Pergamon

Cement and Concrete Research 32 (2002) 657–663

CEMENT AND CONCRETE RESEARCH

A study of the bond degradation of rebar due to cathodic protection current

J.J. Chang*

Department of Harbor and River Engineering, National Taiwan Ocean University, Keelung 202, Taiwan, ROC

Received 26 July 2001; accepted 12 November 2001

Abstract

Bond degradation of rebar embedded in concrete due to impressed cathodic protection current was studied and is reported in this paper. Different mix designs of concrete are found to have influence on the degradation percentage of bond strength. More specifically, bond strength degradation percentage with higher water-to-cement (w/c) ratio is found to be larger than that with lower w/c ratio. The microstructure scanning electron microscope (SEM) photos of the concrete near the rebar–concrete interface showed that a loose structure with larger microvoids existed in the interface zone. Further, microhardness tests on the concrete near the interface and chemical titration to determine contents of potassium and sodium ions were performed to ensure that the main cause of bond degradation is the softening effect of concrete. A unified parameter, which combined the effects of cathodic current density and polarization time, is used to build up the relationship between experimental data. This concept allows engineers to quickly obtain design information from the experimental data of accelerated tests. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Bond strength; Cathodic protection; Polarization time; Degradation

1. Introduction

Cathodic protection now is well accepted as a suitable method for corrosion prevention of reinforcing steel in concrete. The Federal Highway Administration [1] even suggested that the only effective corrosion prevention method for a contaminated reinforcing concrete member is the impressed cathodic current method. However, there exist many possible side effects when the cathodic protection method is used. Physical and chemical inhomogeneities and instabilities inherent to the concrete material may lead to nonuniform distribution of the cathodic protection currents and result in localized overprotected areas [2,3]. The hydrogen permeation current for a cathodically protected steel membrane with concrete cover has been reported to increase nonlinearly with the concrete cover thickness [4]. It was studied [5,6] that the overprotection cathodic current softened the C-S-H gel in concrete so that both the compressive strength and the durability of concrete could be reduced. It was also found that the alkali–silica reaction would be accelerated by the cathodic current [5]. Besides, it was found [7–10] that the bond strength between rebar and concrete decreased due to the cathodic current. For the above-mentioned drawbacks of the cathodic protection, the bond degradation may be one of the most important factors to engineers. It is well known that many parameters, such as the developed length and splice length, depend mainly on the bond quality of rebar–concrete interface. Therefore, it is quite important for us to investigate the effect of cathodic current on the bond quality from the viewpoint of practice. It has been reported that the potassium and sodium ions will migrate to the interface during cathodic polarization of the rebar and result in softening of C-S-H gel [8]. However, in this study, only few data were used in time intervals, and it is not easy to draw a conclusion. The author and his coworkers have reported the effect of current density and polarization time on bond degradation [9]. They proposed a unified parameter to combine the effect of current density and polarization time. From their results, it then became possible for engineers to design a cathodic protection system by experimental data from an accelerated test. However, they took the concrete quality as a control parameter and only one mix was used.

In this paper, the quality of concrete is taken into consideration by using different mix designs of concrete.

---

* Tel.: +886-2-2462-2192; fax: +886-2-2463-2932.

E-mail address: jjchang@mlab.hre.ntou.edu.tw (J.J. Chang).

PII: S0008-8846(01)00740-2

Table 1
Mix designs for concrete

	Mix proportion (kg/m^3)			
w/c	Water	Cement	Sand	Aggregate
0.48	192	400	714	1100
0.58	200	345	750	1090
0.66	201	305	765	1105

In addition, the microscale experiments of interface were performed to understand the mechanism of bond degradation. Further, a unified parameter approach was used to analyze data, and it could be applied in engineering practice.

2. Experimental program

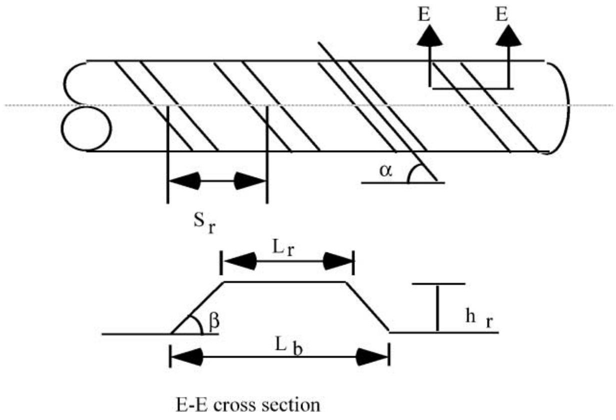
In this study, Type I Portland cement conforming to ASTM 150 was used. River sand and crushed stone were from local sources. The concrete mix design is tabulated in Table 1, and three water-to-cement (w/c) ratios, 0.48, 0.58 and 0.66, were used. The reinforcing steel was made of medium carbon steel with a Young's modulus of 203 GPa (29,435 ksi) and a yield strength of 410 MPa (59.5 ksi). The nominal diameter of rebar was 1.27 cm (4/8 in.), and the details of rebar geometry are given in Table 2.

The pullout specimen was cast in a ∅ 10 × 20 cm (∅ 4 × 8 in.) steel mold with reinforcing steel positioned at the center. The embedded length of rebars was 6 cm. It has been reported that the bond strength is independent of embedded length [11]. After demolding, the specimens were cured for 28 days. Then, the pullout specimens were immersed into a 3.5% NaCl solution. The cathodic current densities applied to the pullout specimens were 0, 400 and 1200 μA/cm^2. The polarization times were 0, 1, 3 and 5 months. After a given polarization time, the pullout tests were performed on five specimens for each group. Pullout test setup basically followed the specification of ASTM C-234-91a [12], but the cylindrical specimens were used instead of prismatic specimens. The bearing plate was designed to accommodate the specimens. The pullout test was performed in a universal material testing machine at a maximum stroke rate of 1.27 mm/min. The maximum pullout forces were recorded, and they were divided by the corresponding embedded area to obtain the bond strengths. The deviation of the bond strengths for specimens of each group was below 9%, and the average bond strength was used for analysis. It should be noticed that only specimens with wholly pullout type failures were taken into consideration. Splitting type failures or combined splitting–pullout type failures were ignored since these are mainly related to the concrete property and not the bond quality. The setup of measurement equipment is illustrated in Fig. 1. After the pullout test was performed, the concrete near the interface was taken, and specimens were prepared for scanning electron microscope (SEM), microhardness and chemical titration. The SEM photos, for which a 5000 × scale was selected, provided microscopic evidence of the microstructure. The microhardness results were expressed by a hardness index, H_V, and it represents the mechanical property of concrete on a microscale. Basically, the microhardness test is a Vicat hardness test on a microscale. The H_V value can be obtained by the following formula (Eq. (1))

$$H_V = \frac{0.1891P}{d^2} \tag{1}$$

where H_V is the Vicat hardness value, P (N) is the load and d (mm) is the length of the diagonal line for the

Table 2
Details of the rebar geometry



Number of steel rebars	Nominal diameter (d_n), cm (in.)	Nominal area, cm^2 (in.^{2})	α, °	β, °	S_r, mm (in.)	L_r, mm (in.)	h_r, mm (in.)	L_b, mm (in.)
4	1.27 (0.5)	1.2668 (0.1964)	65	53.7	7.84 (0.309)	1.81 (0.071)	0.84 (0.033)	3.05 (0.120)

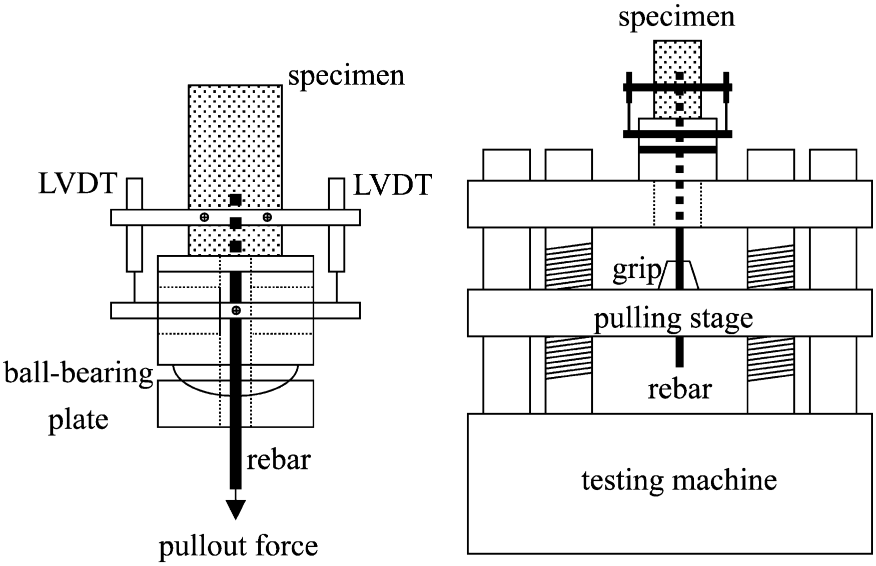


Fig. 1. Pullout measurement setup.

concave stamp made by the diamond pyramid. Ten spots at the concrete near the interface (within 2 mm of the rebar–concrete transition zone) were tested for each specimen, and an average value was taken to represent the interface hardness.

In addition, the chemical titration of potassium and sodium ions existing in the interface zone was performed in order to understand the relationship between the ion content and other studied parameters. The samples for the ion concentration test were selected by taking the interface concrete samples, which were within 1 cm from the rebar surface. In the previous literature [8], it was concluded that the bond strength degradation was proportional to the content of potassium and sodium ions. In this study, we attempted to reexamine their conclusion.

3. Results and discussions

The compressive strength development is shown in Fig. 2. The compressive strength attained higher values as the age of concrete increased and w/c ratio decreased. In Figs. 3–5, the bond degradation due to the current density and polarization time are shown for concrete of w/c = 0.48, 0.58 and 0.66, respectively. It can be seen that the bond strength decreased as the polarization time increased and/or the cathodic current density increased, which are similar to the results reported in the previous study [9]. In our previous study [9], the w/c ratio was not taken into account. From these results, it can be concluded that the bond strength showed lower values for concrete of higher w/c ratio. This is

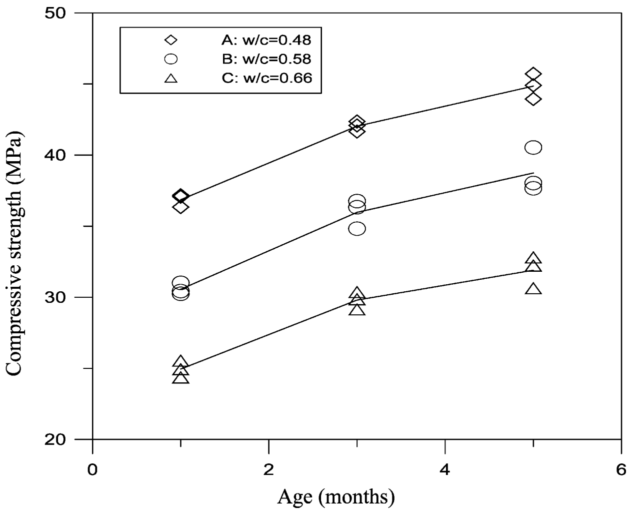


Fig. 2. Development of compressive strength.

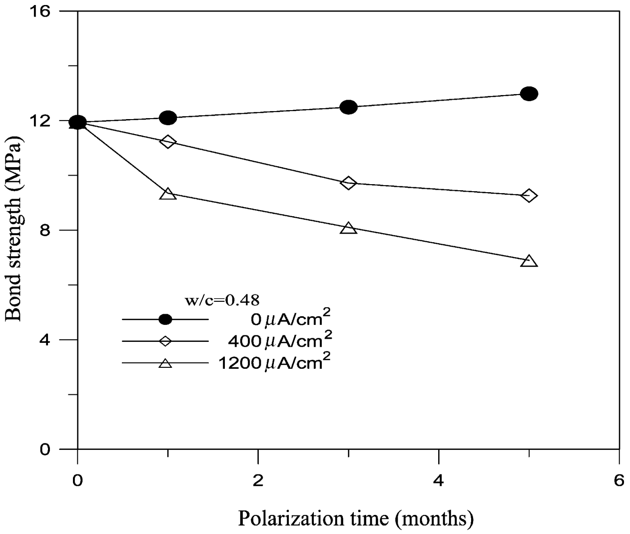


Fig. 3. Bond strength development for specimens with w/c = 0.48.

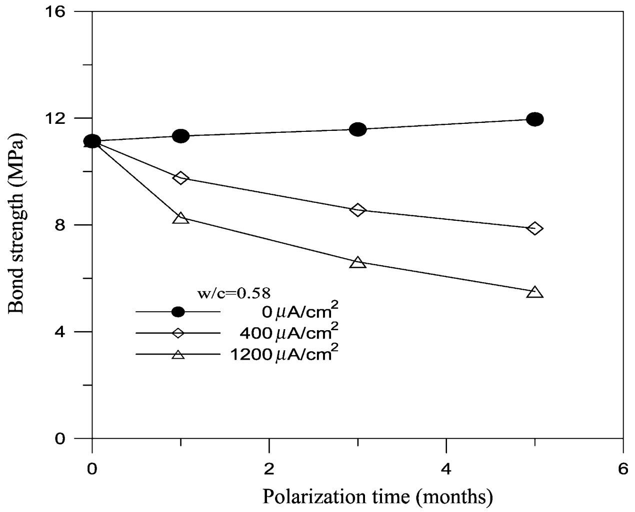


Fig. 4. Bond strength development for specimens with w/c = 0.58.

because the concrete of lower w/c ratio has denser microstructure. It can also be seen that the bond degradation was most significant for concrete with w/c = 0.66. In Figs. 6(a) and (b), the percentage of bond strength reduction versus w/c ratio is illustrated. The percentage of bond strength reduction is defined as (Eq. (2))

$$s \equiv \left\{ \begin{array}{ll} \frac{\|\sigma_p - \sigma_0\|}{\sigma_0} \times 100\% & \text{when } \sigma_p \leq \sigma_0 \ , \\ 0 & \text{when } \sigma_p > \sigma_0 \end{array} \right\} \qquad (2)$$

where s is the percentage of bond strength reduction, σ_p is the bond strength for the specimens at a specific polarization time and σ_0 is the bond strength for the control specimens at the corresponding time. It can be seen that the maximum reduction percentage in bond strength was about 55% when the current density was 1200 μA/cm^2 and polarization time was 5 months. Furthermore, under the same polarization current density and polarization time, it can be seen that the degradation percentage of bond strength increases as the w/c ratio increases. Concretes with higher w/c ratios were observed to have a loose microstructure. This facilitated the ingress of potassium and sodium ions from the nearby environment towards the rebar–concrete interface under the high current gradient and resulted in more serious degradation of the bond. This observation is supported by the results of chemical titration of accumulated potassium and sodium ions near the interface presented later.

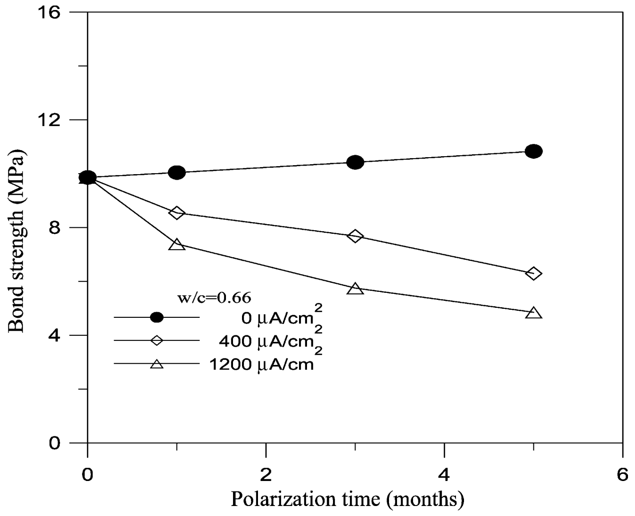


Fig. 5. Bond strength development for specimens with w/c = 0.66.

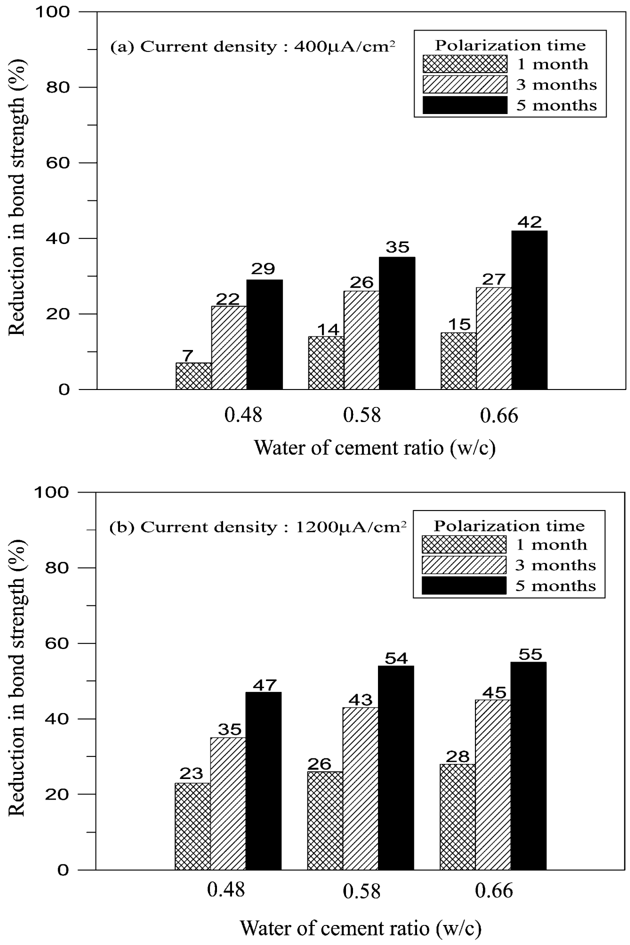


Fig. 6. Reduction percentage in bond strength for specimens. (a) Polarization current density 400 μA/cm^2, (b) polarization current density 1200 μA/cm^2.

In a previous study [9], the effect of current density (i_c) and polarization time (t_p) was combined to define a new parameter $\phi = i_c \times t_p$. It was reported [9] that the bond strength degradation data due to various current densities and polarization times could fit in a unified regression curve. However, it was suggested in Ref. [9] that a research of family of curves for different concrete qualities should be conducted before using such a concept in the engineering practice. In the present study, three w/c ratios were chosen. Although these three mix designs cannot represent all concrete designs neither can they provide an upper bound and lower bound, we believe that these three mixes give a

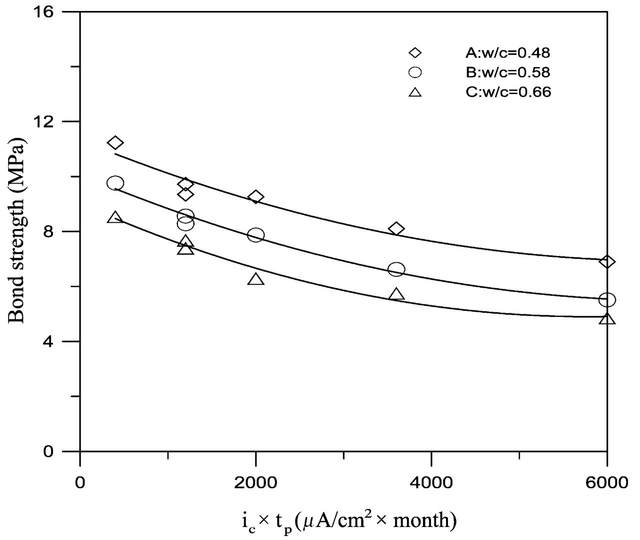


Fig. 7. Regressive curves for bond strengths versus the polarization parameter ϕ.

reasonable spread of the trend in engineering practice. In Fig. 7, the bond strength versus the parameter ϕ is shown. It can be seen that at all w/c ratios, the bond strength decreases exponentially as ϕ increases. For each curve, at the parameter $\phi = 1200$ μA/cm^2 month, there exists two points (one represents for polarization current density 1200 μA/cm^2 and polarization time of 1 month and the other represents for polarization current density 400 μA/cm^2 and polarization time of 3 months), and bond strengths of these two data were very close. It confirms our previous conclusion [9] that under similar polarization condition (that is the same ϕ value), the degradation of bond strength will be very close. An application of data from accelerated experiments is possible according to the suggestion in Ref. [9]. For example, assume that $w/c = 0.58$ and required minimum bond strength is 8 MPa. From Fig. 7, it can be concluded that when $\phi = 2400$ μA/cm^2 month, bond strength reduces to the critical value. If a cathodic current density of 2 μA/cm^2 is used, which is commonly used in engineering practice, then the predicted service life is 1200 months (100 years).

In order to study the softening of concrete nearby the rebar–concrete interface due to the cathodic impressed current, several microscale experiments were performed. Fig. 8 shows the hardness values versus the parameter ϕ. It can be seen that the microhardness values decreased as the parameter ϕ increased, which was evidently supported by the facts of interface softening. Further, concrete with lower w/c ratio showed higher microhardness value due to its denser structure. In Fig. 9, the accumulated potassium and sodium ion concentrations are found to have a nonlinear

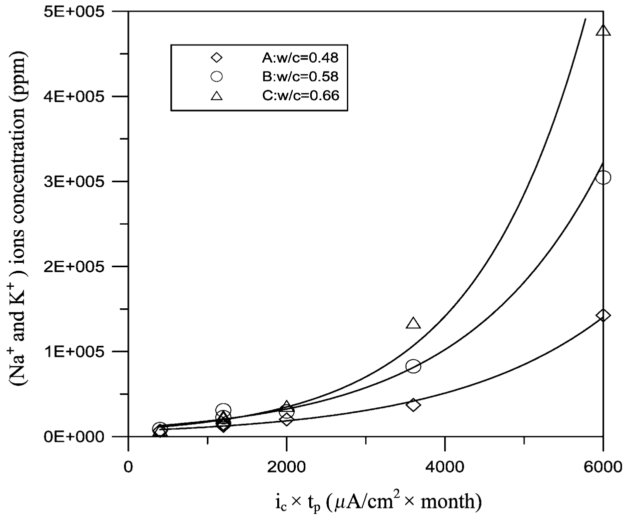


Fig. 9. Total concentration of potassium and sodium ions versus the polarization parameter ϕ.

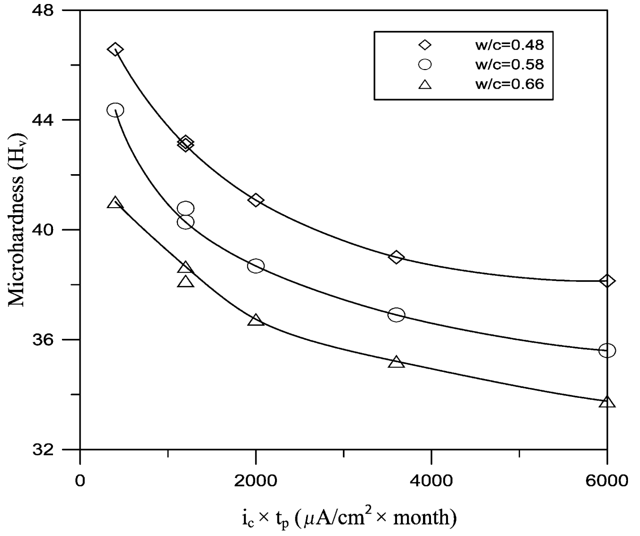


Fig. 8. Microhardness values versus the polarization parameter ϕ.

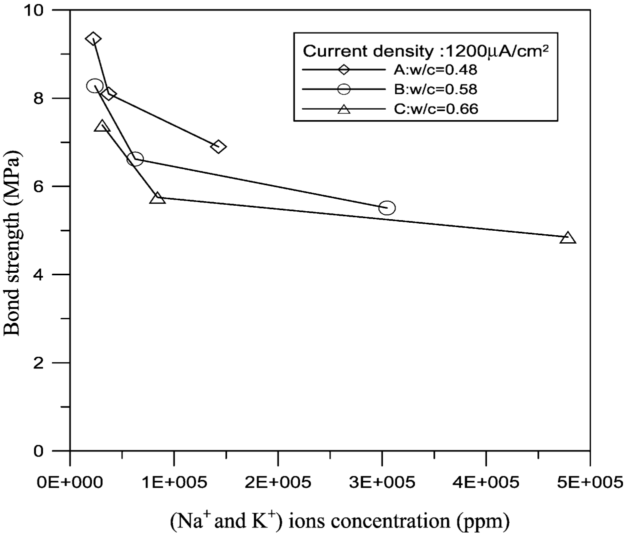


Fig. 10. Bond strengths versus total concentration of potassium and sodium ions.

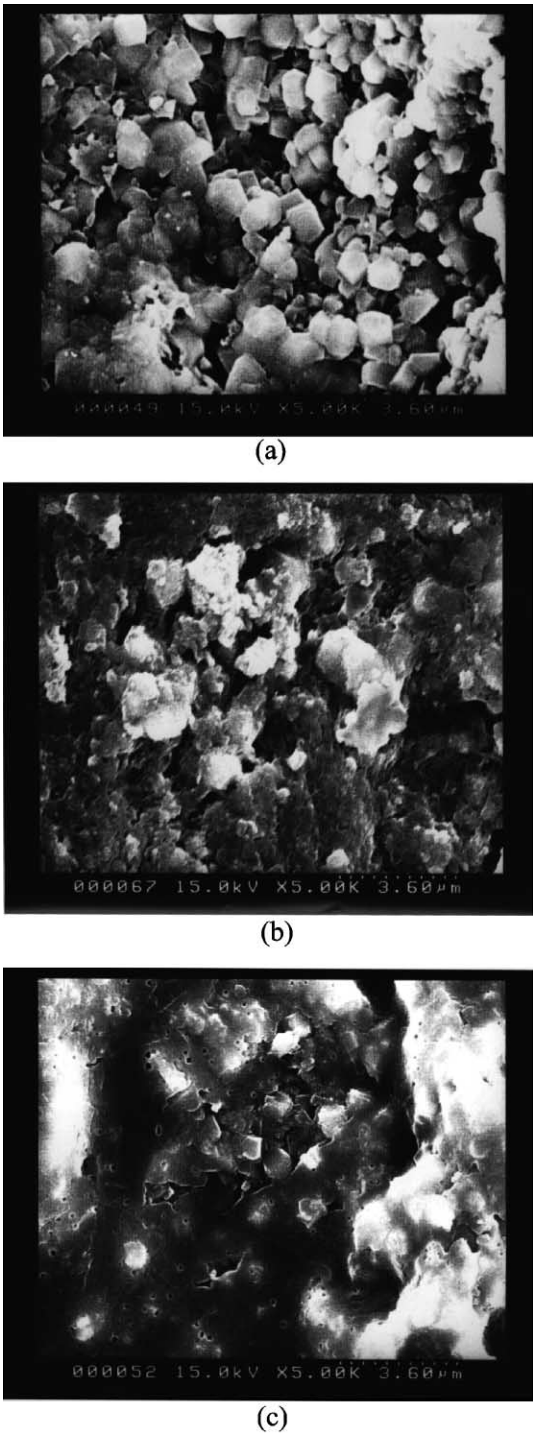


Fig. 11. SEM photos for interface microstructures for specimens with w/c = 0.66 after 5 months of polarization. (a) Polarization current density 0 μA/cm^2, (b) polarization current density 400 μA/cm^2, (c) polarization current density 1200 μA/cm^2

increment as the parameter ϕ increased. It can also be found that the increasing rate became higher as the parameter ϕ increased, which meant that the penetration of potassium and sodium ions into the concrete became faster and faster. Two possible mechanisms are explained as follows: (1) the concrete pore structure became looser such that the ion penetration was easier, (2) the potassium and sodium ions migrated faster to cathodically charged rebar when the applied current was stronger. Further, one can find from this figure that this trend is more severe for concrete with higher w/c ratio. In Fig. 10, the average bond strengths of specimens impressed by 1200 μA/cm^2 for 1, 3 and 5 months were found to decrease as the total potassium and sodium ion concentrations increased. However, the linear proportional property reported in Ref. [8] is not found in our current study. A possible reason is that the potassium and sodium ions were preadded in the specimens in Ref. [8] to simulate the contaminated concrete; however, the main source of sodium ions in our study was from the artificial seawater where the specimens were immersed. We did not add any sodium and potassium ions inside concrete in the mixing process. In addition to microhardness and potassium and sodium ion concentration tests, the scanning electronic microscopic pictures were taken to examine the changes in the microstructure due to the impressed cathodic current. Figs. 11(a) shows the interface microstructure of concrete of w/c equal to 0.66. Figs. 11(b) and (c) shows the interface microstructures of concrete with w/c = 0.66 but impressed for 5 months by 400 and 1200 μA/cm^2 cathodic current densities, respectively. By comparing Figs. 11(a), (b) and (c), we can conclude that the microstructure became looser as the impressed current density was higher. From our microscale experiments, we can conclude that the interface is deteriorated due to the cathodic current.

4. Conclusions

In this paper, the degradation of bond strength due to the impressed cathodic current has been studied. The impressed current density and polarization time have been combined into a parameter, ϕ. It has been found that the bond strength decreased as the parameter increased. The degradation percentage of bond strength for concrete with higher w/c ratio has been found to be bigger due to its looser microstructure nature. The microhardness test, potassium and sodium ion concentration test and scanning electronic microscopic pictures have supported our conclusions.

References

[1] R.A. Barnhart, FHWA position on cathodic protection systems, Memorandum of FHWA, FHWA, Washington, DC, 1982.

[2] B.S. Wyatt, D.J. Irvine, A review of cathodic protection of reinforced concrete, Mater. Perform. 26 (1987) 12–21.

[3] J.A. Lehmann, Cathodic protection of reinforced concrete structures, Mater. Perform. 26 (1987) 79–81.

[4] J.J. Chang, R. Huang, W. Yeih, Effect of concrete cover thickness on hydrogen permeation through cathodically protected steel membranes, Mater. Chem. Phys. 49 (1997) 16–21.

[5] M.G. Ali, Rasheeduzzafar, Cathodic protection current accelerates alkali–silica reaction, ACI Mater. J. 90 (3) (1993) 247–252.

[6] C.E. Locke, C. Dehghanian, L. Gibbs, Effect of impressed current on bond strength between steel rebar and concrete, NACE Corrosion 83, Paper No. 178, Materials Performance and Corrosion Conference, Anaheim, 1983, pp. 178/1–178/16.

[7] N.M. Ihekwaba, B.B. Hope, C.M. Hansson, Pull-out and bond degradation of steel rebars in ECE concrete, Cem. Concr. Res. 26 (2) (1996) 267–282.

[8] Rasheeduzzafar, M.G. Ali, G.J. Al-Sulaimani, Degradation of bond between reinforcing steel and concrete due to cathodic protection current, ACI Mater. J. 90 (1) (1993) 8–15.

[9] J.J. Chang, W. Yeih, R. Huang, Degradation of the bond strength between rebar and concrete due to the impressed cathodic current, J. Mar. Sci. Tech. 7 (2) (1999) 89–93.

[10] R.N. Parkins, M. Elices, V. Sanchez-Galvez, L. Caballero, Environment sensitive cracking of pre-stressing steel, Corros. Sci. 22 (1982) 379–405.

[11] J.J. Chang, Effect of Cathodic Protection Current on Hydrogen Permeation and Interface Properties of Reindorced Concrete, PhD Thesis, National Taiwan Ocean University, Keelung, 1997.

[12] ASTM C234-91a, Standard test method for comparing concrete on the basis of the bond developed with reinforcing steel, ASTM annual book of standards: Section 4. Construction, Philadelphia, 1991.