CORROSION SCIENCE AND TECHNOLOGY, Vol.4, No.4(2005), pp.130~135

Characteristic of Steel Corrosion in Carbonated Concrete

JeiJun You[1] and †Yoshiteru Ohno[2]

[1]Advanced Structure Research Station, Department of Architecture, Hanyang University
1271 Sa-1, Sangnok, Ansan, Kyunggido 425-791, KOREA
[2]Graduate school of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka 565-0871, JAPAN

In this study, accelerated corrosion tests were conducted on concrete specimens with and without accelerated carbonation beforehand for the purpose of elucidating the effects of carbonation, cover depth, and water-cement ratio (W/C) on the reinforcement corrosion. During testing, the corrosion current between the anode steel and cathode stainless steel was measured to continuously monitor the progress of corrosion throughout the test period, thereby investigating the mechanism of reinforcement corrosion and the relationship between corrosion and crack width, as well as other parameters.

Keywords *: corrosion of steel, crack, carbonation, corrosion of current, reinforced concrete*

1. Introduction

Corrosion of reinforcing steel, which governs the durability of reinforced concrete structures, is related to such factors as concrete quality, cover depth, and cracking. Whereas requirements for concrete quality and cover depth may be determined by other performance requirements, crack width is required to be not more than 0.1 to 0.3 mm depending on the environmental conditions by most standards and guidelines worldwide from the aspect of reinforcement corrosion.[1)] However, such standards did not select these values based on their own independent data but determined them by referring to other standards, since allowable limits regarding reinforcement corrosion have yet to be elucidated. Past research into the relationship between reinforcement corrosion and crack width includes the following:

Yachida *et al.* revealed from surveys of reinforced concrete bridges that reinforcement corrosion substantially depends on crack width and cover depth in beams at an age between 10 and 40 years but that it depends on cover depth and carbonation depth in beams at an age between 40 and 60 years, with the effect of crack width being relatively limited.[2)] Tottori *et al.* conducted exposure tests of cracked reinforced concrete members over 40 years and reported that reinforcement corrosion began at an age between 11 and 20 years and that the crack width affected the time of corrosion onset.[3)]

According to these reports, it is inferred that crack width strongly affects the time of onset and early stage of reinforcement corrosion but that the effect progressively weakens thereafter while the effect of carbonation becomes significant.

On the other hand, extensive research has been conducted on carbonation of concrete, based on which the durability of concrete structures has been discussed. However, such discussion pertains only to flawless concrete. A crack should allow permeation of CO_2, accelerating carbonation of concrete near reinforcement in the cracked area.

In this study, accelerated corrosion tests were conducted on concrete specimens with and without accelerated carbonation beforehand for the purpose of elucidating the effects of carbonation, crack width and water-cement ratio (W/C) on the reinforcement corrosion. During testing, the corrosion current between the anode steel and cathode stainless steel was measured to continuously monitor the progress of corrosion throughout the test period, thereby investigating the mechanism of reinforcement corrosion and the relationship between corrosion and crack width, as well as other parameters.

2. Experimental

2.1 Geometry and type of specimens

Specimens were reinforced concrete beams 450 mm in

†Corresponding author: oono@arch.eng.osaka-u.ac.jp

length, embedding a polished plain bar (SS 41) 14 mm in diameter with a test length of 38 mm in the center (anode) and two stainless steel bars (SUS 304) (cathode), with the surface area ratio of anode to cathode being 1/7 as shown in Fig. 1. An epoxy-coated deformed bar was also provided as a simple flexural reinforcement. At the beginning of testing, the polished plain bar and stainless steel bars were electrically connected with a lead to form a macrocell. Cracked specimens were subjected to accelerated carbonation prior to corrosion testing, while being loaded as shown in Fig. 1.

The test parameters are tabulated in Table 1. The target crack width was in three levels: 0 mm (no loading, N), 0.1 mm (reinforcement stress: 150 N/mm^2, S), and 0.2 mm (250 N/mm^2, L). S and L specimens were subjected to flexural loading by combining two specimens of the same type after being notched at the corners in the center on the tension side to induce cracking at the center of the beam length. These specimens were then subjected to corrosion testing while maintaining the crack width. The crack widths measured using contact gauges on the specimen side at the bar level were 0.03 to 0.08 mm and 0.14 to 0.19 mm with a bar stress of 150 and 250 N/mm^2, respectively, for both cover depths of 20 and 40 mm.

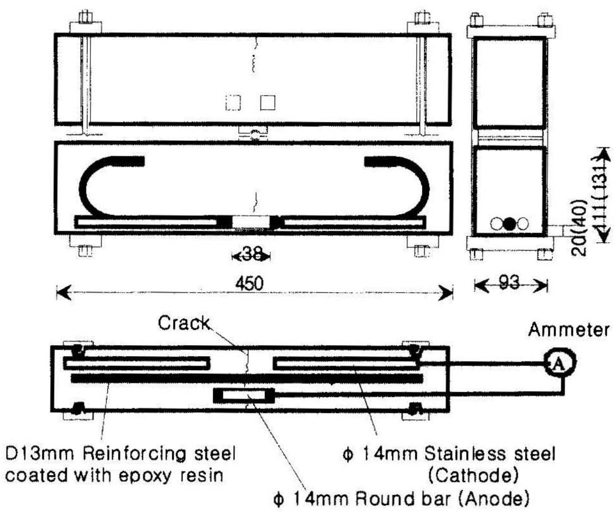

Fig. 1. Details of specimens

2.2 Accelerated carbonation and accelerated corrosion tests

2.2.1 Accelerated carbonation period

Series II specimens were subjected to accelerated carbonation for 9 months at a temperature of 20 ℃, relative humidity of 60%, and CO_2 concentration of 5% followed by 2 months at a CO_2 concentration of 10%.

2.2.2 Method of accelerated corrosion

Specimens in which the anodic plain bar was electrically connected with the cathodic stainless steel bars using a lead wire were subjected to wet-dry cycles of immersion in salt water assuming seawater with a temperature of 65 ± 3 ℃ and NaCl concentration of 3.2% for 24 hours and drying in air for 24 hours. The test period was 35 cycles, i.e., 70 days.

2.3 Measurement items

2.3.1 Carbonation depth

Specimens were cleft after completion of accelerated corrosion cycles to examine the carbonation depth, crac-

Table 1. Test parameters

(Series I)

Specimen Symbol	Crack width (mm)	Cover depth (mm)	Water cement ratio (%)
N-C20-WC50	N (Crack 0)	20	50
N-C40-WC50		40	
N-C40-WC70		40	70
S-C20-WC30	S (0.1 mm)	20	30
S-C40-WC30		40	
S-C20-WC50		20	50
S-C40-WC50		40	
S-C40-WC70		40	70
L-C20-WC30	L (0.2 mm)	20	30
L-C40-WC30		40	
L-C20-WC50		20	50
L-C40-WC50		40	

(Series II)

Specimen Symbol	Crack width (mm)	Cover depth (mm)	Water cement ratio (%)
N-C20-WC50	N (Crack 0)	20	30
N-C40-WC30		40	
N-C20-WC50		20	50
N-C40-WC50		40	
N-C40-WC70		40	70
S-C20-WC30	S (0.1 mm)	20	30
S-C40-WC30		40	
S-C20-WC50		20	50
S-C40-WC50		40	
L-C40-WC30	L (0.2 mm)	40	30
L-C40-WC50		40	50
L-C40-WC70		40	70

king, and state of carbonation near reinforcement. Carbonation depth was measured by spraying 1% phenolphthalein solution.

2.3.2 Corrosion current

The corrosion current between the plain bar assuming the anode and the stainless steel bars assuming the cathode was measured at 20-min intervals using an automatic measuring system consisting of a resistance-free ammeter, scanner, and computer.

2.3.3 Corroded area ratio and weight loss by corrosion

The anodic plain bar was removed from concrete after testing to measure the corroded area and weight loss by corrosion. The corroded area ratio was determined by tracing the corroded area on a cellophane film, measuring the area with a planimeter, and dividing it by the total surface area of the plain bar. The weight loss was determined by immersing the bar in 10% solution of diammonium citrate to remove the rust was measured to correct the value.

3. Results and discussion

3.1 State of carbonation

The results of accelerated carbonation of series II specimens are as follows: Carbonation was limited to 2 to 3 mm from the surface of specimens with a W/C of 30%, with no carbonated area near the crack. In specimens with a W/C of 50%, carbonation proceeded to 25 mm from the surface, with carbonated areas present along the crack in the shape of a V and along the reinforcement. In the case of 70% W/C, carbonation progressed over 40 mm from the surface, with the carbonated area completely covering the reinforcement.

3.2 Corroded area ratio

Fig. 2 shows the relationship between the corroded area ratio and W/C. The corroded area ratio of series II specimens was 3 to 4 times higher than that of series I specimens and increased as the W/C increased. This is because a higher W/C leads to a greater carbonation depth, and carbonation near reinforcement strongly affects the state of corrosion.

With a W/C of 30%, reinforcement in series I specimens was scarcely corroded. In series II, corrosion did not progress in flawless specimens, but cracked specimens in which carbonation depth was only 2 to 3 mm did show progress of corrosion. This is presumably because concrete near the reinforcement was carbonated in cracked series II specimens, though apparently colored by phenolphthalein spraying, due to CO_2 permeation through the crack, which reduced the pH value of concrete on the crack surfaces to around 10 to 11.[4)]

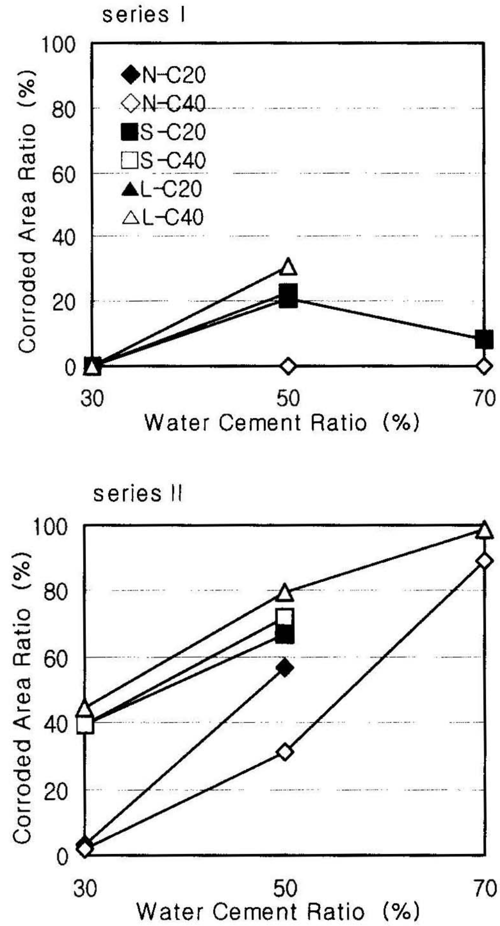

Fig. 2. Relationship between the corroded area ratio and W/C

With a W/C of 50%, reinforcement was corroded in cracked specimens, whereas it remained intact in flawless specimens in series I. In series II, corrosion also occurred in flawless specimens.

Specimens with a W/C of 70% showed tendencies similar to the case of 50%W/C, but the corroded area ratio was highest.

Fig. 3 shows the relationship between the corroded area ratio and the crack width. Whereas the corroded area ratio increased as the crack width increased in series I, the effect of the crack width on the corroded area ratio was marginal in series II. This may be because carbonation of concrete around the anodic plain bar proceeded beyond the test length of the bar in both S and L cracked specimens.

The differences between the corroded area ratios of specimens with and without cracking were significant, because CO_2 permeated into concrete through the cracking, accelerating carbonation of concrete near the reinforcement in cracked specimens with a W/C of 30% and 50%. In flawless 70% W/C specimens, carbonation proceeded

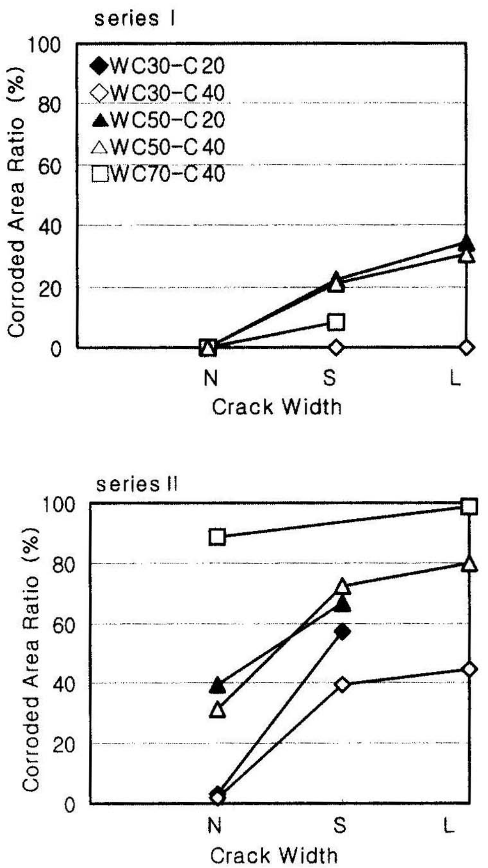

Fig. 3. Relationship between the corroded area ratio and the crack width

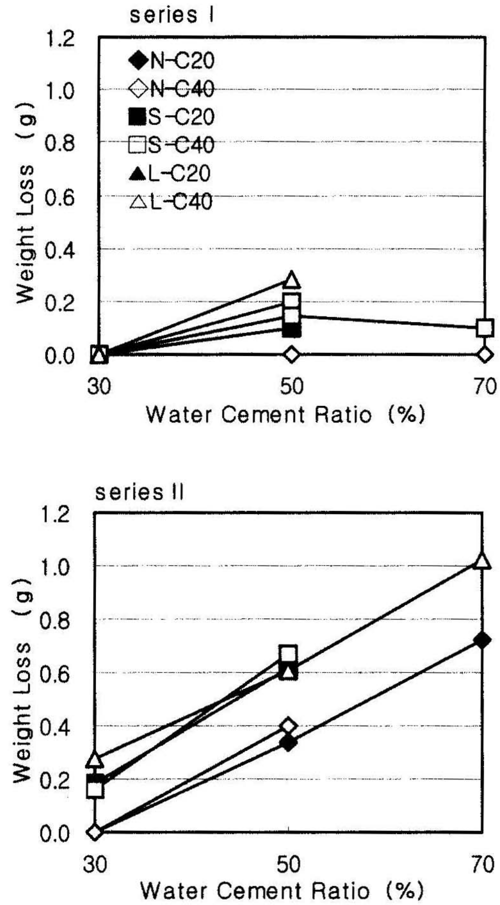

Fig. 4. Relationship between the weight loss and W/C

around the reinforcement, despite the absence of cracking, resulting in corroded area ratios similar to those of cracked specimens. Accordingly, it is considered that cracking strongly affects the corroded area ratio of specimens with little carbonation but that the effect of cracking is weakened when carbonation reaches near the reinforcement.

3.3 Weight loss by corrosion

The weight loss by corrosion is related to various parameters in Figs. 4 and 5. Tendencies similar to those of the corroded area ratio are observed in both series I and II. The weight loss increases as the W/C increases. The crack width affects the weight loss in series I, while the effect of crack width is reduced in series II.

As stated above, Yachida *et al.* reports that the effect of cracking decreases as carbonation progresses.[2] This is also the case in the present study .

3.4 Accumulated corrosion current

Fig. 6 shows typical time-related changes in the macrocell corrosion current between the anodic plain bar and the cathodic stainless steel bars. The peaks and bottoms correspond to the immersion and drying phases, respectively.

Fig. 7 shows the relationship between the W/C and the accumulated corrosion current determined by integrating the macrocell corrosion current with respect to time. In series I, the relationship between the W/C and the accumulated corrosion current shows a tendency similar to that between the W/C and the weight loss, indicating that primarily macrocell corrosion occurs in series I specimens. In series II, however, no marked effect of W/C is observed on the accumulated corrosion current in contrast to the weight loss, which increases as the W/C increases. This suggests that microcell corrosion, which is not detected by macrocell corrosion current reading, occurs in series II. While the macrocell corrosion with 70% W/C is the same as that of 50% W/C, the weight loss is greater in specimens with 70% W/C, indicating that the percentage of microcell corrosion in the total corrosion amount is greater in specimens with 70% W/C than in specimens with 50% W/C. Ohtsuki *et al.* reported that a lower W/C tends to lead to microcell formation

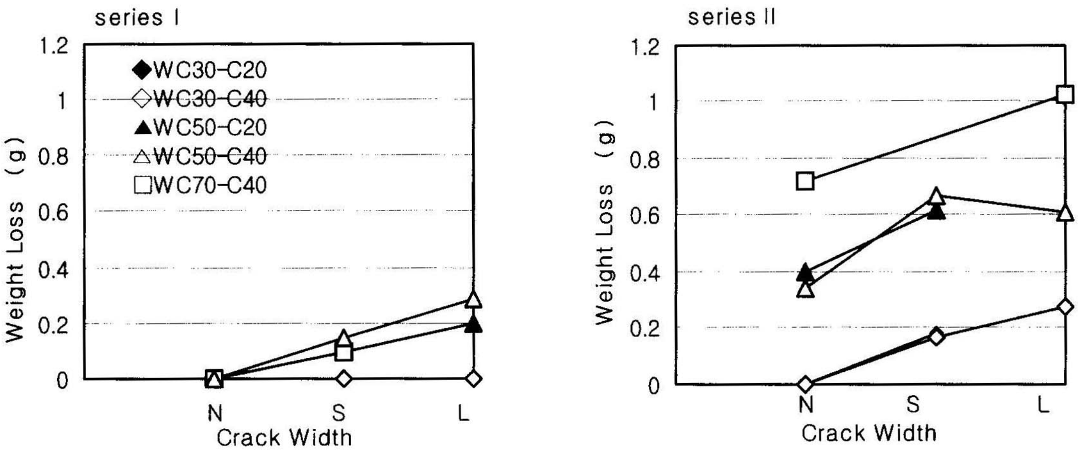

Fig. 5. Relationship between the weight loss and the crack width

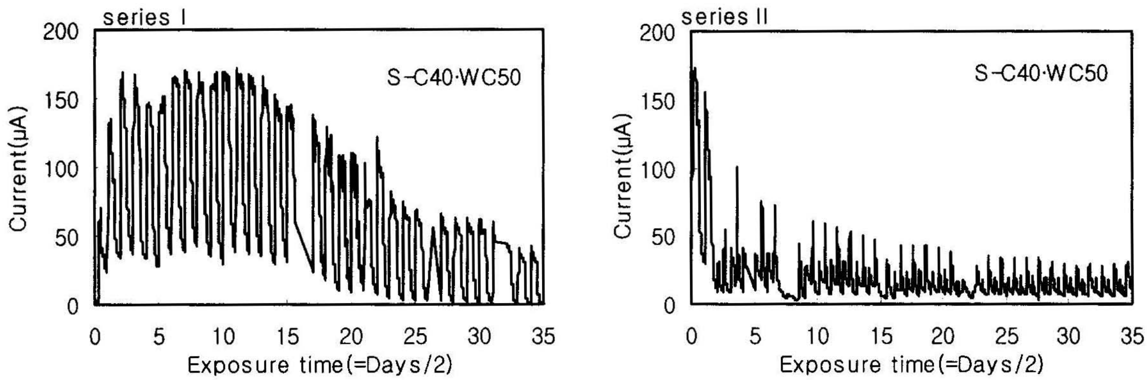

Fig. 6. Current-Time curves

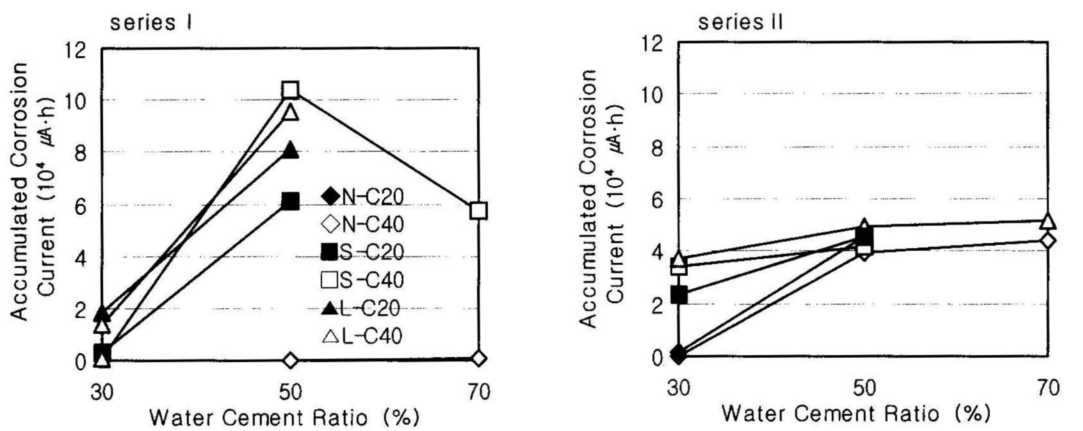

Fig. 7. Relationship between the W/C and the accumulated corrosion current

while a higher W/C tends to lead to macrocell formation.[5] In the present tests as well, the effect of microcells on reinforcement corrosion is considered to become stronger as the W/C increases in carbonated concrete.

Fig. 8 shows the relationship between the accumulated corrosion current and the weight loss. The accumulated corrosion current is greater in series I than in series II, whereas the weight loss is greater in series II than in series I. As stated above, this can be attributed to microcell corrosion in series II, which cannot be detected by the macrocell corrosion current.

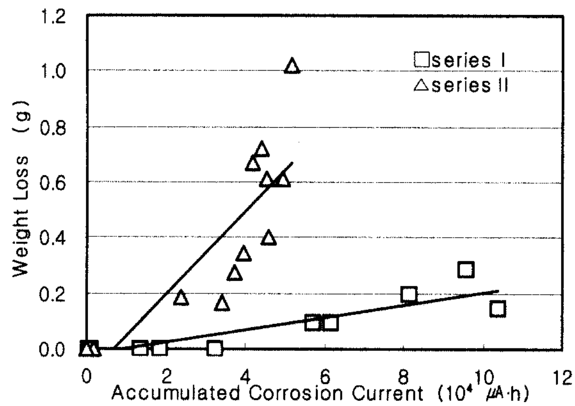

Fig. 8. Relationship between the accumulated corrosion current and the weight loss.

4. Conclusions

Accelerated corrosion tests were conducted on reinforced concrete specimens with and without accelerated carbonation, with the parameters being W/C, presence/absence and width of cracking, and cover depth. The results are summarized as follows:

(1) The amount of reinforcement corrosion tends to increase as the W/C increases. The amount of reinforcement corrosion in substantially carbonated concrete is significantly greater than that in uncarbonated concrete.

(2) The effect of crack width on corrosion is significant in specimens with uncarbonated concrete. On the other hand, the effect of crack width is marginal in specimens with substantially carbonated concrete, but the presence/absence of cracking strongly affects reinforcement corrosion. When the concrete around the reinforcement is completely carbonated, the effect of the presence/absence of cracking also tends to be weakened.

(3) The weight loss of reinforcement by corrosion was greater in specimens subjected to accelerated carbonation than in uncarbonated concrete. Conversely, the accumulated corrosion current of reinforcement in carbonated concrete was smaller than in uncarbonated concrete. This indicates that microcell corrosion prevails in carbonated concrete over macrocell corrosion. This tendency is more evident in concrete with a higher W/C.

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