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## Startup Thailand: A New Innovative Sacrificial Anode for Reinforced Concrete Structures

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**Abstract.** Severe damage reinforced concrete structures affected by corrosion are increasing. The study of prevention and protection technique play an important role to cope this urgent issue. Usage of different types of surface coatings on concrete/rebar are highly depend on workmanships of construction. Thus, sacrificial anodes are offered as one of the corrosion prevention technique. The discrete sacrificial anodes are comprise of zinc metal covered with a high alkalinity mortar which sacrifices itself to protect the corrosion of rebar. The key parameter of sacrificial anode in concrete is the activating mortar. It will help the overall cathodic reaction to efficiently protect reinforcing steel. Therefore, a new sacrificial anode was then accomplished in new activating mortar components. Two different activating mortar type have been established. This research investigated the performance of the new sacrificial anodes installed in the concrete prisms, slabs, and concrete water tanks in order to explore the corrosion prevention performance as per NACE [1], ISO [2] and ASTM standards [3-4]. This experimental study was tested on ASTM G109 [3], ASTM C876 [4] and small-scale water tank suffering from chloride-induced corrosion of the reinforcement. The performance of the anodes was determined at 28 days age and 365 days after installation to assure the activating time dependency for the mortar. The results of concrete prisms and slabs revealed that the anode polarized the rebar at a significant potential. For the water tank test results, two different concrete type were conducted with exposing chloride solution and assessed using close-interval potential mapping. The results showed a good agreement with enhance the structural durability.

**Keywords:** Sacrificial anode, Zn alloy, reinforced concrete, corrosion.

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## 1. Introduction

Application of cathodic protection system (CP) on reinforced concrete structure has been developed to prevent the onset of corrosion either for existing reinforced concrete structures or to new RC structures [5].

Normally, the alkaline environment of concrete will change the condition of reinforcing steel from corrosion state to passive state. This passive state will help to prevent the reinforcing steel from corrosion. However, concrete is porous. If concrete is surrounded by water or moisture containing chloride such as seawater, brackish water, deicing salt, salty ground water and etc. for many years, the concrete will be contaminated with chloride ions. Finally, chloride ions will attack the reinforcing steel and cause corrosion [6-10].

Carbonation is another serious problem for reinforced concrete. Carbonation reduces pH in concrete from between 12.6 and 13.8 to about 8 which will cause the condition of the reinforcing steel to shift from passive state back to corrosion state.

To prevent these corrosion problems, there are two desired techniques. The first is to minimize or delay penetration of chloride ions or carbon dioxide using coating techniques or some additive to make concrete more difficult for penetration. The second is to allow chloride ions or carbon dioxide into the reinforced concrete but prevent the reinforcing steel from corrosion using cathodic protection technique.

The first method cannot control the corrosion completely because the coating is damaged or the concrete is cracked always. Prevention of the coating or concrete from damage or crack is nearly impossible. Therefore, prevention of chloride ions or carbon dioxide to penetrate concrete is nearly impossible as well or will cost a lot of money.

For cathodic protection system (CP), there are two types, impressed current cathodic protection (ICCP) and sacrificial anode cathodic protection (SACP). ICCP needs external power supply, inert anodes and wiring to complete the circuit of cathodic protection system. Thus, the ICCP will require additional maintenance and monitoring which will result in additional operating costs [11].

SACP uses sacrificial anodes such as zinc, aluminium, magnesium and their alloys which have lower electrochemical potentials than steels or cathodes. Therefore, current flow in the cathodic protection system comes from the potential difference between the anodes and cathodes. The major advantages of SACP are easier installation, less initial cost, maintenance and monitoring, higher reliability and less risk to hydrogen embrittlement in high strength prestressed steel because of low driving voltage.

The present invention relates to sacrificial anode cathodic protection of reinforcing steel in concrete. The sacrificial anodes for reinforced concrete in many patents are zinc, aluminium and alloys thereof. In this invention, zinc and its alloys are preferred as sacrificial anode [12-16]. Zinc has a relatively low rate of expansion compared to other metals including steel [17]. Aluminium and its alloys tend to cause cracking in concrete because of higher volume expansion after they provide the current to the reinforcing steel for some period of time.

The zinc or zinc alloys must be surrounded in the environment with high pH to prevent passivation. The pH should be at least 14. LiOH, NaOH or potassium hydroxide (KOH) can be used to activate zinc or zinc alloys [12-16]. However, NaOH and KOH will react with silica aggregates to form gel. This reaction is called alkali silica reaction or ASR. Lithium ion can provide protection against ASR in concrete so LiOH is preferred as activator. NaOH or KOH can also be used as activator for zinc and zinc alloys but they need to mix with LiOH to prevent ASR.

Conventionally, the amount of LiOH, NaOH and KOH in mortar is greater than 2%, 4% and 5% by weight respectively. However, the concentration of LiOH, NaOH and KOH in mortar will become lower after the anode has been used for many years because of the reaction and dilution. This will result in the passivation of anodes. To prevent this problem and enhance the anode performance in concrete, higher concentration of the chemicals (LiOH, NaOH or KOH), is needed.

According to the standard EN ISO 12696 [2], current densities to be applied for cathodic prevention range between 0.2 mA/m<sup>2</sup> and 2 mA/m<sup>2</sup> of steel reinforcement surface compared with a range of 2 mA/m<sup>2</sup> to 20 mA/m<sup>2</sup> of steel reinforcement for cathodic protection on existing structures [2]. The standard states that protection is ensured when one of the following three conditions is verified for the whole reinforcement:

In this paper, the effect of environmental conditions on the corrosion behavior of reinforcing steel with different concrete properties and structure types in NaCl solution were investigated. Two different activating mortar properties and the activating time dependent were considered. This efficiency was assessed analyzing the ability of CP prevention treatments on the reinforcing according to 100 mV potential decay criteria. Moreover, the potential mapping was conducted to determine the performance.

## 2. Experimental Program

This section describes the testing regime employed to evaluate the performance of the sacrificial anode.

### 2.1. Testing Regime

Assessing the sacrificial anode against the EN ISO 12696 standard and the potential of standard reference electrode is well established non-destructive monitoring technique. The ASTM standard specimens and slabs were prepared for determination of the relative corrosion prevention by different concrete using macrocell corrosion measurements. Three testing procedure were conducted. The procedures were taking in to account the effect of time dependency while activating the anode: 1) activating anode by exposing NaCl solution after anode was manufactured in order to validate the performance of the anode to meet the EN ISO 12696 standard, two different type of sacrificial anode, anode type A and B, were installed. And, 2) activating anode by exposing NaCl solution after anode was manufactured and preinstalled for 365 days. Finally, 3) sacrificial anodes were applied to twelve concrete water tank poured with NaCl solution and measured the potentials. The activating histories was given in Fig 1. Comparing corrosion behavior with concrete coating specimens were then focused.

### 2.2. Materials and Mixture Proportions

Galvanic anode with diameter of 68 mm and a thickness of 30 mm, each containing of zinc and cover with high alkaline mortar as given in Fig 2, were preinstalled in concrete specimen and tied to steel reinforcing. A galvanized steel wire integrated with the galvanic anodes made a connection to the steel reinforcement. The core of anode shall consist of a minimum of 60 grams of electrolytic high grade zinc alloy in compliance with ASTM B418 Type II [18] cast around a pair of steel tie wires and encased in a highly alkaline cementitious shell with a pH of 14, the materials that uses activation methods to assure performance. The properties of zinc and cementitious shell are presented in Table 1. In this study, the cementitious shell sacrificial anode type A consisted of LiOH less than type B. Others chemicals were identical.

The concrete in this study using Ordinary Portland cement (OPC) Type I as per ASTM C150 [19]. Fine aggregate with a specific gravity of 2.476 in saturated surface dry (SSD). Coarse aggregate with specific gravity of 2.598 in saturated surface dry and a maximum size of 19 mm. All specimens were undertaken to determine half-cell potential and corrosion current density. The mix proportions of concretes are summarized in Table 2. Mix1 was used for test procedure 1) and 3). Mix2 was used for test procedure 2) to ensure that sacrificial anode show a good performance in different concrete strength, three concrete mixtures in Mix2 were designed. Thus, cylindrical concrete specimens 150 mm in diameter and 300 mm height were cast to evaluate the compressive strength in accordance with standard ASTM C39 [20].

Furthermore, coating technique is focused in this study. The crystalline coating material is grey powder consisting of Portland cement, silica sand, calcium dihydroxide and chemical compounds. The coating are mixed with water to form a slurry and applied to the surface of the concrete structure with a brush. The coating area is in only a ponding well. For brush application, the ratio between crystalline coating material and water ratio was 5:2 by bulk volume.

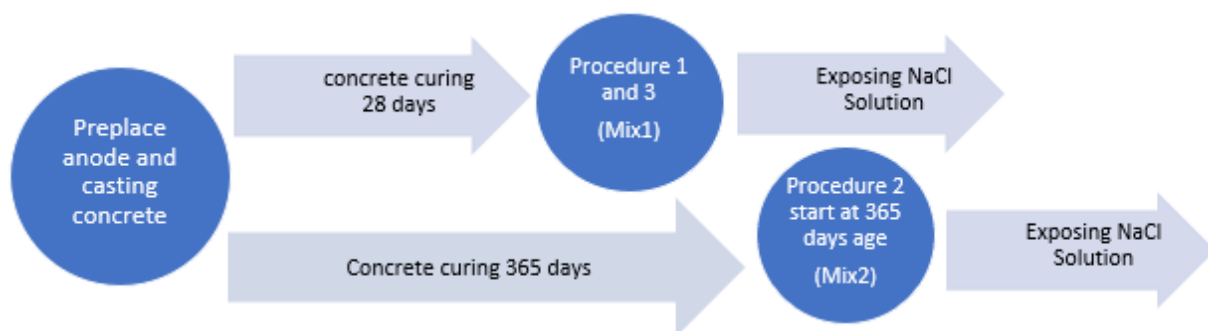


Fig. 1. Schematic diagram of test procedure.

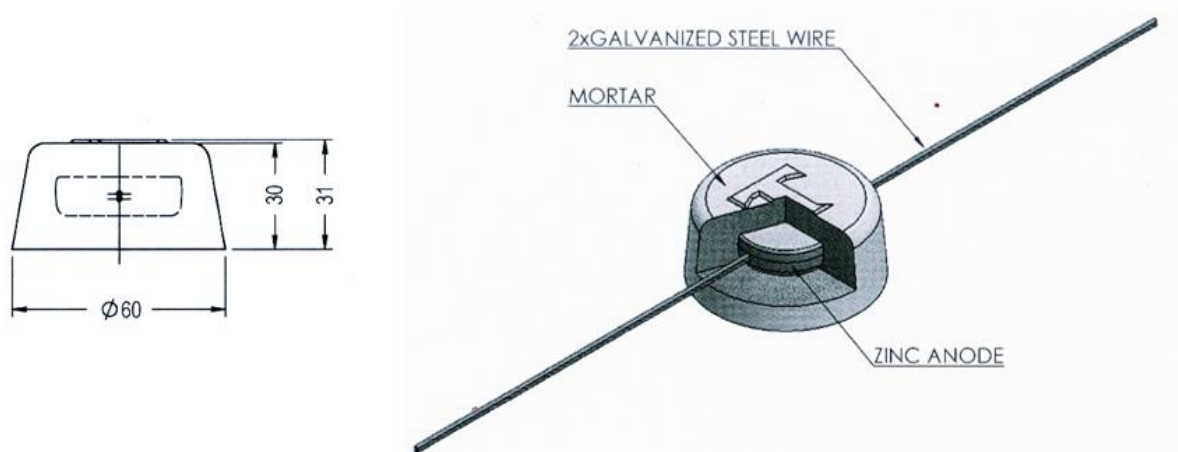


Fig. 2. A new innovative sacrificial anode for reinforced concrete structures.

Table 1. Properties of sacrificial anode and cementitious shell.

Property	Element or Component (%)					
	Pb	Fe	Cd	Al	Cu	Zn
Zinc Alloy	0.003max	0.014max	0.003max	0.005max	0.002max	remainder
Cementitious Shell	LiOH		NaOH or KOH		Mortar	
	4min		8-10		remainder	

Table 2. Mix proportions of concrete.

Mix Proportion	Mix1		Mix2	
water to cement ratios	0.86	0.6	0.5	0.45
Cement:Sand:Aggregate	1:2:4	1:2.13:2.82	1:1.65:2.35	1:1.4:2.1
Cement (kg/m <sup>3</sup> )	324	342	410	456
Water (kg/m <sup>3</sup> )	278	205	205	205
Sand (kg/m <sup>3</sup> )	912	730	678	641
Gravel (kg/m <sup>3</sup> )	1,582	964	964	964

### 2.3. Specimens Preparation

For prism specimens, an experimental study was conducted on specimens in accordance with ASTM G109 and was used for the determination of the relative corrosion protection by using macrocell corrosion measurements. All Specimen size was 280 mm x 150 mm x 115 mm (11 x 6 x 4.5 in) containing three lengths of 12 mm diameter deformed bars: one bar at the top with a cover depth of 25 mm and two at the bottom with a same cover depth as top bar as shown in Fig. 3. The rebars were cleaned and coated with epoxy resin to prevent extraneous effects. Each three prism specimens were installed with anode type A and B. The concrete with 3% of NaCl added (by weight) was produced. In addition, six slab specimens of 700 mm x 700 mm x 100 mm were separated into three categories by mixing with 0%, 1% and 3% NaCl (by weight) in the mixing water (Fig. 4). Each anode type A and B were used in three specimens. The specimen consisted of five horizontal and vertical steel bars at spacing 150 mm c/c with 12 mm diameter. Reinforcing steel bar could be electrically connected to allow the measurement a macro cell corrosion. Before sacrificial anodes were installed on the reinforcing steel, a multi-meter was used to verify proper anode connection and effectiveness. Electrical continuity was confirmed between the anode tie wires and reinforcing steel, if the resistance in circuit is less than 1 ohm, the anode is properly installed [2].

In order to evaluate the activating time dependent and different concrete type, by using Mix2, six prism specimens were manufactured as a control and four specimens were pre-installed using sacrificial anodes type B. The sacrificial anode was wired to only the top reinforcing steel. The specimens were exposed to wet-dry cycles of 0.856 mol/L NaCl solution as they were considered to correspond to a situation that was assumed to obviously fulfil the conditions for the occurrence of the reinforcement corrosion process.

In addition, twelve reinforced concrete water tank specimens of 600 mm x 600 mm x 600 mm were separated into two categories by using Mix1 with adding 0% and 30% fly ash. The specimens details are presented in Fig. 5. Each two specimens were control, sacrificial anode installed, and crystalline coating specimens. All tanks were poured 0.856 mol/L NaCl solution. Only sacrificial anode type B were installed at the center of the wall. The coated specimens were applied on only the surface inside of the water tanks. Curing time was three days before pouring the NaCl solution. The main reinforcing steel were 12 mm diameter at spacing 150 mm c/c and lateral reinforcing bars were 9 mm diameter. Reinforcing steel bar could be electrically connected to allow the measurement a macro cell corrosion.

For the coated specimens, the concrete mixture was Mix2. The coated area was considered defective to the different degrees 0, 1, 2 and 3%. These specimens were exposed to severe environment with wet-dry 0.856 mol/L NaCl solution. A total of concrete specimens as shown in Table 3.

### 2.4. Surface Treatments

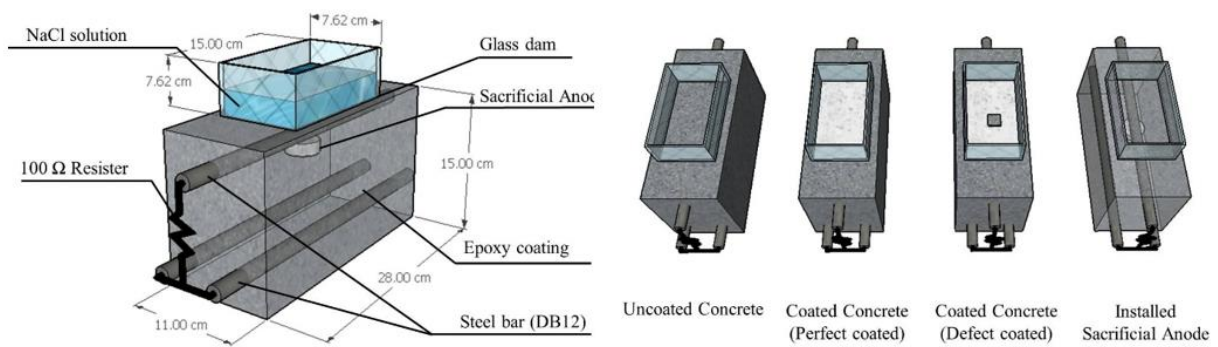
The coating treatment are conducted on concrete aged 28 days. The specimens are prepared in saturated surface dry condition. In order to produce a good bond, the surface must be free of oil, grease, dirt, and loose friable material, leaving a clean, sound concrete surface for coating application. Surface cleanliness is essential before applying crystalline coating with brush. The coating must be uniformly applied and should be approximately 1 mm thickness as shown in Fig. 6. The coverage rate for each crystalline coating is approximately 0.65-1.0 kg/m<sup>2</sup>. Coated concrete prism specimens need to be cured for 3 days and allowed to set for 18 days before exposed to severe environment as per the manufacturer's specifications. However, the water tank specimens were cured in only 3 days before pouring NaCl solution.

### 2.5. Exposure Chloride Environment

In marine environment, both temperature and chloride concentration in seawater change with time. The reinforced concrete structure commonly deteriorate in splash or tidal zone. The main goal of the research is to investigate the reinforcing steel due to corrosion. All specimens had been exposed to humidity room environment. Thus, the concrete specimens were exposed to wet-dry cycles chloride environment (NaCl mixture or solution by weight).

Table 3. No. of uncoated and coated concrete prism specimens.

Specimens	Uncoated specimen	Pre-installed sacrificial anode specimen	Coated specimens with Crystalline material			
			Perfect coated	Defect Coated		
				1%	2%	3%
Concrete (w/c = 0.45)	6	4	6	6	6	6
Concrete (w/c = 0.50)	6	4	6	6	6	6
Concrete (w/c = 0.60)	6	4	6	6	6	6



(a) Schematic illustration of concrete specimen

(b) Type of concrete specimen

Fig. 3. The concrete prism specimens were exposed to chloride environment.

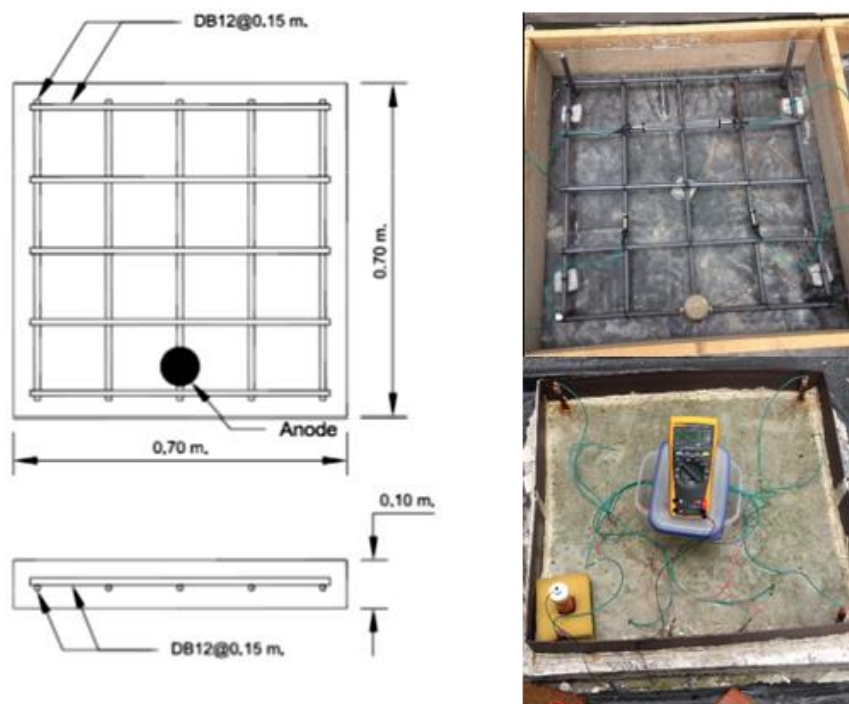


Fig. 4. The concrete slab specimens detail and preparation.



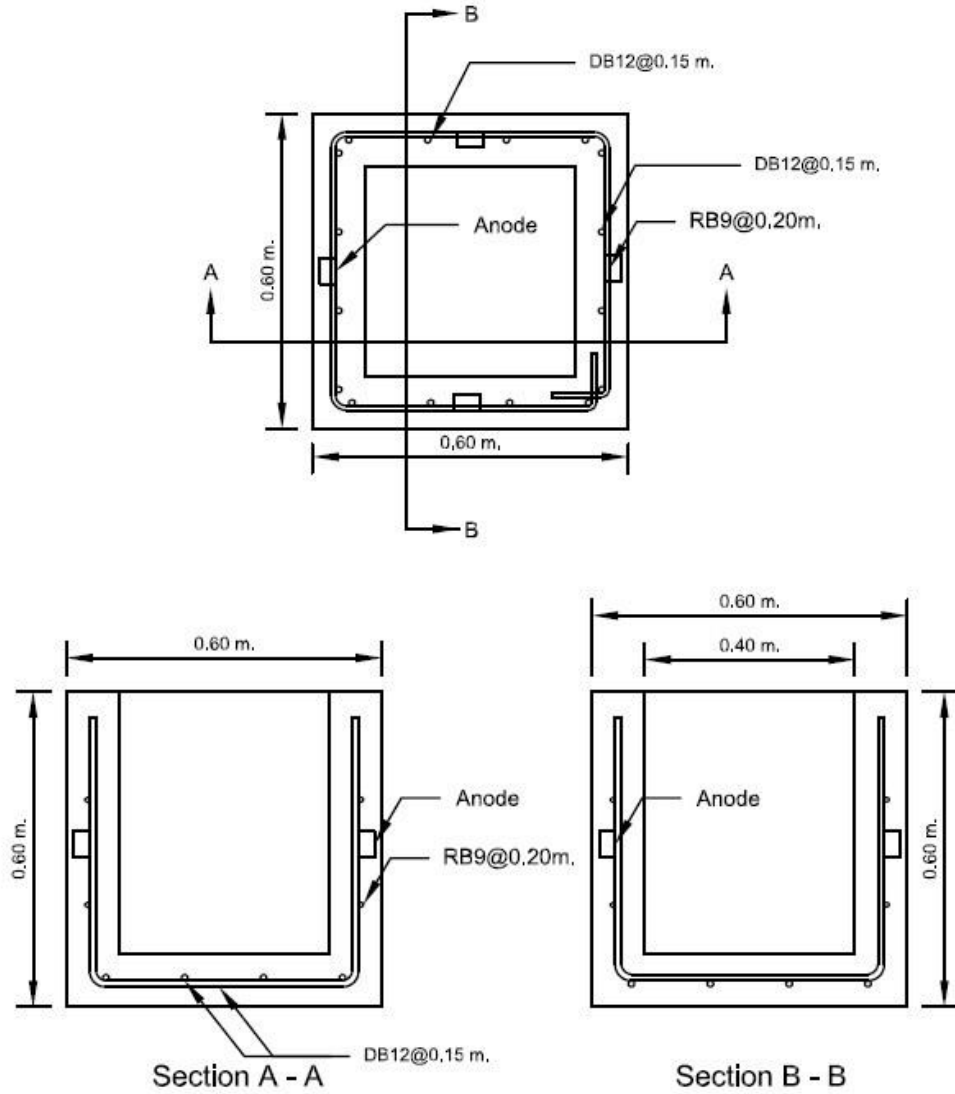


Fig. 5. The concrete water tank specimen schematic.



(a) Perfect Coated

(b) Defect 1%

(c) Defect 2%

(d) Defect 3%

Fig. 6. The specimens was coated on the area expose chloride environment with crystalline coating material.

### 3. Test Method

#### 3.1. Compressive Strength

The concrete cylinders specimens with diameter of 150 mm and 300 mm in length were stored in moist air for 24 hours and after this period the specimens were marked and removed from the molds. The entire specimens were kept cured and submerged for 28 days in clear fresh water until taken out prior to test. The results of concrete aged 28 days were average from three specimens. All specimens were tested in accordance with ASTM C39.

#### 3.2. Half-cell Potential Measurements

The half-cell potential measurement is undertaken generally as per ASTM C876. The probability of corrosion rate measurements are in Table 4 to obtain electrochemical condition of the specimens and to enable a clearer interpretation of test results. The surface of each prism specimen was marked to identify the measurement location. In addition, the surface of the concrete was wetted prior to measuring. The potential results were used to develop a potential map for the area tested.

Table 4. Probability of corrosion according to corrosion potential as per ASTM C876.

Corrosion potential (CSE)	Corrosion activity
> -200 mV	90% probability of no corrosion
-350 to -200 mV	Uncertain
< -350 mV	90% probability of corrosion

#### 3.3. Current Measurements

Corrosion current density,  $i_{corr}$  ( $\mu\text{A}/\text{cm}^2$ ) was calculated as per Eq. (1) from corrosion current ( $\mu\text{A}$ ) per exposed surface area of the reinforcing steel in 18 cm of length ( $\text{cm}^2$ ), the current was evaluated by measuring voltage (mA) and resistor ( $\Omega$ ). Calculate the current ( $I_j$ ) is calculated based on Ohm's law as per Eq. (2),  $R$  from the measured voltage across the resistor and  $V_j$  from measured in volts (drop across the resistor). [21] The following criteria for corrosion have been developed from field and laboratory investigations [22, 23] as shown in Table 5. The specimens were measured simultaneously with Half-cell potential was measured.

$$i_{corr} = I / A \quad (1)$$

$$I_j = V_j / R \quad (2)$$

Table 5. Corrosion current

Corrosion current ( $I_{corr}$ )	Condition of the rebar	Corrosion level
$I_{corr} < 0.1 \mu\text{A}/\text{cm}^2$	Passive condition	Negligible
$I_{corr} 0.1 - 0.5 \mu\text{A}/\text{cm}^2$	Low to moderate corrosion	Low
$I_{corr} 0.5 - 1.0 \mu\text{A}/\text{cm}^2$	Moderate to high corrosion	Moderate
$I_{corr} > 1.0 \mu\text{A}/\text{cm}^2$	High corrosion rate	High



## 4. Results and Discussions

### 4.1. Compressive Strength

The results of Mix1 concrete compressive strength was 17.4 MPa for control concrete and 16.3 MPa for 30% fly ash concrete. This compressive strength were slightly low. Because the Mix1 was a first procedure prepared to verify whether the new sacrificial anode was appropriately used in concrete matrix. The compressive strength of concrete (Mix2) at the age 28 days for control concrete with w/c ratios 0.45, 0.50 and 0.60 were 41.4, 38.2 and 31.3 MPa respectively. The results show that higher w/c ratios lead to lower compressive strength.

After the coating was done, compressive strength of uncoated and coated were tested again. The value in the uncoated concrete specimens with w/c ratios 0.45, 0.50 and 0.60 were 58.4, 56.2 and 44.2 MPa respectively. In the coated concrete with w/c ratios 0.45, 0.50 and 0.60 were 59.6, 56.8 and 44.5 MPa respectively. The results show that coated concrete with crystalline material slightly increased compressive strength. The results revealed that there is no significantly different in both types of specimens as shown in Fig. 7.

### 4.2. Half-cell Potential and Corrosion Current Density

The half-cell potential can serve as the most stable indicator for rebar corrosion initiation in chloride contaminated concrete [24]. The polarization and depolarization of the reinforcement are evaluated. All the potential are expressed versus the SCE reference. For Anode A, the polarization decay is 138 mV (Fig. 8(a)). Anode B show the potential of steel reinforcement at On Potential equal to -635 mv, Instant Off Potential equal to -615 mv and the Final Off Potential = -440 mV. Therefore, the polarization decay is 175 mV as per NACE and ISO criteria (Fig. 8(b)). The macrocell data are given in Fig. 9. It demonstrates that the sacrificial anode B show a uniform distributed current in protection afforded to steel than sacrificial anode A.

For the slab specimens, the half-cell potential results were collected and compared with the distance from sacrificial anode at every 150 mm. Sacrificial anode A and B potentials are demonstrated in Figs. 9 to 12. At dry cycles, the potential results were gradually increase because of the increasing of concrete resistivity. Thus, both sacrificial anode behave in the same trend. However, the potential mapping in Figs. 13 to 15 revealed that sacrificial anode B provided more uniform potential than sacrificial anode A. Especially, sacrificial anode B were found to be more efficient than sacrificial anode A at 16 weeks. Moreover, the polarization decay shift results for both anode were then gathered in Figs. 16 and 17. These were concluded that sacrificial anode B showed a significant performance than sacrificial anode A. Consequently, sacrificial anode B was then used for the rest of experimental test procedure.

The half-cell potential results of all control specimens are shown in Fig. 18. The potential of w/c =0.60, 0.50 and 0.45 began to reduce less than -350 mV after 56, 98 and 140 days respectively. It illustrated that the risk of steel corrosion is high. The half-cell potential measures increase with increasing w/c ratios, The compressive strength resulting from w/c ratios is one of the most important and useful properties of concrete, lower strength concrete shows the greater steel corrosion than higher strength concrete. Besides, the lesser water to cement ratio concrete showed the higher corrosion resistant by comparing with the current density results in Fig. 19. The current density results of control specimens showed that the corrosion of steel was initiate at 14 days. In contrast, the installed sacrificial anode specimens were protected by galvanic cathodic reaction. The potentials were between -500 mV to -660 mV. Monitoring verified that all the installed sacrificial anode specimens had their protection condition at the first 14 days. Moreover, there were the corrosion current density average about  $0.2 \mu\text{A}/\text{cm}^2$  which indicates that low to moderate corrosion activity as shown in Fig. 18. The current density results were slightly scatter due to wet or dry condition. The higher water to cement ratio specimens with sacrificial anode, the current density was average about  $0.6 \mu\text{A}/\text{cm}^2$  at 56 days which also resulted from cathodic polarization.

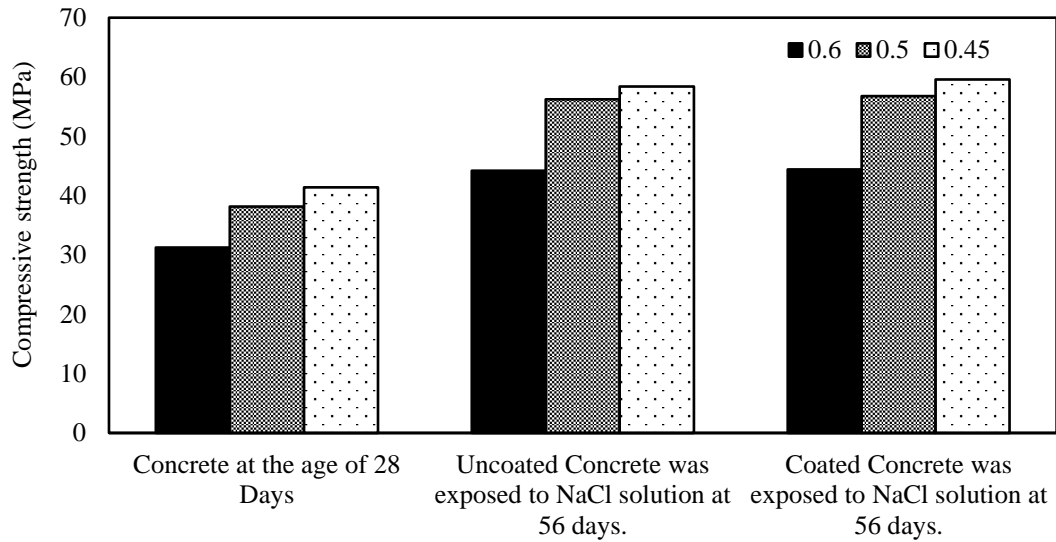
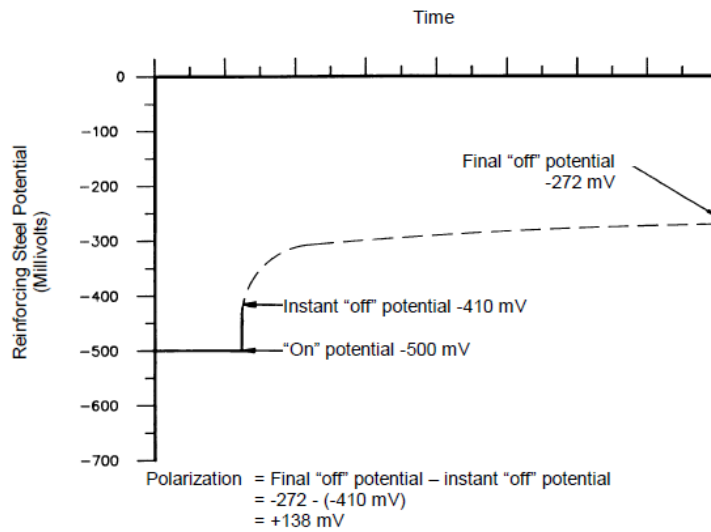


Fig. 7. Compressive strength of uncoated concrete and coated concrete after was exposed to humidity room environment for 365 days before investigate the possibility of steel corrosion.



a) Polarization decay result of sacrificial anode A



b) On Potential



c) Instant Off Potential



d) Final Off Potential

Fig. 8. Polarization decay measurement of sacrificial anode B.

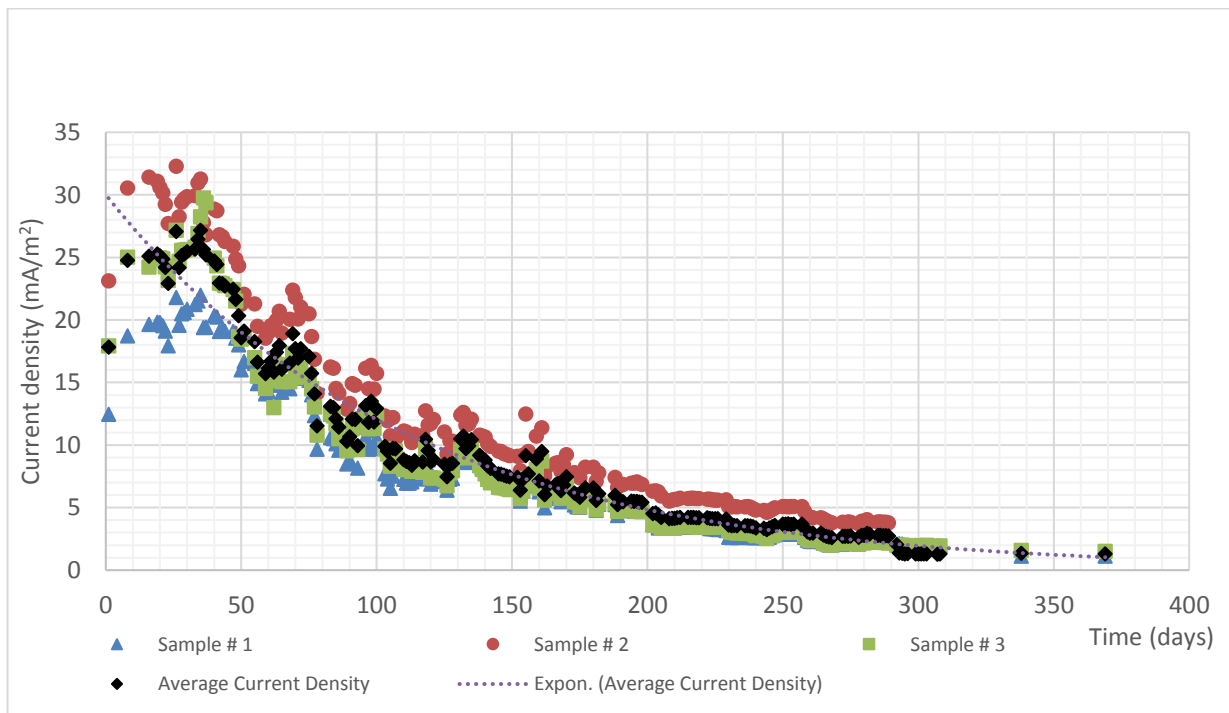
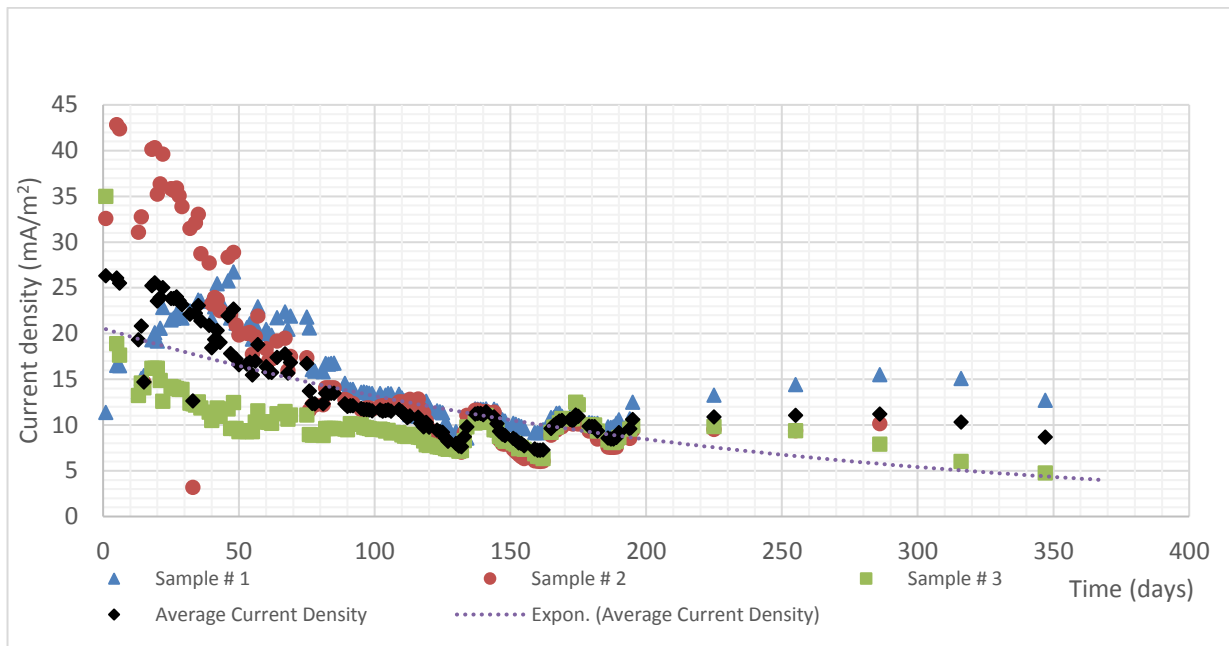
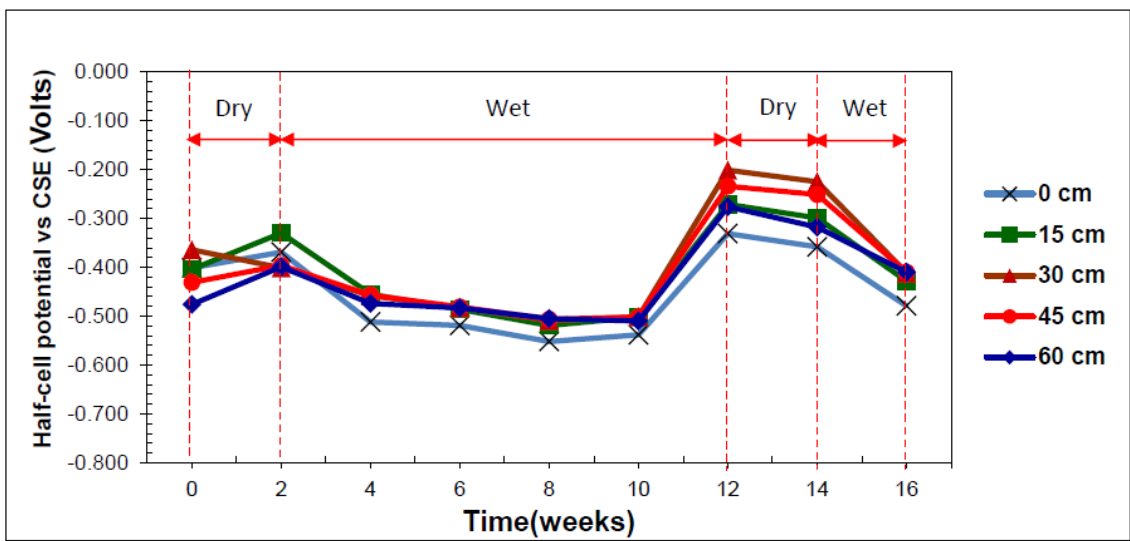
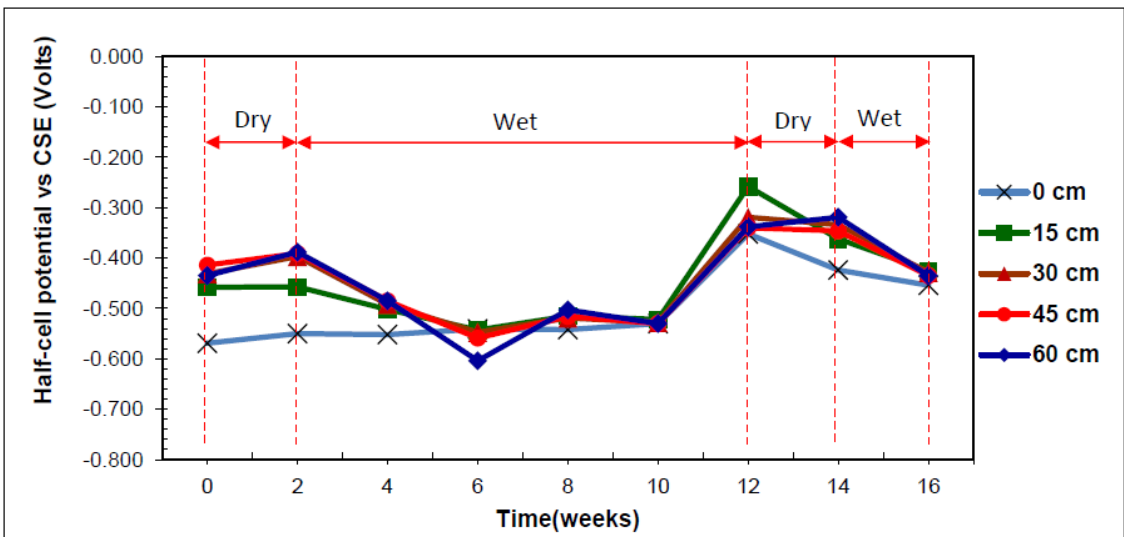


Fig. 9. Corrosion current density of reinforcing steel in prism specimens.

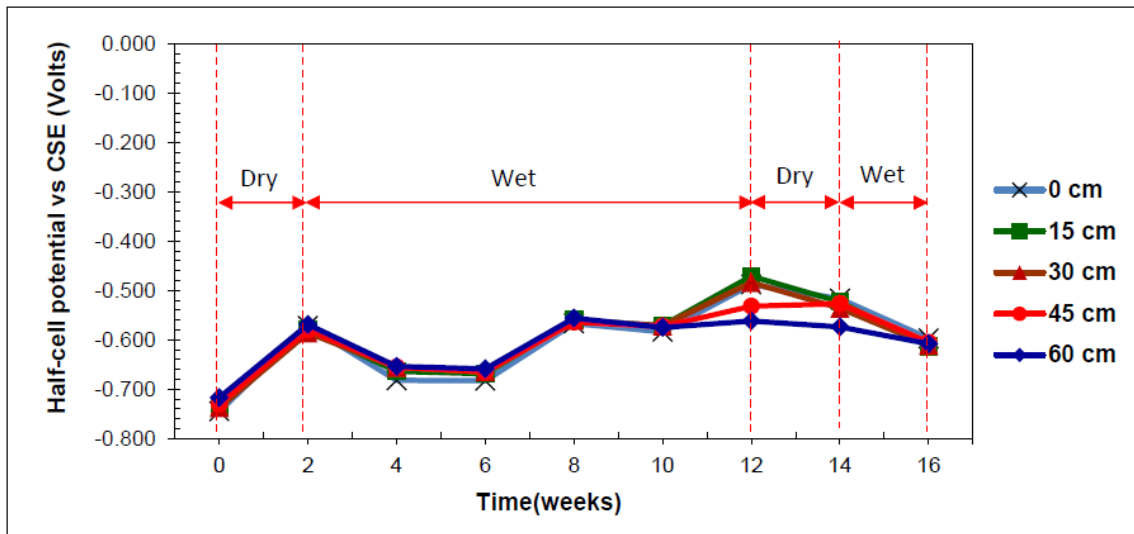


(a) Sacrificial Anode A

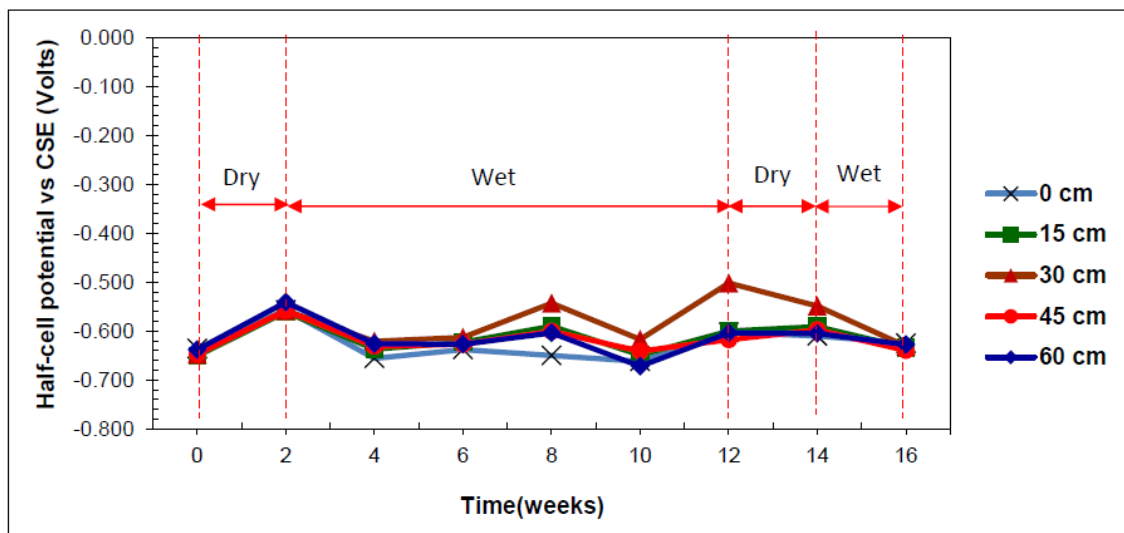


(b) Sacrificial Anode B

Fig. 10. Half-cell potentials of reinforcing steel for slab specimen exposing wet-dry cycles 0% NaCl.

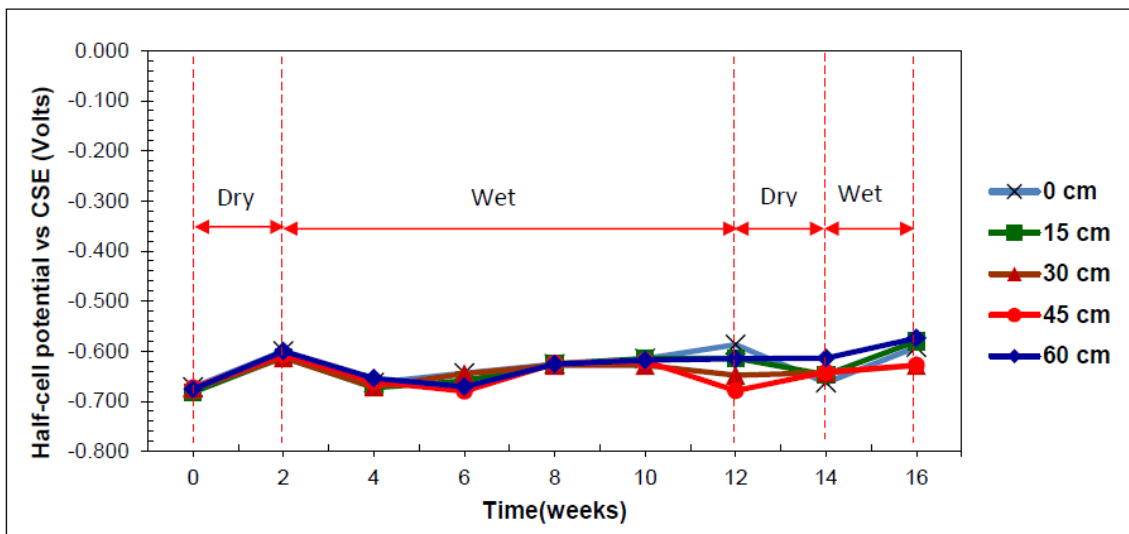


(a) Sacrificial Anode A

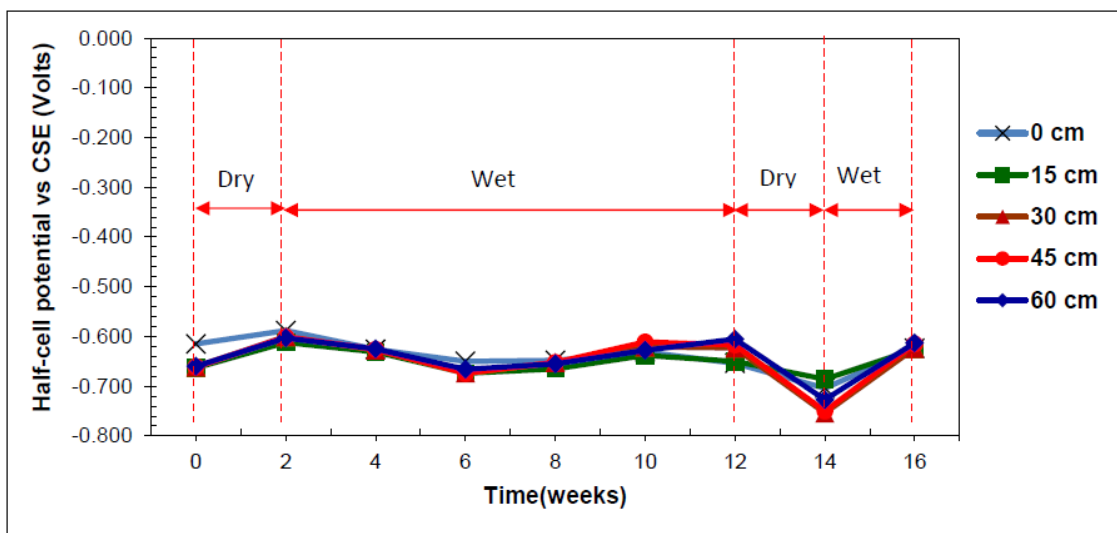


(b) Sacrificial Anode B

Fig. 11. Half-cell potentials of reinforcing steel for slab specimen exposing wet-dry cycles 1% NaCl.



(a) Sacrificial Anode A



(b) Sacrificial Anode B

Fig. 12. Half-cell potentials of reinforcing steel for slab specimen exposing wet-dry cycles 3% NaCl.

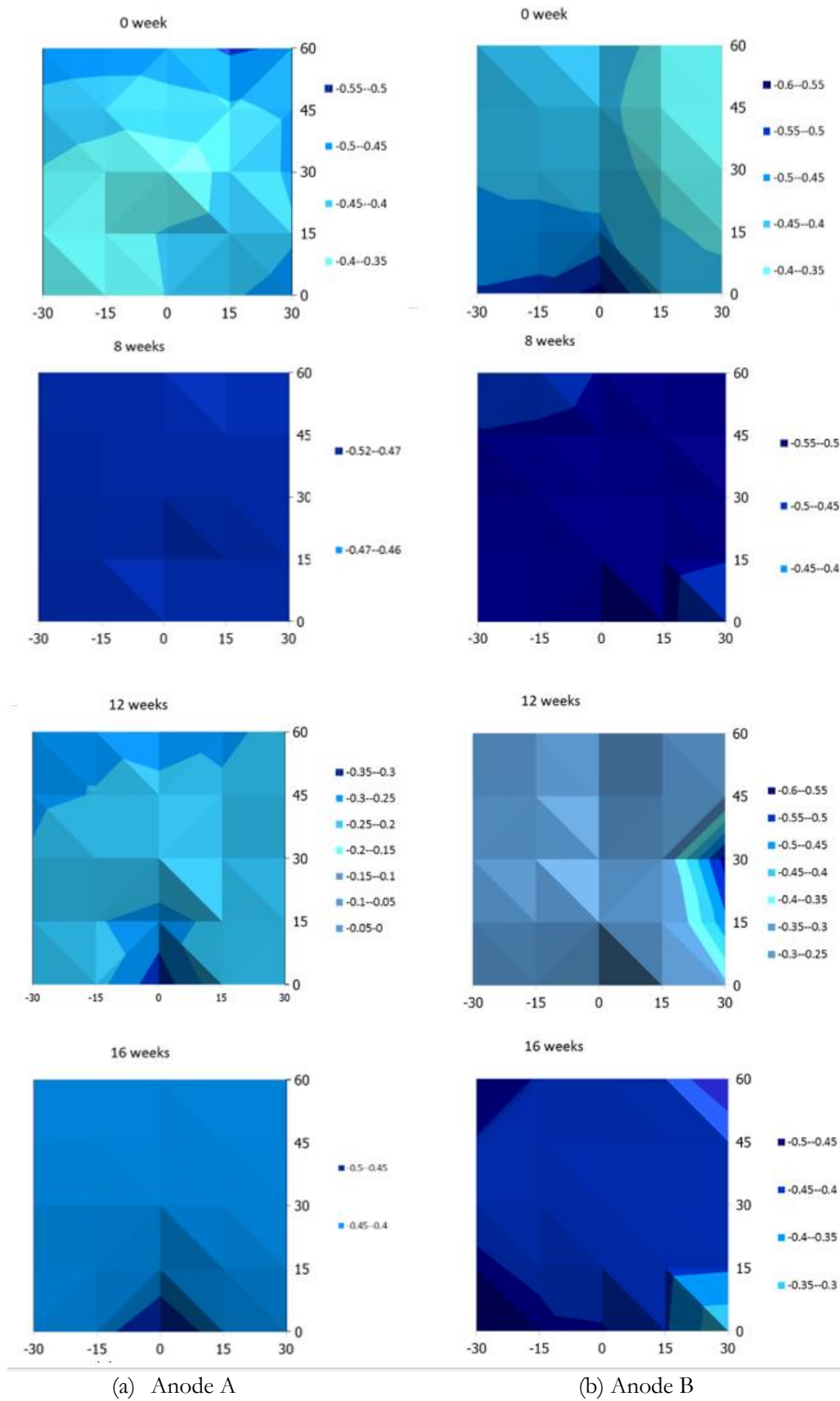


Fig. 13. Half-cell potentials mapping for slab specimen exposing wet-dry cycles 0% NaCl.



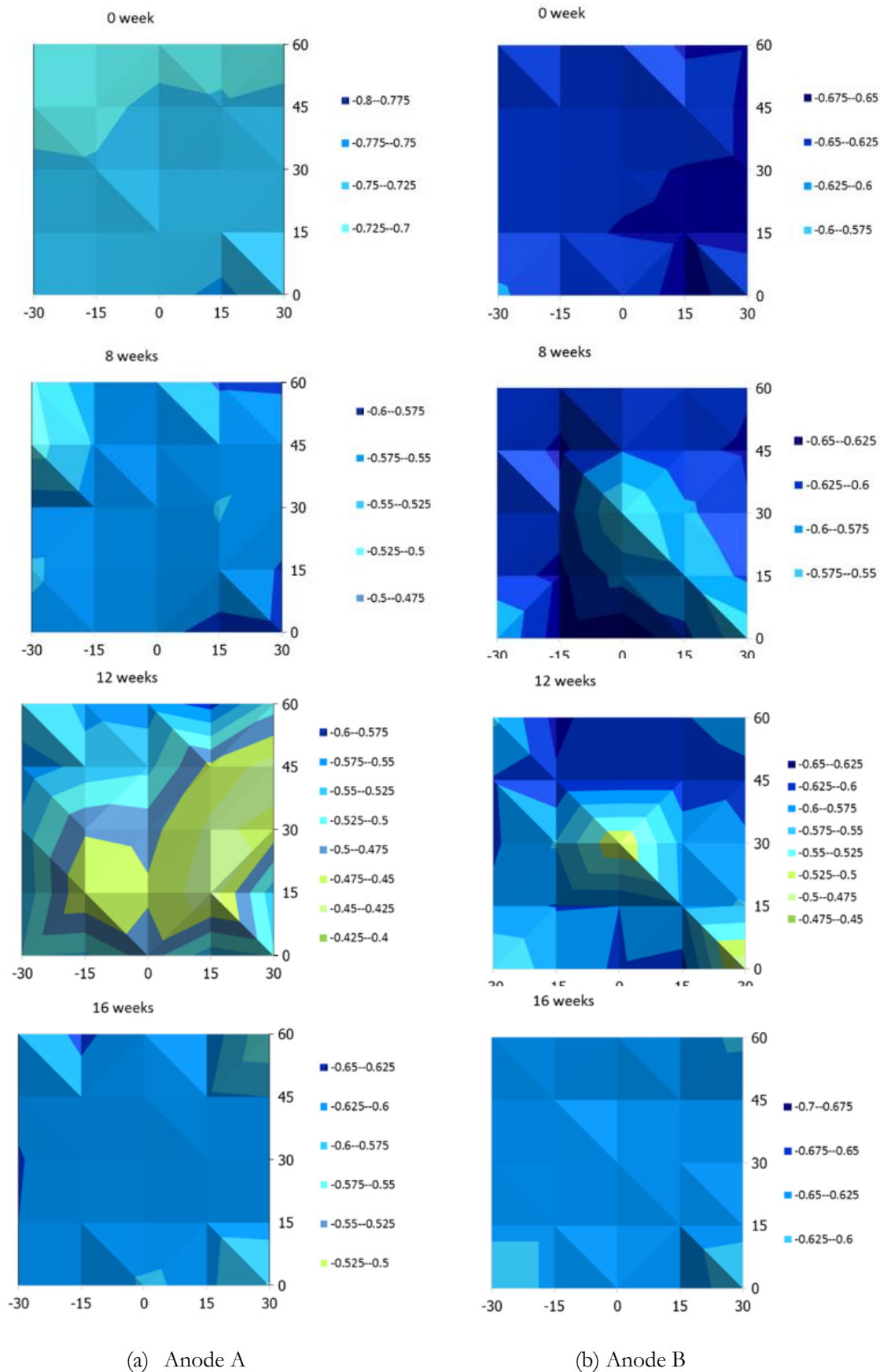


Fig. 14. Half-cell potentials mapping for slab specimen exposing wet-dry cycles 1% NaCl.

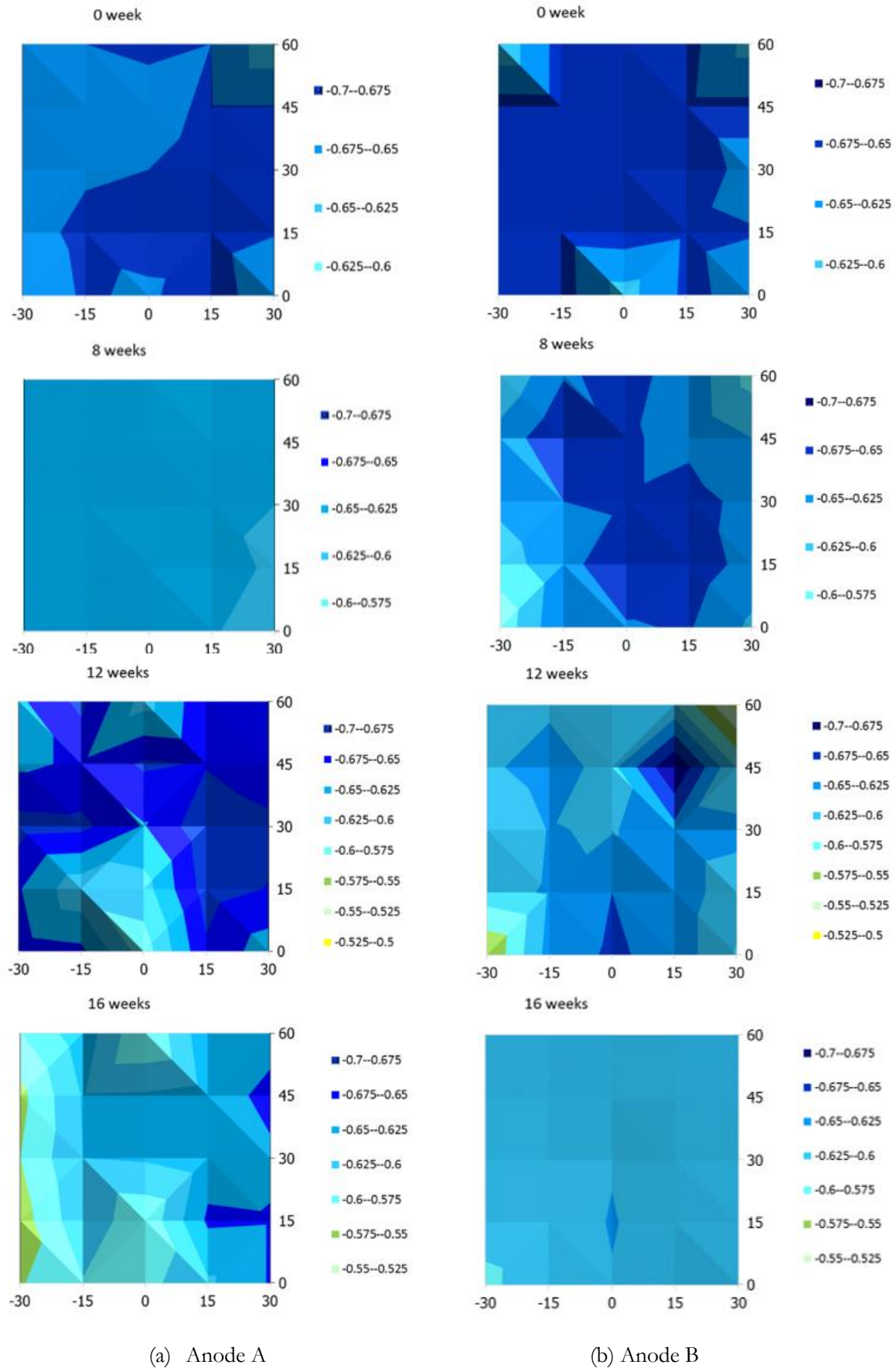
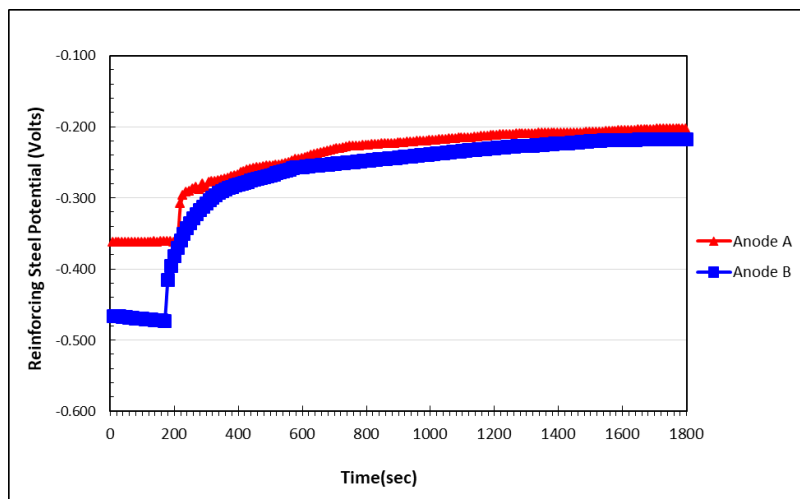
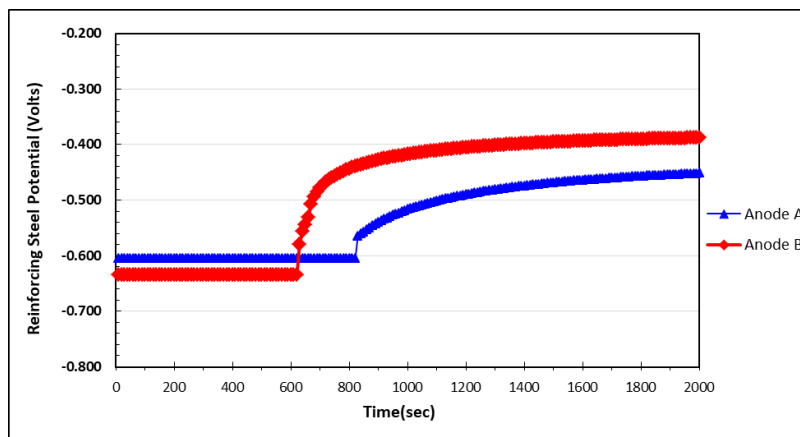


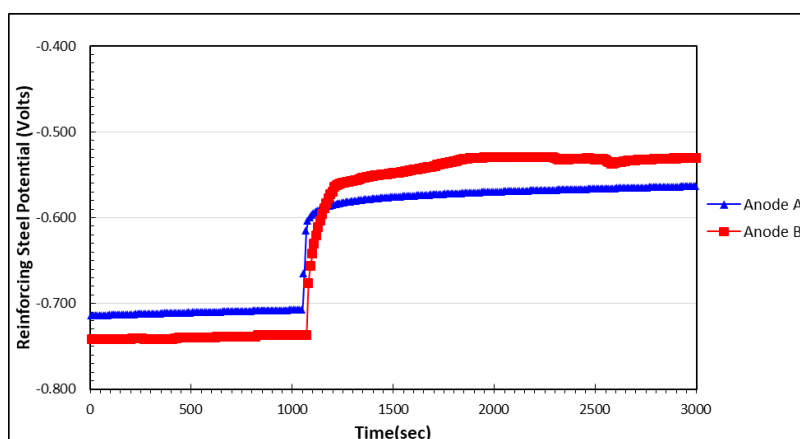
Fig. 15. Half-cell potentials mapping for slab specimen exposing wet-dry cycles 3% NaCl.



(a) 0% NaCl



(b) 1% NaCl



(c) 3% NaCl

Fig. 16. Polarization decay shift for slab specimen.

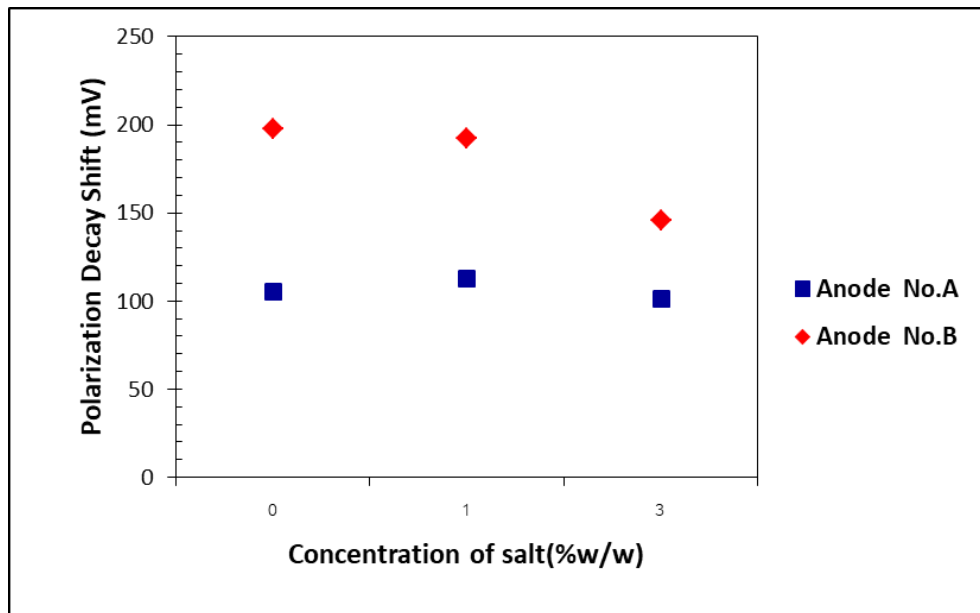


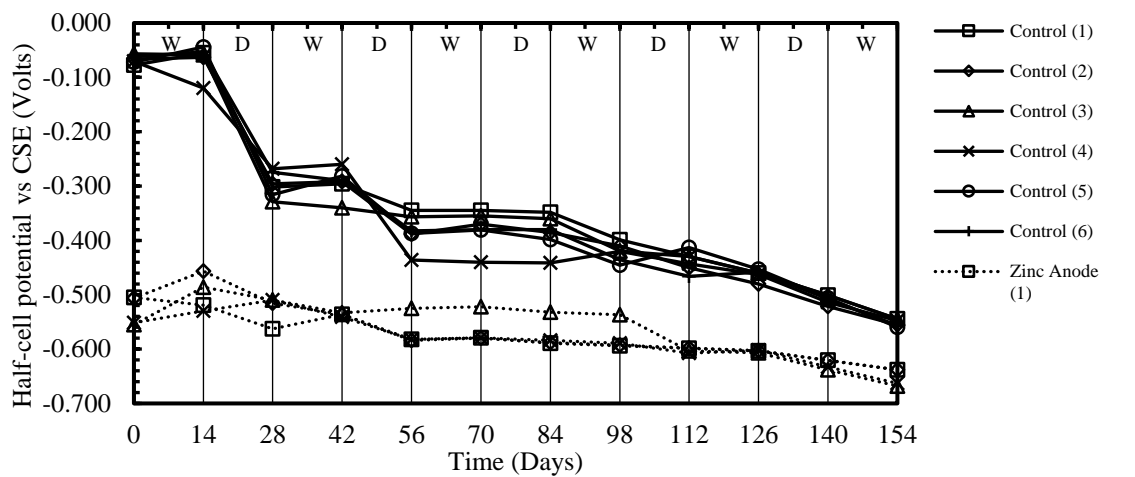
Fig. 17. Comparison of polarization decay shift for slab specimen.

The cementitious capillary crystalline waterproofing coatings significantly delayed the onset of corrosion compared to the uncoated control samples [25]. There were no significantly different for the potential results in all coated specimens because the discontinuities are too small, in contrast to coating defects on metal only a small defect significantly affect the corrosion activity [26]. The results of half-cell potential measurements indicate that there was greater than 90% probability of no corrosion in coated concrete whereas it showed greater than 90% probability of corrosion in 0.6 water to cement ratios – uncoated (Fig. 20). However for the others mix of uncoated concrete, the corrosion activity was uncertain.

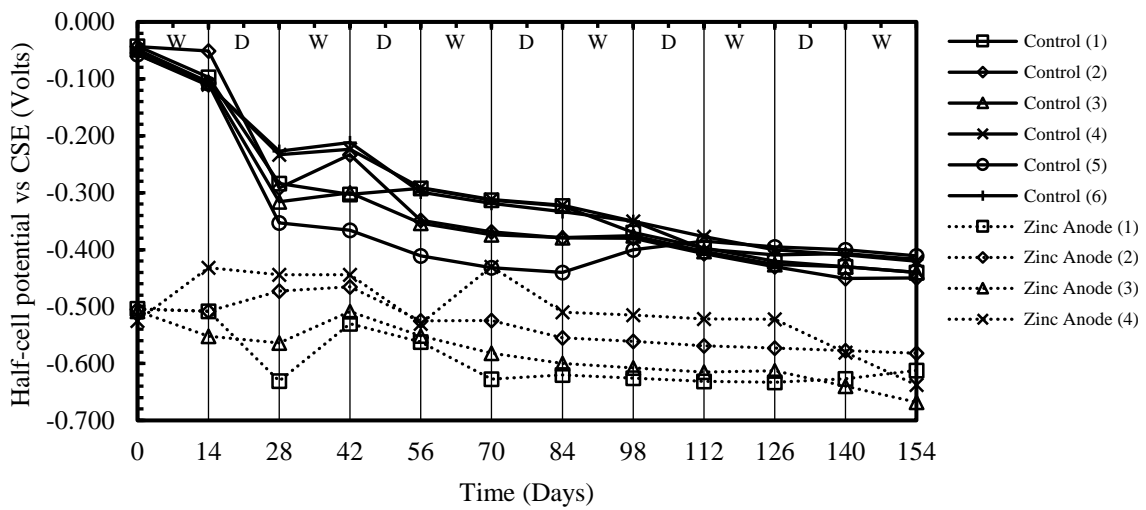
The corrosion current results showed that concrete with water to cement ratio 0.60 showed the greater corrosion steel than water to cement ratios 0.45 and 0.50 as shown in Fig. 21. Concerning the relationship between the free and total chloride diffusivity in concrete, lower water to cement ratios lead to lower chloride concentration in concrete [27]. It's known that the possibility of corrosion of reinforcing steel in concrete depends on the chloride concentration at steel surface. Coated concrete show that condition of the rebar is still in passive condition in all water to cement ratios while uncoated concrete is low to moderate corrosion in water to cement ratios 0.50 and 0.60 following in Table 5. The corrosion current density of the reinforcing steel in coated concrete is lower than corrosion current density of those in uncoated concrete. The higher chloride content cause an increase in corrosion current density [28].

The water tank specimen results appeared to confirm the efficiency of sacrificial anode. The results were monitored using half-cell mapping in four side of the specimens (Fig 22). All specimen only kept values above -300 mV for 7 days. However, sacrificial anode specimens show its capability to keep and return to steel protections in 15 days on both control and fly ash concrete. For the coated specimens, the steel reinforcement had their protection condition.

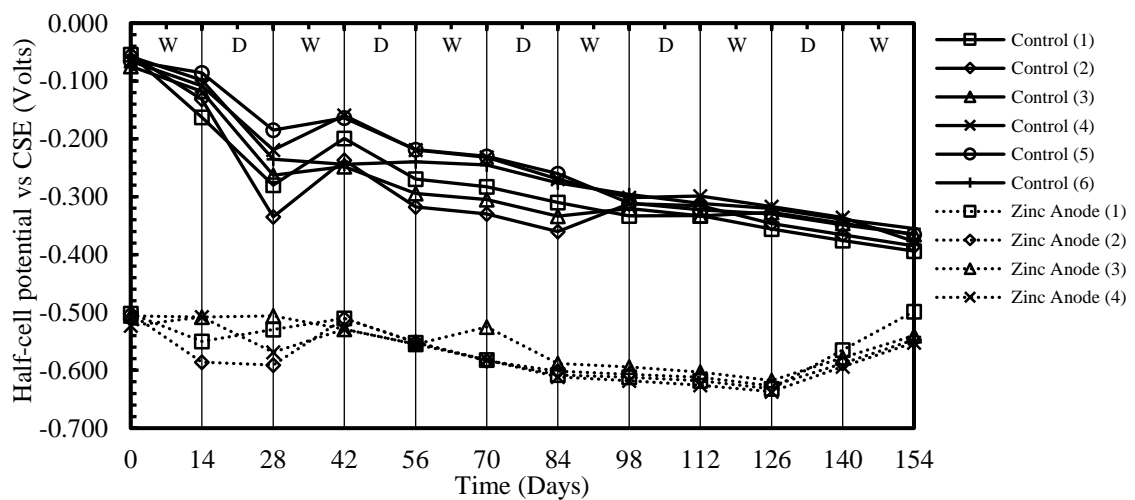
Finally, the prism specimen and water tank specimen were demolished to evaluate the area of intense active corrosion. The reinforcing steel of prism and water tank specimen with sacrificial anode (Figs. 22 and 23(b)) show a good condition after 180 days. It is interesting to note that the sacrificial anode B is a significant cathodic prevention in reinforced concrete. In contrast, control specimen is detectable in the rise in corrosion rates observed in Fig. 23(a).



(a)  $w/c=0.6$



(b)  $w/c=0.5$



(c)  $w/c=0.45$

Fig. 18. Half-cell potentials of reinforcing steel for prism.

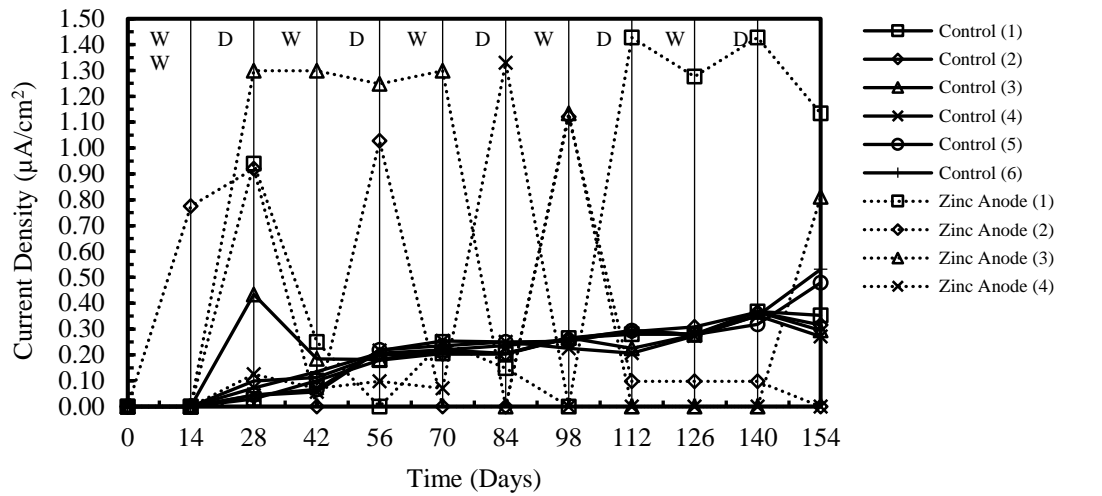
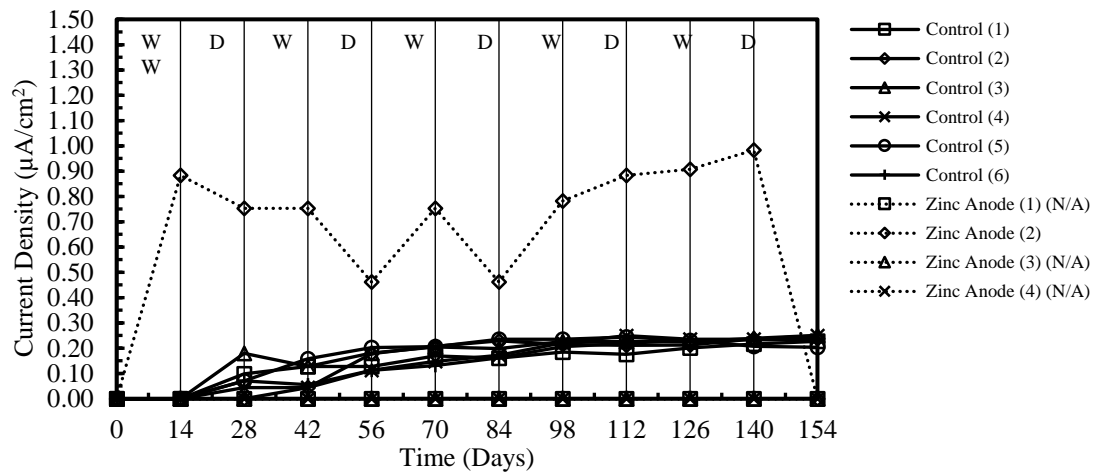
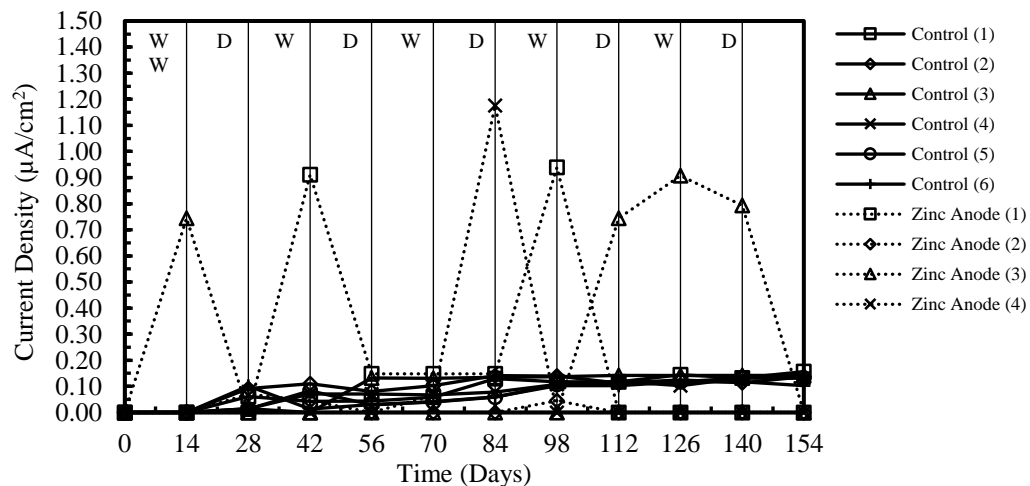
(a)  $w/c=0.6$ (b)  $w/c=0.5$ (c)  $w/c=0.45$ 

Fig. 19. Corrosion current density of reinforcing steel for prism specimen.

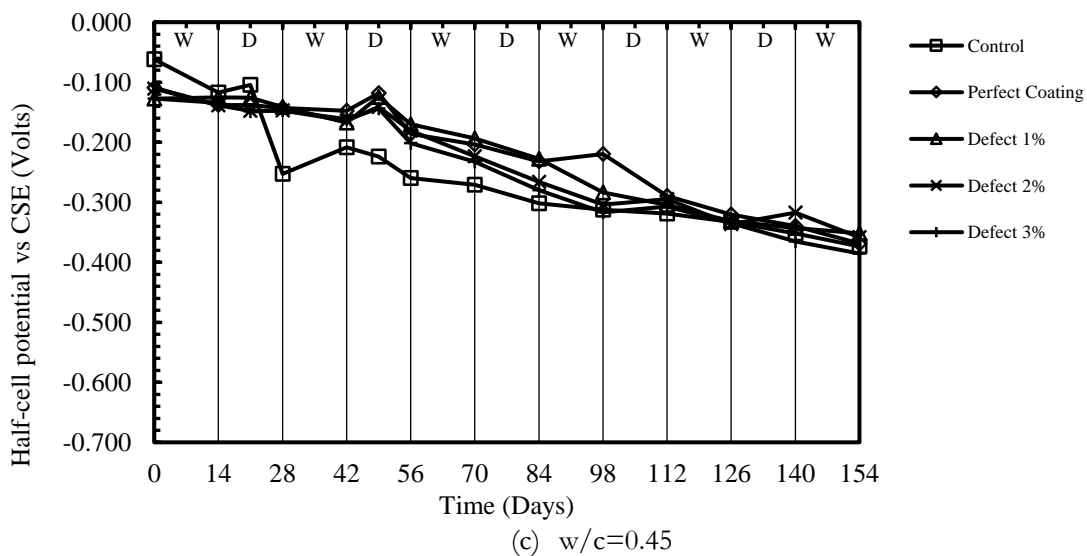
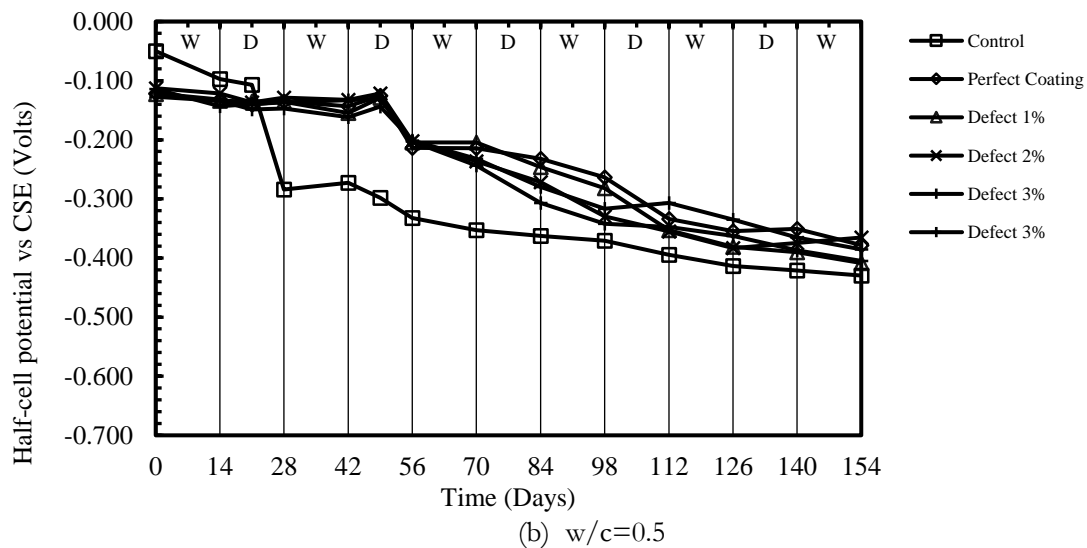
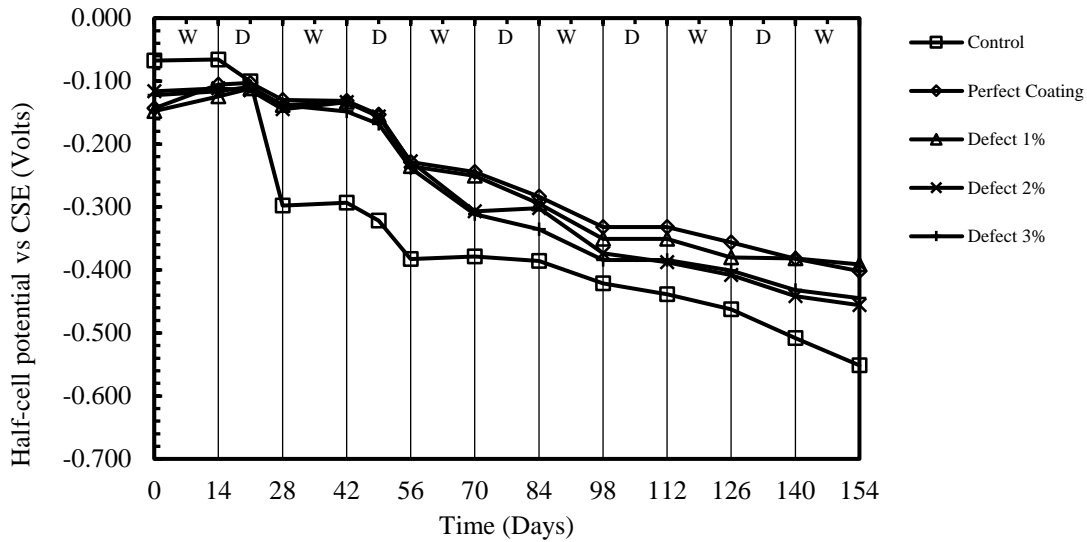


Fig. 20. Half-cell potentials of reinforcing steel in uncoated and coated concrete.



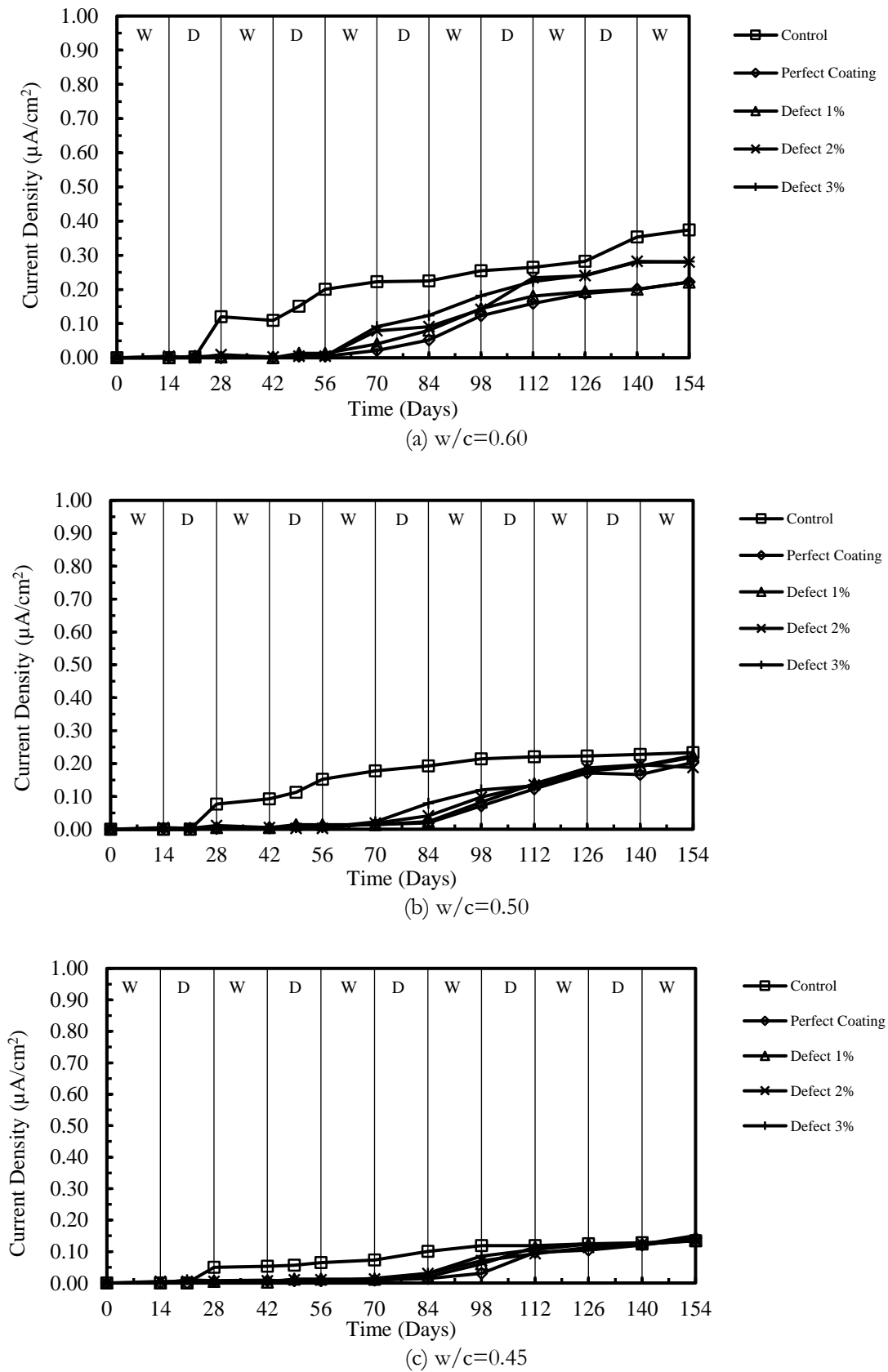


Fig. 21. Corrosion current density of reinforcing steel in uncoated and coated concrete.

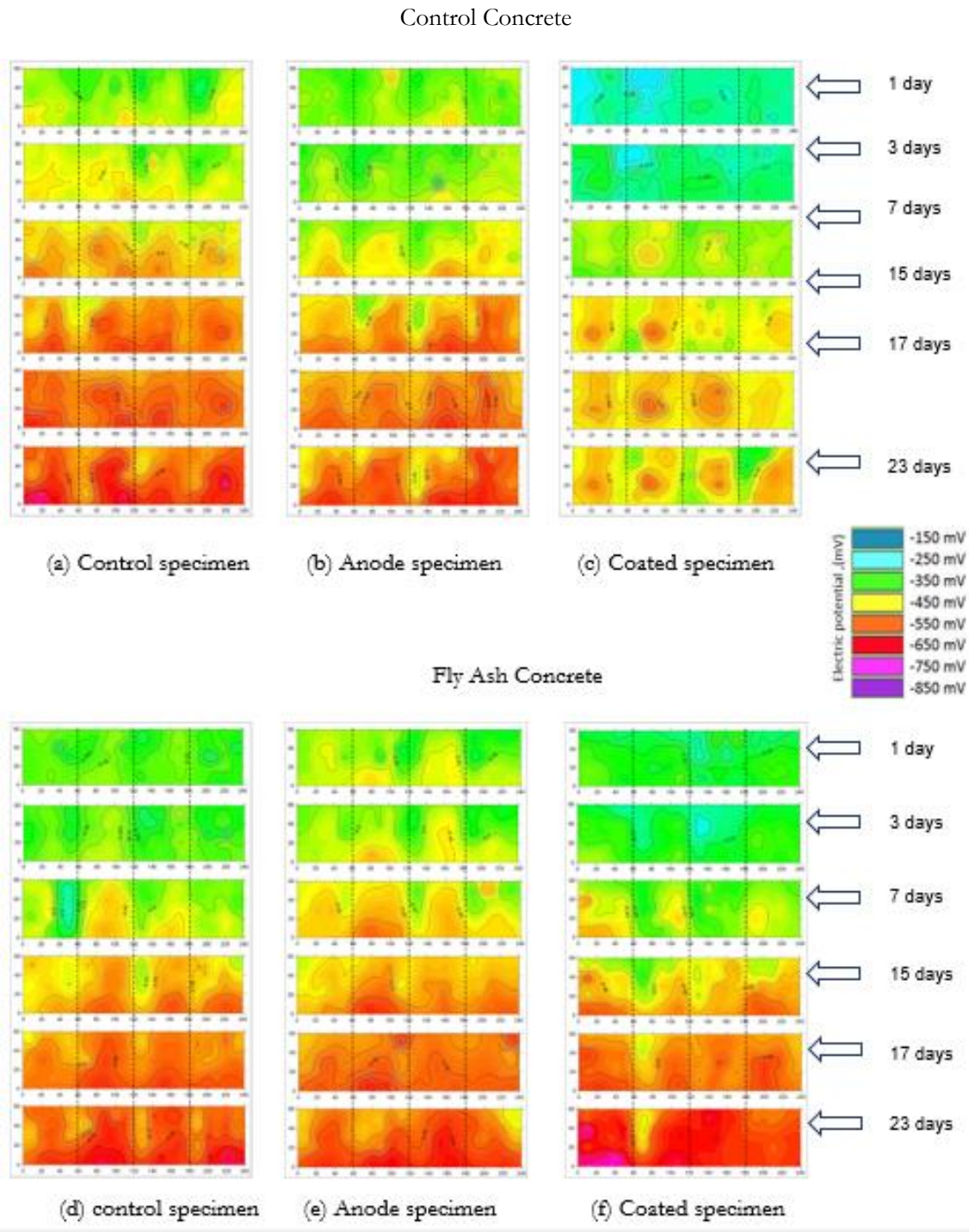


Fig. 22. Half-cell potentials mapping of reinforcing steel in water tank specimens.



Fig. 23. Reinforcing steel of prism specimen after 180 days of exposure to chlorides.



(a) control specimen



(b) Sacrificial anode specimen

Fig. 24. Reinforcing steel of water tank specimen after 23 days of exposure to chlorides.

## 5. Conclusions

From the study to investigate the possibility of corrosion of reinforcing steel in concrete structure with a new innovative sacrificial anode in different conditions, the following conclusions can be drawn.

1. The higher amount of LiOH (Sacrificial Anode B) shows a sufficient level of polarization, keeping the steel rebar in protection conditions. Therefore, Sacrificial Anode B is advisable. Consequently, the polarization area of Anode B is extensively larger than Anode A with the radius up to 600 mm. Influences of water to cement ratios, higher water to cement ratios showed the greater steel corrosion than lower water to cement.
2. Sacrificial anode has proved its good performance to apply CP without significant damages in the severe conditions tested in this work.
3. The protective current density is 2 mA/m<sup>2</sup> at 14 days. The sacrificial anode fulfill the requirement needed to the protective current criterion of cathodic protection between 2 - 20 mA/m<sup>2</sup>.
4. Influences of water to cement ratios, higher water to cement ratios showed the greater steel corrosion prevention than lower water to cement ratios.
5. Coating concrete with crystalline material resulted in retarding the corrosion process. And, in order to consider the effect of defect degree on coated surface, the results of half-cell potential and corrosion current density of coated concrete having a defect on coated area were resemble regardless the degree of defects on coated areas.

## References

- [1] *Cathodic Protection of Prestress Concrete Cylinder Pipeline*, NACE RP0100-2000 Standard, 2000.
- [2] *Cathodic Protection of Steel in Concrete*, BS EN ISO 12696 Standards, 2012.
- [3] *Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments*, ASTM G109 Standard, 2000.
- [4] *Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*, ASTM C876 Standard, 1999.
- [5] S. Laurens and R. Francois, "Cathodic protection in reinforced concrete structures affected by macrocell corrosion: A discussion about the significance of the protection criteria," *Rilem Technical Letters*, vol. 2, pp. 27-32, 2017.
- [6] L. Bertolini, B. Elsener, P. Pedferri, E. Redaelli, and R. Polder, "General Aspects," in *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*, 2nd ed. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2013, pp. 71–77.
- [7] T. Dyer, "Corrosion of steel reinforcement in concrete," in *Concrete Durability*. Boca Raton, Florida, United States: CRC Press, 2014, ch. 4, pp. 183-210.
- [8] T. Dyer, "Construction of durable concrete structures," in *Concrete durability*. Boca Raton, Florida, United States: CRC Press, 2014, ch. 6, pp. 313-321.
- [9] J. P. Broomfield, "Causes and mechanisms of corrosion in concrete," in *Corrosion of Steel in Concrete: Understanding, Investigation, and Repair*, 2nd ed. Oxfordshire, United Kingdom: Taylor & Francis, 2007, pp. 16–30.
- [10] A. Goyal, H. S. Pouya, E. Ganjian, and P. Claisse, "A review of corrosion and protection of steel in concrete," *Arabian Journal for Science and Engineering*, vol. 43, no. 10, pp. 5035-5055, May 2018.
- [11] K. Wilson, M. Jawed, and V. Ngala, "The selection and use of cathodic protection systems for the repair of reinforced concrete structures," *Constr Build Mater*, vol. 39, pp. 19-25, Feb. 2013.
- [12] J. J. Bartholomew, J. E. Bennett, B. L. Martin, and T. A. Mitchell, "Method and apparatus for cathodically protecting reinforced concrete structures," U.S. Patent 5,292,411, March 8, 1994
- [13] Y. Kawabata, T. Tanizawa, and T. Hara, "Chromene compound," U.S. Patent 6,022,496, February 8, 2000
- [14] N. Davison and C. D. Gorrill, "Connector for use in cathodic protection and method of use," U.S. Patent 6,193,857, February 27, 2001
- [15] J. E. Bennett, D. W. Griffis, and R. J. Bechkowiak, "Anode assembly for cathodic protection," U.S. Patent 7,488,410, February 10, 2009
- [16] J. E. Bennett, "Activating matrix cathodic protection," WO. Patent 2007/126715, November 8, 2007

- [17] V. Rajendran and R. Murugesan, "Performance of the sacrificial galvanic anodes in rehabilitation of marine structure at port Blair, Andaman and Nichobar Islands, India," *ARPJ-JEAS*, vol. 6, no. 5, pp. 45-55, May 2011.
- [18] *Standard Specification for Cast and Wrought Galvanic Zinc Anodes*, ASTM B418 Standard, 2004.
- [19] *Standard Specification for Portland Cement*, ASTM C 150 standard, Annual Book of ASTM Standards, vol. 04.01, West Conshohocken, PA, 2004.
- [20] *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM C39 Standard, 1999.
- [21] H. W. Song and V. Saraswathy, "Corrosion monitoring of reinforced concrete structures—A Review," *Int. J. Electrochem*, vol. 2, pp. 1-28, 2007.
- [22] *An Initial Effort to Use the Corrosion Rate Measurements for Estimating Rebar Durability* Editors, ASTM STP1065 Standard, 1990.
- [23] C. Andrade, C. Alonso, and B. Elsener "Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarization resistance method," *Materials and Structures*, vol. 37, no. 9, pp. 623-643, 2004.
- [24] B. Pradhan and B. Bhattacharjee, "Half-cell potential as an indicator of chloride-induced rebar corrosion initiation in RC," *Journal of Materials in Civil Engineering*, vol. 21, no. 10, pp. 543-552, 2009.
- [25] X. Pei, M. Noël, M. Green, A. Fam, and G. Shier, "Cementitious coatings for improved corrosion resistance of steel reinforcement," *Surface and Coatings Technology*, vol. 315, pp. 188-195, 2017.
- [26] R. Vedalakshmi, K. Kumar, V. Raju, and N. S. Rengaswamy, "Effect of prior damage on the performance of cement based coatings on rebar: macrocell corrosion studies," *Cement and Concrete Composites*, vol. 22, no. 6, pp. 417-421, 2000.
- [27] L. Xinying, C. Li, and H. Zhang, "Relationship between the free and total chloride diffusivity in concrete," *Cement and Concrete Research*, vol. 32, pp. 323-326, 2002.
- [28] R. Vera, J. Apablaza, A. M. Carvajal, and E. Vera, "Effect of surface coatings in the corrosion of reinforced concrete in acid environments," *Int. J. Electrochem.*, vol. 8, pp. 11832 – 11846, 2013.