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Communication

Oxygen permeability in cracked concrete reinforced with plain and deformed bars

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Abstract

Deformed bars are commonly used as reinforcing bars because of its good bonding ability compared to plain (smooth or round) bars. However, only a few studies were carried out comparing the corrosion performance of plain and deformed bars. With this background, the authors carried out detailed investigations on the corrosion of plain and deformed bars. Here, the results of oxygen permeability of multicracked concrete beams reinforced with plain and deformed bars are presented. For this, reinforced concrete beams of size $150 \times 150 \times 1250$ mm were made with plain and deformed bars separately. In each beam, a steel bar specially made with segmented steel elements was embedded to measure the distribution of oxygen permeability along the beam after cracking. The cracking load was kept the same for the beams. W/C was 0.5. It was found that the oxygen permeability of cracked concrete reinforced with deformed bars is significantly higher than one reinforced with plain bars. The results indicate that deformed bars are more prone to corrosion than plain bars in cracked concrete.

Keywords: Corrosion; Oxygen permeability; Plain and deformed bars

1. Introduction

Deformed bars are commonly used to reinforce concrete structures because of its good bonding capability compared to plain bars. However, only a few studies were carried out comparing the corrosion performance of plain and deformed bars. A cracked beam with deformed bars has more number of cracks compared to a cracked beam with plain bars [1]. In addition, microcracking in concrete for a beam with deformed bars is much more than that of a beam with plain bars [2]. These characteristics will certainly influence the corrosion process of steel bars in concrete. In one study, it was reported that limiting the crack frequency rather than the crack width is more important in order to reduce the corrosion rate of steel bars in concrete [3]. As the beam with deformed bars has a greater number of cracks, therefore, it seems to be more prone to corrosion compared to plain bars. With this background, a study on the corrosion performance of plain and deformed bars was carried out and reported elsewhere [1]. In Ref. [1], oxygen permeability in single-cracked mortar specimens was also reported. It was understood that further investigation on the oxygen permeability of cracked concrete made with plain and deformed bars is still necessary. Therefore, the investigation on the oxygen permeability of multicracked concrete beams was carried out and reported here.

It is found that the oxygen permeability of cracked concrete reinforced with deformed bars is about five times higher than the same with plain bars. The results with the combination of the previous studies [1] support that deformed bars are more prone to corrosion than plain bars in cracked concrete.

2. Experimental plan and evaluation method

2.1. Materials

Cement Association of Japan (CAJ) research cement was used. The physical properties and chemical compositions are listed in Table 1.

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Table 1
Physical properties and chemical compositions of cement

Physical properties		Chemical compositions (%)	
Specific gravity	3.17	SiO_2	21.3
Blaine fineness	3270 cm^2/g	Al_2O_3	5.3
Ignition loss	0.6%	CaO	64.4
		MgO	2.2
		SO_3	1.9
		Na_2O	0.28
		K_2O	0.6
		TiO_2	0.37
		MnO	0.1
		Fe_2O_3	2.6
		P_2O_3	0.2
		C	0.01
		S	0.0

Table 3
Mixture proportioning of concrete

Items	W/C = 0.5
G_{max}, mm	20
Slump, cm	8 ± 2
Air, %	5 ± 1
W/C	0.50
s/a	45
W, kg/m^3	165
C, kg/m^3	330
S, kg/m^3	803
G, kg/m^3	988
AE, P-70, ml/m^3 [a]	743
AE, N-303, ml/m^3 [b]	13.2

[a] Air-entraining and water-reducing agent.
[b] Air-entraining agent.

River sand and crushed granite coarse aggregate were used. Specific gravity, absorption (%) and fineness modulus of sand were 2.62, 1.73 and 2.8, respectively. The values were 2.63, 0.68 and 6.68, respectively, for coarse aggregate.

Japanese Industrial Standard (JIS) hot-rolled plain and deformed steel bars (yield strength = 3000 kgf/cm^2) were used. Chemical compositions of the bars are listed in Table 2. There was some difference in the chemical compositions of the steel bars. However, both satisfy the specifications provided by the JIS. To remove the black cover over the steel bars with less mechanical effort, the steel bars were immersed in a 10% diammonium hydrogen citrate solution for 24 h. Then the bars were polished with a steel wire brush manually. In this process, the black cover was removed very easily without any significant rise in temperature and scraping over the surface.

2.2. Specimen

The mixture proportioning of concrete is shown in Table 3. The slump of fresh concrete was 8 ± 2 cm and air content 5 ± 1%.

The details of the specimens are shown in Fig. 1. In the bottom face (tensile face), three steel bars were embedded. To measure the distribution of oxygen permeability of concrete over the steel bars, the middle steel bar was specially made with segmented steel elements of 5 cm length each. It is composed of 14 steel elements, which were joined with epoxy. Lead wires were connected with each steel element. The surface area of the deformed steel elements was measured by volume replacement method. The other steel bars were coated with epoxy in order to avoid any possible connections with the middle steel bar. The diameter of the bars was 13 mm. A titanium mesh was embedded in concrete at the cover concrete zone of the tensile face. This may cause changes in crack widths and microcracking pattern in concrete. However, in both of the beams reinforced with plain and deformed bars, the titanium mesh was embedded. The setup is supposed to be sufficient to compare the oxygen permeability in cracked concrete reinforced with plain and deformed bars. After casting, the beams were cured in the mold for 2 days at a relative humidity of about 80% and temperature of about 20°C. After that the specimens were demolded and stored under the wet jute bags for further curing in room of temperature of about 20°C. At the age of 30 days, the beams were cracked by bending tests. The maximum load was kept constant. At the maximum load, crack widths were checked by an optical microscope. The location of cracks and widths were recorded. After removing the load, the beams (one with deformed bars and one with plain bars) were anchored as shown in Fig. 2. The crack widths were controlled as in the bending tests. With this condition (keeping the cracks open), the oxygen permeability in concrete along the tensile face of the beam (over the 14 steel segments) was measured consecutively. One pair of the beam was only investigated due to the complicacy in making the specimens. However, in each beam electrically isolated 14 steel elements were embedded to measure the distribution of oxygen permeability over the tensile face. Oxygen permeability was measured at the 14 different locations of each beam. During the measurements of oxygen permeability over a particular steel segment, the steel segment was isolated from others.

Table 2
Chemical compositions of steel bars

Bars	C (%)	Si (%)	Mn (%)	P (%)	S (%)
Deformed	0.22	0.16	0.76	0.025	0.031
Plain	0.17	0.27	0.72	0.024	0.012

2.3. Evaluation method

The oxygen permeability was calculated by using the following equation [4]:

$$\frac{dQ}{dt} = -\frac{I_{lim}}{nF}$$

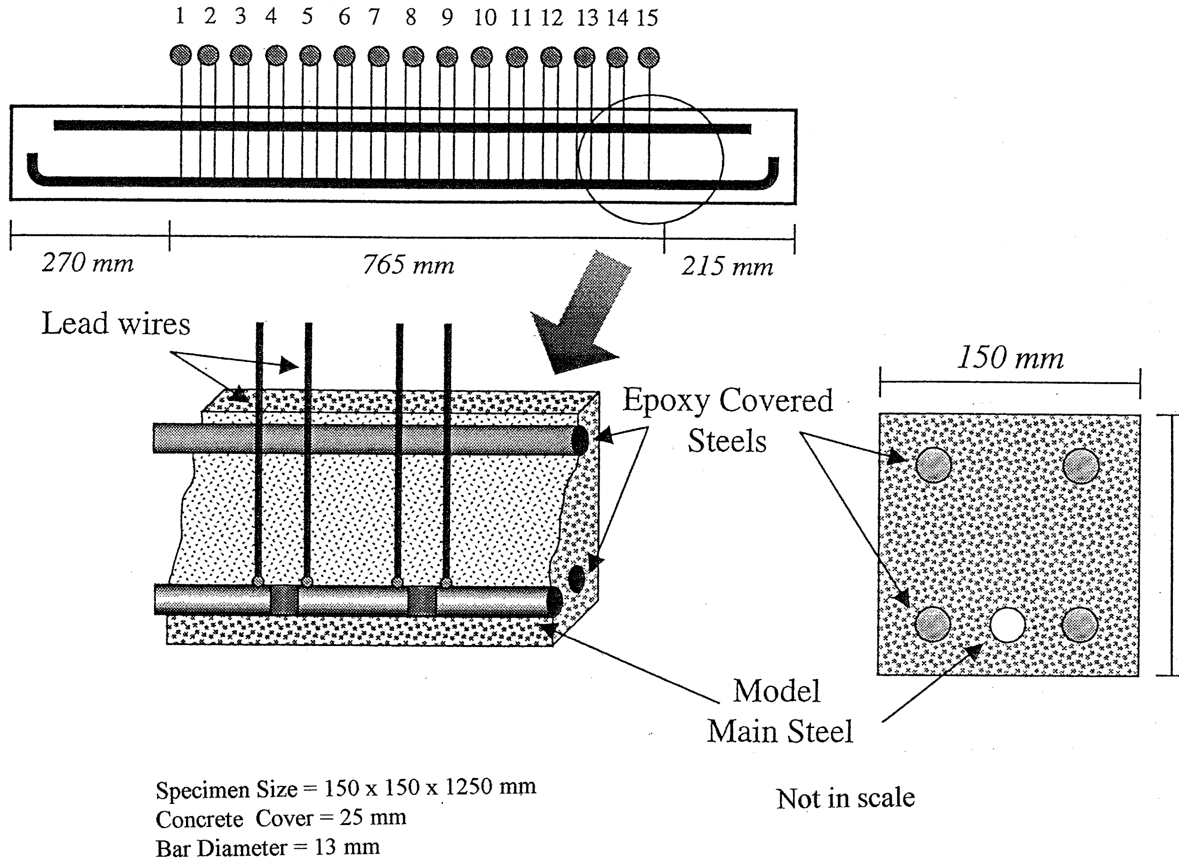

Fig. 1. Detailed layout of the specimens.

where, $(dQ)/(dt)$ is the oxygen permeability in mol/cm^2/s (on steel surface), $I_{\lim}$ is the limiting cathodic current density in A/cm^2, F is the Faraday's constant (96500 C/mol) and n is 4. The limiting cathodic current density was measured by potentiostat. The potential difference between the titanium mesh anode and steel segment was fixed at 860 mV. Fig. 3 shows the details of the measurement. It is already noted that during this measurement the steel elements under investigation were isolated from others to focus on the concrete over a particular steel element only.

3. Results

The crack maps of the beams together with the oxygen permeability in concrete are shown in Fig. 4. The maximum load was 4.5 tons for the beams with deformed and plain bars. The total numbers of crack of the beams with deformed and plain bars were 9 and 6, respectively. Maximum crack widths of the beams with deformed and plain bars were 0.2 and 0.4 mm, respectively. Large number of cracks and relatively narrower cracks for the beams with deformed bars were also reported in Ref. [1]. The oxygen permeability of concrete of the beam with deformed bars was about five times higher than one with plain bars. In the case of single cracked mortar specimens, it was found that the oxygen permeability at the cracked region is relatively higher than the uncracked region [1]. However, for the multicracked specimens, more oxygen permeability at the cracked region was not necessarily observed.

4. Discussions

The anodic and cathodic chemical reactions related with corrosion of steel bars in concrete are listed below:

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

Cathodic $\quad \frac{1}{2}O_2 + 2e^- + H_2O \rightarrow 2OH^-$

The anodic reaction is associated with the dissolution of iron and the cathodic reaction is associated with the consumption of the electrons generated in the anodic process and formation of hydroxyl ions. In order to complete the corrosion cell, the hydroxyl ions move to the location of anode from the cathode through concrete. The speed of movement depends on the concrete resistance. In Ref. [1], it was concluded that for the cracked beam reinforced with deformed bars, the concrete resistance is lower than one reinforced with plain bars. It is also true that once the passivity of steel bars in concrete is destroyed, it is the

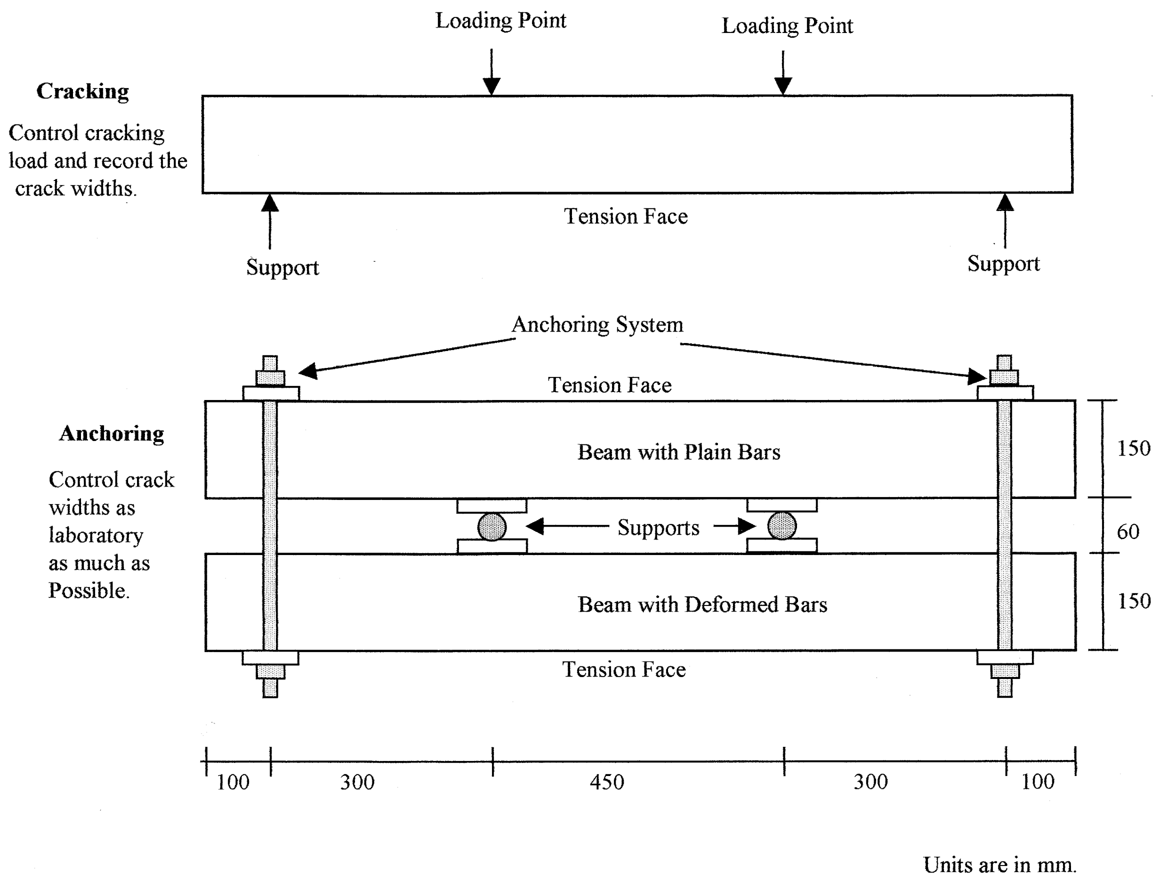

Fig. 2. Cracking and anchoring of the beams.

cathodic process and the electrical resistivity of concrete which control the rate of corrosion [5]. With more oxygen permeability as well as less concrete resistance, the cathodic reaction in the case of beam with deformed bars will be faster. The results will cause more corrosion of deformed bars. More discussions on this matter are noted below.

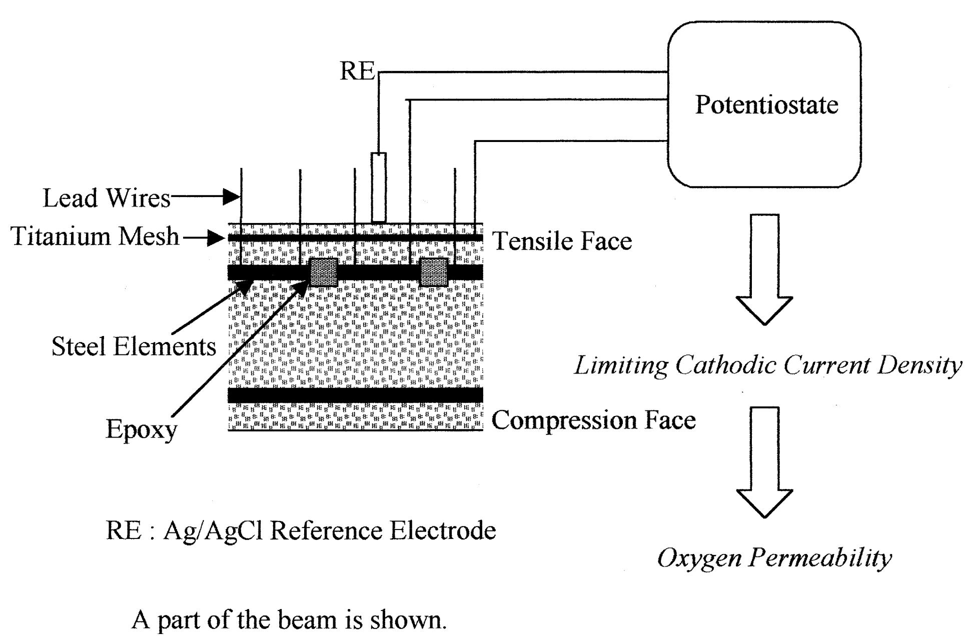

Fig. 3. Measurement of oxygen permeability in concrete over a steel element.

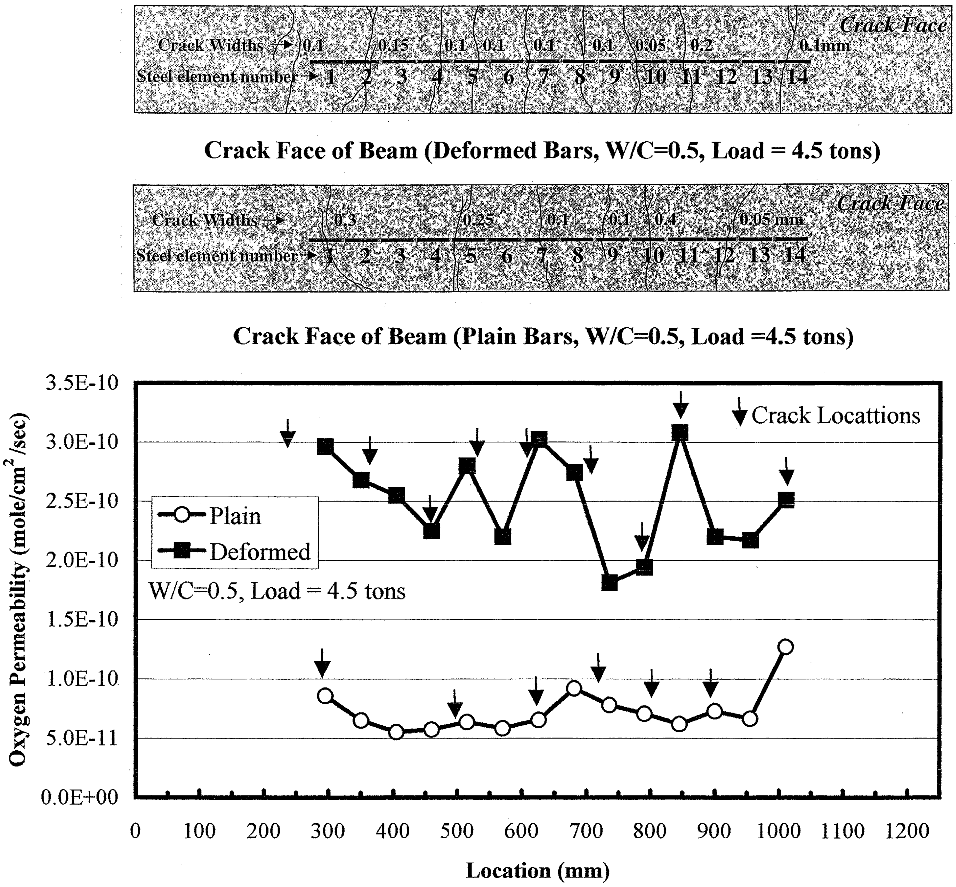

Fig. 4. Crack maps and oxygen permeability of beams with plain and deformed bars.

Based on the study of crack formation mechanism around deformed tension bars, it was found that the microcracks start from the ribs of the deformed bars and some of them come to the surface as surface cracks [2]. It supports that microcracking in concrete will be much more in the case of a beam with deformed bars. It was also reported in Ref. [1] that when saltwater is sprayed over the cracked beam reinforced with deformed and plain bars, the beams with plain bars dry very quickly compared to a beam with deformed bars. Significant internal cracking of the beam with deformed bars cause the retention of the water for a relatively long time. Chloride-ion concentrations were also found more in the case of a beam reinforced with deformed bars compared to the same with plain bars [1]. In another study on the crack frequency and corrosion rate, it was concluded that the corrosion rate can be reduced significantly by limiting the crack frequency rather than the surface crack widths [3]. In a detailed study on the crack width and corrosion rate, it was also reported that for the investigated crack widths (<0.7 mm) there is no significant relation between crack width and corrosion rate [1]. In this study, it is noted that the maximum crack width for the beam with deformed bars is lower than the beam with plain bars. However, it will not cause more corrosion of steel bars for the beams reinforced with plain bars. More surface (higher crack frequency) as well as internal cracking of the beams reinforced with deformed bars will result in more corrosion.

5. Conclusions

From the scope of this investigation, it is concluded that cracked concrete with deformed bars has significantly higher oxygen permeability compared to the same with plain bars. This eventually supports that the cathodic reaction of corrosion will be faster for the cracked beams reinforced with deformed bars compared to the same reinforced with plain bars. On the other hand, deformed bars are more prone to corrosion than plain bars in cracked concrete.

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