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Condition Assessment of Reinforced Concrete Beams Relative to Reinforcement Corrosion

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Abstract

The main aim of this paper is to evaluate the corrosion condition of reinforced concrete (RC) beams and to assess the structural behavior of corroded reinforced concrete beams. Thirty two beams were tested, of which 16 had predetermined cracks. An impressed current was applied to the beams in order to accelerate steel corrosion. Electrochemical measurements were carried out to obtain open circuit potentials and corrosion rates of the embedded steels and loading tests were conducted on the beams to measure the ultimate moment. Test results show that there existed a fair relationship between the loading capacity reduction and the corrosion condition of the RC beams. © 1997 Elsevier Science Ltd.

Keywords: Condition assessment, reinforcement corrosion, concrete beams. electrochemical test, corrosion thickness, load capacity.

INTRODUCTION

Reinforced concrete is one of the most durable construction materials. However, the presence of soluble chlorides from deicing salts or marine exposure can destroy the passive oxide film around the steel and induce corrosion of reinforcement.[1] The primary cause of the deterioration of reinforced concrete members is corrosion of reinforcing steel. Corrosion of reinforcing steel may affect structural response and is the major cause of the deterioration of reinforced concrete members.[2] Billions of dollars have been spent to repair damage to highway bridges and the cost is increasing at the rate of $500 million per year.[3]

Corrosion damage to metals in concrete is usually evaluated using the half-cell method,[4] DC polarization method, or AC impedance method. The half-cell potential method, which can obtain the potential contours, can only indicate the corrosion probability, but not the corrosion rate.[5] The DC polarization method does not consider the IR drop effect, so the corrosion rate may be under-estimated.[6] Theoretically, the AC impedance method is more precise in estimating the corrosion rate of reinforced concrete members compared to other methods. However, in corrosion detection in RC members, use of the electrochemical method is relatively new. The slow development of techniques for assessing the condition of concrete members is due to the complexity of concrete material. Further, there is still a need to standardize the testing procedure in order to develop rational strategies for rehabilitation of concrete components. It has been a difficult task to predict the behavior and performance of concrete structures subject to corrosion damage. Damage resulting from corrosion of steel includes delamination, the reduction of steel areas, cracking, debonding between rebar and concrete, and spalling.[7] Thus, the loading capacity and stiffness of an RC component may deteriorate or failure of an RC structure may occur.

A preferable criterion for rehabilitation depends on a reliable evaluation of the structural integrity of concrete members. In this study, an effort was made to correlate the structural performance (represented by the ultimate moment and stiffness) with the corrosion condition of reinforcement. The objective of this study was to provide a possible approach for detecting damage resulting from corrosion of steel in concrete. The experiments involved electrochemical tests and loading tests to determine whether the structural capacity could be related to corrosion rates, to half-cell potentials, or to loss of steel thickness.

EXPERIMENTAL DETAILS

Tests were conducted in the NTOU (National Taiwan Ocean University) material laboratory using modeled reinforced concrete beams with dimensions of 150 × 150 × 500 cm. A total of 32 beams and 48 $150\phi \times 300$ cm cylinders were cast. The designation and concrete mix proportion were as listed in Table 1.

The first letter represents the mix design and the second letter represents the beam surface conditions (*S* for beams without cracks, *K* for beams with a middle surface crack 150 cm(L) × 1 mm(W) × 10 cm(D)). All the specimens were demolded 24 h after casting and cured in water for 28 days. Two #4(12.7 mmϕ) rebars were cast in the RC beams with an epoxy resin coating at both ends as shown in Fig. 1.

After, the curing process, all the specimens were immersed in artificial sea water. Then, to accelerate the corrosion process, an impressed current (5 A/mm^2) was applied to the specimen using a DC power supply. Strain gauges were mounted on the top and bottom surfaces. A potentiostat/galvanostat (NP-G100/ED) was used to measure the open circuit potentia-l(OCP) and to obtain the DC polarization current. The AC impedance was obtained using an impedance spectroscopy and a potentiostat was used to obtain the corrosion rates. Details of the corrosion measurements are shown in Fig. 2.

All the specimens were loaded in the middle after completing the corrosion and crack measurements by using a 100 ton universal testing machine. The middle deflection and surface strains were recorded during the tests. The beams were simply supported at both ends. The failure modes were observed and analyzed. Once every 16 h, the impressed current was cut off and the OCP values, DC polarization resistance and AC impedance were sequentially measured for each specimen 1 h after current cut-off. After the electrochemical measure-

Table 1. Concrete mix design (kg/m^3)

Designation	*w/c ratio*	*Water*	*Cement*	*F.A.*	*C.A.*	*S.P.*
AS	0.4	180	450	733	1011	4.95
AK	0.4	180	450	733	1011	4.95
BS	0.3	156	520	738	1011	8.84
BK	0.3	156	520	738	1011	8.84

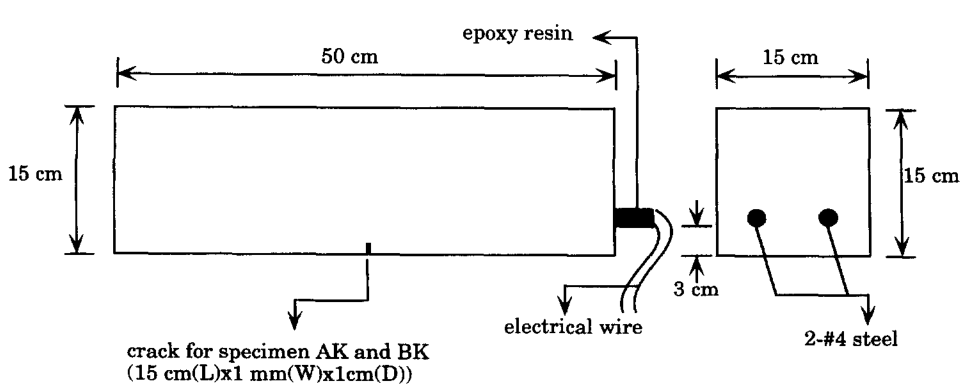

Fig. 1. Beam specimen.

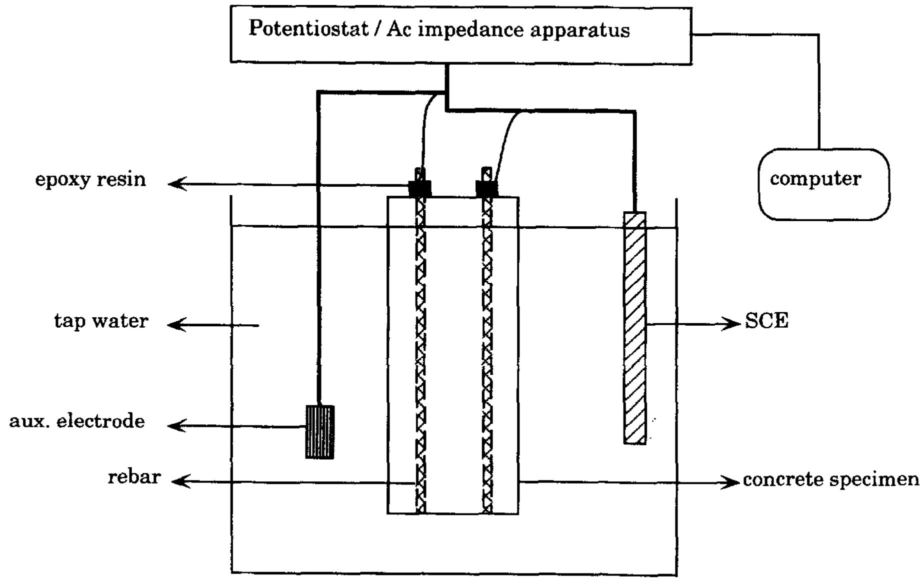

Fig. 2. Corrosion test set-up.

ments were made, the specimens were removed from the tanks, and a loading test was conducted.

RESULTS AND DISCUSSION

Concrete strength

For each mix, three cylindrical specimens were tested at various ages. The compressive strength development curves are shown in Fig. 3. The 28 day compressive strength was about 50 MPa for mix A and 67 MPa for mix B.

OCP values vs. Immersion time

Open circuit potentials (OCP) represent the thermodynamic trend of steel corrosion. It has been suggested by ASTM C867-91[8] that the corrosion probability is less than 10% when OCP is higher than −200 mV Cu/$CuSO_4$ (−120 mV, SCE) and higher than 90% when OCP is lower than −350 mV Cu/$CuSO_4$ (−270 mV, SCE). The OCP values vs immersion time for each group are illustrated in Figs 4 and 5. Test results show that the OCP values of cracked beams dropped faster than did those of intact beams. This is because the chloride ions, oxygen and water more easily penetrated the cracked beams. Crackings were observed in almost all the beams after the 108 h accelerated corrosion process and the water/cement ratio of the concrete was no longer the major factor controlling rebar corrosion. Tensile failure resulting from the expansive reaction products

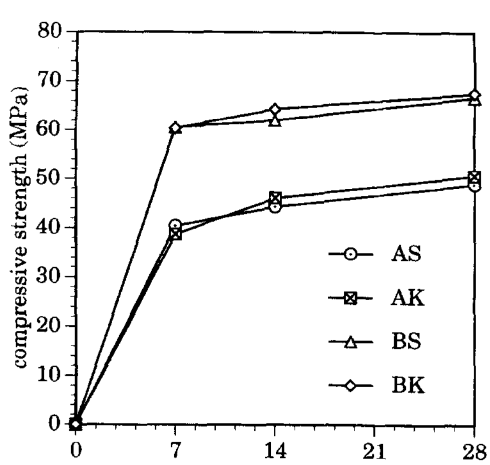

Fig. 3. Compressive strength development curves.

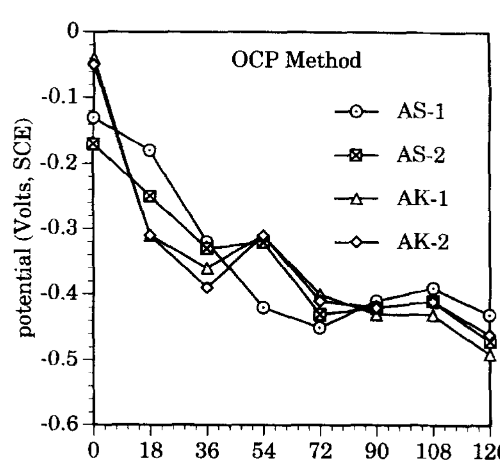

Fig. 4. Open circuit potential vs time curves (AS and AK).

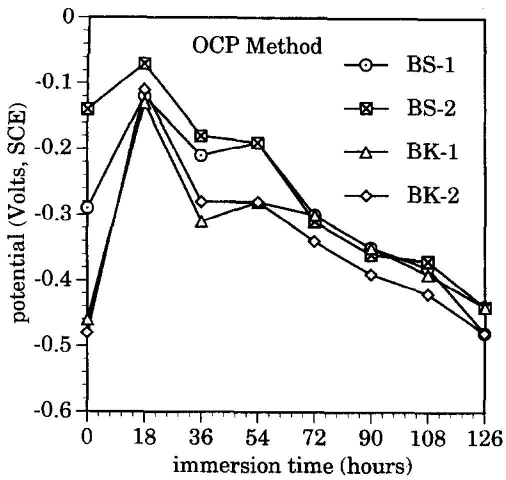

Fig. 5. Open circuit potential vs time curves (BS and BK).

from the corrosion of steel in concrete was recorded.

Corrosion rates and rebar thickness loss

With either the DC linear polarization method or the AC impedance method, the polarization resistance, Rp, can be measured. The corrosion current density, i_{corr} (Amp/cm^2), can be expressed as follows.

$$i_{corr} = \left[\frac{\beta a \beta b}{2.303(\beta a + \beta b)}\right] = B \times \frac{1}{Rp}.$$

This formula is called the Stern–Geary equation.[9] βa and βb represent the Tafel's slopes of the anodic polarization curve and the cathodic polarization curve, respectively. The value of B is often taken to be 26 mV[10] for steels in an alkaline environment (the pH value for a concrete environment is above 12.8). After the corrosion current density is obtained, the instantaneous corrosion rate can be calculated from Faraday's law as follows.

$$\Gamma_{corr} = \frac{i_{corr}}{n\mathrm{F}} \times \frac{W_{Fe}}{D_{Fe}}.$$

In the above equation, Γ_{corr} (cm/s) represents the thickness loss of the steel per unit of time and corrosion engineers sometimes choose mpy (mils per year) or μm/year as the unit of Γ_{corr}. F is the Faraday's constant, which is 96,500 Coulomb/mole and n is the valence of the oxidant for the following oxidation reaction:

$$Fe^{2+} + 2e^- \rightarrow Fe$$

Thus, n is equal to 2. W_{Fe} (55.8 g/mole) is the atomic weight of the steel and D_{Fe} (7.86 g/cm^3) is the density of the steel. The instantaneous corrosion rates versus the immersion time from the DC linear polarization method and the AC impedance method are plotted in Figs 6 and 7, respectively. The equivalent rebar thickness loss can be obtained by integrating the area of the instantaneous corrosion rate vs time curve. The reason for using corrosion thickness loss as a corrosion index is explained as follows. During the corrosion process, the corrosion product itself will become a passive film such that the corrosion rate will slow down and the corrosion open circuit potential will become nobler. Therefore, neither the instantaneous corrosion rate nor the open circuit potential is a monotonically increasing function with respect to time. However, corrosion thickness loss is a monotonically increasing function with respect to time. If one makes a judgment about whether or not the rebar is corroded based on the instantaneous corrosion rate or open circuit potential, an inaccurate conclusion may be drawn. It has been suggested[11] that one should use the long-term trend of the instantaneous corrosion rate and OCP values to make a judgment. A record of electrochemical measurements is necessary. It seems that the corrosion thickness index can help us make a decision according to the current value; however, while corrosion thickness is obtained from the record of corrosion rate measurements, the current corrosion thickness is obtained by integrating the entire area below the corrosion rate vs time curve.

Corrosion thickness loss vs stiffness and ultimate loads of RC beams

The load-middle deflection relationships of the beams were observed in the loading tests. The stiffness was determined by the slope of the load–deflection curves for each tested beam. The corrosion thickness vs stiffness curves are presented in Figs 8(a) and 9(a) for group A specimens and group B specimens, respectively. The figures show that the stiffness of the RC beams with lower water/cement ratio concrete or predetermined cracks decreased faster as the corrosion product increased. This was because the chloride ions could penetrate into the cracked beams easier than they could into those

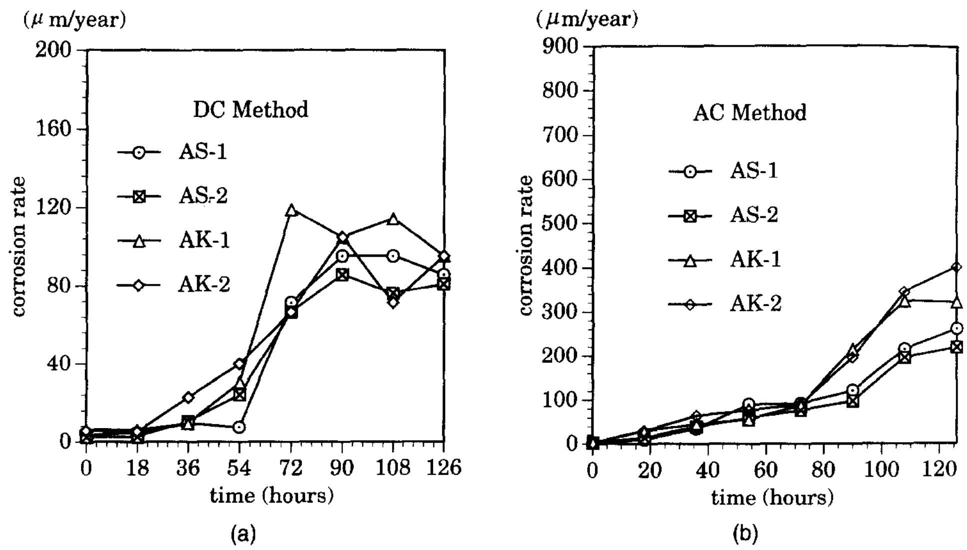

Fig. 6. Corrosion rate vs time curves (AS and AK).

without cracks. In addition, lower water/cement ratio concretes have smaller pores, which show lower energy-absorption capacity. Once cracks occur, the high strength concretes may fail faster than may low strength concretes. Figures. 8(b) and 9(b) show the relationship between the ultimate moments and corrosion thickness for each specimen. It appears that the loading capacity of a RC beam decreased as the corrosion product increased. This phenomenon was more significant in the beams with low water/cement ratios or predetermined cracks. This means that corrosion damage was more crucial in high strength concrete beams or defected beams.

General discussion

By using linear regression on the testing data, the slopes of the curves could be obtained. The descending slopes indicate a reduction of the loading capacity of the corroded RC beams. Steeper slopes reflect a larger reduction of the stiffnesses or ultimate loading capacity of the RC beams. The percentage of the reduction of loading capacity or of the stiffness of an RC beam subject to corrosion could be approximated by the calculated thickness loss of rebar. In this study, an effort was made to correlate the relationship. Based on the testing data, it appears that for a 10% reduction in the loading

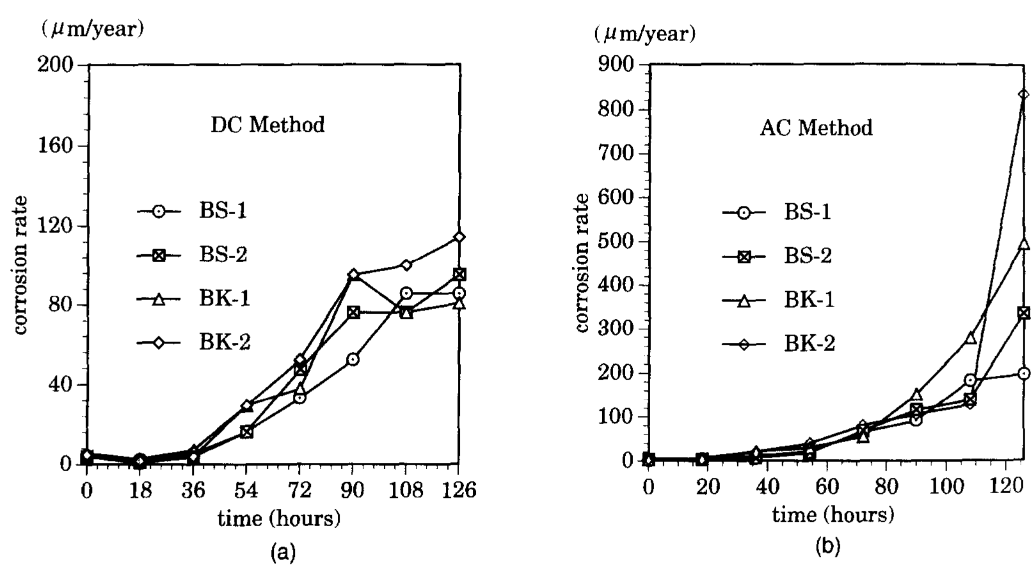

Fig. 7. Corrosion rate vs time curves (BS and BK).

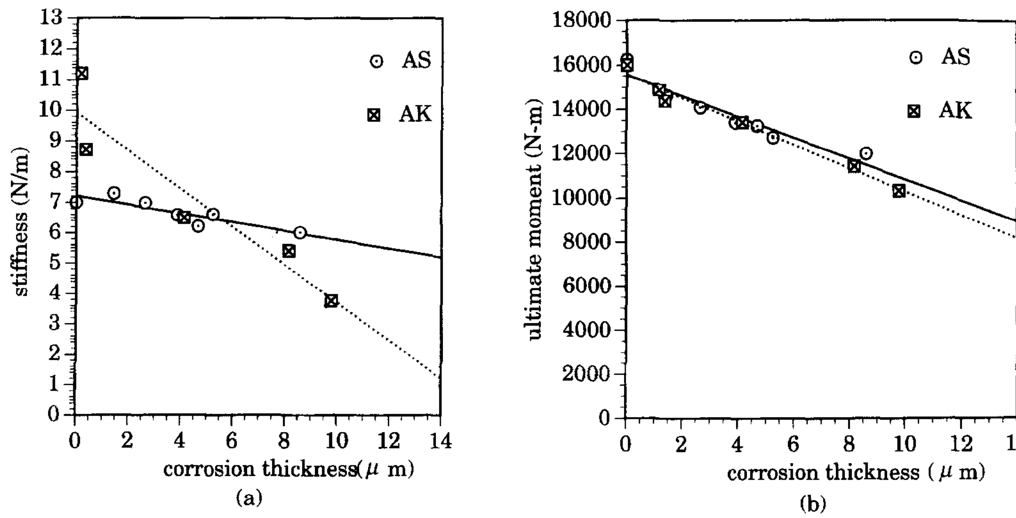

Fig. 8. (a) Corrosion thickness vs stiffness; (b) corrosion thickness vs ultimate moment (AS and AK).

capacity of an RC beam, the calculated thickness loss of the steel was about 1.44 μm for group AS, 1.16 μm for group AK, 0.7 μm for group BS, and 0.2 μm for group BK, respectively. Comparing the steel thickness loss with the reduction of the stiffness or loading of the capacity of the RC beams, it appears that a small thickness loss may cause a significant reduction of loading capacity for higher strength concrete beams or defected beams. It can be concluded that RC beams with high strength concrete or with existing cracks are more susceptible to corrosion damage.

CONCLUSIONS

Based on the experimental results presented in the paper, the following conclusions can be drawn.

(1) The electrochemical test method can be used for rapid determination of steel corrosion in concrete.
(2) The corrosion thickness (or the thickness loss of the steel) can be obtained by integrating the entire area below the curve of the corrosion rate vs time curve. It is a good index for quantifying the continuous corrosion effect.
(3) The reduction of the loading capacity of an RC beam has been found to have a fair relationship with the electrochemical parameters in accelerated corrosion experiments.
(4) The corrosion thickness can provide information about the structural damage of RC beams. The corrosion thickness determined in this study can be used as a quality parameter for evaluating the loading capacity of RC beams.

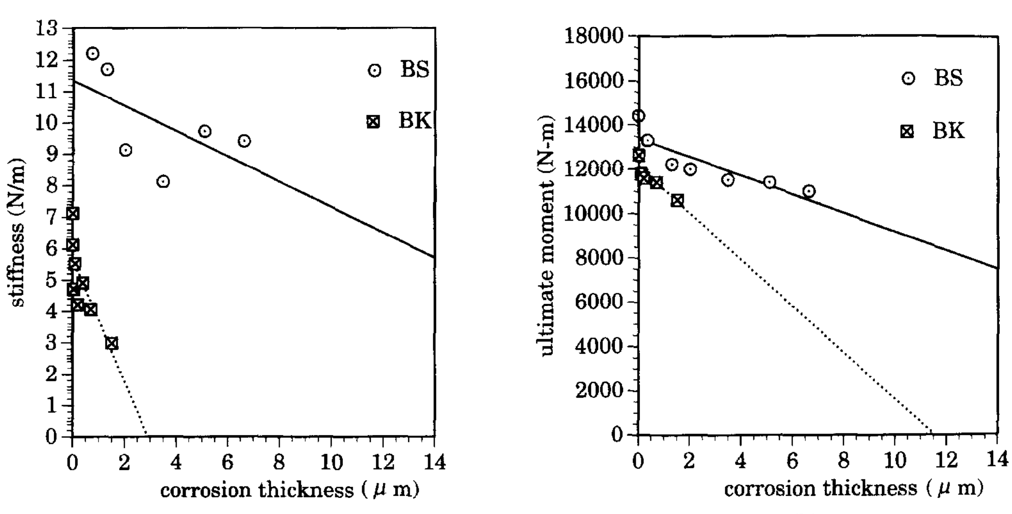

Fig. 9. (a) Corrosion thickness vs stiffness; (b) corrosion thickness vs ultimate moment (BS and BK).

(5) The reduction percentage of the ultimate load and stiffness of an RC beam subject to corrosion was dependent on the concrete quality and predetermined cracks. When the corrosion thickness was below 0.4 μm, there was no significant development of cracks. However, when the corrosion thickness was above 1.76 μm, many visible cracks were found on the specimen and a significant reduction of stiffness would affect the structural response of RC beams.

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