A SIMPLE ARRANGEMENT AND PROCEDURE FOR IN-SITU MEASUREMENT OF CORROSION RATE OF REBAR EMBEDDED IN CONCRETE

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Abstract—An arrangement for the in-situ measurement of the corrosion current density, i.e. corrosion rate, of rebar embedded in concrete through a linear polarisation technique is described. It incorporates a simple experimental method being suggested for determination of the ohmic resistance of concrete, which enables the ohmic drop to be eliminated mathematically from the polarisation data. The error due to non-uniform distribution of the applied electric signal through a small size counter electrode to the working electrode (rebar) is removed by using the transmission line model. A calculation procedure for estimating Tafel slopes has also been suggested for precise estimation of the Stern-Geary constant. The utility of the arrangement and the experimental procedure suggested for in-situ corrosion rate measurement is demonstrated through a carefully planned experimental scheme.

INTRODUCTION

Electrochemical corrosion studies leading to corrosion rate measurement, for example, linear polarisation measurement, in high resistivity media such as those encountered in large concrete structures, pose a number of difficulties. Notable amongst such difficulties are the following, which may even render the in-situ measurement highly erroneous. (i) The high resistance of concrete between the rebar (i.e. working electrode) and the reference electrode, which offers a potential drop commonly referred to as an ohmic drop, must be either compensated for externally or eliminated mathematically. (ii) The sample being large compared to the counter electrode, the distribution of the electrical signal applied for polarisation of the rebar is non-uniform throughout the cross-section of the beam and this aspect must be considered duly. (iii) The corrosion current density, $I_{corr}$, being related to the polarisation resistance through a factor $B$, given as

$$ I_{corr} = \frac{B}{R_T} $$

where $B$ is the Stern-Geary constant and is given by

$$ B = \frac{\beta_a \beta_c}{2.3(\beta_a + \beta_c)} $$

and $R_T$ is the true polarisation resistance, and $\beta_a$ and $\beta_c$ are Tafel constants; these
Tafel constants must be known accurately for error free estimation of the corrosion current density, \( I_{\text{corr}} \).

A method for obtaining the true polarisation resistance, \( R_T \), from a knowledge of the apparent polarisation resistance, \( R_p \), has been suggested by Feliu et al., \(^2\) together with a relationship between concrete resistivity and ohmic resistance, taking into account the non-uniform distribution of the applied current between the disk shaped counter electrode and the working electrode (rebar) in a large R.C. specimen.

A few methods for the estimation of Tafel slopes from polarisation data have been reported in the literature, by Mansfeld\(^3\) and Bandy.\(^4\) However, there are some inherent shortcomings in these techniques as discussed by LeRoy.\(^5\) These techniques rely on the non-linearity of polarisation data between the overpotential and applied current, which must be of high quality, accurate to two decimal points, otherwise it may result in mathematically infinite solutions for Tafel slopes. For example, if data points fall on a straight line within experimental error, a wide range of \( \beta_a \) and \( \beta_c \) values would give reasonable fits.

Further, for the estimation of the error free corrosion current density, it is also necessary that the ohmic drop of concrete must be eliminated from the polarisation data, either by estimation or by instrumental means.

In this paper a simple arrangement and a calculation procedure are presented, whereby the ohmic resistance measurement of concrete and the polarisation resistance measurements of rebar can be carried out separately. The separate determination of the ohmic resistance allows a mathematical correction for the ohmic drop from the polarisation data. By applying this mathematical correction to the polarisation data, the precise value of the apparent polarisation resistance has been determined. The true polarisation resistance, \( R_T \), has been evaluated from the apparent polarisation resistance, \( R_p \), using a method suggested by Feliu.\(^2\) A very simple tabulation procedure for determination of the Tafel slopes, \( \beta_a \) and \( \beta_c \), using the polarisation data, has been described and is demonstrated to be good enough for the estimation of the Tafel slopes accurately even when the polarisation data points fall on a straight line within experimental error. Further, the methods of estimating (i) ohmic resistance, (ii) resistivity, (iii) polarisation resistance, (iv) Tafel slopes, and (v) the corrosion current density, are all integrated together in the procedure in order to demonstrate the utility of the set-up for in-situ corrosion rate measurements. The results of an experimental scheme undertaken using sufficiently large sized laboratory cast beams are also presented in order to facilitate the above demonstration.

**DESCRIPTION OF SET-UP**

The determination of ohmic resistance using the proposed arrangement is based on the principle of determining the internal resistance of a cell.\(^6\) When a half-cell, i.e. a Cu/CuSO\(_4\) reference electrode, is contacted on the surface of the concrete via a sponge, soaked in contact fluid (normally water with detergent or alcohol), it forms a complete electrical cell together with the reinforcement and concrete. The cell so formed generates a potential, the half-cell potential or corrosion potential or open circuit potential of the cell and it has an internal resistance equal to the ohmic resistance of the concrete to be determined.

For measurement of the apparent polarisation resistance the traditional galva-
nostatic or constant current technique has been adopted here as it is advantageous over potentiostatic and potentiodynamic methods.\textsuperscript{7} One of the advantages is that the mathematical correction of the ohmic drop is found to be suitable in the case of the galvanostatic mode of operation. With this method, the electrochemical processes remain apparently unaltered and the potential drift whether in an active or noble direction is not affected by the polarisation measurements. Potential fluctuations due to localised crevice corrosion are not affected during the polarisation measurements.

The electrical circuitry for determination of the ohmic resistance, $R$, of concrete and the polarisation resistance measurements, is shown in Fig. 1, and the principle of the measurements with the calculation procedure is described subsequently.

\textit{Ohmic resistance determination}

Referring to Fig. 1, first, with the key switches $K_1$ and $K_2$ being off, the circuit is the same as that for a half-cell potential determination, recommended in ASTM C-876.

In this case, the voltage reading, $V$, is given as:

$$V = \frac{E}{R + R_v}.$$

usually, $R_v \gg R$. Therefore, $V \approx E = E_{corr}$, where $E_{corr}$ is the corrosion or open circuit potential.

Secondly, with the switch $K_2$ being off and $K_1$ being on, the circuit is same as that for the internal resistance determination of a cell as explained by Frank.\textsuperscript{6} In this case, the terminal voltage of the corrosion cell may be measured with a high-impedance millivoltmeter for various settings of the standard decade box resistor, $R_L$, both connected directly across the cell terminals, i.e. R.E. and W.E.. The switch $K_1$ permits $R_L$ to be connected momentarily, whenever a voltage reading is desired, thus avoiding excessive current drain over a prolonged period of time. The terminal voltage of the cell, under load, is given by the voltmeter reading $V$, when the key switch, $K_1$, is closed. Application of the voltage divider rule yields:

$$V = \frac{ER_L}{R + \frac{R_L}{R_v} + R_L}.$$

If $R_v \gg R_L$, which will almost invariably be true, then equation (3) becomes:

$$V = \frac{ER_L}{R + R_L}.$$

Assuming $E$ and $R$ to be constant, and rewriting equation (4) in the following linear form in terms of $1/V$ and $1/R_L$:

$$\frac{1}{V} = \left(\frac{R}{E}\right) \cdot \frac{1}{R_L} + \frac{1}{E}.$$

If $1/V$ is plotted against $1/R_L$, this equation indicates that the result will be a straight line with slope $R/E$ and intercept $1/E$. Further, for $R_L = R$, $1/V = 2/E$. For
several $R_L$ vs $V$ data points determined experimentally, the best fit straight line drawn through them will lead to the value of $R$.

**Polarisation resistance determination**

With $K_1$ being off and $K_2$ being on, a constant current $I_2$, can be supplied through the constant voltage DC power source as shown in Fig. 1. Applying Kirchoff's rule to a closed loop when $K_2$ is on and $K_1$ is off:

![Diagram of polarisation resistance determination](image)

**Key**
- $R_L$ = standard decade box resistor;
- $R_V$ = voltmeter resistance;
- $V$ = voltmeter capable of reading 0–1.0 V with a least count of 0.1 mV;
- $K_1$ and $K_2$ = key switches;
- R.E. = standard Cu/CuSO$_4$ reference electrode as per ASTM C-876;
- C.E. = disk-shaped counter electrode made of copper with a central hole of 25 mm diameter;
- W.E. = working electrode (rebar);
- $A$ = ammeter capable of reading 0–100 $\mu$A with a least count of 0.1 $\mu$A;
- $R$ = ohmic resistance of concrete;
- $E$ = E.M.F. of corrosion cell;
- $I_2$ = cathodic current applied to the rebar for polarisation;
- P.S. = constant voltage power supplier;
- $Y$ = variable resistance to keep circuit resistance high enough to maintain constant current.

Fig. 1. Arrangement for determination of half-cell or corrosion potential, ohmic resistance and polarisation resistance.
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\[-I_2R - E + V = 0\]

or

\[E = V - I_2R.\] (6)

The value of \(E\) given by equation (6) is the polarised potential of a cell with the ohmic drop \((I_2R)\) being eliminated mathematically. The overvoltage \((\epsilon)\) induced by the cathodic polarising current \((I_2)\) is given by \(\epsilon = E - E_{corr}\) and the apparent polarisation resistance, \(R'_p\), is given by the initial slope of the polarisation curve (i.e. \(I_2\) vs \(\epsilon\)) as:

\[R'_p = \frac{\Delta \epsilon}{\Delta I_2}.\]

For a number of non-linear data points, say \(n\), near \(\epsilon = 0\), the apparent polarisation resistance can be determined through the following expression\(^8\)

\[R'_p = \frac{\sum_{i=1}^{n} (\epsilon_i)^2}{\sum_{i=1}^{n} (I_2\epsilon_i)}.\] (7)

But \(R'_p\) is only the apparent polarisation resistance and the effect of a non-uniform distribution of current through the small counter electrode has to be taken into account in estimating the true polarisation resistance \(R_T\). This can be done for reinforced concrete beams and slabs using the transmission line model suggested by Feliu et al.,\(^{2,9}\) and the relevant relationship for the position of the counter electrode (C.E.) away from the ends of the beam, i.e. at intermediate points, is given by:

\[R_T \frac{4(R'_p)^2}{R_e} (P),\] (8)

where \(R_e\) is the electrolytic resistance of the concrete, and is equal to \(\rho/s\), where \(\rho\) is the concrete resistivity and is related to the ohmic resistance, \(R\) as: \(\rho = 2RD\), for a counter electrode of diameter \(D\), \(S\) is the area of the cross-section of the beam and \(P\) is the perimeter of the rebar or the sum of the perimeters of the rebars if there are several rebars.

The determination of Tafel slopes

To determine the correct value of the Stern–Geary constant, \(B\), an accurate determination of Tafel slopes \(\beta_a\) and \(\beta_c\) is necessary. The values of \(\beta_a\) and \(\beta_c\) should be such that they satisfy the following polarisation equation\(^3\) simultaneously for all sets of polarisation data points:

\[2.3R'_p I_i = \frac{\beta_a \beta_c}{(\beta_a + \beta_c)} \left[ \exp \left( \frac{2.3\epsilon_i}{\beta_a} \right) - \exp \left( \frac{-2.3\epsilon_i}{\beta_c} \right) \right].\] (9)

The apparent applied current and the apparent polarisation resistance, \(R'_p\), have been used in the above expression instead of the true polarisation resistance because
the true value of the current applied for polarisation is unknown, and is likely to be quite different from the apparent value of the current applied, due to distribution of current in different paths.

As discussed earlier, the determination of $\beta_a$ and $\beta_c$ using available methods becomes difficult and sometimes even impossible, for example, when polarisation data between overvoltage and applied current is absolutely linear within instrumental error, one of the solutions for $\beta_a$ and $\beta_c$ is then $\beta_a = \beta_c = \infty$, and at the same time, unique definite solutions for $\beta_a$ and $\beta_c$ may not be feasible. A routine least squares procedure may result in an infinite number of solutions of $\beta_a$ and $\beta_c$.

To overcome the above problem, the minimum value of the sum of error squares, $Z$, has been obtained by a simple tabulation method and contour plotting within the feasible domain as described below. The method of estimating $\beta_a$ and $\beta_c$ described here consists of tabulating all possible combinations of $1/\beta_a$ and $1/\beta_c$ values within the feasible domain. The combinations of $1/\beta_a$ and $1/\beta_c$, i.e. $(1/\beta_a + 1/\beta_c)$ values, are limited by the lower value of the bound $(1/\beta_a + 1/\beta_c)$ for a passive state of corrosion and higher value of the bound $(1/\beta_a + 1/\beta_c)$ for an active state of corrosion of steel in concrete as:

$$\left(\frac{1}{\beta_a} + \frac{1}{\beta_c}\right)_{\text{low}} \leq \left(\frac{1}{\beta_a} + \frac{1}{\beta_c}\right) \leq \left(\frac{1}{\beta_a} + \frac{1}{\beta_c}\right)_{\text{high}}.$$

Gonzalez and Andrade have demonstrated the values of the Stern–Geary constant, $B$, for the active and passive states of corrosion of a rebar in concrete to be: 26 mV for the active state and 52 mV for the passive state.

However, LeRoy suggests that the value of the factor

$$\left(\frac{2.3}{\beta_a} + \frac{2.3}{\beta_c}\right)$$

seldom lies outside the range

$$0.02 < \left(\frac{2.3}{\beta_a} + \frac{2.3}{\beta_c}\right) < 0.12.$$

The above conditions yield the extreme bounds of the feasible region of the solution as

$$8.3612 \times 10^{-3} \leq \left(\frac{1}{\beta_a} + \frac{1}{\beta_c}\right) \leq 5.2115 \times 10^{-2}.$$

In equation (9), putting $2.3R_iJ_i = A_i$ and $B_i = 2.3 \epsilon_i$,

$$A_i = \frac{1}{\left(\frac{1}{\beta_a} + \frac{1}{\beta_c}\right)} \left[\exp\left(\frac{B_i}{\beta_a}\right) - \exp\left(-\frac{B_i}{\beta_c}\right)\right].$$

(10)

The sum of the error squares, $Z$, for polarisation data points, can be written as
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The sum of error squares $Z$ would be a minimum. As mentioned earlier, the usual minimisation procedure by the method of calculus, by setting $(\partial Z/\partial \beta_a) = 0$ and $(\partial Z/\partial \beta_c) = 0$, does not yield the desired result, therefore, a simple method of tabulation has been adopted, whereby the values of $Z$ are tabulated for a large number of possible values of $1/\beta_a$ and $1/\beta_c$ at equal spacings within the feasible region and the minimum value of $Z$ is then sought. Using a small computer program, the time required for the computing procedure described above is less than 1 min. A typical contour plot of $Z$ for various combinations of $1/\beta_a$ and $1/\beta_c$ is demonstrated subsequently whereby the solution point of $\beta_a$ and $\beta_c$ is indicated.

The correct value of the Stern–Geary constant, $B$, now can be calculated using the $\beta_a$ and $\beta_c$ values so obtained and subsequently the corrosion current density, i.e., corrosion rate, $I_{corr}$, can be calculated using the $B$ and $R_T$ values in equation (1).

EXPERIMENTAL METHOD

Test specimens

In order to demonstrate the applicability of the arrangement and the calculation procedure suggested, reinforced concrete beams, 150 cm long with $10 \times 20$ cm$^2$ cross-section were cast. The concrete used was with a W/C ratio of 0.64 and three different concentrations of CaCl$_2$, namely: 0%, 1% and 2.5% by mass of cement were used as the corrosion inducing admixture. Each beam had two twisted steel reinforcing bars (grade 'HY 420), 1.2 cm in diameter and 145 cm in length embedded in concrete and 5 cm length extended outside for electrical connections. A common clear cover of 25 mm was used for all three specimens. After normal curing of 7 days the beam specimens were exposed to the outdoor atmospheric conditions for a period of about 7–9 months. Each of these beams was tested for corrosion potential ($E_{corr}$), ohmic resistance ($R$) and corrosion rate ($I_{corr}$) at eight different intermediate points on the beam surface using the present arrangement and the results were evaluated using the calculation procedure presented.

Preparation of surface at test points

Since poor electrolytic contact of the reference electrode with the specimen is probably the most common cause of (i) error in the recorded corrosion potential values, and (ii) variation of the corrosion potential during the polarisation measurements, as reported by Gonzalez et al. it is essential that the reference electrode tip should be in good physical contact with the concrete surface point under test. Hence, to ensure proper physical contact, the surface skin, if any, should be removed, either with abrasive paper or with a sharp knife. Then a very light prewetting of the surface points under test is done through a sponge soaked in soap solution, and allowed to be there for 20-30 min in order that the moisture can soak in before commencement of the readings. For recording of the reading, the tip of the reference electrode is placed on the wetted sponge placed over the surface point under test. Any degree of wetting will cause an imbalance in the local corrosion cell so this technique has to be used with care.

The procedure for the determination of the ohmic resistance

Referring to Fig. 1, for obtaining the data for determining ohmic resistance, $R$, key $K_2$ is off throughout and then $R_1$ is fixed at several values one after another by connecting momentarily the switch $K_1$, just long enough to read the voltmeter in each case.

The data so obtained for $R_1$ and $V$ are plotted as $1/R_1$ vs $1/V$ as shown in Fig. 2. The best fit straight line joining these points gives the solution for ohmic resistance, $R$. Referring to equation (5) and Fig. (2), the
best fit straight line is found to be equal to $R/E$ and the corresponding intercept is found to be $1/E$. Therefore, ohmic resistance

$$R = \frac{\text{Slope} \ (R/E)}{\text{Intercept} \ (1/E)}.$$  

As a further check, the value of $1/V$ corresponding to $R_L = R$, is found to be equal to $2/E$ as demonstrated in Fig. 2 which satisfies equation (5) derived earlier.

**Polarisation procedure**

Referring to Fig. 1, the polarisation measurements are carried out keeping switch $K_1$ off throughout. First, the corrosion potential ($E_{corr}$) is recorded at the $K_2$ off position, allowing a sufficient response time of 30–60 s, i.e. time taken for measurements to stabilise. Once the stabilised value of $E_{corr}$ is recorded the switch $K_2$ is put on and the cathodic polarising current is applied in steps until the maximum value of the overvoltage ($e$) is reached, which is usually 20 mV for the polarisation curve to be in linear range, with the help of a variable resistor, $Y$, which helps to keep the circuit resistance high enough to maintain a constant current. The initial cathodic polarising current taken was usually 2 μA, and then the second current step was 4 μA, the third 6 μA, etc. After allowing a response time of 2–3 min at each current step the steady state voltmeter reading was recorded.

With the help of the polarisation data, i.e. $V$ vs $I$, and the ohmic resistance obtained, the polarised potential $E$ with ohmic drop being eliminated was obtained using equation (6). Then the apparent and true polarisation resistances $R_p$ and $R_T$ were determined subsequently, using equations (7) and (8). Tafel slopes were determined using the procedure described earlier. A typical contour plot of the sum of error squares, $Z$, as a function of $1/b_a$ and $1/b_c$ is shown in Fig. 3 whereby the solution point for $b_a$ and $b_c$ is indicated as the point corresponding to the local minima of $Z$ within the bounds of the feasible region shown. Further, for confirmation, the L.H.S. of equation (9) has been plotted against the R.H.S. of the same equation in Fig. 4. In this figure a typical set of five experimentally observed polarisation data between $I$ and $e$, together with the estimated values of $R_p$ and Tafel constants $\beta_a$ and $\beta_c$, have been used. For the above set of five points and the origin (i.e. $I = 0$, $e = 0$), the best fit straight line has a slope equal to $1.00894 = 1.0$, demonstrating the validity of the estimated $R_p$, $\beta_a$ and $\beta_c$. Knowing the values of $\beta_a$, $\beta_c$ and $R_T$, values of the Stern–Geary constant, $B$, the corrosion current density, $I_{corr}$, i.e. corrosion rate of rebar, were determined using equation (1).
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Fig. 3. Contour plot of sum of error squares $Z$ against $(1/\beta_a)$ and $(1/\beta_c)$.

Fig. 4. Plot of L.H.S. against R.H.S. of equation (9).
Table 1. Average values and measured ranges of $E_{\text{corr}}$, $R$, $\rho$, $\beta_a$, $\beta_c$, $B$ and $I_{\text{corr}}$

<table>
<thead>
<tr>
<th>W/C ratio (wt% of cement)</th>
<th>$E_{\text{corr}}$ (mV)</th>
<th>$R$ (Ω)</th>
<th>$\rho$ (Ω-cm)</th>
<th>$\beta_a$ (mV)</th>
<th>$\beta_c$ (mV)</th>
<th>$B$ (mV)</th>
<th>$I_{\text{corr}}$ ($\times 10^{-8}$A cm$^{-2}$)</th>
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<tr>
<td>0.0</td>
<td>-111</td>
<td>5064</td>
<td>75950</td>
<td>210</td>
<td>256</td>
<td>50</td>
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<td></td>
<td>(4306--5938)</td>
<td>(64618--8073)</td>
<td>(199-217)</td>
<td>(229-266)</td>
<td>(47-52)</td>
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<td>48</td>
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<td>(2259--5746)</td>
<td>(33885--6197)</td>
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<td>(217-265)</td>
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EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained through the above experimental procedure are presented in Table 1. The results observed show that the corrosion is uniform over the entire length of the reinforcing bar and values of $E_{\text{corr}}$, $\rho$, $I_{\text{corr}}$, $B$, etc., measured at eight points on the beam did not demonstrate considerable variation except for one or two extreme values. This was expected as CaCl$_2$ was mixed uniformly throughout the concrete. Thus, it is expected that the type of corrosion is likely to be general. In Table 1 average values of $E_{\text{corr}}$, $R$, $\rho$, $\beta_a$, $\beta_c$ and $I_{\text{corr}}$ are presented for all the beams together with their measured ranges within parentheses.

It is evident from the results in Table 1 that the corrosion parameter of the rebar are in the usual expected pattern in accordance with the likelihood of active corrosion that can be expected in three different beams. Thus, the corrosion potential is most negative for concrete with maximum CaCl$_2$, indicating the chance of active corrosion is more in such a concrete environment. Similarly, the concrete resistivity is least and the Stern–Geary constant $B$ also deviated from the value representing the passive condition, namely 52, and the corrosion rate is highest for the same concrete, whereas the corrosion parameters for 0% CaCl$_2$ show fully the passive state of corrosion. Further, the reproducibility of the test results as computed from three iterations at a number of points, indicated the maximum coefficient of variation in the test results to be about 11.5%.

CONCLUSIONS

A simplified arrangement and a calculation procedure have been proposed in this work, whereby it is demonstrated through an experimental scheme, that this technique can be used for laboratory as well as for in-situ corrosion studies in R.C. structures with the following relevant advantages:

1. The same arrangement can generate polarisation data as well as data to determine the ohmic resistance of concrete. The ohmic resistance value of concrete can be used to eliminate the error due to the ohmic drop mathematically and to obtain an approximate estimate of the concrete resistivity. Further, the estimation of concrete resistivity facilitates the correction to be applied to the polarisation resistance, to take care of the non-uniform distribution of electric signals applied for polarisation through the small disk shaped counter electrode.

2. Using the calculation procedure presented, one can have an accurate estimate of Tafel slopes, instead of assuming them arbitrarily, by adopting the least squares
technique described, which in turn gives an estimate of the corrosion current density with a fair degree of accuracy.

REFERENCES