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CORROSION CURRENT DENSITY OF MACROCELL OF HORIZONTAL STEEL BARS IN REINFORCED CONCRETE COLUMN SPECIMEN

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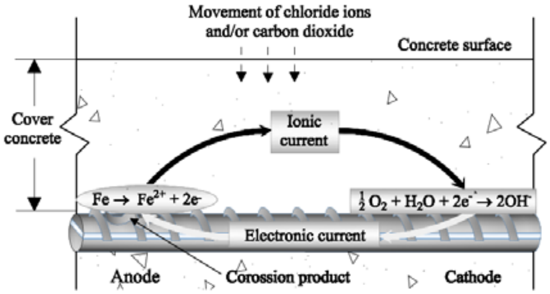
ABSTRACT: Chloride-induced corrosion of steel bar in concrete is one of the main problems affecting the durability of reinforced concrete (RC) structures. Expansive products are formed due to corrosion at the interface between concrete and steel bar. In this study, the differences in the magnitude of the macrocell corrosion current density in RC column specimens cast using copper slag fine aggregate and fly ash replacement were examined. This study aimed at investigating corrosion formation with respect to macrocell corrosion current density. The experimental study was carried out through dry and wet (NaCl 10%) cycles for specimens with different cover depths, which was investigated by electrochemical measurements. The result shows that the largest macrocell corrosion current density was measured in the steel bars located at the upper part of reinforced column specimens for each case of the specimens with a cover depth of 30 mm. This could be partly attributed to the loss of the integrity of the steel and concrete interface which is examined based on the oxygen permeability in the upper and lower sides of segmented steel bars. The variation of oxygen permeability contributes to the macrocell corrosion formation especially in the steel bars affected by bleeding water. Besides the integrity between steel bars and concrete cover, the quality of concrete cover and variations in chloride ion concentrations are significant factors contributing to the macrocell corrosion formation.

Keywords: Chloride-induced corrosion, Macrocell corrosion current density, Oxygen permeability, Horizontal steel bar, Copper slag fine aggregate

1. INTRODUCTION

Chloride-induced corrosion is a concern for RC structures that are attacked by chlorides from seawater especially in the tidal, splash and spray water zones. The mechanisms of chloride-induced corrosion of steel in concrete structures are complex. Some research on the corrosion process and the influencing parameters have been carried out. Measurement of macrocell corrosion current flow is one of electrochemical technique investigating the mechanisms and the influencing factors of chloride-induced corrosion of steel in concrete. Locally separated anodes and cathodes in concrete specimens have been measured by electrical current [1].

Steel bars in good quality concrete do not corrode even if sufficient oxygen and moisture are available. This is due to the spontaneous formation of a thin passive film on the steel surface in highly alkaline (pH 12.5-13.5) of the pore solution of the concrete. This passive film can be destroyed by carbonation of concrete or by the presence of chloride ions, and the steel bar is then depassivated. Once the passive layer breaks down then areas of rust will start appearing on the steel surface in the presence of water and oxygen. The corrosion of steel in concrete is an electrochemical process, where at the anode iron is oxidized to iron ions that pass into solution and at the cathode oxygen is reduced and together with electrons and water are converted into hydroxyl ions. Anode and cathode form a short-circuited corrosion cell, with the flow of electrons in the steel and of ions in the pore solution of the concrete [2, 3].



$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$ Ferrous hydroxide
$4Fe(OH)_2 + 2O_2 + 2H_2O \rightarrow 4Fe(OH)_2$ Ferric hydroxide
$2Fe(OH)_2 \rightarrow Fe_2O_3 . H_2O + 2H_2O$ Hydrated ferric oxide (rust)

Fig. 1 The anodic, cathodic and oxidation and hydration reactions for corroding steel [3]

According to the different spatial location of anode and cathode, corrosion of steel in concrete can occur as microcells leading to uniform iron removal and macrocells causing local iron removal or pitting corrosion:

(a) Microcell corrosion, consisting of pairs of immediately adjacent anodes and cathodes, leading to uniform iron dissolution over the whole surface. Uniform corrosion is generally caused by carbonation of the concrete over a wide area or uniformly very high chloride contents in the vicinity of the steel.

(b) Macrocell corrosion, consisting of spatially isolated anodes and cathodes, normally where the critical chloride content has been reached, and large cathodes being next to the anodes or sometimes also quite far away from the anodes up to a distance of a few meters. Macrocells occur mainly in the case of chloride-induced corrosion (pitting). Generally, the anode is small respect to the total (passive) rebar surface. A typical coplanar or face to face situations of anode and cathode can be distinguished by macrocell corrosion [1-5].

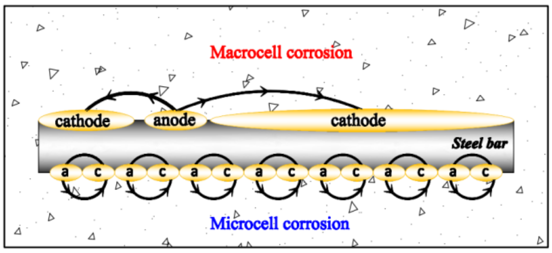


Fig.2 Microcell and macrocell corrosion

Macrocell corrosion is of great concern because the local dissolution rate (reduction in cross-section of the rebar) may greatly be accelerated due to the existence of large active steel bar areas in electrical contact with passive areas [1, 2, 5]. The values of local corrosion rates up to 1 mm/year will lead rapid corrosion attack to the structure if not detected early [2]. Chloride content, concrete quality, concrete cover and environmental conditions are parameters influencing the corrosion rate of macrocell in a concrete structure. Additionally specific resistance of anodic, cathodic and the electrolyte (concrete), and geometry of the corrosion cell also influence the macrocell corrosion rate directly. It affects the prediction of the macrocell current becomes quite difficult [1].

In this study, bleeding is unavoidable when column specimens are cast from the height of 1.5 m. Bleeding in the form of segregation is one of the factors affects the quality of concrete. Bleeding significantly influenced the macrocell and microcell corrosion rates in the steel bars. As a result of bleeding, water pockets trapped under the coarse aggregates and underneath the steel bars caused the formation of gaps between the steel and concrete. This vulnerable zone affects the integrity of reinforced concrete, allowing corrosion cells to develop on the horizontal bar. Also, the presence of gaps/vulnerable zone at the steel-concrete interface causes the complete loss of passivity with the presence of chloride. A part of concrete affected by bleeding exhibited weaker strength, higher permeability, lower concrete resistance, and higher oxygen permeability [6, 7].

It was reported that the rate of oxygen permeability is an influencing factor greatly affecting the corrosion of steel bars in concrete in which oxygen is consumed on the surface of the steel bars [8-10]. The concentration of oxygen in corrosion process was shown in the behavior of the cathodic polarization curve. The reduction in oxygen content shifts the cathodic curve to lower current densities over a wide range of potentials. This curve indicates the improvement of corrosion performance when used fly ash as a material replacement which attributes to the reduction of available oxygen by densifying the pore structure by the pozzolanic reaction around steel bars [9, 10]. Thus the cathodic reaction is controlling the overall reaction in the macrocell in the case of chloride-induced corrosion [11]. Also, the electrical resistivity of concrete depth is a significant factor contributing to the corrosion processes when macrocell formation occurs, and corrosion rate increased with a decrease in cover depth [12].

In this study, common acceleration technique by wet and dry cycles was used. Copper slag (CUS) and fly ash (FA) as replacement for fine aggregate and cement were used. This paper examines the corrosion formation respect to the differences in the magnitude of the macrocell corrosion current density of reinforced concrete column specimens. Both oxygen permeability and macrocell corrosion current density within the concrete cover are considered in the electrochemical analysis.

2. METHODOLOGY

2.1 Specimen Overview

Concrete column specimens of the cross-section 300 x 300 mm and the height of 1500 mm were cast with water to binder ratio (W/B) of 47% for FA mixtures and 55% for CUS and OPC mixtures in this study (Figure 1). After casting, the specimens were cured for 28 days in room conditions. Segmented steel bars comprising D32 deformed steel bars were embedded at the height of 250, 750, and 1250 mm from the bottom surface.

The smaller specimens (300 x 100 x 132) mm were subsequently cut out from the column with the cover depths of 30 and 40 mm and then chloride-induced corrosion tests were carried out. Table 1 shows the mix proportions of concrete mixtures in this experiment. The fine aggregate was crushed sand obtained from sandstone (S1), and limestone (S2) with a specific gravity, water absorption capacity and F.M. of S1 (2.61 g/cm^3, 1.06 %, and 2.88), S2 (3.55 g/cm^3, 0.04 %, and 2.29). The coarse aggregate was crushed sandstone (G1) with a specific gravity and water absorption are 2.62 g/cm^3 and 0.64 %. The slump and air content were specified as 8.0 cm and 4.0% respectively.

Table 1 Mix proportions of concrete specimens

Mixtures	W/B (%)	Unit weight (kg/m^3)						(g/m^3)	
		W	C	FA	Fine aggregate		Coarse aggregate	Chemical admixtures	
					S1	S2	G1	AEAWRA	AEA
FACUS 30	47	165	281	70	587	342	912	5265	35.1
CUS30	55	175	318	-	596	347	925	3818	-
OPC	55	175	318	-	857	-	932	4772	15.9

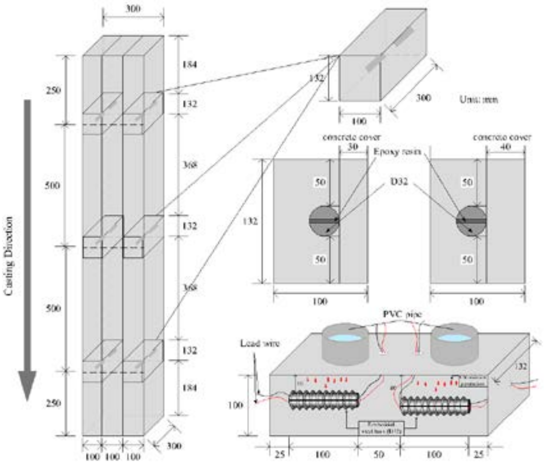


Fig. 3 Reinforced concrete column specimen

2.2 Interfacial Transition Zone

The strength of a bond between concrete and steel bars is of considerable importance concerning structural behavior. In the case of deformed bars, bond arises primarily from friction and adhesion between concrete and steel, and from mechanical interlocking. The bond strength involves not only the properties of the concrete but also the geometry of the reinforcement and the structure such as the thickness of cover to the reinforcement [13].

The interfacial transition zone is a layer (usually several tens of micrometers thick) of hydrated cement paste in contact with aggregates. It is the strength limiting phase in concrete. The transition zone becomes the weakest link in concrete mass on account of the dissimilar material, lack of bond, higher w/c ratio, and bleeding water. Under load and the increasing of stress level, microcracks propagate and spreads throughout the mass further starting from largest microcracks. The micro cracks in the transition zone at the interface with steel bars becomes more permeable than the corresponding hydrated cement paste or mortar and admits air and water to promote corrosion of steel reinforcement. The volume of voids and microcracks present of the interfacial transition zone has a great influence on the stiffness of concrete. Also, bleeding which some of the water in the mix tends to rise to the surface gets intercepted by aggregates then gets accumulated at the interface between paste and aggregates.

2.3 Macrocell (Corrosion Rate)

The macrocell corrosion current density in the steel bar was measured using an ammeter. The equipment is permanently set up and can be used to monitor the total charge passing with time between steel elements in segmented steel bars connected with epoxy resin. The macrocell current flowing can be calculated based on Eq. (1), the readings obtained from the ammeter and dividing them with the surface area of the steel [7].

$$I_{macro} = \frac{I_i}{S_i}$$

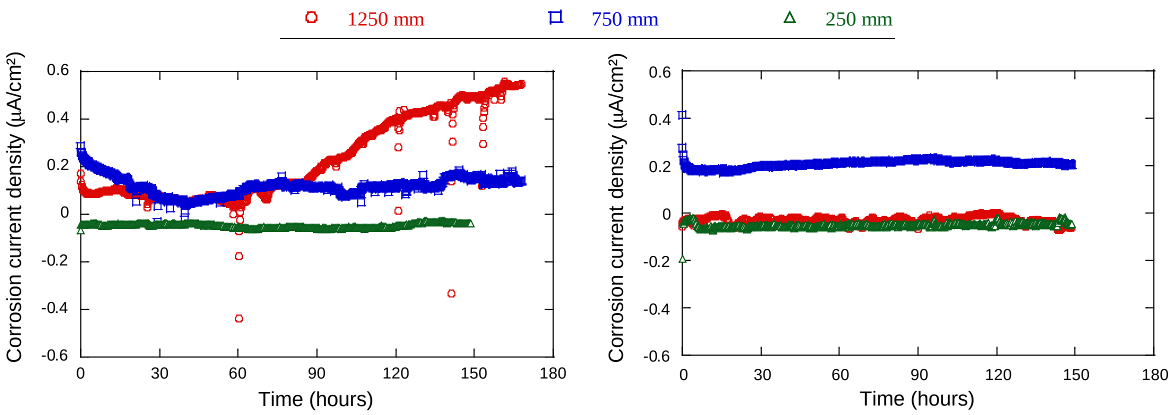
where I_{macro}: macrocell corrosion current density (A/cm^2); I_i: current flowing of steel element (A); and S_i: surface area of steel element i (cm^2)

2.4 Oxygen Permeability

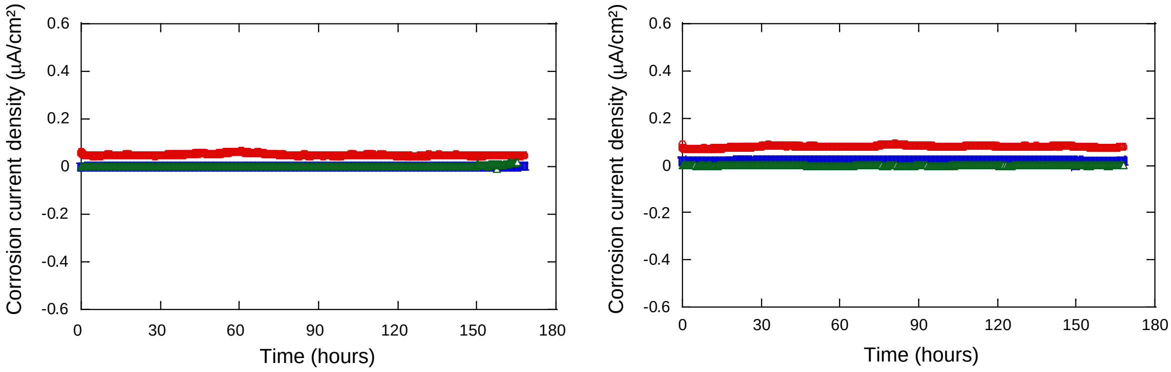
The electrochemical measurement set up for the cathodic polarization consisted of a counter electrode (steel plate), a working electrode (steel bar with lead wire attached to it) and a reference electrode (Ag/AgCl). For this measurement technique, the half-cell potential of the steel bar was gradually shifted to -1V, and the current density was measured. The rate of oxygen permeability was calculated based on Eq. (2) when the potential difference was assumed to reach the limiting current density (-860 mV) [7].

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

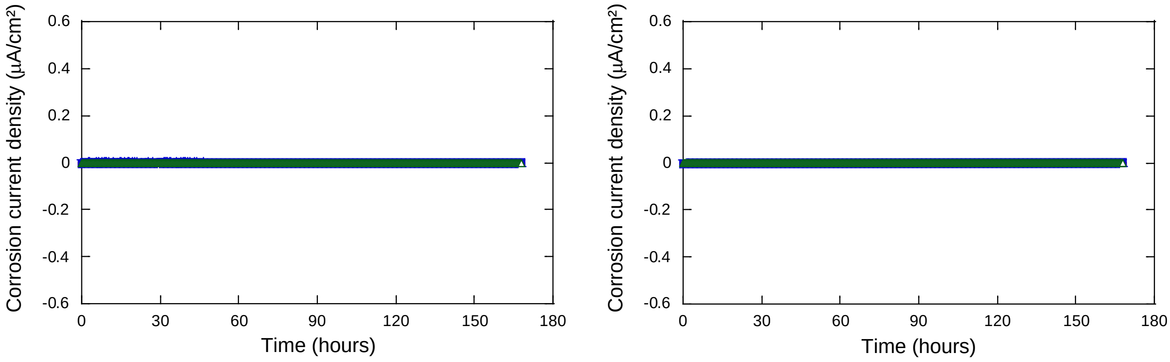
where dQ/dt: the rate of oxygen permeability (mol/cm^2/sec); $i_{\lim}$: limiting current density (A/cm^2); F: Faraday's constant (96,500 coulombs/mol); and n: the number of electron exchanged equal to 4.



a) OPC cover depth 30 mm (d) OPC cover depth 40 mm



(b) CUS30 cover depth 30 mm (e) CUS30 cover depth 40 mm



(c) FACUS30 cover depth 30 mm (f) FACUS30 cover depth 40 mm

Fig. 4 Macrocell corrosion current density

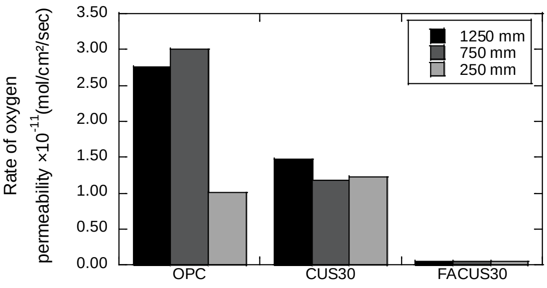
3. RESULTS AND DISCUSSION

3.1 Macrocell (Corrosion Rate)

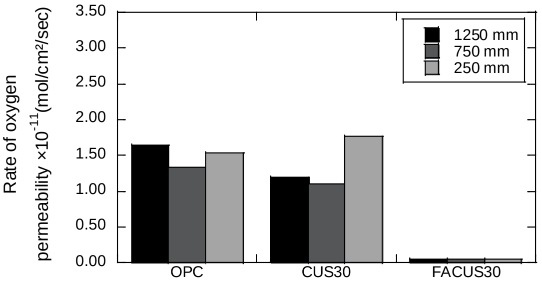
The macrocell corrosion current density measured at the ages of 420 days at a cover depth 30 mm and 40 mm are shown in Fig. 4 for the different type of specimens. The largest macrocell current density was measured in the steel bars located in upper part (1250 mm from the bottom surface) for each case of the specimens with 30 mm cover depth. OPC specimens showed the higher value of the macrocell corrosion current density. This could be partly attributed to the loss of the integrity of the steel and concrete interface which is examined based on the oxygen permeability in the upper and lower sides of segmented steel bars.

The smaller macrocell corrosion current density was shown from the specimens of 40 mm cover depth. This could be explained by the fact that concrete cover depth influences the ingress of chlorides and oxygen into the concrete. The smaller the cover depth reduces the time interval of the oxygen and the chloride ions to reach embedded steel bar, and vice versa. Also, the quality of the concrete cover, especially with respect to its permeability, determines the ease of ingress of the chloride ions, and it is a significant factor contributing to the macrocell corrosion formation. On the other hand, FA specimens with the cover depth of 30 mm and 40 mm showed the lowest values of macrocell corrosion current density. Based on the results obtained, it assumed that more uniform pore structure in the FA specimens. The pozzolanic reaction of FA could densify the pore structure around steel bars and protected the steel bars from the ingress of chloride ions and lead to a lower rate of oxygen permeability.

3.2 Oxygen Permeability



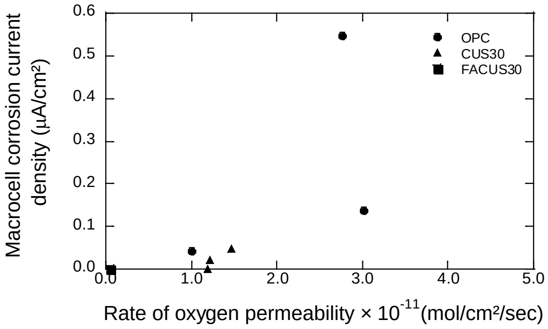
(a). Specimens for case 1 (cover depth 30 mm)



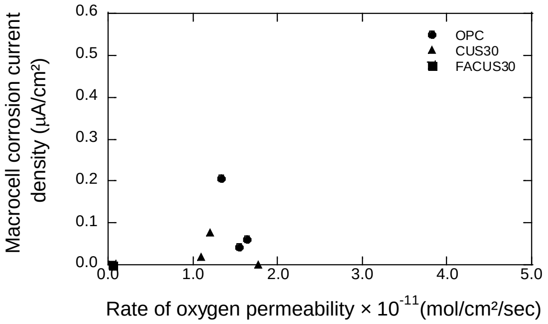
(b). Specimens for case 1 (cover depth 40 mm)

Fig 5. The rate of oxygen permeability

Figure 5 shows the rate of oxygen permeability was obtained by cathodic polarization curve at the age of 420 days. As expected, higher oxygen permeability ensued due to the poor quality of concrete in the upper layer, which was 64% higher, compared to the rate of oxygen permeability in the bottom layer in the case of OPC specimen with the cover depth of 30 mm. But for OPC specimens with cover depth 40 mm, CUS30 with the cover depth of 30 mm and 40 mm, the rate of oxygen permeability was comparable among all parts of the column specimens. The rate of oxygen permeability of FA mixtures is very low compared to the OPC and the CUS30 mixtures. This could be explained by the fact that pozzolanic reactions of FA mixture reduce the influence of material segregation due to bleeding. Based on the results, a more permeable condition in the upper part of the concrete column specimen affected more prone to corrosion. This condition may be due to the adverse effect of bleeding on the concrete cover and lack of integrity cover concrete and horizontal steel bars in the vulnerable zone.



(a). Specimens for case 1 (cover depth 30 mm)



(b). Specimens for case 1 (cover depth 40 mm)

Fig 6. Microcell corrosion current density and the rate of oxygen permeability

Figure 6 shows the relationship between the macrocell corrosion current density and the rate of oxygen permeability. The macrocell corrosion current density was increased with the higher rate of oxygen permeability regardless of the mixtures and concrete cover. The CUS30 specimens showed lower macrocell corrosion current density compared to OPC. The results displayed that the partial replacement of CUS30 and FACUS30 in fine aggregate could enhance the resistance against chloride ingress. Also, increasing of cover depth decreased the corrosion current density.

4. CONCLUSION

This study aimed at examining corrosion formation respect to macrocell corrosion current density. The variation of oxygen permeability contributes to the macrocell corrosion formation which was affected by the integrity of steel and the concrete interface. The result shows that the largest macrocell corrosion current density was measured in the steel bars located at the upper part of reinforced column specimens for each case of the specimens with 30 mm cover depth. This could be partly attributed to the loss of the integrity of the steel and concrete interface which is examined based on the oxygen permeability in the upper and lower sides of segmented steel bars. Besides the integrity between steel bars and concrete cover, the quality of concrete cover is significant factors contributing to the macrocell corrosion formation. The more uniform pore structure in the FA specimens could be formed which led to higher corrosion resistance. The pozzolanic reactions of fly ash specimens exhibited the ability to reduce oxygen availability which leads to enhancement in corrosion performance. Also, CUS30 shows lower macrocell corrosion current density compared to OPC. This could be advantageous for the partial replacement of CUS in fine aggregate in improving corrosion-resistance.

5. ACKNOWLEDGEMENTS

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