- Technical Paper -

EFFECT OF CURING AND CRACK WIDTH ON POTENTIAL PERFORMANCE OF STEEL WITH SACRIFICIAL ANODE IN CRACKED CONCRETE

Muhammad Akbar CARONGE[*1], Hidenori HAMADA[*2], Yasutaka SAGAWA[*3] and Daisuke YAMAMOTO[*4]

ABSTRACT

The effectiveness of sacrificial anode to protect embedded steel in cracked concrete under different curing conditions; air curing, immersion in a 3% NaCl solution and dry/wet cycle is presented. Reinforced concrete prism in size of 150x150x500 mm^3 with water-to-cement ratio of 0.4 and pre-crack of 0.1 to 0.4 mm in width was evaluated. The result showed that sacrificial anode was effective to protect the embedded steel in cracked concrete. Also, crack width significantly influences the corrosion rate.

Keywords: Sacrificial anode, potential performance, corrosion, cracked concrete

1. INTRODUCTION

Cracks reduce the service life of the structure by permitting more rapid access of moisture; chloride ions and oxygen to the reinforcement, thus accelerating the onset of corrosion [1]. Limitation of cracking in reinforced concrete is desirable, thereby preventing easy access of aggressive ions into the interior of concrete and as a result, producing a more durable concrete structure. However, the limitation of crack width does not guarantee the corrosion of steel reinforcement in the long term.

Several protection techniques have been developed including the use of corrosion inhibitor. The results showed the addition of corrosion inhibitor did not perform well to prevent macro-cell corrosion in cracked concrete [2,3]. Another way through the use of cathodic protection to reinforced concrete cracked using sacrificial anode. The use of cathodic protection for new constructions is relatively expensive. But it is more advantageously applied as a rehabilitation technique for reinforced concrete structure. Moreover, prevention of further corrosion of deteriorated reinforced concrete structures can be competitively achieved through cathodic protection [4]. This paper aims to evaluate the effectiveness of sacrificial anode for protecting embedded steel in cracked concrete.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Ordinary Portland Cement (OPC) was used for concrete mixes. The physical properties and chemical analysis of cement are shown in Table 1. Further, the properties of aggregates and admixtures are shown in Table 2. Also, a sacrificial anode used in this study is commercially available. The anode material is Zn based metal coated by porous mortar contained a lithium monohydrated solution with sizes of 60 mm in diameter and 30 mm in thickness as depicted in Photo 1.

Table 1 Physical and chemical compositions of OPC

Items	Value
Density, g/cm^3	3.16
Fineness, cm^2/g	3390
MgO, %	1.2
SO_3, %	2.23
LOI, %	2.15
Total alkali, %	0.51
Ion chloride, %	0.019

Table 2 Properties of materials

Material	Specification
Fine aggregate	Sea sand (SSD density = 2.58 g/cm^3)
Coarse aggregate	Crushed river gravel (SSD density = 2.85 g/cm^3, MSA = 20 mm)
AEWR agent	Polycarboxylate ether based
AE agent	Alkylcarboxylic

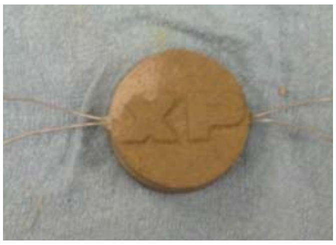


Photo 1 Sacrificial anode

*1 Student, Graduate School of Engineering, Kyushu University, M. Eng., JCI Member
*2 Professor, Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*3 Associate Prof., Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*4 Technical Officer, Dept. of Civil and Structural Engineering, Kyushu University, M. Sci., JCI Member

2.2 Mixture Proportion

Concrete mix with water to cement ratio (w/c) of 0.4 was used throughout all specimens. Both air-entraining agent and water-reducing admixture were used based on the cement mass to obtain the slump and air content in the range of 10±2.5 cm and 4.5±1% respectively. The mix proportion of concrete is summarized in Table 3.

Table 3 Mix proportion

Material	Value
Water-cement ratio w/c, %	40
Sand-aggregate ratio s/a, %	41.5
Water, kg/m^3	161
Cement, kg/m^3	403
Sand, kg/m^3	680
Gravel, kg/m^3	1108
Water-reducing admixture, kg/m^3	1.25
Air-entraining agent AE, mL/m^3	1163
Slump, cm	7.5
Air content, %	4.0

2.3 Specimen Designs

Specimens were produced in the form of reinforced concrete prism with 150x150x500 mm^3 in dimensions. The specimen had a plain steel bar of 13 mm diameter placed at the bottom with 30 mm clear cover. Each concrete specimen contained plain steel bar (PS) and plain steel bar with sacrificial anode (PSCP). Detail of specimens design is shown in Fig. 1.

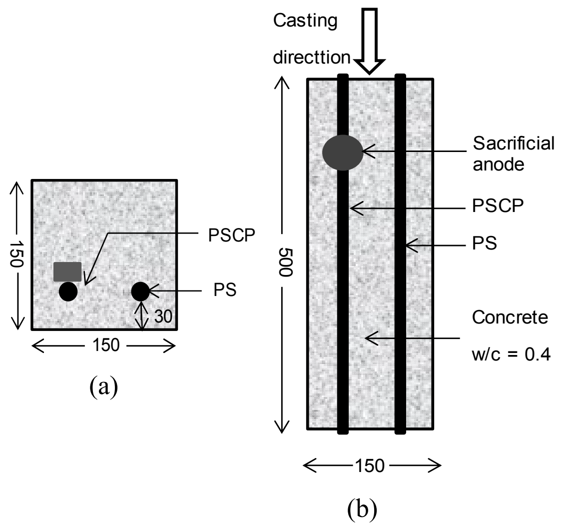


Fig. 1 Detail of specimen (in mm): (a) Cross section; (b) Longitudinal cross section.

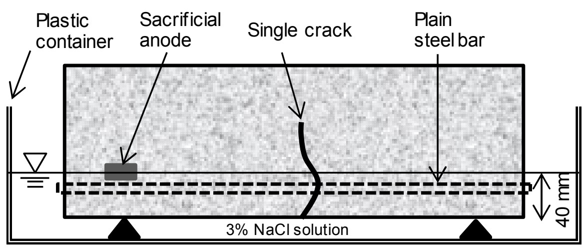


Fig. 2 Immersion in 3% NaCl solution

Before placing concrete in molds, sacrificial anode was installed on the steel bar and checked the maximum resistance of 0.3 Ω by using ampere meter, then concrete was placed and demolded after 24 hours. The specimens were cured under sealed conditions in a wet towel for 28 days in constant room temperature at 20±2°C. To determine the mechanical properties of concrete, Φ100x200 mm^3 concrete cylinders were fabricated and tested after 28 days of curing in water.

After 28 days curing, all specimens were pre-cracked under one point flexural loading. One set of pi displacement transducer (±2 mm) was fixed in the bottom side of the specimen in order to check the crack width. Ten data were measured immediately after loading for each side (bottom and lateral) of specimen in order to calculate an average crack width. Photo 2 shows pre-cracking loading and crack width measurement. In total, twelve test prisms were prepared in this experiment.

2.4 Experimental Method

After pre-cracking, both ends of specimens were sealed with epoxy. Then, specimens were placed in three curing conditions namely air curing, immersion in 3% NaCl solution and dry/wet cycle as summarized in Table 4. For specimen in 3% NaCl solution, only 40 mm from bottom surface was immersed (Fig. 2).

The presence of corrosion in each bar was monitored using half-cell potential measurement. Half-cell potential measurement is one of the most common methods used to evaluate the risk of steel corrosion. Silver/silver chloride electrode (CSE) was used as a reference electrode for measurement of

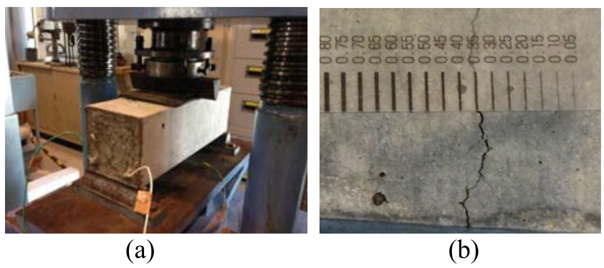


Photo 2 (a) Pre-cracking loading; (b) Crack sizes measurement

Table 4 Summary of specimen test

Specimen Series	Average Crack Width (mm)	Curing Condition
A1	0.06	Air curing at temperature 20±2°C
A2	0.15	
A3	0.25	
A4	0.31	
B1	0.09	Immersed in a 3% NaCl solution
B2	0.17	
B3	0.20	
B4	0.32	
C1	0.09	Dry/wet cyclic (2 days in 3% NaCl solution & 5 days dry)
C2	0.18	
C3	0.29	
C4	0.34	

potential. The interpretation of potential readings of plain steel bar with sacrificial anode (PSCP) was carried out according to JSCE Concrete Library 107 [5]. Sacrificial anode applied to steel in concrete normally considered effective if the difference between steel bar with and without sacrificial anode is more than 100 mV. While potential evaluation of plain steel bar without sacrificial anode (PS) based on ASTM C876-09 [6] is described in Table 5.

Table 5 Corrosion probability (ASTM C876-09)

Half-cell potential (mV, CSE)	Corrosion activity
-200 < E	90% no corrosion probability
-350 < E<-200	Uncertainty
E< -350	90% corrosion probability

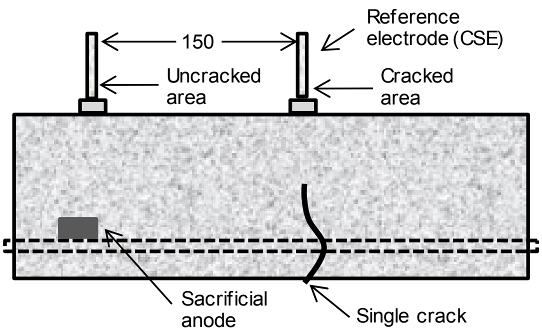


Fig. 3 Measurement map of specimen

The half-cell potential was measured in cracked and un-cracked area. The initial reading of the potential was taken immediately after pre-cracking. Fig. 3 illustrated the measurement mapping of specimen. Uncracked area closed to sacrificial anode and cracked area closed to crack location.

Anodic polarization curve of plain steel bar without sacrificial anode (PS) was conducted at uncracked and cracked area. The anodic polarization curve was measured for evaluating the condition of passivity film of steel bar, using the passivity grade proposed by Otsuki [7]. When the current density becomes larger, the grade of passivation film of steel bar becomes worse.

3. RESULTS AND DISCUSSION

Pre-cracked specimens with compressive strength of 46.6 MPa at 28 days were investigated by half-cell potential and polarization curve.

3.1 Half-cell potential

(1) Air curing

Fig. 4 and Fig. 5 shows the half-cell potential values of PS at cracked and uncracked area for specimens in the air curing. It is observed that the potential of PS was about -250 mV for all crack widths after 8 weeks. However, after 8 weeks the half-cell potential of steel bars became increasingly more positive with time around -150 mV both cracked and uncracked area. It is found that relationship between

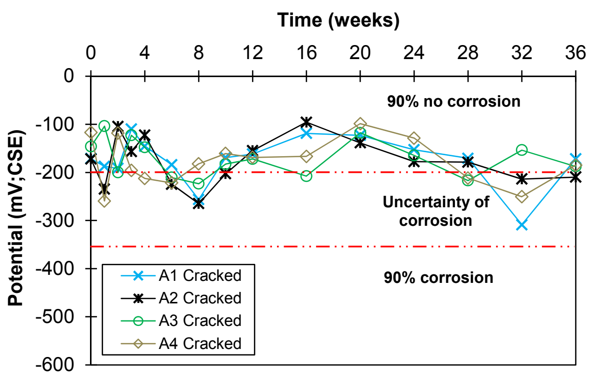


Fig. 4 Half-cell potential PS at cracked area (Air curing)

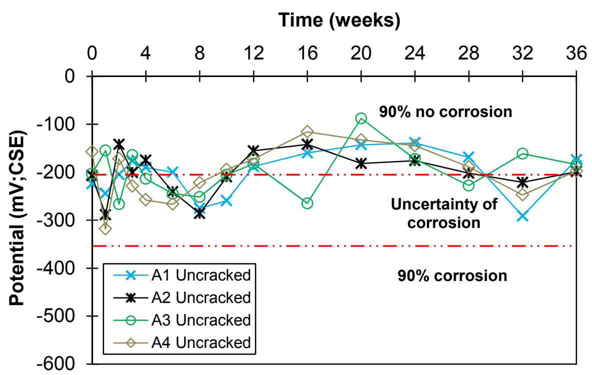


Fig. 5 Half-cell potential PS at uncracked area (Air curing)

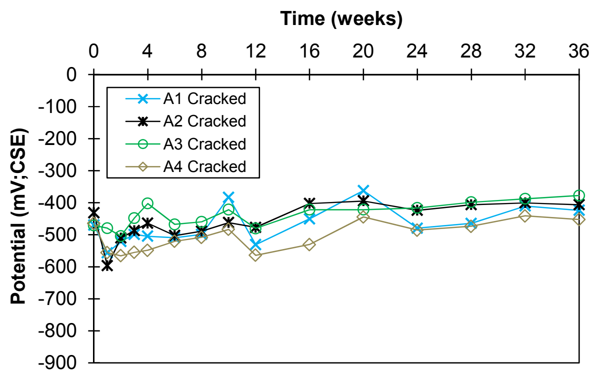


Fig. 6 Half-cell potential of PSCP at cracked area (Air curing)

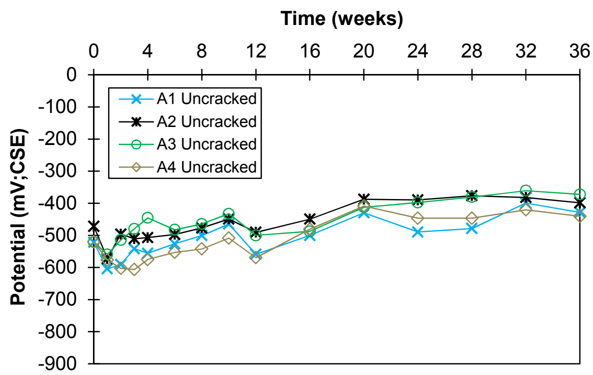


Fig. 7 Half-cell potential of PSCP at uncracked area (Air curing)

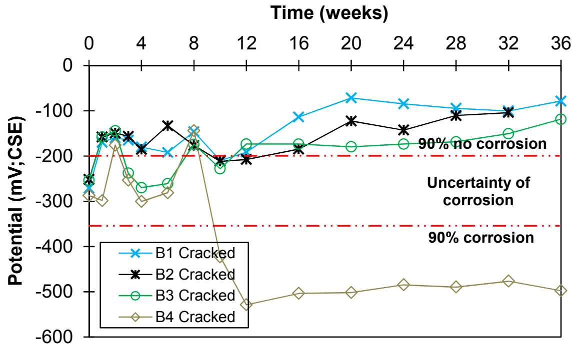


Fig. 8 Half-cell potential PS at cracked area (Immersion in 3% NaCl solution)

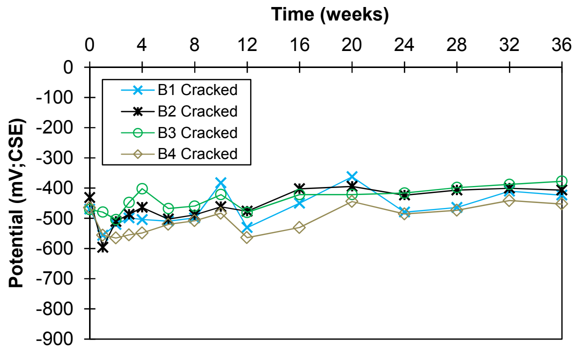


Fig. 10 Half-cell potential PSCP at cracked area (Immersion in 3% NaCl solution)

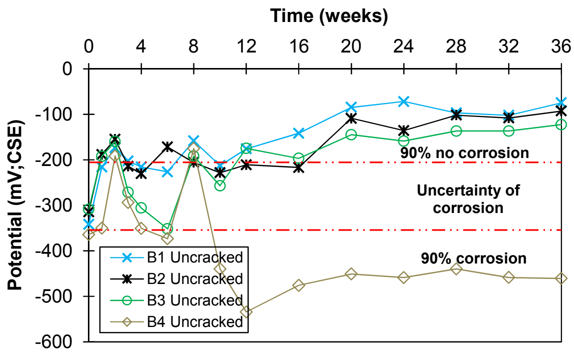


Fig. 9 Half-cell potential PS at uncracked area (Immersion in 3% NaCl solution)

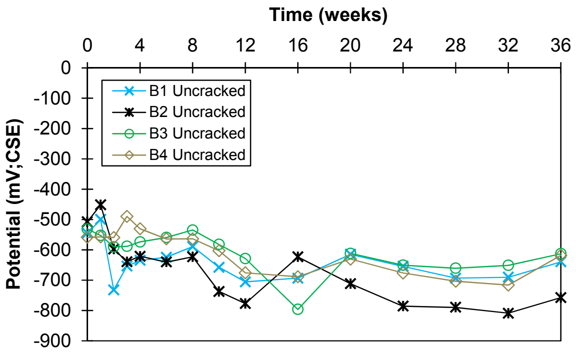


Fig. 11 Half-cell potential PSCP at uncracked area (Immersion in 3% NaCl solution)

potential of PS and crack width at the early age is existed and changed by time due to the steel bars remain passive condition.

The half-cell potentials of PSCP with time at cracked and uncracked area are shown in Fig. 6 and Fig. 7. Both uncracked and cracked area, it is observed that the potential value of PSCP has become more negative around -500 mV for all crack widths. This is attributed to the sacrificial anode, which has shifted the potential of steel bars about 300 mV to negative potential. The difference more than 100 mV between PS and PSCP indicates that sacrificial anode is effective to prevent corrosion of steel bars.

(2) Immersion in 3% NaCl solution

Fig. 8 and Fig. 9 show the potential of PS by time at cracked and uncracked area immersed in 3% NaCl solution. The figures shows that the potential value of PS becomes more positive with time for carck width less than 0.20 mm. While for crack width of 0.20 mm or more, the potential of PS reached about -300 mV to -350 mV at early age and decreased with time for both cracked and uncracked area. On the contrary, for specimen with crack width of 0.32 mm, it is observed that, at 8 weeks, the potential value of PS falls to -450 mV and categorized the 90% probability of corrosion for both cracked and uncracked area. It indicates that crack width affect the corrosion rate even the steel bar is fully immersed, in spite of little oxygen supply. Also, both cracked and uncracked area have similar potential values. This implies that the presence of cracks can accelerate the onset of corrosion even in the uncracked area.

Fig. 10 and Fig. 11 shows the half-cell potential value of PSCP for cracked and uncracked area respectively. In the area close to the anode (uncracked), potential value is -700 mV, which is more negative than cracked area around -550 mV. It seems that the distance from sacrificial anode significanly affect the potential value. From the figures it is also observed that the potential difference between PSCP and PS is more than 100 mV for all crack widths for both uncracked and cracked area. It indicats that the sacrificial anode is effective to prevent corrosion activity in cracked concrete.

(3) Dry/wet cycles curing

The half-cell potential of PS under dry/wet cycles at cracked and uncracked area are shown in Fig. 12 and Fig. 13. In the cracked area, crack width of 0.09 mm shows the potential value around -350 mV at early age. After 12 weeks, the relationship between crack width and potential value changed by time. It is due to the amount of chloride ions and oxygen does not sufficient to accelerated corrosion of steel bars. While, larger crack widths shows more negative potential value less than -400 mV and categorized 90% probability of corrosion. Similar trend is found in uncracked area with potential value less than -350 mV. This is attributed to the effect of crack widths permitted easy access of chloride ions and oxygen to the steel bars and accelarated the onset of corrosion.

The half-cell potential value of PSCP at uncracked and cracked area under dry/wet cycles are shown in Fig. 14 and Fig. 15. The figures shows that both uncracked and cracked area achieved the half-cell

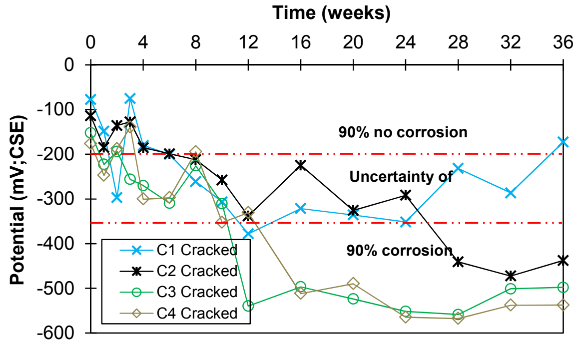


Fig. 12 Half-cell potential PS at cracked area (Dry/wet cycles curing)

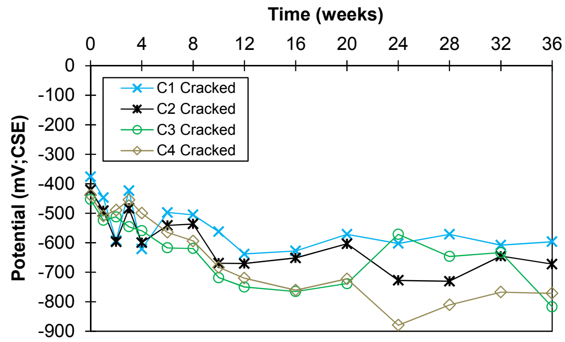


Fig. 14 Half-cell potential PSCP at cracked area (Dry/wet cycles curing)

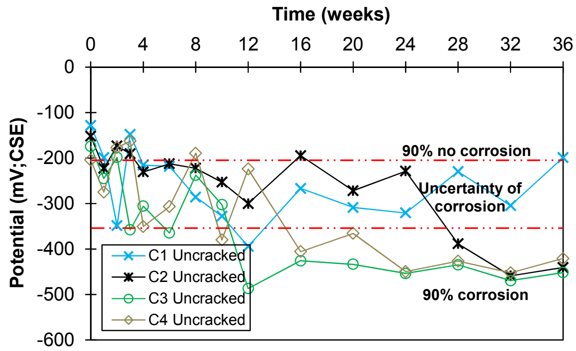


Fig. 13 Half-cell potential PS at cracked area (Dry/wet cycles curing)

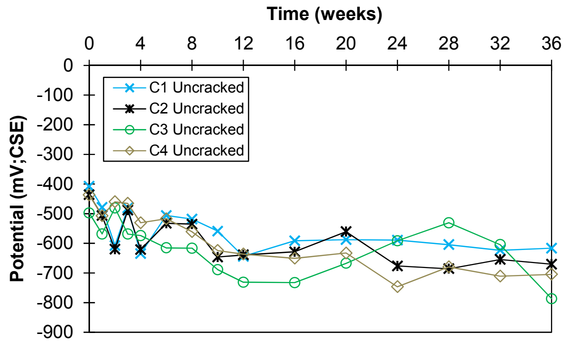
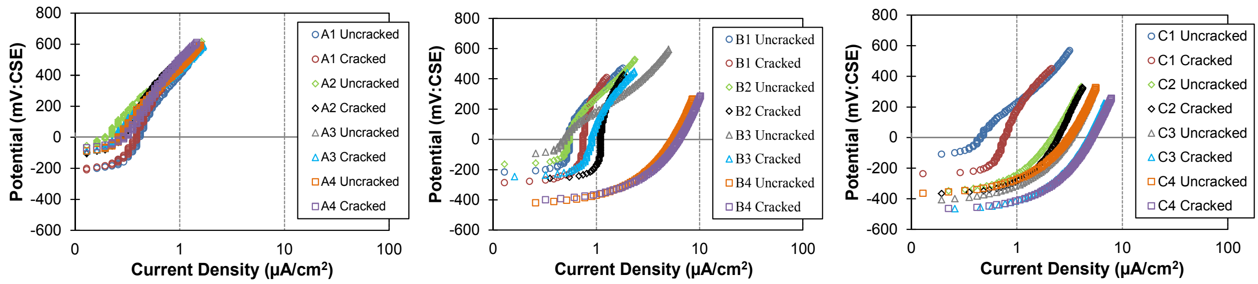


Fig. 15 Half-cell potential PSCP at cracked area (Dry/wet cycles curing)



(a) (b) (c)

Fig. 16 Anodic polarization curve of PS (a) Air curing; (b) Immersion in 3% NaCl solution; (c) Dry/wet cycles curing

potential values between -650 mV to -750 mV. The potential difference between PSCP and PS is more than 100 mV, which indicates that the sacrificial anode is effective to protect the steel bars. Also, the sacrificial anode is active at an earlier time and have stable values after 12 weeks.

3.2 Anodic Polarization Curve

Fig. 16 shows anodic polarization curve of the PS in air curing, immersion in 3% NaCl solution and dry/wet cycles at the age of 36 weeks. The passivity of all PS was Grade 4 (good condition) for both uncracked and cracked area in air curing. While for specimens immersed in a 3% NaCl solution, it is observed that B1, B2 and B3 are categorized into Grade 4 (good condition) and B4 is into Grade 3 (fair condition). It means passivation film of B4 becomes worse.

On the other hand, conditions of PS under dry/wet cycles of C2, C3 and C4 are into Grade 3. It can be said that the specimen under dry/wet cycles exhibit higer corrosion rate in both uncracked and cracked area than air curing or immersion in 3% NaCl solution.

4. CONCLUSIONS

From the test results, following conclusions can be drawn:

(1) Crack widths significanly affect corrosion of steel bars in concrete even immersed in 3% NaCl solution, it little oxygen supply.
(2) The relationship between crack width and corrosion rate of PS in early age is observed for both air curing and immersion in 3% NaCl solution.
(3) Sacrificial anode is effective to protect steel bars

in cracked concrete and could fulfill the 100 mV potential difference of steel bar with and without sacrifificial anode for all curing conditions.

(4) The passivitiy of PS under dry/wet cycles becomes worse both uncracked and cracked area. This is attributed to the effect of crack widths permitted easy access of chloride ions and oxygen to the steel bars and accelarated the onset of corrosion.

ACKNOWLEDGEMENT

The authors would like to thank the Denki Kagaku Kogyo Kabushiki Kaisha (DENKA), who has provided us the sacrificial anodes for our experiments.

REFERENCES

[1] ACI Committee 222., "Corrosion of Metals in Concrete", 1996.

[2] Berke, N.S. et al., "Corrosion of Steel in Cracked Concrete", Corrosion Engineering., NACE, Vol. 49 (11), 1993, pp. 934-943

[3] Collepardi, M. et al., "Use of Nitrite Salt as Corrosion Inhibitor Admixture in Reinforced Structures Immersed in Sea Water", Chapman & Hall, London, 1990, pp. 279-288

[4] Fratesi, R. et al., "Ctahodic Protection of Cracked Reinforced Concrete Structure Under Sea Water", IMMT International Confrence, La Spezia, Italy, 1-3 Oct. 1992

[5] JSCE Concrete Library 107., "Recommendation for Design and Construction of Electrochemical Corrosion Control Method"., Nov. 2010

[6] ASTM C 876-87., "Half-cell Potentials of Uncoated Steel in Concrete", West Conshohocken, Pa., 1987

[7] Otsuki, N., "A Study of Effectiveness of Chloride on Corrosion of Steel Bar in Concrete", Report of Port and Harbor Research Institute, 1985, pp. 127-134