

Corrosion Measurements of Reinforcing Steel by Different Electrochemical Techniques

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Electrochemical techniques of the corrosion measurements of reinforcing steel in concrete have been evaluated. These techniques include half-cell potential measurements, impressed voltage method, impressed current method and potentiostatic polarization technique. The results of corrosion behaviour of the steel in both 5%NaCl and 5%MgSO₄ show that each electrochemical technique provides some information about the condition of the steel bar or the corrosivity of the environment being evaluated, yet none provides a complete data regarding the corrosion resistance of reinforcing steel in aggressive media.

1. Introduction

Corrosion process of reinforcing steel in concrete produces a problem of catastrophic failure of structure which results in injuries death, and financial losses. Concrete is a porous solid containing an alkaline pore solution (pH=12.6) in which the reinforcing steel is protected^[1-5] against corrosion by the formation of a passive layer of iron oxide. However, since concrete is a porous material, moisture, oxygen and salts (electrolytes) are free to penetrate and disrupt the passive iron oxide film. In particular chloride ions have been found to be the most vigorous in promoting this kind of attack^[6-9], and still remain in solution leaving them free to break down additional protective layers. Ingress of Cl⁻ ions from the environment into the concrete, along with water and oxygen, corrodes the reinforcing steel bar, and rapidly weakens the structure integrity of the system.

The corrosion of steel in concrete is an electrochemical reaction, hence many of the commonly available electrochemical techniques have been used to determine the corrosion rate. The techniques used for steel in concrete systems include, weight loss^[10], linear polarization^[10,11], electrochemical impedance spectroscopy^[12,13].

The aim of the present study is to investigate the

corrosion behaviour of reinforcing steel embedded in concrete of different water/cement ratios immersed in 5% of both NaCl and MgSO₄ solutions. Different electrochemical techniques were used for the steel in concrete system.

2. Experimental

Throughout this work, the ingredients of concrete mix used were ordinary Portland cement, sand, and water. The chemical composition and Blaine specific surface area of the used cement is given in Table 1. The water/cement ratio (W/C) was varied from 0.4 to 0.7 while the sand/cement ratio was maintained constant at 2 by weight.

Cylindrical specimens of 100×150 mm were cast with a 12.5 diam. steel bar embedded in them for corrosion testing. These were cast in steel moulds and demoulded at 24 h holding, then cured in fresh water at 25°C for a specified period before testing. The chemical analysis as well as the mechanical properties of the reinforcing steel are given in Table 2. The rods were mechanically polished to remove the firmly adherent mill scales on the steel surface and then coated with wax in such a manner that a predetermined area was always exposed between the waxed areas.

The environmental conditions selected in these studies were 5% NaCl and 5%MgSO₄ solutions. Four test methods adopted for corrosion rate evaluation of

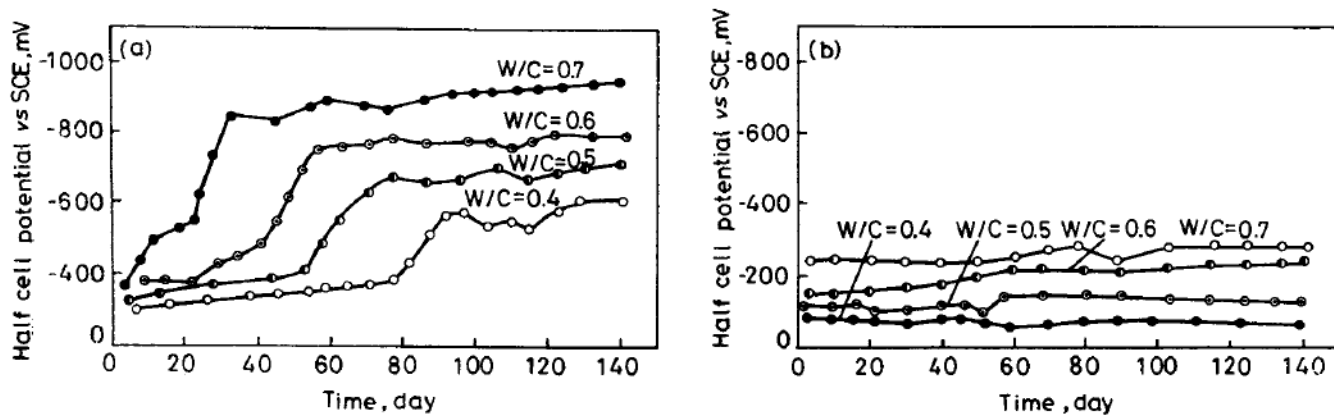
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Table 1 Chemical composition and Blaine specific surface area of ordinary Portland cement

Component	Loss on ignition	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	SO ₃	Free lime	Na ₂ O	K ₂ O	Blaine, cm ² g ⁻¹
%	1.17	20.1	3.26	5.19	62.06	2.62	2.37	0.30	2.48	0.75	3659

Table 2 Chemical analysis and mechanical properties of reinforcing steel

Chemical analysis, %				Mechanical property		
C	S	P	Mn	yield stress, MPa	ultimate stress, MPa	elongation, %
0.12	0.022	0.063	0.43	388.0	493	23.0

Fig.1 Variation of corrosion potential with time for reinforcing steel in concrete in 5%NaCl (a) and 5%MgSO₄ (b) solutions

reinforcing steel were: 1) half-cell potential measurement, 2) impressed voltage method, 3) impressed current method, and (4) potentiodynamic polarization method.

3. Results and Discussion

3.1 Half-cell potential measurement

Such measurement can be employed in a general manner to interpret corrosion phenomenon, as they can furnish information on whether the anodic or cathodic process or both are controlling factors of corrosion. They can also provide useful information on film repair or film breakdown. It can not be used to predict or measure corrosion rate.

Figure 1 shows the variation of corrosion potential with time of reinforcing steel embedded in pastes of ordinary Portland cement with different water/cement ratio in presence of 5%NaCl and 5%MgSO₄ respectively. In case of 5%NaCl solution specimens have attained active potential and the time of active potential is higher for specimens with lesser W/C ratio. While for specimens in 5%MgSO₄ solu-

tion, a steady state potential was observed and remained passive in all cases with different W/C ratio. The delay in initiation of corrosion for low W/C ratio may be attributed to significantly reduced ingress of chloride ions and oxygen to the steel bar.

It is noted that for high quality concrete of low permeability, the W/C ratio should be less than 0.45 and preferably around 0.4^[1].

The half-cell potential of reinforcing steel in Portland cement has been found to be a valid indicator of corrosion activity^[4]. A half-cell potential value more positive than -220 mV vs SCE is considered as a non-corrosive (passive) state for steel, while a value more negative than -270 mV is an indication of active corrosion, for a value between -220 and -270 mV, the steel surface may be active or passive^[4].

By this technique, the performance of specimens could be compared by measuring the time needed for an abrupt increase in half-cell potential value, longer duration indicates better corrosion resistance.

It is noted from the results that, the behaviour of specimens in 5% MgSO₄ solution is passive, but in 5%NaCl solution attains active potentials. These

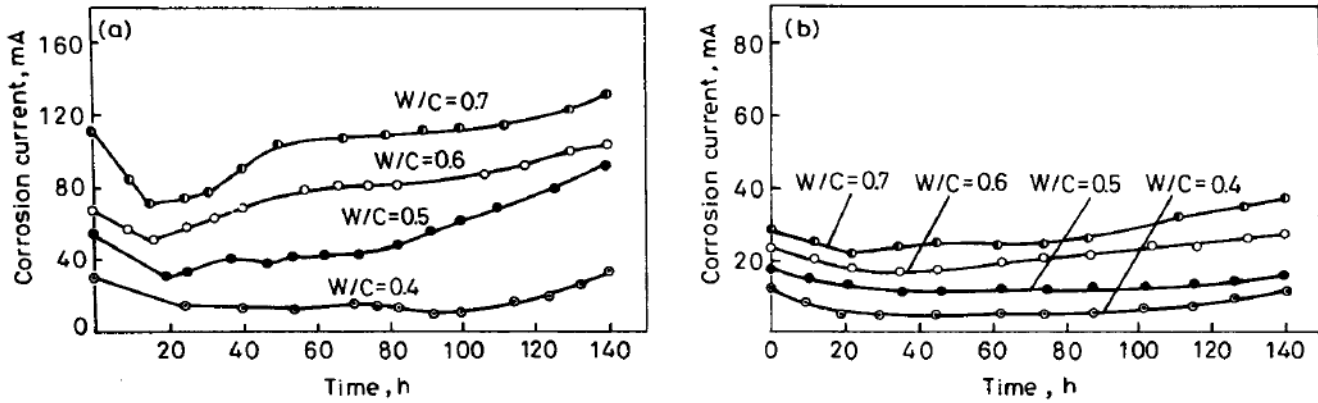


Fig.2 Current-time relationship for reinforcing steel in concrete in 5%NaCl (a) and 5%MgSO₄ (b) solutions

Table 3 Corrosion in weight loss at different water/cement ratio

W/C ratio	Weight loss, g 5% NaCl	Weight loss, g 5%MgSO ₄
0.4	0.252	0.161
0.5	0.779	0.242
0.6	0.940	0.322
0.7	1.480	0.482

results indicate that corrosion of reinforcing steel in Portland cement can only occur under specific conditions and that the presence of Cl⁻ ions is necessary to destroy the protective oxide film on the steel surface.

3.2 Impressed voltage method

In this method a constant positive potential (5 V) was applied to the steel bar embedded in concrete and current from the reinforcing steel to counter electrode was measured periodically. A sharp rise in current is indicative of the onset of corrosion^[14]. The anode is the specimen to be tested and the cathode is a steel bar of same dimension as the anode. The current impressed into steel bar was obtained from DC power supply at constant 5 V. This volt was sufficient to cause a significant change in current value.

The degree of corrosion intensity was estimated^[14] using Faraday's law:

$$w = k(I \cdot t)$$

where w is the mass of substance liberated, I is the intensity of corrosion and t is the prolonged time. K is a proportional constant and equals to 0.0167 g/A·min for steel. The quantity ($I \cdot t$) represents the area under the current-time relationship. The weight loss (w) of iron can be determined quantitatively from the above equation and is proportional to the area under current-time curve ($I \cdot t$).

Figure 2 shows the current-time relationship for

reinforcing steel in 5% NaCl and 5%MgSO₄ solutions for different W/C ratios. The trend in most cases indicates a general decrease in current with time followed by a sudden increase. The size of area under the current-time curve increases with increasing W/C ratio. Therefore, corrosion intensity rises with increasing W/C ratio. The considerable change in current value with time obtained can be divided into three stages:

1) First stage is characterized by an initial decrease in current value with time, due to formation of passive layer of iron oxide which protect temporarily the steel.

2) Secondly, a sharp increase in current with time is due to the initiation of a microcrack resulted from steel corrosion which is accompanied by a volume expansion. In this stage, the resistivity decreases and chloride ions penetrate fast into the concrete.

3) The third stage is characterized by relatively small current variations, since resistivity reaches constant value.

The amounts of iron dissolved due to corrosion of steel bar at different W/C ratios in 5%NaCl and 5%MgSO₄ are listed in Table 3. The change of W/C ratio from 0.4 to 0.7 increases the amount of iron dissolved 5 times in case of 5%NaCl while about 3 times in case of 5%MgSO₄. The reduced current in MgSO₄ solution under impressed voltage is a result of low electrical conductivity of MgSO₄ solution as compared with NaCl solution.

3.3 Impressed current method

In this method a constant current density 20 $\mu\text{A}/\text{cm}^2$ was applied between the specimen and stainless steel counter electrode and the electrode potential of the specimen was measured as a function of time. This test is the most reliable accelerated corrosion test for determining, whether a given medium

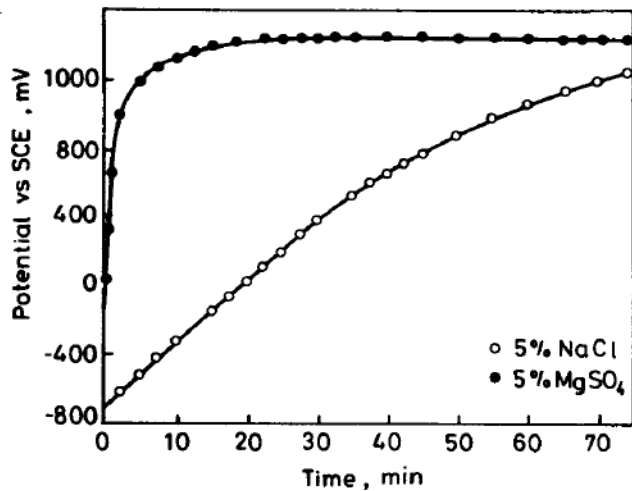


Fig.3 Potential-time relationship of reinforcing steel in concrete in different solutions: (impressed current $20\mu\text{A}/\text{cm}^2$ and $W/C=0.4$)

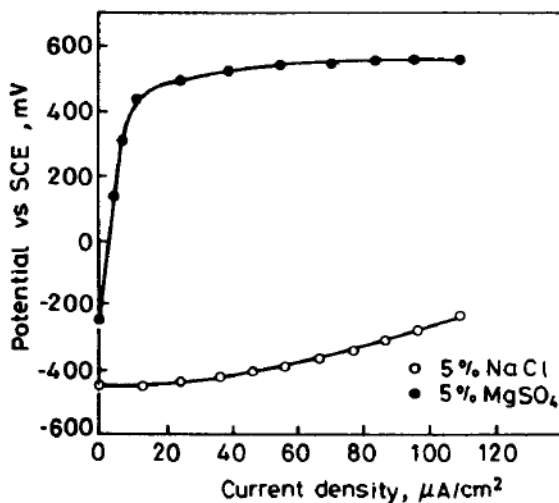


Fig.4 Potentiodynamic polarization relationship of reinforcing steel in concrete in different solutions: scan rate 10 mV/s , $W/C=0.4$

is corrosive or inhibitive^[8].

Figure 3 presents the potential-time curve at a constant impressed current $20\mu\text{A}/\text{cm}^2$ for reinforced concrete in 5%NaCl and 5%MgSO₄. It is noted that in case of 5%NaCl, the steel potential rises very slowly towards the noble direction. On the other hand, in case of 5% MgSO₄ solution, the steel shows sharp rise in the potential in the noble direction and shorter time to reach passivity state (the oxygen evolution potential state).

The measurement of stationary potential and polarization of reinforcement in concrete under impressed current gives a deeper insight into the electrochemical behaviour of reinforcement and helps to es-

tablish the dependence of the corrosive process on the concrete moisture content which changes both concrete permeability by oxygen and ohmic resistance.

3.4 Potentiodynamic polarization method

The potentiodynamic polarization was carried by a controlled potential scan, 10 mV/s using Wenking potentiostat, the reinforced concrete specimen was used as anode and stainless steel rod of the same size of anode was used as counter electrode and the potential was recorded against standard calomel electrode.

Figure 4 shows the potentiodynamic polarization curve (anodic) of reinforced steel concrete in 5%NaCl and 5%MgSO₄ solution.

The potentiodynamic curve characterizes the electrochemical state of steel in concrete. Unlike active steel, the passivity polarizes intensively i.e. its potential markedly shifts into the passive direction already with a low current density as shown in case of 5%MgSO₄ solution.

The corrosion rate measure is the amount of electricity flowing between the cathodic and anodic regions, its value being controlled by the anodic or cathodic process, or by the ohmic resistance of the electrolyte.

Electrochemically, the effect of the anodic process of ionization over voltage is indeed minor. It is affected much more by the concentration polarization from the obstructed diffusion of metal ions, particularly a static electrolyte, as the one in a capillary-porous body of concrete.

4. Conclusions

(1) Corrosion rate evaluations by electrochemical techniques for reinforced steel in concrete have been studied. Each technique provides some information about the condition of the steel bar (passive or active), or the corrosivity of the environment being evaluated.

(2) Half-cell potential of steel in concrete has been found to be a fast indicator of corrosion activity. The change in potential occurs when the corrosion-inducing agent diffuses to the steel surface through the concrete and initiates the corrosion.

(3) Electrochemical polarization technique is used as a valid indicator for measuring corrosion rate and an accelerated method for determining whether given medium is corrosive or inhibitive.

REFERENCES

- [1] P.D.Cady: STP 169 B, American Society for Testing Materials, 1987, 275.

- [2] J.E.Slater: STP 818, American Society for Testing Materials, 1983, 83.
- [3] ACI Committee 222, *Journal of the American Society for Testing Materials*, 1985, 82.
- [4] M.Rasheeduzzafar, F.H.Dakhil and M.A.Bader: *The Arabian Journal for Science and Engineering*, 1986, 11(2), 129.
- [5] G.J.Verbeck: ACI Committee 222, SP-49, American Concrete Institute, 1975, 21.
- [6] D.A.Hausmann: *Mater. Prot.*, 1967, 19.
- [7] V.K.Gauda: *Br. Corros. J.*, 1970, 5, 198.
- [8] H.A.El-Sayed: *Icemento* 1992, 4, 209.
- [9] G.H.Verbeck: *Corros. Sci.*, 1986, 34, 11.
- [10] J.A.Gonzalez, S.Algaba and C.Andrade: *Br. Corros. J.*, 1980, 15, 135.
- [11] J.A.Gonzalez and C.Andrade: *Br. Corros J.*, 1982, 17, 21.
- [12] C.Andrade and V.Castelo: *Br. Corros. J.*, 1984, 19, 98.
- [13] D.D.MacDonald, M.C.J.McKurbe and M.Urquidi-MacDonald: *Corrosion*, 1988, 44(1), 2.
- [14] R.L.Yuan and W.F.Chen: *Performance of Concrete Marine Environment*, American Concrete Institute, SP-65, 1980, 291.