to better confinement and, subsequently, an increased \( R_p \).

The potential of the steel-in-concrete system was found to shift in the cathodic (more negative) direction after wetting, and it stabilized some time after the wetting. These trends were observed to become more pronounced as the resistivity of the concrete and the cover thickness of the concrete increased. This is because water fills the concrete pores and impedes the access of atmospheric oxygen to the rebar.

Reproducibility of \( R_p \) measurements was markedly improved by:

- making the concrete surface planar (intimate probe contact);
- decreasing the contact resistance between the probe and concrete surface by using water or conducting paste;
- symmetric positioning of the probe over the rebar; and
- taking \( R_p \) measurements only after the corrosion potential stabilized.

Use of a GE confines the polarized area of a steel rebar far more effectively than a single CE. The polarized area decreases by an order of magnitude when a GE is used. The GE was able to confine signal distribution in a highly resistive medium over a separation of 28 cm. Therefore, for field testing of concrete structures, which generally have smaller cover thickness, much better confinement can be expected.

The degree of success in the application of the GE technique depends on the magnitude of the polarization resistance \( (R_p) \), concrete cover thickness, and the design of the CE system used. The most significant parameter is concrete cover thickness. The polarized area increases dramatically as thickness increases. The separation distance between the CE and the GE is another important parameter. Signal confinement was improved by decreasing the separation between the CEs and GEs and by increasing the width of the GE. If the GE width is larger than the concrete cover thickness, the polarized area does not change very much with increases in GE size.

During polarization resistance measurements, the top portion of the rebar (facing the electrode) is polarized to a much greater extent than the entire circumference, as is commonly assumed. Furthermore, the polarization can occur exclusively on the top half of the rebar. The conventional assumption leads to an underestimation of the corrosion rate by up to half its real value. This unusually strong focusing of the current on the top half is greater than theoretically predicted when a uniform
$R_0$ is assumed, but it is more in line with modeling results when considering localized corrosion (macrocells), which has a lower $R_0$ than the adjacent passive surfaces.

A rebar becomes more corroded when anodic currents are applied from both the CE and the GE, compared to when the polarization is only applied through the CE.

High polarization resistance values will occur near edges and internal discontinuities due to limited signal distribution arising from the lack of a medium in which to spread.

The GE used in the experiments to measure polarization resistance values for locating corroding areas was unable to confine the signal distribution completely below the CE. Even with an ineffective GE, polarization resistance measurements can be used to identify and estimate the extent of the corroding area. These measurements can be used in conjunction with the corrosion potential measurements to better define corroded areas in reinforced concrete structures.

When a GE is used in conjunction with an active/passive couple (macrocell), it is the active part of the couple that controls current distribution to the polarized area rather than the whole couple, as is usually assumed. The results obtained with macrocells indicate that confinement is only obtained when measurements are carried out, using a GE, over the active part (which is surrounded by passive areas) of the macrocell. Poor confinement is achieved when measurements are made over the passive part (which is surrounded by active areas) of the macrocell.

A linear correlation observed between polarization resistance values of small mortar specimens shows that the results obtained by electrochemical impedance spectroscopy and the CorroCatch device will be similar for specimens with comparable working electrode and CE areas.

It was found that the tested devices gave comparable results in the laboratory for small mortar specimens and large slabs with actively corroding steel; however, none of these instruments were able to confine the signal distribution for a highly resistive, passive, steel-in-concrete system. Of the three devices tested, the Gecor 6 device gives the best current confinement for active steel-in-concrete systems.

**FIELD VALIDATION STUDIES**

Electrochemical measurements were carried out on bridges in three states with the use of the three devices to evaluate their performance in the validation of the corrosion rate of steel reinforcement in concrete. The measurements were taken on bridges chosen in areas representing a marine environment and regions with mild and cold winters where the use of de-icing agents was low or more extensive, respectively. Corrosion currents were estimated from the polarization resistance. The main results and conclusions are given below.

Corrosion currents (I) were low and almost independent of corrosion potentials ($E_C$) when the potential was more positive that about -0.25 V relative to the copper/copper sulfate half-cell, whereas they increased as $E_C$ shifted in the negative direction.

The observed relationship between corrosion current and half-cell potential correlated well with the predictions of corrosion probability based on the potential measurements alone (ASTM C876-87).

Corrosion currents were inversely proportional to the concrete resistance. Visual observations indicated that high corrosion currents were found at sites of high moisture content in the concrete. Therefore, it is supposed that high corrosion currents were closely related to high moisture of the concrete.

Values of corrosion current obtained using the different devices were compatible, and they indicated the same trend in their dependence on the half-cell potential. The corrosion current values decreased in the sequence 3LP-NBS1>CorroCatch>Gecor 6.

Reproducibility of the data, as expressed by the standard error of the mean, was nearly the same for all the devices and on all of the bridges. The standard error increased with the increasing mean of corrosion current in almost the same way for all of the bridges and devices.

Values of $I$ from various devices were interrelated. Values obtained
by any one of the devices can be, to some approximation, recalculated into values of another device by using empirical formulae. This suggests that any of the three devices can provide meaningful information on the corrosion rate of steel reinforcement in concrete structures.

Preliminary results on the comparison of the measured and true corrosion currents suggest that among the instruments used, the Gecor 6 device gives the k-values which most closely match the true values.

**TEST METHOD**

On the basis of the laboratory findings and field work, a draft Standard Test Method for Determining Instantaneous Corrosion Rate of Uncoated Steel in Reinforced Concrete was prepared. It was considered for AASHTO provisional standard status but failed balloting because the test method was dependent on the selected device. The test method is being made more generic and will be reballoted in October, 1995.

Appendix A of *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 8: Procedure Manual* (SHRP-S-330) presents the test method as it was originally drafted. The six steps in the test procedure are summarized in this section.

1. Visually inspect the reinforced concrete structure to determine which areas are to be tested.

2. Locate and mark the entire reinforcing steel grid in the area of interest with a water-permeable, nonconductive, non-metallic marking material (chalk, for example). Record the depth of cover and the steel bar diameters of all bars in the grid. Make note of any areas of steel bar overlaps or splices.

3. Make electrical connection with the reinforcing steel grid in accordance with ASTM C876.

4. Determine the electrochemical potential in the region of interest directly over the centroid of the reinforcing steel bar(s) of interest. Record the(s) potential(s).

5. Determine the corrosion rate using one of the three devices.

   5.1 Test Apparatus A: 3LP-NBS1 – Pre-wet the concrete surface and the probe sponge with potable water containing wetting agent. Weight the probe with a load of about 1 kg. Switch on the device and start the polarization procedure after the corrosion potential has almost stabilized. Polarize the object by manual continuous increase of cathodic current and record the current values for the polarization of 4, 8, and 12 mV. The polarization should be complete in about 2 minutes.

   5.2 Test Apparatus B: Corro-Catch – Pre-wet the concrete surface with a saturated potassium chloride solution over an area matching the probe footprint (use a squirt bottle or a damp sponge). The chosen site shall be exactly over the centroid of the rebar. Wet the probe and a sponge thoroughly with the same potassium chloride solution, and place the sponge and the probe over the chosen site. Weight the probe with a load of about 0.5 kg. Switch on the device and record the readings of corrosion potential, polarization resistance and concrete resistance. It is recommended that a high frequency pulse of 1.300 Hz and low frequency pulse of 0.02 Hz be used. The readings can be recorded after the corrosion potential has almost stabilized. Usually it takes at least 10 minutes to achieve stability of the potential.

   5.3 Test Apparatus C: Gecor – Pre-wet the concrete surface and the probe sponge with potable water. Weight the probe with a load of about 20 kg. Wait until the corrosion potential is stable, then switch on the device and make measurements of polarization resistance and concrete resistance.

6. Whatever instrument is used, make three measurements on each site with the affixed probe. Be certain that the probe is centered over the rebars and the active corrosion sites (as indicated by the covermeter and half cell readings, respectively). Switch off the polarization between the measurements and disconnect the rebar, but do not detach the probe. The time interval between consecutive measurements shall be long enough to allow the half-cell potential to recover its initial value and stabilize. This requires at least 10 minutes.

Reports on the procedure should indicate the type of device used
and include a description of the measurement site (location, surface orientation, visual inspection information) and the weather. Values of corrosion currents obtained with the device, and of the half cell potentials measured with a copper-copper sulfate (CSE) half cell (or converted to CSE if determined with a different type of half cell) should be reported. The concrete resistance should be included if the device allows its measurement. Equipotential contour maps should be prepared showing the location of reinforcing steel contact and the location and values of corrosion current readings.

### ALTERNATE CORROSION RATE DEVICE

An alternative corrosion rate device, the PR Monitor, is based on the same principle as the Gecor 6 device. It is equipped with an external GE and its operation is very similar to that of the Gecor 6. Cortest Instrument Systems in Texas supplies the PR Monitor for $10,000 (USD).

Although the PR Monitor was not available at the time of the SHRP research, this device is included in the FHWA Demonstration Project 84, Corrosion Detection for Concrete Structures. The contractor, CONCORR Inc., has considerable operational experience with the PR Monitor and has proposed to FHWA that it replace the Corro-Catch in future implementation endeavours.

---

For full details of this research see:

SHRP-S-324


SHRP reports are available for sale at reasonable prices ($5 - $35 USD):

Transportation Research Board
Box 289
Washington, DC 20055
Tel. (202) 334-3214
Fax (202) 334-2519

---

This technical brief prepared and distributed by:

Canadian Strategic Highway Research Program – C-SHRP

Transportation Association of Canada
2323 St. Laurent Blvd.
Ottawa, Ontario K1G 4X6
Tel. (613) 736-1350
Fax (613) 736-1395
ISBN 1-55187-012-6