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Durability of cracked reinforced concrete beams in chloride environment

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ABSTRACT: The aim of this paper is to evaluate the corrosion activity of cracked flexural reinforced concrete elements in marine environment. When a crack occurs in cover concrete, steel corrosion may be initiated or accelerated because chloride ions can reach the rebar surface more quickly. Therefore, the effect of cracking on the service-life prediction of RC structures should be taken into account. In this paper, some of nondestructive test results of a comprehensive research project are presented and discussed. In this regard, corrosion activity of several small cracked reinforced concrete beams under sustained loading, which are located in tidal zone of a field exposure station in the Persian Gulf region, are assessed using three nondestructive testing techniques. The 5-month and 9-month results of the project are presented in this study. The results show that corrosion of steel reinforcement under the cracks becomes more severe by increasing crack width to cover ratio. Moreover, the corrosion was less active after 9 months of exposure compared to 5 months of exposure because of higher concrete resistivity and lower ambient temperature at the later age. Furthermore, the corrosion current density and electrical resistivity values were more sensitive to the distance of testing point to the crack point compared to the half-cell values.

1 INTRODUCTION

In marine areas, chloride penetration into reinforced concrete is the most dominant cause of rebar corrosion. In this field, most of the studies have been performed on non-cracked concrete. However, it is almost impossible to produce crack-free concrete. When a crack occurs in cover concrete, steel corrosion may be initiated or accelerated because chloride ions can reach the rebar surface more quickly. Therefore, the effect of cracking on the service-life prediction of RC structures should be taken into account.

In this paper, some of nondestructive test (NDT) results of a comprehensive research project, which is conducted by Amirkabir University of Technology and Road, Housing & Urban Development Research Center to study the durability of cracked reinforced concrete, are presented. In this project, several small cracked reinforced concrete (RC) beams under sustained loading with 0.5 m length and six large RC beams with the length of 5 m were made. Some of the small beams and all the large beams were located in tidal zone of a field exposure station in the Persian Gulf region and the rest of small beams were situated in a chamber which has facilities to simulate the conditions of real chloride exposure. The parameters which have been considered to be investigated in this project include crack width, cover thickness, water to cementitious materials ratio and replacement level of silica fume.

2 EXPERIMENTAL PROCUDURE

2.1 Test specimens

In this project, some of the specimens are 50 cm concrete prisms (small beams) reinforced with single ϕ10 steel bar with different concrete covers. Four factors are investigated: 1) prisms with crack and without crack; 2) two binder types (plain portland cement and portland + silica fume); 3) three concrete covers (30, 50 and 75mm); 4) crack width ranging from 0.08 to 0.47mm. For this purpose, totally, 24 small beams were made.

In table 1and Table 2, the chemical compositions of the binders and concrete mixture proportions are presented. As can be seen in Table 2, two different concrete mixtures were made. In the first mixture, plain portland cement was used as binder and in the second one, silica fume was used to replace 7.5% by weight of portland cement. The cementitious materials (cm) and water to cementitious materials ratio (w/cm) were kept constant at 400 kg/m^3 and 0.4 for both concrete mixtures. These amounts are typical for concrete mixtures of coastal reinforced concrete structures constructed in the Persian Gulf region, south of Iran.

Table 1. Chemical properties of binderes

Oxide composition (%by mass)								
SiO_2	Al_2O_3	Fe_2O3	CaO	SO_3	MgO	Na_2O	K_2O	Loss on ignition
21.4	5.25	4.0	62.2	1.5	2.0	.35	.75	2.2
93.2	1.1	0.7	0	0.05	1.6	0	0	1.6

Table 2. Concretes mixture proportions and slumps

	Mixture proportions (kg/m^3)									
	Cement	SF	Water	Sand	Gravel	Supperplasticizer	Air (%)	SF replacement level (%)	w/cm	Slump (cm)
Control	400	-	160	1024	689	2	2.7	0	0.4	14
SF	370	30	160	1027	692	3.2	2.9	7.5	0.4	14

All the specimens were cured in water for 28 days and remained in atmosphere for one month. Then, all the faces of the small beams were coated with epoxy leaving only one face in tension uncoated. The small beams were cracked at mid-span applying three-point loading. The prisms were paired and loaded back-to-back using stainless steel frames. Bolts of the frames were tightened to achieve the desired crack widths. In Figure 1, a coupled small beams loaded with stainless steel frame can be seen.

The small beams were located in tidal zone of the Persian Gulf as illustrated in Figure2. It should be added that six large-scaled beams with length of 5 m have been also made in this project and put in the tidal zone (Figure 3). The obtained results of the large beams will be presented in future papers.

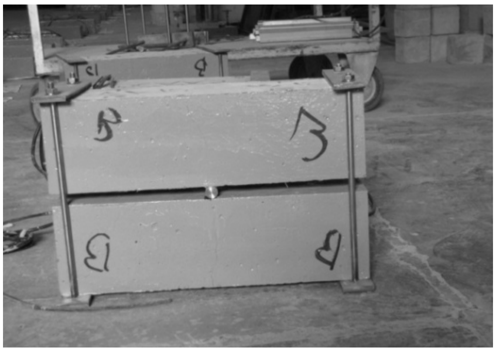


Figure 1.Coupled small beams.

Figure 2.Small beams located in tidal zone of the field exposure station.

Figure 3.Large beams located in tidal zone of the field exposure station.

2.2 *Testing methods*

To assess the corrosion, three NDT techniques including galvanostatic pulse, concrete resistivity, and half-cell potential measurements were used. The galvnostatic pulse method was used to rapidly measure the corrosion current density (i_{corr}) of steel bar in RC elements. The electrical resistivity of the specimens was measured with a four-probe (Wenner) apparatus. Half-cell potential method was utilized to detect the potential for steel reinforcement corrosion. The reference electrode used in this experiment was a copper-copper sulfate electrode.

The NDTs are conducted periodically on the beams. As shown in Figure 4, the NDT measurements are performed on the cracks (point b) and on points a and b which are 150mm away from the crack.

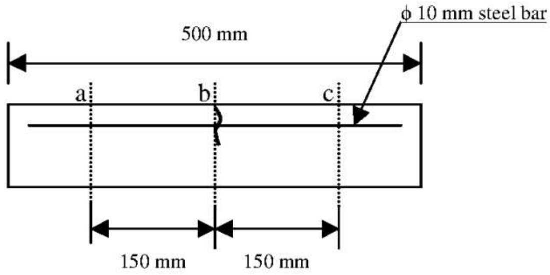


Figure 4. Location of the NDT measurements.

3 RESULTS AND DISCUSSION

In Figures 5-7, the effect of crack width to cover ratio (W_{cr}/C) on the three NDT results have been shown for exposure periods of 5 months and 9. As can be seen in these figures, corrosion current density, i_{corr} increases and electrical resistivity and half-cell potential decrease with higher W_{cr}/C. In other words, corrosion of steel reinforcement becomes more severe by increasing W_{cr}/C.

According to Faraday's Law of electrochemical equivalence, the corrosion current density, i_{corr} can be directly related to section loss (corrosion rate) of steel reinforcement, where 1 μA/cm^2 equals to 11.5 μm/year (equation 1) (Broomfield (1997)). Therefore, increasing *Wcr/C* leads to faster section loss of reinforcement under cracks and hence faster structural deterioration of reinforced concrete structures. As shown in Figure 5, relatively good direct linear relationships exist between *Wcr/C* and i_{corr}.

$$corrosion\, rate = \; 11.5 \times i_{corr} \tag{1}$$

According to various studies, electrical resistivity of concrete can be used to indirectly evaluate the corrosion activity and hence predict the service life of reinforced concrete structures (Andrade & Gonzalez (1998), and Otieno et al. (2010)). Some studies have shown that the corrosion rate is inversely proportional to resistivity of uncracked concrete (Otieno et al. (2010)). However, no generally accepted rules exist for relating concrete resistivity to the corrosion rate. Similar to previous studies, the obtained results in this study indicate that resistivity of cracked concrete is inversely related to corrosion rate (compare Figures 5 and 6).

Half-cell test method is widely used for the detection of the corrosion potential for steel reinforcement embedded in concrete. It should be noted that there is no general correlation between the corrosion rate and half-cell potential, because these two parameters are differently depended on variables, particularly moisture (or oxygen availability), temperature, and concrete resistivity (Otieno et al. (2010)). However, similar to corrosion current density and electrical resistivity results, half-cell potential results show that the corrosion of steel bar reinforcement become more severe with increasing W_{cr}.

By comparing the 5-month and 9-month NDT results, it is found that the corrosion is less intense after nine months of exposure in both concrete mixtures (Figures 5-7). Lower corrosion density, higher electrical resistivity and lower negative half-cell values have been obtained after nine months of exposure in sea water. Two reasons can be proposed for justifying this phenomenon.

Firstly, the resistivity of the concrete mixtures have been increased with time, which is attributed to ongoing hydration and hence a reduction in pore solution conductivity and additional microstructure densification. As can be seen in Figure 6, the electrical resistivity of uncracked beams (W_{cr}/C=0) have been increased for both control an SF mixtures. Due to pozzolanic reaction, this improvement with time is more considerable for the SF mixture. This has been also observed in other works (Ahmadi & Shekarchi (2010)). The resistivity of concrete has a significant effect on the rate of corrosion of embedded reinforcing steel after the break down of passivity. Generally, the larger the electrical resistivity of electrolyte of corrosion cell (in this case concrete), the smaller the corrosion rate of reinforcement will be (Cusson et al. (2006), and Broomfield (1997)).

Secondly, the 5-month and 9-month measurements were performed in summer with ambient temperature of 40ºC and winter with ambient temperature of 26ºC, respectively. Temperature affects the corrosion rate directly. The rate of the oxidation reaction is influenced by the amount of heat energy. The concrete resistivity also reduces with increased temperature because ions become more mobile in the pore solution and salts become more soluble (Broomfield (1997)).

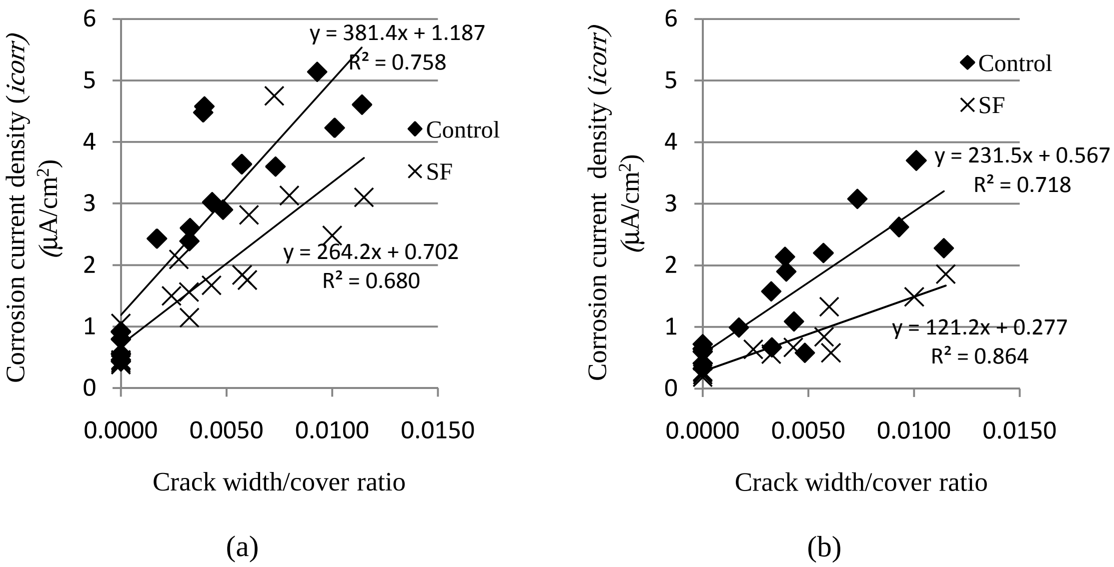
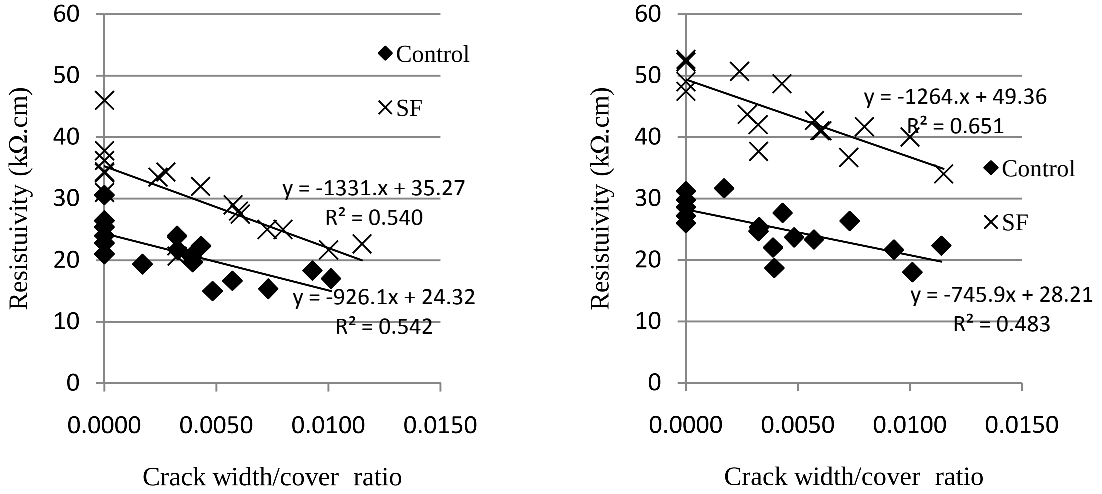
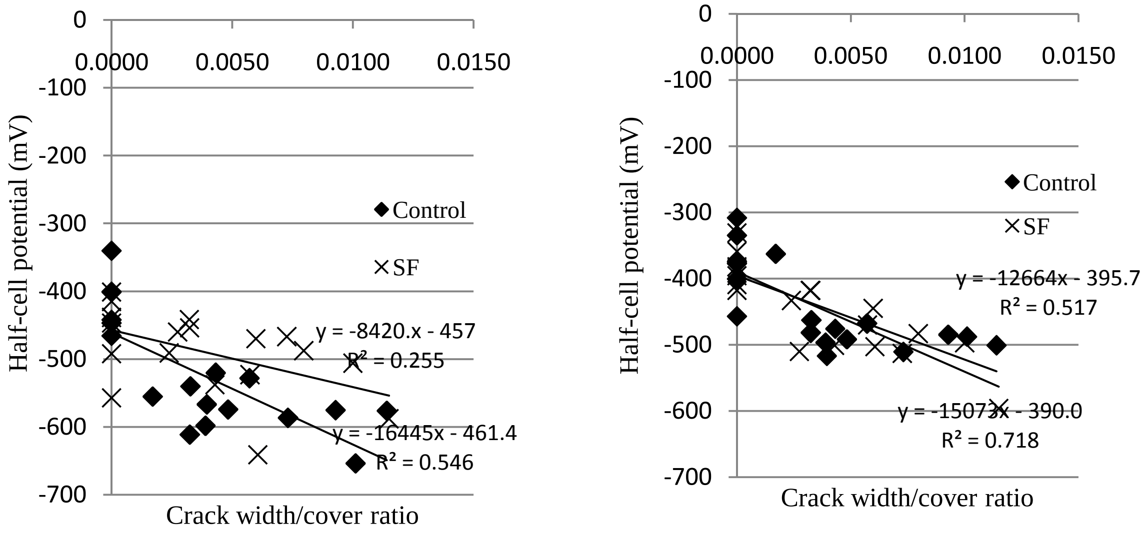


Figure 5.Relationship between corrosion current density and W_{cr}/C: (a) 5-month exposure and (b) 9-month exposure.



(a) (b)

Figure 6. Relationship between electrical resistivity and W_{cr}/C: (a) 5-month exposure and (b) 9-month exposure.



(a) (b)

Figure 7. Relationship between half-cell potential and W_{cr}/C: (a) 5-month exposure and (b) 9-month exposure.

The effect of measurement location on NDT results have been shown in Figures 8 As can be seen in this figures, the corrosion current density and electrical resistivity values are considerably different on the crack location with adjacent points (points a and c in Figure 4). While, there is no significant difference between half-cell values obtained on the crack with the adjacent points. Similar trend was also observed for the other small beams. Therefore, it can be concluded that the corrosion current density and electrical resistivity results are more sensitive to the distance of testing point to the crack point compared to the half-cell results. Accordingly, conducting only half-cell might not be appropriate for evaluating the corrosion condition of steel bars under cracks and it should be accompanied by other NDT techniques for better interpretation.

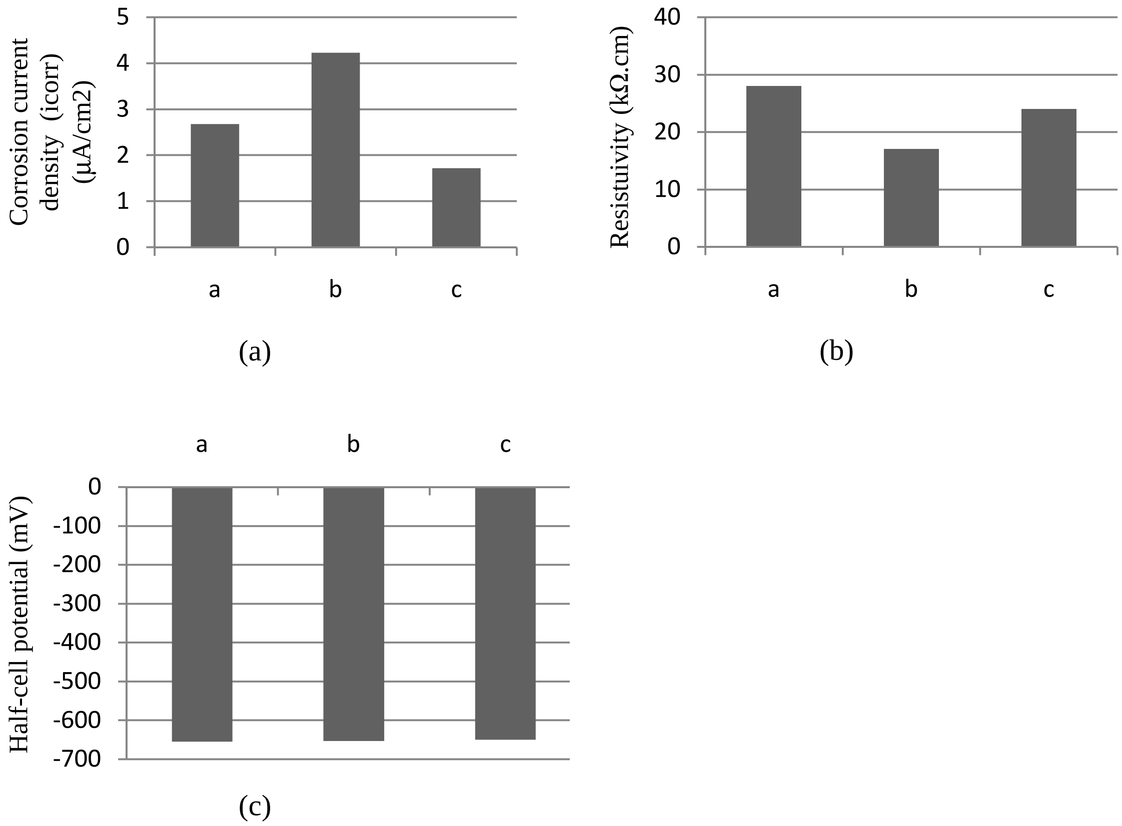


Figure 8.Effect of measurement location on NDT results: (a) corrosion current density, (b) electrical resistivity and (c) half-cell potential (binder: plain portland cement, crack width: 0.31mm, cover: 30mm, exposure duration: 5 months)

4 CONCLUSUINS

The main conclusions of this study about NDTs performed on cracked reinforced concrete beams to evaluate the corrosion of steel reinforcement are as follows:

- Corrosion current density, i_{corr} increases and electrical resistivity and half-cell potential decrease with higher crack width to cover ratio. Thus, corrosion of steel reinforcement becomes more severe by increasing crack width to cover ratio.
- The corrosion rate is inversely related to the electrical resistivity on the crack location. Therefore, electrical resistivity can be used to indirectly evaluate the corrosion activity of steel reinforcement under crack.
- By comparing the 5-month and 9-month NDT results, it is found that the corrosion is less intense after nine months of exposure in both concrete mixtures (Figures 5-7).

Lower corrosion density, higher electrical resistivity and lower negative half-cell values have been obtained after nine months of exposure in sea water. Two reasons can be proposed for justifying this phenomenon.

- Corrosion was less active on crack location after 9-month exposure in the tidal zone compared to 5-month exposure as electrical resistivity of the concrete increased with time due to ongoing hydration of the cementitious materials and the ambient temperature at 9 months was far less than the ambient temperature at 5 months.
- The corrosion current density and electrical resistivity values were more sensitive to the distance of testing point to the crack point compared to the half-cell values. Hence, half-cell test should be accompanied by other NDTs for better evaluation of steel corrosion under crack.

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