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Correlation between corrosion potential and polarization resistance of rebar in concrete

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Abstract

The relationship between corrosion potential thermodynamics and polarization resistance (electrode kinetics) was analyzed. The influence of cement replacement materials (fly ash and slag) on corrosion resistance of steel in concrete in 3.5% NaCl solution was also investigated by corrosion potential and polarization resistance measurements. Replacement of cement by 10% fly ash shows improved corrosion resistance by reinforcing steel in concrete while concrete with 15 and 30% replacement of cement with slag results in a significant reduction in corrosion resistance of reinforcing steel.

Keywords: Corrosion potential; Polarization resistance; Steel reinforced concrete; Rebar; Fly ash; Slag

1. Introduction

Reinforced concrete has been known for several decades to deteriorate due to chloride-induced corrosion in marine environments [1]. Corrosion is the degradation of reinforcing steel by electrochemical reaction. The chloride ions are not consumed by the electrochemical catalytic reactions but remain available for prolonged serious corrosion [2]. The anodic reactions will produce iron ions, causing pH to fall and further increasing the corrosion tendency [3]. The final corrosion products have a much higher volume and create high bursting pressure, resulting in cracking and spalling of concrete. The corrosion activity of reinforcing steel (rebar) in concrete associated with the corrosion potential was defined in ASTM C876-87 [4]. If potentials are more positive than -0.2 V (versus $Cu/CuSO_4$), there is a greater probability for corrosion. Currently, the method of half-cell surface-potential measurements is widely employed for corrosion monitoring of reinforced concrete structures [5,6]. Determination of polarization resistance of rebar in reinforced concrete has been used to evaluate the corrosion influence of cement replacement materials in concrete [7,8]. The main purpose of this work was to study the correlation between corrosion potential and polarization resistance of rebar in concrete. The influence of cement replacement materials (fly ash and slag) on

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Table 1
Details of mixes and specimens

Specimen	Cement (g)	Sand (g)	Fly ash (g)	Slag (g)	Water/cement ratio
1	1000	2000	–	–	0.35
2	900	2000	100	–	0.35
3	800	2000	200	–	0.35
4	850	2000	–	150	0.35
5	700	2000	–	300	0.35
1	1000	2000	–	–	0.45
2	900	2000	100	–	0.45
3	800	2000	200	–	0.45
4	850	2000	–	150	0.45
5	700	2000	–	300	0.45
1	1000	2000	–	–	0.55
2	900	2000	100	–	0.55
3	800	2000	200	–	0.55
4	850	2000	–	150	0.55
5	700	2000	–	300	0.55

corrosion tendency and electrode kinetics of reinforced concrete is also reported.

2. Experimental

2.1. Preparation of specimens

Details of mixes are listed in Table 1. The control specimens were prepared with type I Portland cement and siliceous sand in the weight ratio of 1/2, and the water/cement ratios were kept at 0.35, 0.45

Table 2
Chemical compositions of cement replacement materials

	Fly ash	Slag
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	86.94	–
SiO_2 (%)	–	33.5
C (%)	–	–
Fe_2O_3 (%)	–	0.6
Al_2O_3 (%)	–	15.7
CaO (%)	0.45	38.8
MgO (%)	0.40	7.7
K_2O (%)	1.07	0.47
Na_2O (%)	0.27	0.07
SO_3 (%)	–	2.0
specific gravity (g/cm^3)	2.06	2.93
moisture (%)	0.53	–
loss of ignition (%)	7.50	–

Table 3
Chemical composition of reinforcing steel

Element	C	Cu	Si	Mn	P	S
wt%	0.36	0.23	0.20	0.61	0.04	0.03
Element	Ni	Cr	Mo	Sn	Fe	
wt%	0.36	0.23	0.20	0.61	balance	

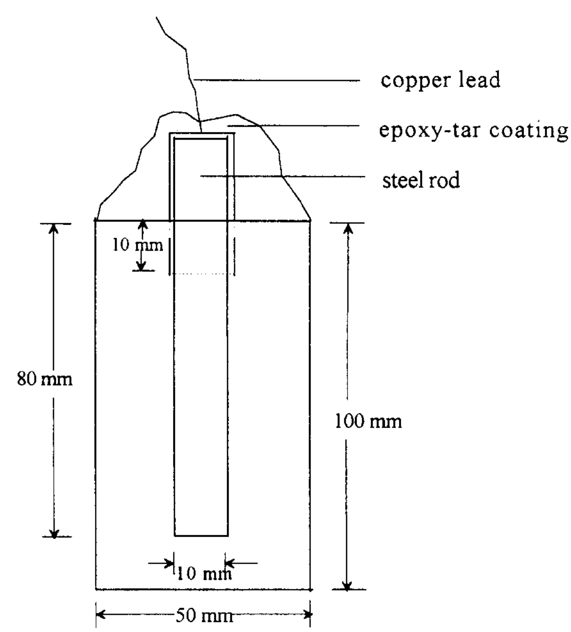

Fig. 1. Configuration of the reinforced concrete specimen.

and 0.55, respectively. In mixes, partial cement was replaced by 10 and 20% fly ash and 15 and 30% slag, respectively. The chemical compositions of the cement replacement materials are given in Table 2. The chemical compositions of reinforcing steel are listed in Table 3. The test specimens for the measurements were in the form of a cylinder. The details of cylindrical reinforced concrete specimen are shown in Fig. 1. The exposed surface area of rebar in 3.5% NaCl solution was approximately 22.8 cm^2, and the rest of the surface area was insulated with epoxy-tar paint. Air bubbles were eliminated by mechanical vibration after pouring the concrete into the steel mold. Standard curing for 28 days was proceeded after the final setting.

2.2. Test methods

All specimens were immersed in 3.5% NaCl solution for conducting the electrochemical tests. Electrochemical measurements were performed using a three-electrode system. The electrode consisted of a reinforced concrete specimen, a counter (Pt) electrode and a saturated calomel electrode. A Nichia model G1001E potentiostat was used for the electrochemical measurements. The variations of corrosion potential (ϕ_{corr}) with time were recorded with respect to a saturated calomel electrode (SCE) in stagnant solution at room temperature. Polarization resistance (R_p) measurements were scanned from 5 mV cathodic to 5 mV anodic of corrosion potential, at a

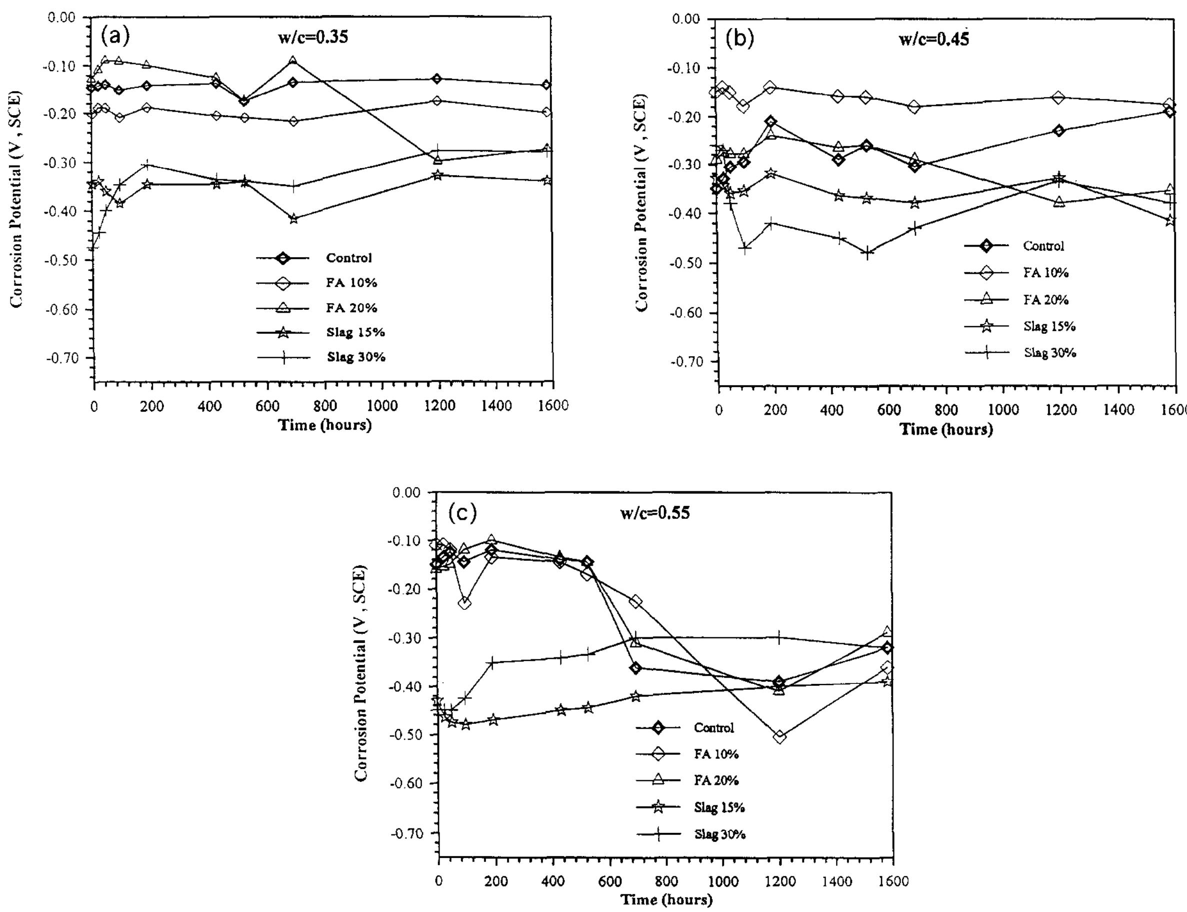

Fig. 2. Corrosion potential as a function of immersion time for the reinforcing steel in concrete containing 10 and 20% fly ash, and 15 and 30% slag, with a water/cement ratio of (a) 0.35, (b) 0.45 and (c) 0.55, respectively.

rate of 0.1 mV/s. Polarization resistance, R_p, was determined as the slope at zero current on the potential versus current graph obtained from the experiment.

3. Results and discussion

Corrosion potential measurements for specimens in 3.5% NaCl solution and their variation with time are shown in Fig. 2a–2c. The control specimens generally show noblest (most positive) potentials, and the specimens with slag show most negative potential among the test specimens. The specimens with fly ash show some intermediate values of corrosion potentials, but the specimens containing 10% fly ash show best potentials. The more negative potentials indicate greater corrosion tendency which is accompanied by greater pore fluid chloride concentrations and higher $[Cl^-]/[OH^-]$ ratios in the specimens with cement replacement materials. The specimens with the water/cement ratio of 0.55 show slightly less negative potentials than those with water/cement ratios of 0.35 and 0.45. It is due to their greater pore size causing chloride ions easily to diffuse or fill in concrete.

The polarization resistance versus exposure time graphs of the specimens are shown in Fig. 3a–3c. The control specimens and specimens containing fly ash also show superior corrosion resistance, and the

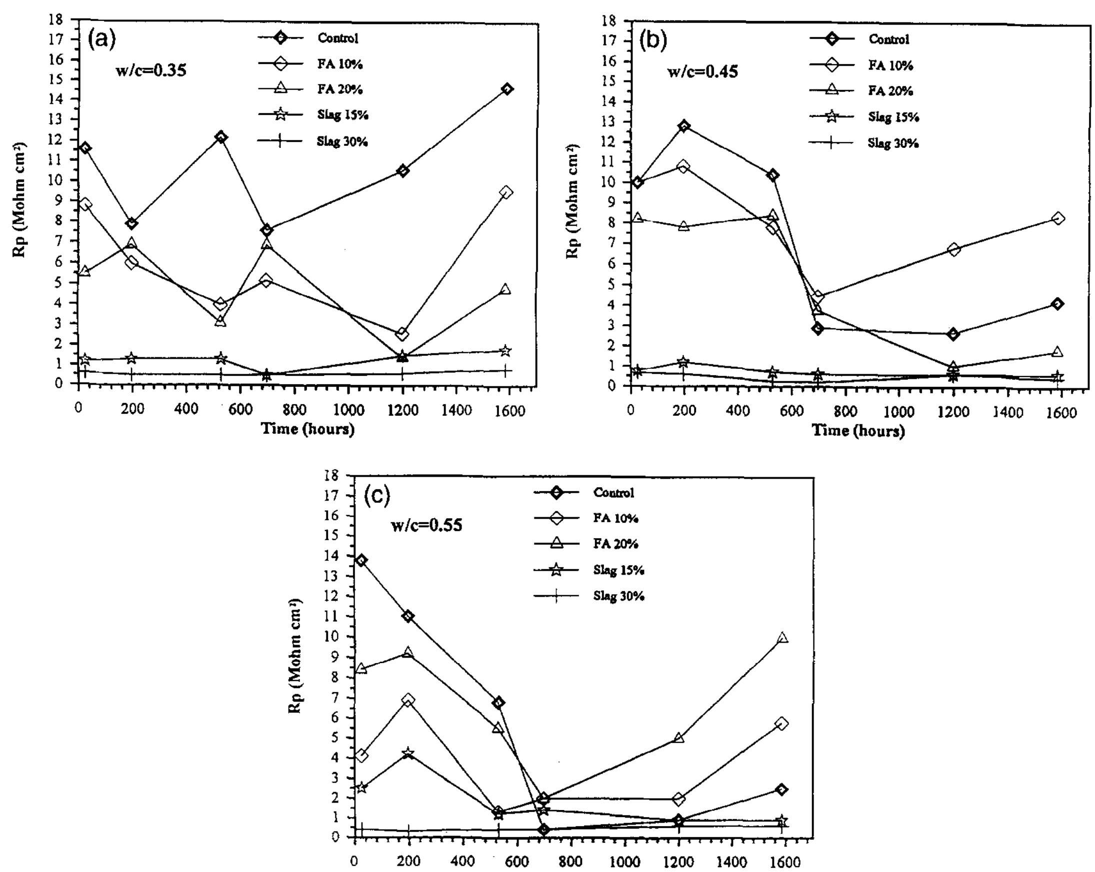

Fig. 3. Polarization resistance as a function of immersion time for specimens with water/cement ratios of (a) 0.35, (b) 0.45 and (c) 0.55, respectively.

specimens containing slag show inferior corrosion resistance in reinforced concrete. Correlations between corrosion potential and polarization resistance are plotted in Fig. 4a–4c. The results indicate that the more negative the value of corrosion potentials, the greater the probability of corrosion. It can be seen that there is a tendency for the specimens containing slag to have a greater tendency to corrode in 3.5% NaCl solution than the control specimens and the specimens containing fly ash. The standard method [9] gives criteria that the corrosion potential is more positive than −0.20 V versus the $Cu/CuSO_4$ reference electrode (−0.12 V, SCE), there is less than 5% probability to corrode, and the potential is more negative than −0.27 V, SCE, there is greater than 95% probability to actively corrode. For the corrosion potential between −0.12 and −0.27 V, the corrosion activity is considered uncertain.

The values of corrosion current density (i_{corr}) can be calculated from R_p by the following expression

$$i_{corr} = B/R_p,$$

where the constant B has values between 0.024 and 0.029 [10–12]. From testing results, the lowest value of R_p is 4×10^6 cm^2 at which the potential is above −0.12 V, SCE, and the corrosion rate can be obtained as $(2.8\text{–}3.3) \times 10^{-3}$ mpy (mil per year). It appears that the corrosion tendency of reinforcing steel in concrete can be predicted reliably from the criteria [9].

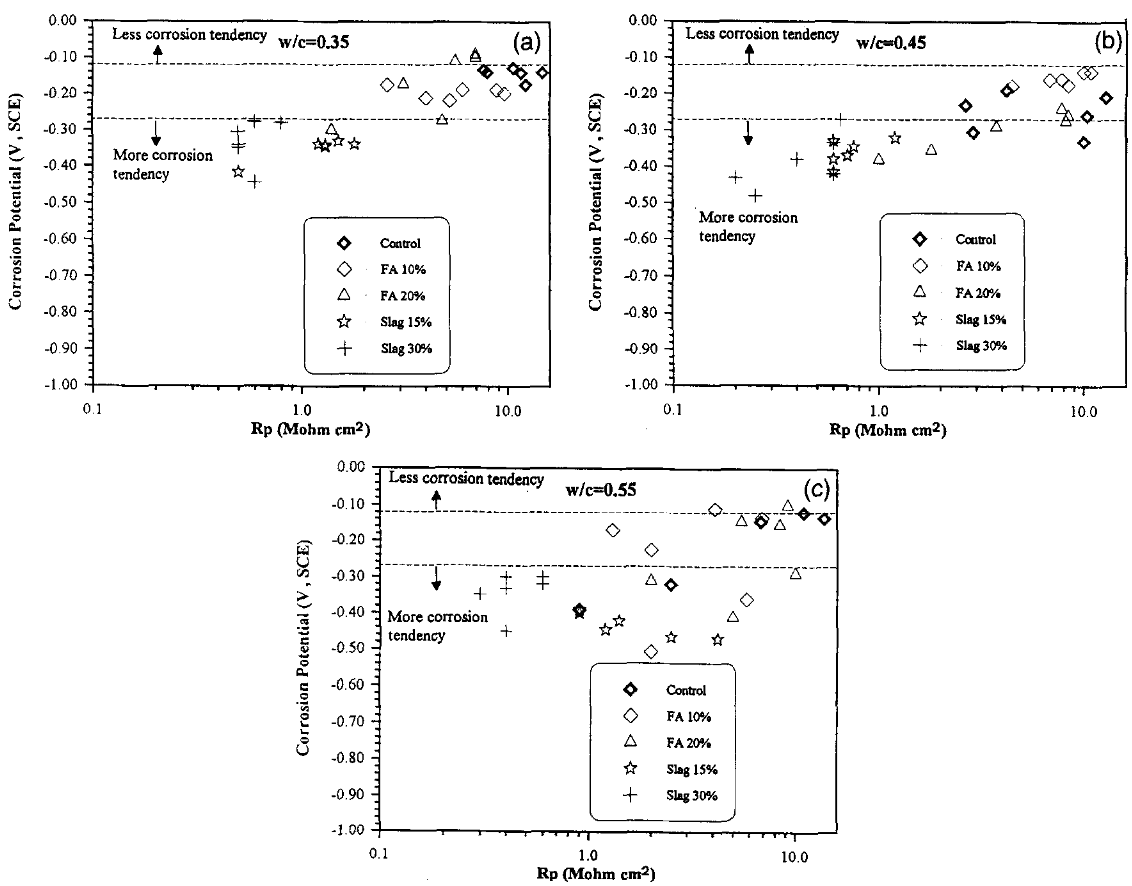

Fig. 4. Plot of the corrosion potential versus polarization resistance for specimens with water/cement ratios of (a) 0.35, (b) 0.45 and (c) 0.55, respectively.

4. Conclusions

(1) The corrosion tendency is strongly dependent upon the corrosion potential and polarization resistance. The corrosion resistance of rebar in concrete can be predicted reliably from the thermodynamic data (corrosion potential), in our results.

(2) Replacement of cement by 10% fly ash shows improved corrosion resistance of reinforcing steel in concrete.

(3) Corrosion resistance of reinforcing steel is significantly reduced for concrete with 15 and 30% replacement of cement by slag.

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