# ELECTROCHEMICAL BEHAVIOR OF STEEL IN CRACKED CONCRETE -INFLUENCE OF CRACK WIDTH, COVER, EXPOSURE CONDITIONS AND SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs)

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### ABSTRACT

Reinforced concrete prism with w/b ratio of 0.5 had dimensions of 150x150x500 mm, while concrete cover were 30 mm, 50 mm and 70 mm. The crack widths investigated were 0.3 mm and 0.5 mm. These specimens were exposed to three conditions: (1) dry-wet cycles in tap water; (2) dry-wet cycles in seawater; and (3) continuously immersed in 3% NaCl solution. The results show crack width has influence at constant concrete cover. However, by increasing concrete cover, the crack width has less affected. Further, exposure condition and SCMs (BFS) has an effect particularly in high chloride environment. Keywords: electrochemical evaluation, corrosion, cracked concrete

# 1. INTRODUCTION

Cracks influence the durability of reinforced concrete (RC) structures. If the concrete has any cracks on the surface, corrosion is accelerated due to additional intrusion of harmful ions such as chloride. These cracks can cause rapid chloride diffusion and water permeation, so that they may reduce the service life of RC structures exposed to chloride attack. It is believed that cracks accelerate both corrosion initiation and propagation, but these are dependent on the concrete quality (w/b ratio and binder type) and concrete cover [1-2]. Further, utilization of supplementary cementitious materials by blast furnace slag (BFS) to increase corrosion resistance. Supplementary cementitious materials by BFS up to 50% replacement level in concrete imparted the best corrosion resistance [3].

In this study, several reinforced concrete prisms with various of crack width and concrete cover were monitor and evaluate. The influencing parameters such as crack width, concrete cover, exposure condition and utilization of SCMs. Therefore, the aim of this study is to understand the effect of crack width, concrete cover and the exposure conditions as well, with associated supplementary cementitious materials by BFS on electrochemical behavior of steel in cracked concrete.

## 2. EXPERIMENTAL PROCEDURE

#### 2.1 Materials

The specimens were made with plain cement by Ordinary Portland Cement (OPC) and supplementary cementitious materials by Blast Furnace Slag (BFS<sub>4000</sub>). The physical properties such density, fineness and water absorption are shown in Table 1.

Table T Physical properties						
Material	Density, g/cm <sup>3</sup>	Fineness, cm²/g	Water Absorption %			
OPC	3.16	3300	-			
BFS4000	2.91	4060	-			
Lime Stone	2.70	-	0.25			
Washed Sea Sand	2.53	-	2.08			

Table 4 Dhuaiaal muan antiaa

## 2.2 Mix Proportions

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The mix proportions of reinforced concrete prisms are summarized in Table 2. There are two types of mix, OPC only and OPC with BFS as supplementary of cement with supplementary level of 50%. "N" is for OPC mixed concrete, "B" is for BFS mixed concrete. The water-to-binder ratio (w/b) of concrete was 50%. Limestone with 20 mm maximum size was used as coarse aggregate and washed sea sand was used as fine aggregate. The ratio of fine aggregate to total aggregate volume (s/a) was 45%.

Table 2 Mix proportions of concrete					
Material	N (OPC)	B (BFS)			
W/B, %	50	50			
s/a, %	45	45			
Tap water, kg/m <sup>3</sup>	160	160			
Cement, kg/m <sup>3</sup>	320	160			
BFS, kg/m <sup>3</sup>	-	160			
Sand, kg/m <sup>3</sup>	805	800			
Gravel, kg/m <sup>3</sup>	1030	1023			
Water-reducing, kg/m <sup>3</sup>	1.3	1.3			
Air-entraining agent, mL/m <sup>3</sup>	2000	2000			
Slump, cm	5.5	6.5			
Air content, %	4.0	5.0			

#### 2.3 Specimen Design

The dimension of the reinforced concrete prism specimen is 150x150x500 mm. Plain bar with diameter

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\$10 mm, and with a clear concrete cover of 30 mm, 50 mm and 70 mm. A wire was attached to one end of the bars. Detail of reinforced concrete prism specimens design is shown in Fig.1. The specimen was demolded at one day after casting, then cured in the tap-water until 28 days. After that, both ends surface for reinforced concrete prism were coated by epoxy resin before subjected to various exposure condition with specimen condition full immersion. For dry-wet cycle, one cycle was 7 days, consisted of 5 days drying (air dry) and 2 days wetting (immersed in tap-water and sea-water). Then, for continuous immersed, specimen put into in 3% NaCl solution. All of the specimen put in the uncontrolled room temperature (atmosphere condition). Variation of reinforced concrete prisms and influencing parameters are summarized in Table 3 and Table 4, respectively.



Fig.1 Detail of specimen (in mm)

Table	93\	/ariation	of	concret	te s	pecimer	۱
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	Concrete Cover (mm)						
	30		50	)	70	30	
т	Exposure condition						
I ype	Dry-Wet					Continuous	
			Immersed				
	S.W	T.W				NaCl (3%)	
	Crack Width, mm						
	0.3	0.3					
OPC	С	B/C	B/C A/B A B			С	
BFS4000	D	D	D	-	-	D	

Table 4 Influencing	parameters
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Group	Considerations
	Constant: binder (OPC), w/b 0.50, concrete cover 50 mm
A	Variation parameter: crack width (0.3; 0.5 mm)
D	Constant: binder (OPC), w/b 0.50, crack width 0.3 mm
	Variation parameter: concrete cover (30;50;70 mm)
	Constant: binder (OPC), w/b 0.50, crack width 0.3 mm
С	Variation parameter: exposure condition
	(tap-water; sea-water; NaCl)
	Constant: w/b 0.50, crack width 0.3 mm
D	Variation parameter: binder (BFS), concrete cover (30;
	50 mm)

After 28 days curing, all reinforced concrete prism specimens were pre-cracked through four-point flexural machine loading. Before loading, the  $\pi$ -gauge was mounted on the bottom side to measure the maximum

crack width during loading. Further, the maximum crack width just after unloading was measured also. The crack width was set over the limit value of crack width  $(w_a)$  based on JSCE standard in severely corrosive environment [4]. Photo 1 shows loading condition for pre-cracking by flexural bending and crack width measurement by scale crack. The crack width for each specimen are summarized in Table 5.

Table 5 Crack width

		Crack (mm)			
Group	Specimen		Maximum		
1		Target	Loading	Unloading	
			π-gauges	Scale Crack	
С	N-30-0.3-SW	0.30	0.30	0.30	
B/C	N-30-0.3-TW	0.20	0.24	0.20	
A/B	N-50-0.3-TW	0.30	0.34	0.50	
А	N-50-0.5-TW	0.50	0.65	0.50	
В	N-70-0.3-TW	0.30	0.30	0.25	
С	N-30-0.3-NaCl	0.30	0.48	0.30	
D	B-30-0.3-SW	0.30	0.34	0.30	
D	B-30-0.3-TW	0.20	0.24	0.20	
D	B-50-0.3-TW	- 0.30	0.34	0.30	
D	B-30-0.3-NaCl	0.30	0.32	0.25	



(a) (b) Photo 1 (a) Pre-cracking loading; (b) Crack width measurement

## 2.4 Experimental Methods

The half-cell potential was measured after one hour from the end of wet cycle by using the silver/silver chloride reference electrode (SCE) close to crack location (Fig.2) periodically. Reference electrode put a bit shifted location from the crack portion in order to avoid the potential from incorrect value in case of the filled crack water. Then, potential value is converted to the value against copper/copper sulfate reference electrode (CSE) according ASTM C876-09 [5].



Fig.2 Immersion and measurement condition

Corrosion rate is expressed as the corrosion current density  $(I_{corr})$  is inversely related to the polarization resistance. Interpreting of corrosion rate measurements based on the finding of Andrade [6].

Anodic polarization curve was measured in order to evaluate the condition of passivity film on the steel

surface. When the current density becomes larger, it supposes the grade of passivity film of steel bars becomes worse and the slope of anodic curve towards a more anodic region or high of current density. In the measurement of anodic polarization curve, the potential of the steel bar ( $E_{corr}$ ) was shifted to +700 mV from the natural potential with a sweep rate of 50 mV/min. The maximum current density obtained, then used to judge passivity grade based on the proposal of Otsuki [7].

## 3. RESULTS AND DISCUSSION

# 3.1 Half-cell Potential (HCP) and Corrosion Current Density (I<sub>corr</sub>)

(1) Effect of crack width

Half-cell potential of steel bar in associated with crack width is shown in Fig. 3. N-50-0.3-TW and N-50-0.5-TW had a different crack width but concrete cover was same. According to ASTM C876-09 standard, N-50-0.5-TW showed corrosion initiation start after 170 days, while N-50-0.3-TW at 492 days. These result confirm that potential towards to more negative charge not only in the presence of cracks but also with increasing of crack width.



Fig. 3 Half-cell potential of steel in OPC cement exposed to tap-water dry-wet cycle



Corrosion rate of steel bar in associated with crack width is shown in Fig. 4. N-50-0.5-TW at 184 days of exposure showed just in the threshold line for active corrosion rate. This condition was similar with the HCP which just in the threshold line for corrosion initiation. The surface area of exposed steel in N-50-0.5-TW crack widths higher than in N-50-0.3-TW. This may result an increase in corrosion rate, in the presence of oxygen.



exposed to tap-water dry-wet cycle



cement exposed to tap-water dry-wet cycle

(2) Effect of concrete cover

The half-cell potential of steel bar in associated effect of concrete cover in shown Fig.5. The specimens N-30-0.3-TW, N-50-0.3-TW and N-70-0.3-TW were different concrete cover but same crack width showed the potentials tend to merge. The effect of concrete cover starts to seems after ~500 days. The increase in concrete cover of the specimens would reduce the availability of oxygen to the cathode by increasing the thickness through which the oxygen must pass. The other reason, oxygen and water in cement matrix might be consumed all due to the hydration of cement almost completely. Thereby, potential towards more positive after certain time (i.e., crossed the 90% of no corrosion threshold) in the following order: N-70-0.3-TW (506 days)> N-50-0.3-TW (541 days)>N-30-0.3-TW (569 days). Further, corrosion rate of steel in cracked concrete in the OPC cement which influence concrete cover is shown Fig. 6. The corrosion rate behavior of specimen N-30-0.3-TW, N-50-0.3-TW and N-70-0.3-TW tended to merge together again. It corresponds with

the result of half-cell potential in Fig. 5. Corrosion rate from the start of exposure test until 569 days of exposure, showed in weak corrosion rate.

(3) Effect of exposure condition

The half-cell potential of steel in cracked concrete specimens made with OPC and exposed to the three environments are plotted against time of exposure in Fig.7. The worse condition showed by specimen continuous immersed in 3% NaCl solution. The corrosion initiation started from 16 days of exposure. While specimen exposed into dry-wet cycle in seawater N-30-0.3-SW showed the potentials recover after 81 days of exposure. Further, N-30-0.3-TW showed 90% of no corrosion even after 569 days of exposure. Implies even the oxygen supplies restricted due to continuous immersed, but crack take an important role by accessing chloride easily to reached steel bar surface then make the potentials towards more negative value. The other reason, NaCl increases the conductivity of corrosive liquid thus increasing the rate of the reaction of iron with dissolved oxygen. After about 400 days the potentials showed a slightly recover in all specimens. Indicated the corrosion products may fill the crack and then slow down the migration of chloride [8] (for specimen exposed into sea-water and NaCl) and oxygen [9], then reduces strongly the corrosion activity [10].



Fig. 7 Half-cell potential of steel in OPC cement exposed to the three environments

In the Fig. 8 exemplify the corrosion rate in the three exposure condition. Corrosion rates for the specimen subjected to dry-wet cycle in tap-water and sea-water standing almost in weak corrosion rate during exposure. While N-30-0.3-NaCl which continuous immersed in NaCl showed an active corrosion rates from 37~140 days for a given concrete cover and crack width were same. Then, from 492 days the corrosion rate increased with moderate. It might be due to enter the ascending phase, where the rate of transporting oxygen and moisture is faster than the rate of consuming oxygen and moisture, thus, the corrosion rate tends to increase.

#### (4) Effect of supplementary cementitious materials

The half-cell potential of BFS concretes with contained 50% of blast furnace slag is shown in Fig. 9. The potentials of B-30-0.3-TW and B-50-0.3-TW showed a trend similar. Therefore, implies concrete

cover less influence for a given crack width was same. Further, B-30-0.3-SW in the early six months showed the potentials more negative than -350 mV. However, after 170 days of exposure the potentials was recovery. It is interesting to observed the BFS specimen which exposed into continuous immersed in NaCl solution. The corrosion potentials of steel even reached lower than -700 mV. Granulated blast furnace slag is a glassy by-product of iron-making and it contains manganese and other species such as sulphides (S<sup>2-</sup>, HS<sup>-</sup>, Sn<sup>2-</sup>) that provide a reducing effect and lead to very negative potential values particularly specimen exposed into sodium chloride (NaCl). However, the potentials of BFS specimen tend to recover after 541 days, where in OPC specimen was not recover which also exposed in NaCl.



Fig. 8 Corrosion current density of steel in OPC cement exposed to the three environments



Fig. 9 Half-cell potential of steel in BFS cement exposed to the three environments

The effect of supplementary of cementitious materials noticeable in BFS specimen. The high early corrosion rates in the BFS specimens (Fig. 10) corresponded to the high HCPs measured in these specimens. Corrosion rates in all cases showed an active corrosion rate which cross the threshold for active corrosion (1  $\mu$ A/cm<sup>2</sup>). While OPC specimen showed a weak corrosion rate until 37 days of exposure. Only that in NaCl exposure test of OPC specimen cross the threshold for an active corrosion rates after 37 days. Moreover, the corrosion rate of BFS specimen tend to

decreased into a weak corrosion rate. Except, B-30-0.3-NaCl which exposed to NaCl, the corrosion rate showed an active state during 135~303 days of exposure. These can be attributed to the presence of sulfides in slag concretes [1].



Fig. 10 Corrosion current density of steel in BFS cement exposed to the three environments

## 3.2 Anodic Polarization Curve

#### (1) Effect of crack width

Anodic polarization curve N-50-0.3-TW and N-50-0.5-TW is shown in Fig. 11. N-50-0.5-TW showed the worse passivity condition than N-50-0.3-TW. It indicates for the same concrete cover, crack width experiencing influence. The wider of the crack, the worse of passivity would be.

(2) Effect of concrete cover

Anodic polarization curve after 18 months of exposure is shown in Fig. 11. For a given same crack width but different concrete cover, passivity condition generally better in the following order: N-70-0.3-TW>N-50-0.3-TW>N-30-0.3-TW. Increasing concrete cover mean restricted oxygen supplies in cathodic reaction. Therefore, releasing  $Fe^{2+}$  in anodic area will be delayed. Because of that, then passivity film will keep maintain.

(3) Effect of exposure condition

Anodic polarization curve of specimen subjected into three exposure condition is shown in Fig. 11. N-30-0.3-TW, N-30-0.3-SW and N-30-0.3-NaCl have same concrete cover and crack width. The worse passivity condition showed in NaCl followed Sea-Water and Tap-Water. Noticeable, N-30-0.3-NaCl even that continuous immersed (i.e., oxygen supplies restricted) however has a higher current density. Implies that the amount of chloride near steel bar surface enough to generated higher of current density and towards more anodic region.

(4) Effect of supplementary cementitious materials

Anodic polarization curve of specimen with supplementary cementitious materials is shown Fig. 11. The trend of passivity similar with OPC specimen. The worse condition showed by NaCl followed Sea-Water and Tap-Water. Noticeable that BFS specimens superior than OPC specimen particularly in NaCl environment. After 18 months of exposure, anodic polarization curve of BFS specimen better than OPC specimen. The dense pore structure of BFS cements also impedes the flow of moisture and oxygen to steelconcrete interface, thereby retarding the anodic reaction. Further, BFS cement induced a delay in penetration of chlorides ions compared to OPC cement [11]. Therefore, by delaying of penetration of chlorides, then corrosion will be delayed. Another interesting point showed by B-50-0.3-TW. For a given crack width was same, the anodic polarization behavior similar with B-30-0.3-TW. Concretes containing BFS (supplementary cementitious material) already had suppressed levels oxygen or a sufficiently high resistivity so that a further increase in concrete cover had little effect.





Fig. 12 Development of current for all specimen

(5) Summary of Anodic Polarization Curve

The maximum current from anodic polarization curve for every six months of measurement then plot in Fig.12. While Table 7 showed passivity grade every six months constructed from the Fig.12 based on the criteria for the passivity grade in Table 6. From Fig.12 it can be seen that increased the concrete cover, the better passivity will. This pointed out by N-30-0.3-TW, N-50-0.3-TW and N-70-0.3-TW. The lower of current density in the following order: N-70-0.3-TW < N-50-0.3-TW < N-30-0.3-TW. Further, the specimens subjected to three different environment showed that the worse condition by immersed in NaCl followed by sea-water and tap-water. The specimen which immersed in NaCl has the higher of current density in the four times of anodic polarization measurement. The trend also continues to the BFS specimens. The higher of current density based on the exposure condition as follow NaCl>sea-water>tap-water.

In Table 6 the passive grade determined from the maximum current density obtained in anodic polarization curve and chloride content around steel bar surface provide also. Some of the specimens had a similar grade after certain time. However, during anodic polarization test has a different maximum current density. This is due to a judge of passive grade based on the current ranges. Only specimen in NaCl, both OPC and BFS specimens already in second grade for passivity grade. Further, BFS has a higher corrosion rate than OPC at the beginning. However, beyond about 6 months the corrosion sharply reduced. The higher corrosion rate for BFS compared with OPC may attributable to a reduction in OH concentration as a result of the pozzolanic reaction.

Table 7 Summary of passivity grade and chloride content

	Passive Grade Months			Chloride Content Steel Bar Surface	
				kg/m <sup>3</sup>	
0	6	12	18	Crack	Un-crack
III	IV	IV	IV	2.59	0.86
II	III	III	IV	-	-
II	IV	IV	IV	-	-
IV	IV	III	IV	-	-
III	IV	IV	IV	-	-
II	III	III	II	4.37	0.95
II	IV	IV	IV	0.84	0.89
II	IV	IV	IV	-	-
II	IV	IV	IV	-	-
II	III	II	II	0.65	0.75
	0 III II IV III II II II II II	Passive 0 6 III IV II III IV IV IV IV III IV III IV II IV II IV II IV II IV II IV II IV II IV	Passive Grade       Months     Months       0     6     12       III     IV     IV       II     III     III       II     IV     IV       IV     IV     IV       IV     IV     III       III     IV     IV       III     IV     IV       II     III     III       II     IV     IV       II     IV     IV       II     IV     IV       II     III     II       III     III     II	Passive Grade       Months     Months       0     6     12     18       III     IV     IV     IV       II     III     II     IV       II     III     II     IV       IV     IV     IV     IV       II     IV     IV     IV       IV     IV     IV     IV       II     IV     IV     IV       II     III     III     II       II     IV     IV     IV       II     III     II     II	Passive Grade     Chlorid Steel B       Months     k       0     6     12     18     Crack       III     IV     IV     IV     2.59       II     III     II     IV     -       IV     IV     IV     -     -       IV     IV     IV     -     -       III     IV     IV     IV     -       III     IV     IV     IV     -       II     III     II     14.37     -       II     IV     IV     IV     -       II     III     II     II     0.65 </td

# 4. CONCLUSIONS

This study has contributed towards an improved understanding of the combined influences of crack width, cover, exposure condition and supplementary cementitious materials (SCMs) on electrochemical behavior of steel in cracked concrete. However due to the limitation of any supplementary experimental data to close it with the final conclusion. Therefore, the following possibilities and suggestions for any further research can be drawn:

- Crack width experiencing an influence for a given concrete quality (binder type and w/b ratio) and concrete cover were same. Corrosion rate increased with increasing crack width particularly in OPC. However, it is suggested that utilization of SCMs (50% BFS), the impact of increasing crack width can be possibility reduced.
- 2. Corrosion rate decreased with increasing concrete cover for a given concrete quality (binder type and w/b ratio) and crack width were same. However, it is suggested that the corrosion rate in BFS probably were less affected than in OPC.
- 3. Exposure condition more affected particularly in high of chloride environment such 3% NaCl for a given concrete quality (binder type and w/b ratio), concrete cover and crack width were same. However, the influence of differences w/b ratio is not clear. Therefore, it is suggested for any further research with different w/b ratio.

4. In high of chloride environment, such 3% sodium chloride (NaCl), it is thought that BFS is better than OPC only for a given concrete quality w/b, concrete cover and crack width were same.

# ACKNOWLEDGEMENT

The first author wishes to thank Indonesia Endowment Fund for Education (LPDP) for financial support during study.

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