A MODIFIED IMPRESSED CURRENT CIRCUIT FOR CATHODIC PROTECTION TO ACHIEVE A BETTER POTENTIAL CONTROL AT THE STEEL-MORTAR INTERFACE

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ABSTRACT

A modified impressed current circuit is proposed to attain potential control, within narrow limits, in electrolytic cells with cathodically polarized steel-mortar specimens. A description of the circuit is given as well as a procedure to prepare the specimens and the full design of the cell to carry out studies on cathodic protection under total immersion conditions. These conditions were selected to avoid the uncertainties that arise from changes in the electrolyte resistance when concrete is not immersed. The designed circuit is suitable to keep the polarization potential within narrow limits and is a good replacement of the potentiostatic circuit, which would be expensive if a large number of cells had to be polarized. Furthermore, the cell design suggested is considered to be helpful to study particular variables such as the variation in bond strength caused by the applied cathodic protection, the effect of reactive aggregates present in the mortar, etc.

Key words: rebars, corrosion, cathodic protection, polarization circuit, cell design.

INTRODUCTION

The usual galvanostatic circuit allows the passage of a steady current through an electrolytic cell despite differences in its global resistance (ohmic and polarization resistance). It consists of a voltage divider to which the cell is connected by an external serial resistance. This resistance should be sufficiently high so that the current passing through the cell will depend exclusively on it and will not be affected by variations in the cell resistance /1/.

Polarization circuits used for cathodic protection of reinforced concrete are generally of the galvanostatic type. In the specific literature on the subject, difficulties have been reported in keeping the potential of the specimens under study within certain adequate limits /2-5/.

The aim of this paper is to propose an impressed current circuit suitably modified by the presence of a resistance in parallel with the cell to buffer potential changes that may occur in the cell due to variations in its resistance. Variations in the cell resistance result from the application of cathodic protection, which changes the polarization resistance of the system and, in some cases, leads to gas evolution on steel bars. In non-immersed structures the electrolyte resistance also changes when the humidity content of the mortar mass varies. Together with the modification of the impressed current circuit, an electrolytic cell design is proposed to carry out studies on cathodic protection under total immersion conditions. The operation of the circuit was studied using steel-mortar specimens having a water/cement ratio of 0.5 and three different overpotentials taken with respect to the corrosion potential of bare steel in the electrolytes: tap water (-725 mV vs the saturated calomel electrode, SCE) and 3% sodium chloride solution (-750 mV vs SCE).

MODIFIED IMPRESSED CURRENT CIRCUIT

As stated above, the usual galvanostatic circuit has a serial resistance with the electrolytic cell, which should be much higher than the cell resistance so that a steady current will pass through the mesh where the cell is. Variations in the cell resistance do not cause any changes in the current that passes through the cell but do modify the potential difference between its terminals. The modification suggested consists of maintaining a serial resistance and introducing a resistance in parallel with the cell, which should be fixed and have a value ranging between 10 and 50 ohm. The serial resistance will have a variable value that will be adjusted until the potential difference measured between the steel bars and the reference electrode reaches the desired value. A scheme of the circuit used is shown in Fig. 1.

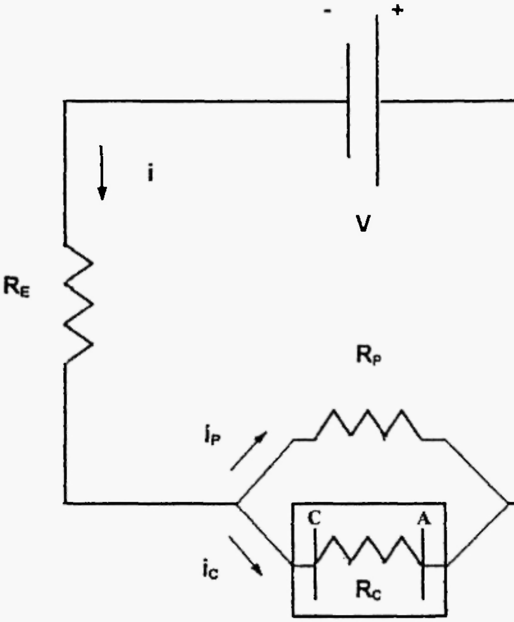

Fig. 1: Impressed current polarization circuit. V: steady power source, C: cathode, A: anode.

The overall circuit resistance is the addition of two contributions: the cell external resistance (R_E) and the result (R) of the addition of the cell resistance (R_C) and the resistance connected in parallel with the electrolytic cell (R_P). The value of R is given by:

$$\frac{1}{R}=\frac{1}{R_C}+\frac{1}{R_P}=\frac{R_C+R_P}{R_C R_P}$$

$$R=\frac{R_C R_P}{R_C+R_P}$$

The potential difference (V) applied by a steady power source is given by the equation:

$$V = i(R_E + R)$$

Potential drops in the resistances R_C and R_P, called V_C and V_P, respectively, are the same and can be obtained by means of the following equation:

$$V_P = V_C = iR = i_C R_C = i_P R_P$$

$$i = i_C + i_P$$

When the cell resistance changes between two values: R_{C1} and R_{C2}, the corresponding potential drops change between V_{C1} and V_{C2}. The relative variation in the potential difference in the cell (V_{C1}/V_{C2}) can be obtained from the equations given below where R_1 and R_2 are the results of the parallel resistance of the circuit and each cell resistance value R_{C1} and R_{C2}:

$$V_{C1} = i_1 R_1 = \left(\frac{V}{R_E + R_1}\right) R_1$$

$$V_2 = i_2 R_2 = \left(\frac{V}{R_E + R_2}\right) R_2$$

$$\frac{V_{C1}}{V_{C2}} = \frac{(R_E + R_2)R_1}{(R_E + R_1)R_2}$$

(R_1 and R_2 can be obtained from the above equation to calculate R).

The relative variation in the potential difference in the cell (V_{C1}/V_{C2}) when its resistance changes has been calculated considering two cases: one in which the cell resistance doubles (a) and the other in which it is reduced to a half (b) from an initial value of 300 ohm. Results are shown in Table 1.

According to the values shown in Table 1, the potential drop in the electrolytic cell does not vary much when the cell resistance changes; it is below 5% when the cell resistance doubles and, in the worst case, when the cell resistance is reduced to a half, it does not exceed 9%. This variation can

Table 1

Relative variation in the potential difference in the electrolytic cell due to changes in its resistance

External Resistance (R_e) (ohm)	Relative variation in potential difference $(V_{C1}/V_{C2})_a$	Relative variation in potential difference $(V_{C1}/V_{C2})_b$
0.01	0.99998	1.0000
0.1	0.99983	1.0003
1	0.99839	1.0032
10	0.98780	1.0244
100	0.96429	1.0714
1000	0.95575	1.0885

Note: The subscript "a" corresponds to values of the cell resistance R_{C1} = 300 ohm and R_{C2} = 600 ohm.
The subscript "b" corresponds to values of the cell resistance R_{C1} = 300 ohm and R_{C2} = 150 ohm.

be minimized by manipulating the cell external resistance. The smaller this is, the lower the variation in the potential drop in the cell will be when its resistance changes. It is worth noting that in the usual galvanostatic circuit, when the cell resistance doubles the relationship (V_{C1}/V_{C2}) doubles, and, in the other case analyzed, this relationship is reduced to a half. In other words, with this circuit the potential can be kept within narrow limits, with fluctuations that do not exceed ± 10%, despite appreciable changes in the cell resistance.

It is clear that the most appropriate way to control the potential between steel rebars (working electrode) and the reference electrode (SCE) would be to use a potentiostatic circuit with ohmic drop compensation. However, for field and laboratory work with a large number of cells, this solution is rather inexpensive.

EXPERIMENTAL SECTION

Preparation of Specimens

Cylindrical mortar specimens were cast. A grooved steel wire of ordinary hardness, 6 mm in diameter, was embedded in the axis of each specimen. The mortar was made with a cement/sand ratio of 1:3 by weight and a water/cement ratio of 0.5. Ordinary Portland cement (ASTM C150 type) and ordinary sand (similar to ASTM C778) were used. The moulds, 5 × 10 cm in size, were filled in three layers, pressing each layer with a compactor and taking care to leave a flat upper surface to avoid stress concentration during the pullout test. The mould used and the finished specimen are shown in Fig. 2. In the first 24 h, the specimens were left in their moulds, in the humid chamber (> 95% HR and 23 ± 2°C). They were then demoulded and kept under lime-saturated water to complete the 28-day curing period under the same conditions of relative humidity and temperature.

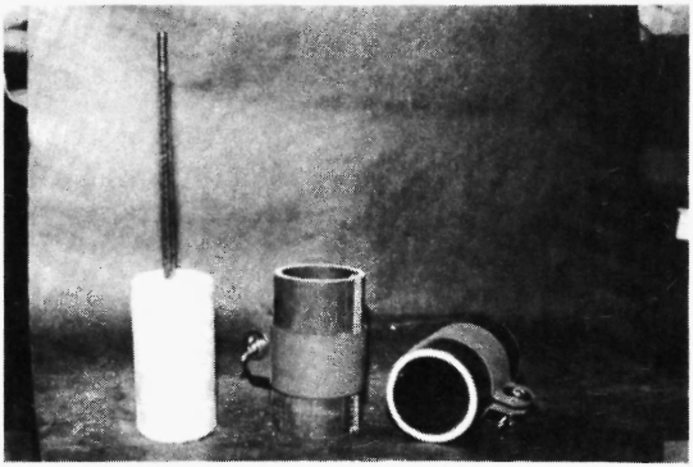

Fig. 2: View of the mould and steel mortar specimen.

At the end of the 28-day curing period, the cylinder bases were painted with two coats of finishing paint, formulated with chlorinated rubber and titanium dioxide, and sealed with a material of paraffinic nature. The emerging portions of the steel wire were painted with red lead-(Pb_3O_4) based anticorrosive paint and chlorinated rubber binder, and two coats of the above-mentioned finishing paint. A sealer of paraffinic nature was finally applied on this painting scheme. In this way, metal surfaces that were not covered by the mortar were kept in a passive state during the test period. Cables were welded to the upper end of steel wires to make the required connections.

Preparation of Electrolytic Cells

Plastic containers 60 × 40 × 20 cm in size were used as tanks; 8 steel-mortar specimens, prepared as described above, were placed and joined one to the other by tin-covered copper conducting wire. Two anodes were placed on each lateral side of the tanks (see Fig. 3). The electrolytes used were tap water and 3% sodium chloride solution.

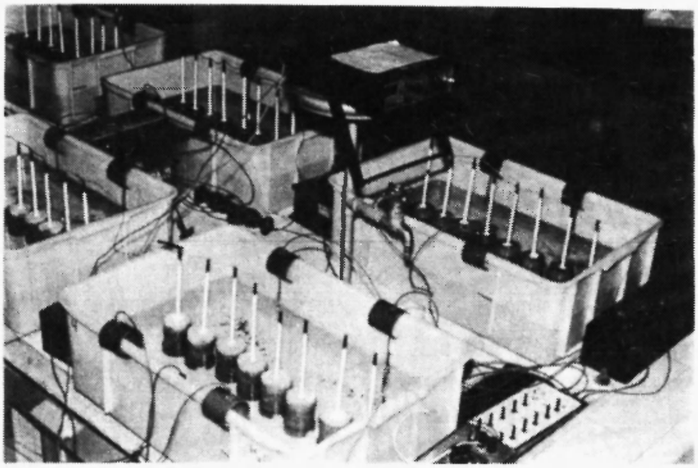

Fig. 3: View of steel mortar specimens polarized by the impressed current circuit.

To control the distribution of current lines inside the cell, the specimens were replaced by platinum wires, 1 mm in diameter, placed exactly in the same place where the steel-mortar specimens would have been. Pt wires were previously washed, dried and weighed. A 0.1 M cupric sulfate acid solution was used as electrolyte. Pt electrodes were connected to the negative pole of a power source. After an adequate period of time had elapsed, polarization was switched off and Pt wires were removed to be washed and dried, and to record their weight again.

Three different materials were tried for making the anodes: platinum, SAE 1010 steel and zinc. In the case of the latter two, the anodic compartment was insulated by ceramic plates properly sealed among them with silicone rubber.

Specimen Polarization

To carry out this research three polarization overpotentials were selected, –100, –250 and –500 mV, taken with respect to the steel corrosion potential in tap water (–725 mV vs SCE) and 3% sodium chloride (–750 mV vs SCE), respectively. Since steel corrosion potential values in concrete are variable, it was decided to choose bare steel corrosion potentials in the selected electrolytes as a fixed point of reference. Although corrosion potentials are very negative, they were chosen because this is the most unfavorable situation, which could occur when, due to cracking on the concrete structure, the rebar is in direct contact with the electrolytic medium.

According to the cathodic polarization curve of rebars, recorded in 3% sodium chloride saturated with cement, the –100 mV overpotential corresponds to the first oxygen reduction wave and the –250 mV overpotential to the second one (Fig. 4). The –500 mV overpotential is negative enough to cause hydrogen evolution /6/. The polarization curve was recorded with a PARC, model 273 A potentiostat-galvanostat, at a scanning rate of 1 mV/s, with scanning being initiated close to the open-circuit potential of the system.

Applied potential values were taken while current was passing. When the current is switched off for 10 seconds the potential increases by 120 mV (on average) for the highest overpotential applied and there are almost no significant differences for the other applied overpotential values. The ohmic drop is not remarkable because specimens were tested under total immersion conditions. In the case of the lowest overpotentials it is assumed that the process is controlled by oxygen diffusion inside the specimen and, thus, small changes were detected in the measured potentials when polarization was switched off. However, the authors think that this matter deserves further study.

Specimens were polarized using the above-described circuit and the potential was regularly monitored with a high-impedance voltmeter. Measurements for three months are shown in Fig. 5.

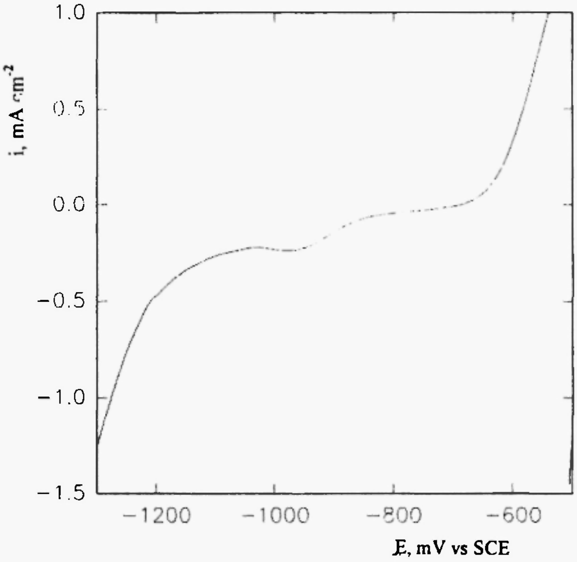

Fig. 4: Rebar polarization curve in 3% sodium chloride solution, saturated with portland cement. Scanning rate 1 mV/s.

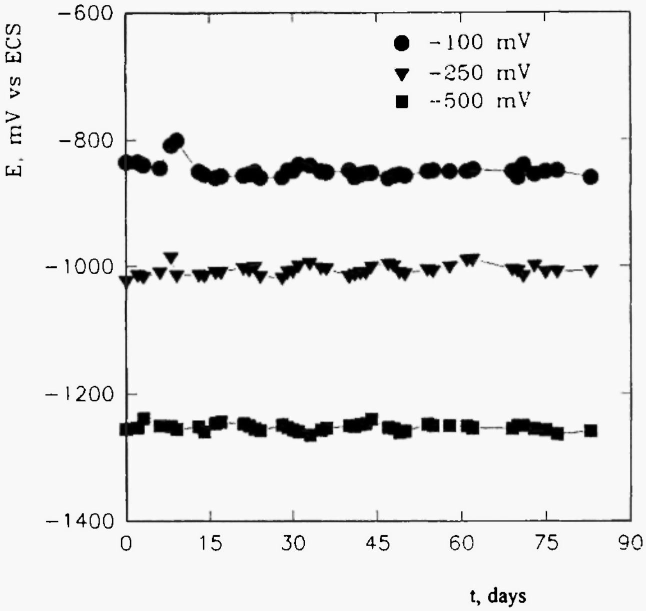

Fig. 5: Control of polarization potential in steel-mortar specimens for different applied overpotentials.

DISCUSSION OF RESULTS

The specimens prepared and protected by the above-mentioned painting scheme were suitable to carry out cathodic protection studies under total immersion conditions of the mortar up to a two-year period. For long-term tests an annual maintenance of the painting scheme has to be done.

To obtain a regular distribution of current lines in the cell, four anodes must be placed, two on each of its lateral sides, at 20 cm from each end of the tank. Specimens were placed at the center of the cell throughout its length.

The anode material was selected according to the type of electrolyte used. Platinum anodes were employed for tap water; the reaction on them was as follows:

$$2H_2O \Leftrightarrow O_2 + 4H^{1+} + 4e^{1-}$$

The use of platinum anodes is not recommended in solutions with high chloride content because chlorine evolution takes place on them according to the following equation:

$$2Cl^{1-} \Leftrightarrow Cl_2 + 2e^{1-}$$

For 3% sodium chloride solution, either SAE 1010 steel or cast zinc anodes were used. The steel anode was selected for the lowest overpotentials and the zinc anode for the highest. When steel anodes were used, ferrous and ferric hydroxide formation was noted according to the following reactions:

$$Fe \Leftrightarrow Fe^{2+} + 2e^{1-}$$
$$Fe^{2+} + 2H_2O \Leftrightarrow Fe(OH)_2 + 2H^{1+}$$
$$2Fe^{2+} = 4OH^{1-} + 1/2O_2 \Leftrightarrow 2FeOOH + H_2O$$

It is clear that the higher the current that passes through, the higher the oxide formation will be. Therefore, zinc anodes were selected for the highest overpotentials. With these zinc anodes, without current passage, by simple electrochemical contrast, a potential of the order of –1135 mV (Vs SCE) was attained. In this way, it is possible to have a –500 mV overpotential with small currents.

In this case, the reaction product is also a solid, basic zinc chloride:

$$Zn \Leftrightarrow Zn^{2+} + 2e^{1-}$$
$$Zn^{2} + (2-x)OH^{1-} + xCl^{1-} \Leftrightarrow ZnCl_{0,4}OH_{1,6}$$

where $x \cong 0,4$.

The sequence of reactions shown for non-noble metal anodes and the decrease in pH caused by oxide precipitation justifies the separation of the anodic and cathodic compartments so that oxide and hydroxides formed during polarization would remain inside the anodic compartment and separated from test specimens.

To check the efficiency of the designed circuit the potential of a set of eight specimens (water/cement ratio of 0.5) was monitored for three months at each of the overpotentials selected for this research. From the data shown in Fig. 5, it can be seen that the proposed polarization circuit can maintain the potential value of test specimens within narrow limits (± 10%).

Due to the fact that the highest overpotential selected corresponds to the hydrogen evolution zone, the system has a fast response to changes in the value of R_E. For the other two lower values, which correspond to the oxygen reduction zone, the system has a slow response, thus changes in the resistance R_E have to be gradual to allow the system to evolve adequately in time. If it is borne in mind that for processes under diffusion control current polarization is not suitable, the adjustment obtained in this case is highly satisfactory. In any case, by controlling closely the potential during the first 4 or 5 days, the system will stabilize regardless of the selected overpotential.

Potential variations observed when specimens were polarized in the above-described manner are not significant from the standpoint of changes in the steel-mortar interface bond, which is the purpose for which the circuit was designed /7/. In the most unfavorable case, changes in bond of about 10% were noted for the highest value of the applied overpotential. When the applied overpotential was changed by 250 mV, bond changes were of the order of 3%; in this sense, the small fluctuations observed during specimen polarization do not influence the studied variables. Changes in the paste microstructure were observed only for the highest overpotential value applied /7,8/, where the circuit has its best adjustment and slowest response time.

FINAL REMARKS

The polarization circuit used allowed adequate potential control in the electrolytic cells that house cathodically polarized specimens. Potential variations observed are not significant from the standpoint of bond changes observed nor from the viewpoint of changes in the mortar microstructure. It is clear that for a close control of the potential a potentiostat has to be used, but this solution is expensive when a large number of electrolytic cells are involved. The disadvantage of this circuit is that a periodic control of resistances and potentials is required.

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REFERENCES

1. J. Galvele, *Corrosión*, Monografía N° 21 OEA, Washington, 1979; pp 31-34.
2. J.P. Nicholson, "New approach to cathodic protection of bridge decks and concrete structures", *Meeting of the Transportation Research Board*, January, 1980, Washington, D.C. Transportation Research Record No. 762, 1980; pp 13-17.
3. I. Rodríguez-Maribona, J.J. Carpio and A. Raharinaivo, "Electrochemical behaviour of concrete reinforcing steel under cathodic polarization: comparison of some test procedures", *Materials and Structures/ Materiaux et Constructions*, **24,** 100-105 (1991).
4. M.G.A. Razheeduzzafar, "Polarization period, current density and the cathodic protection criteria", *ACI Materials Journal*, **89-M27**, 247-251 (1992).
5. M.G.A. Razheeduzzafar, "Cathodic protection current accelerates alkali-silica reaction", *ACI Materials Journal*, **90-M27**, 247-252 (1993).

6. J.B. Vrable and B.E. Wilde, "Electrical requirements for cathodic protection of steel in simulated concrete environments", *Corrosion (NACA)*, 36 (1), 18-23 (1980).
7. V.F. Vetere, O.R. Batic, R. Romagnoli, I.T. Lucchini, J.D. Sosa and R.O. Carbonari, "Evaluacion electroquimica de los criterios de proteccion catodica del acero en el hormigon", *Anales de las Jornadas SAM'96*, 1996; pp 245-248.
8. R. Romagnoli, V.F. Vetere, J.D. Sota, P.J. Maiza, S. Marfil, I.T. Lucchini, O.R. batic and R.O. Carbonari, "Análisis de la interfase acero-mortero en probetas polarizadas catodicamente", *Proceedings of the 1st International Contress of Concrete Technology*, Buenos Aires, 2-4 June, 1998.