

論文

[2105] The Effect of Cover Thickness and W/C Ratio on Corrosion of Steel in Concrete

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1. INTRODUCTION

Under uniform environment, corrosion of steel in concrete may undergo microcell actions. For members subjecting to nonuniform environment, some steels are in active state (anode) comparing to the other (cathode). Corrosion of these members will undergo macrocell actions^{1),2)}. Therefore, concrete cover has to provide two simultaneous roles for corrosion protection. The obstruction of the ingress of anodic activators such as chloride is the first important role. The second one is to resist the penetration of oxygen, which is an essential substance for cathode reactions of both microcell and macrocell corrosion.

The research aims to clarify the effect of cover thickness and water to cement ratio (W/C) of concrete on both macrocell and microcell corrosion. In the investigation of macrocell actions, anode (mild steel in NaCl contaminated concrete) was separated from cathode (stainless steel in plain concrete). One steel bar was embedded in prism specimens in order to investigate the progress of microcell corrosion, i.e. from passive to active states.

2. EXPERIMENTAL PROCEDURES

2.1 PREPARATION OF SPECIMENS

Two types of concrete specimens were shown in Fig. 1. The first type was L-shape specimens and the second one was prism specimens. The long legs, of L-shape specimens, and prisms were made of plain concrete. The short legs of L-shape specimens were made of 1.76% NaCl, by cement weight or 3.2% by mixing water, contaminated concrete. Prisms and the short legs were embedded with mild

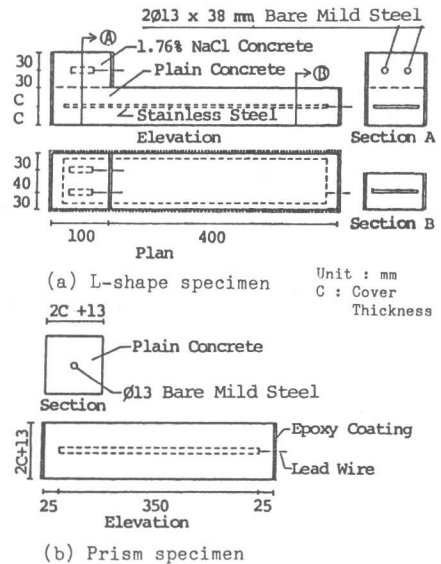


Fig. 1 Details of specimens

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steel rods. The long legs had one stainless steel sheet.

All concrete were made from ordinary portland cement, crushed stone with 10 mm maximum size, river sand and tap water. The mix proportions and strength properties of concrete are presented in tables 1 and 2. The parameters are given in tables 3 and 4. Reinforcing steel bars were $\varnothing 13$ bare mild steel. The stainless steel sheets used in the L-shape specimens and other three additional galvanic cells were type SUS304.

Table 1 Mix proportions and concrete properties of L-shape specimen

Specimen Group	Part of L-Specimen	W/C	C (kg/m ³)	C:S:G	Admixture % of cement	Strength Properties (kg/cm ²)		
						Fc	Ft	Ec
P	Long-Leg	0.40	523	1:1.1:1.8	0.1% WRA	360	40.2	3.39x10 ⁵
Q	Long-Leg	0.55	355	1:2.1:2.6	-	313	32.2	2.77x10 ⁵
R	Long-Leg	0.70	274	1:3.2:3.3	-	226	21.9	2.10x10 ⁵
All Specimens	Short-Leg	0.55	355	1:2.1:2.6	1.76% NaCl	293	26.3	2.65x10 ⁵

Table 3 Parameters of long leg of L-shape specimen

W/C	Size of Stainless Steel (mm ²)	Cover (mm)
P = 0.40	A = 80 x 440	20 = 20
Q = 0.55	B = 40 x 440	30 = 30
R = 0.70		50 = 50

Example of Specimen Title : QA30

Table 2 Mix proportions and concrete properties of prism specimen

Specimen Group	W/C	C (kg/m ³)	C:S:G	Admixture % of Cement	Strength Properties (kg/cm ²)		
					Fc	Ft	Ec
W	0.40	400	1:1.9:2.5	10% WRA	306	27.5	3.08x10 ⁵
X	0.55	400	1:1.8:2.3	-	350	29.0	3.29x10 ⁵
Y	0.70	400	1:1.6:2.0	-	313	26.1	2.58x10 ⁵

Table 4 Parameters of prism specimen

Specimen Group	W/C	Cover (mm)
W	0.40	10, 30, 50
X	0.55	10, 20, 30, 40, 50
Y	0.70	10, 30, 50

2.2 TESTING METHODS

(1) Galvanic cells and exposure conditions

The four galvanic cells are shown in Fig. 2. The first three cells were always immersed in 3.1% NaCl solution. The fourth cell and the prism specimens were subjected to repeated cycles of 1 day wetting in 65°C, 3.1% NaCl solution and 1 day drying under room environment.

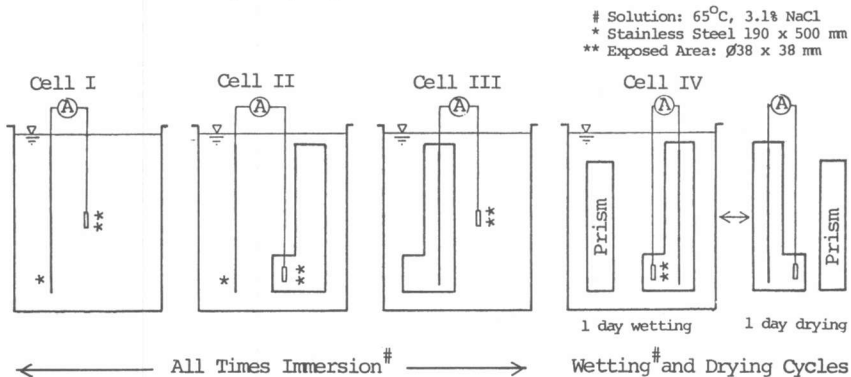


Fig. 2 Galvanic cells and exposure conditions

(2) Measurement and observation

For galvanic cells I to III, the galvanic current was taken once a day. The current of cell IV was measured twice a day, i.e. 2 hrs after changing the exposure conditions and at the end of those exposure conditions. During the 300-day exposure test of the prism specimens, the progress of electrochemical characteristics was observed³⁾. At the end, the prisms were split and the corrosion situations of embedded mild steels were examined.

3. RESULTS AND DISCUSSION

3.1 GALVANIC CURRENT-TIME RELATIONSHIP

Fig. 3 and 4 show the current-time relationships obtained from galvanic cells I and II, respectively. The anodic current (I_a) states that stainless steel plates immersed directly in 3.1% NaCl solution were always cathode of mild steel rods exposed either to 3.1% NaCl solution or to 1.76% NaCl contaminated concrete. The magnitude of galvanic current was much higher in the former than in the latter.

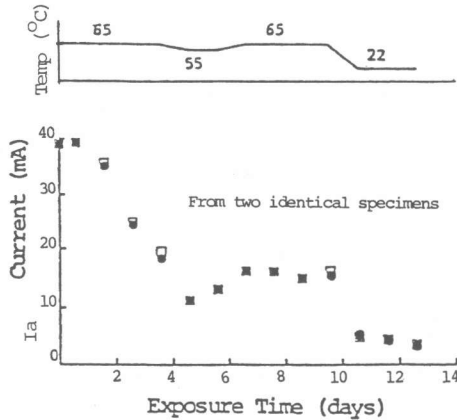


Fig. 3 Current-time relationship of galvanic cell I

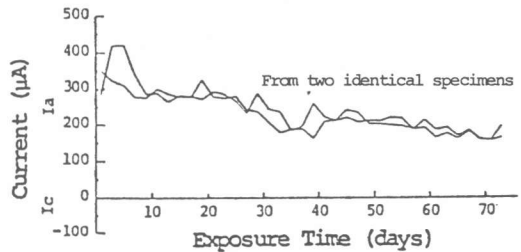


Fig. 4 Current-time relationship of galvanic cell II

The cathodic current (I_c) of galvanic cell III, shown in Fig. 5, indicates that stainless steel embedded in plain concrete was always anode of mild steel immersed directly in 65 °C, 3.1% NaCl solution. Comparing with the results of cells I and II, the polarity reversal was not caused by the presence of chloride ions. The reversal may be resulted from the presence of oxygen as suggested in the literature^(2),4). The magnitude of I_c rather depended on W/C ratio of concrete over stainless steel and it was absolutely independent of size of stainless steel. As shown in the figure, the current increased as W/C ratio decreased.

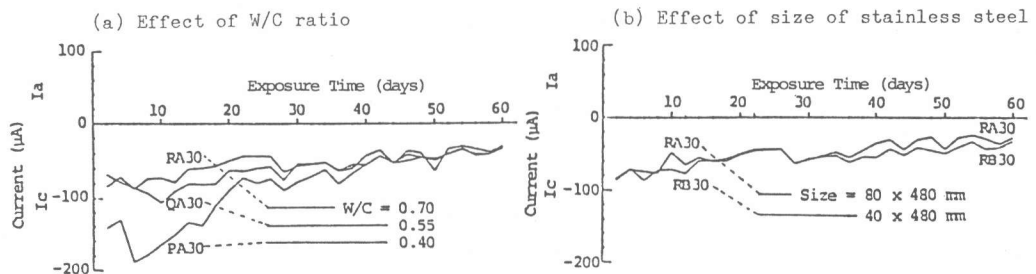


Fig. 5 Current-time relationship of galvanic cell III

The cathodic current presented in Fig. 6 revealed that there was also polarity reversal in the beginning of the exposure test of galvanic cell IV. After time had elapsed, the anodic current was observed signifying that mild steel had changed from cathode to anode of the system. Willkins and Lawrence [2] also found current reversals during the coupling of steel rods

embedded in sound and cracked cylinders.

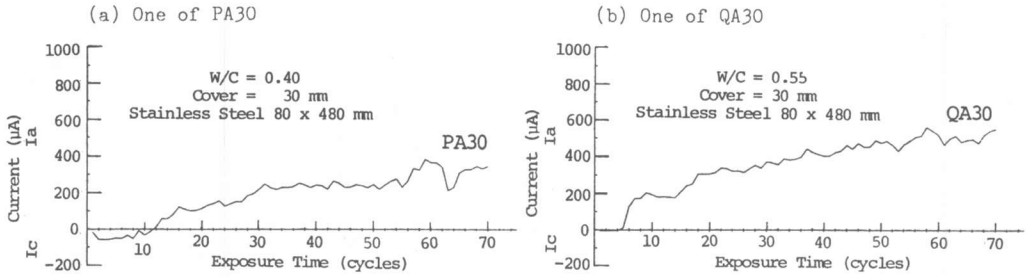


Fig. 6 The typical current-time relationship of galvanic cell IV

The relationships between W/C ratio, cover thickness, of concrete over stainless steel, and magnitude of cathodic current are presented in Fig. 7. As to the results of cell III, the current magnitude increased with decreasing in W/C. The current was rather independent of cover thickness.

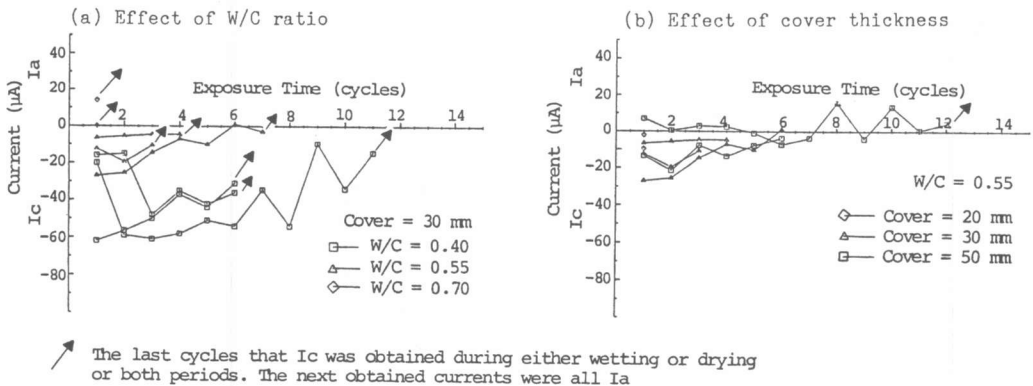


Fig. 7 The relationship between W/C ratio, cover thickness, and magnitude of cathodic current during the polarity reversal period of cell IV

3.2 EFFECT OF W/C, COVER, AND SIZE OF STAINLESS STEEL ON IRON DISSOLUTION OF ANODE STEEL

The anodic current relates to the iron dissolution of steel embedded in NaCl contaminated concrete. The degree of the dissolution can be indicated by the area under current-time curve. The relationships between W/C, size of stainless steel, cover thickness and the degree of dissolution are presented in Fig. 8.

Fig. 8a and 8b indicate that, for a given cover thickness and size of stainless steel, there was a tendency that the dissolution degree decreased with decreasing in W/C. The tendency was more pronounced in the specimens with smaller size of stainless steel. This is due to the fact that oxygen diffusion rate, which is important for oxygen reduction, is lower for lower W/C concrete⁵⁾. Comparing Fig. 8b with 8a indicates that, except for 0.70 W/C, the degree of dissolution increased as size of cathode increased. Fig. 8c shows that for the same W/C and size of stainless steel, cover thickness has less effect on the dissolution. The effect of cover thickness on oxygen diffusion during wetting and drying cycles is rather contrary to that under full immersion of which cover thickness also has a remarkable effect as W/C has⁵⁾.

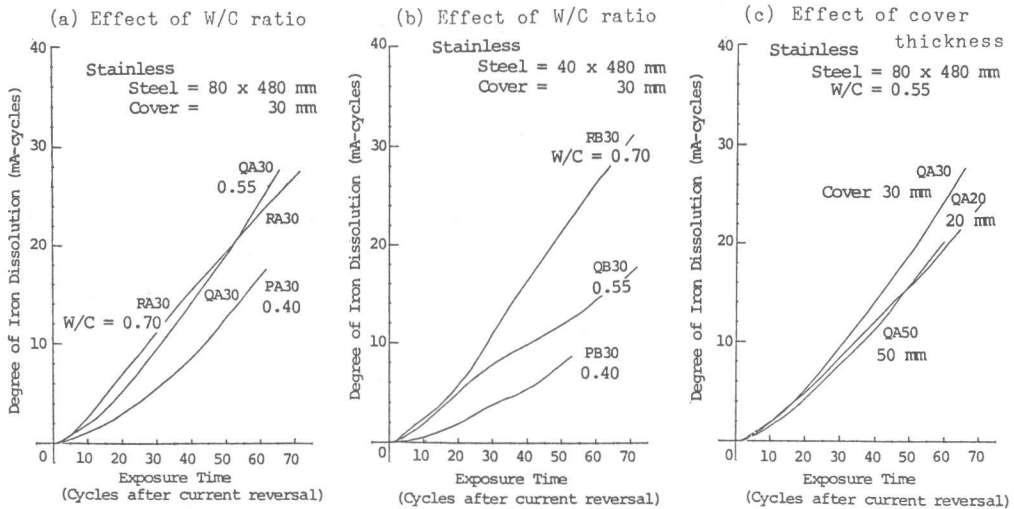


Fig. 8 The relationship between W/C ratio, cover thickness, and degree of iron dissolution of galvanic cell IV

3.3 THE EFFECT OF W/C AND COVER ON MICROCELL CORROSION

The prism specimens had undergone all corrosion states, i.e. from passive to active states. The effect of W/C and cover thickness on microcell corrosion are presented in Fig. 9. Both weight loss and corroded area decreased as W/C decreased and decreased as cover thickness increased. The results are certainly agreeable to the reviewed data presented by Beeby⁶⁾. The results suggest that both W/C and cover thickness have effect on the progress of microcell corrosion. However, it is worth noting that, since corroded areas of some specimens were less than 100% of the total exposed area, these specimens had to undergo macrocell actions to some extent.

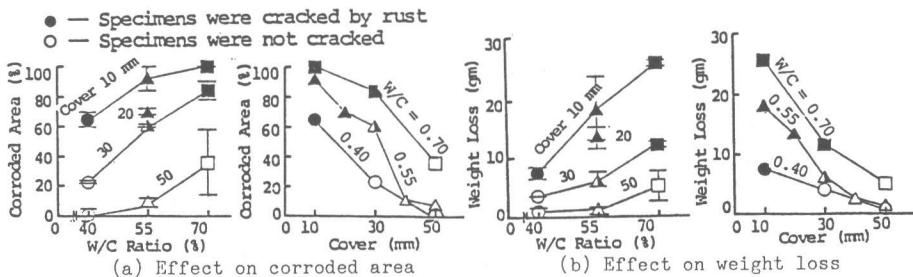


Fig. 9 The effect of W/C ratio and cover thickness on corrosion of prisms

3.4 THE MECHANISM OF MACROCELL CORROSION

(1) Cause of polarity reversal

The polarity reversal was also found in a number of researches^{1),2),4)}. The cause was suggested to be due to either the presence of oxygen⁴⁾ or the difference in oxygen concentrations around the two electrodes²⁾. The magnitude of cathodic current of galvanic cell III, shown in Fig. 5b, depended on W/C, i.e. current increased as W/C decreased. Under full immersion, oxygen diffusion rate decreases as W/C decrease. The 65 °C elevated temperature should facilitate oxygen to reach mild steel easier

than to reach embedded electrodes. Given the higher oxygen concentration around mild steel in the solution as a reference level, the degree of the differential oxygen concentrations between mild steel and embedded stainless steel should increase as W/C decreases. Therefore, it is reasonable to conclude that the polarity reversal in the study was due to the difference in oxygen concentrations and the magnitude of cathodic current was dependent of the degree of the difference.

The cause of the polarity reversal obtained in the beginning of cell IV, as shown in Fig. 6 and 7, may also be described in the same line if the higher oxygen around embedded mild steel is set as a reference level. However, mild steel was also under microcell actions by the presence of 1.76% NaCl in concrete. The oxygen around mild steel in concrete was rapidly depleted resulting in the reversal of oxygen concentration, thus the reversal of current, i.e. from cathodic to anodic current.

(2) The iron dissolution of steel in concrete

In spite of the same conditions of stainless steel and environment, the anodic current of mild steel immersed in 3.1% NaCl solution was much higher than that of mild steel embedded in 1.76% NaCl contaminated concrete (Fig. 3 and 4). Fig. 8a and 8b indicate that the effect of cathode size can not be detected in specimens with 0.70 W/C concrete over cathode. These were certainly due to the restriction of iron dissolution in concrete.

The restriction of iron dissolution can be resulted from two factors. The first is the higher pH and the lower chloride ions⁷⁾ in bulk solution at steel-concrete interface. Secondly, because the rate of metal dissolution is governed by metal ions moving out to the bulk solution⁸⁾, iron dissolution may be limited by the confinement of surrounding concrete.

4. Conclusions

(1) Both W/C and cover thickness have effects on the progress of microcell corrosion (Fig. 9).

(2) Under macrocell actions and wetting & drying environment, W/C of concrete over cathode steel has more effect on anode dissolution than cover thickness has (Fig. 8).

(3) The polarity reversal was observed in the experiments (Fig. 5 and 7). The results strongly suggest that oxygen concentration should play a major role on macrocell corrosion. In other words, the oxygen rich steel will become cathode of the cell regardless of how much chloride content is.

(4) A limitation of iron dissolution of steel in concrete was found. The effect of W/C ratio on iron dissolution was more pronounced in group of specimens with smaller cathode size. For 0.70 W/C, the effect of cathode size can not be seen (Fig. 8a and 8b).

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