*Research Article*

# A study of Different Sacrificial Anode Materials to Protect Corrosion of Reinforcing Steel in Concrete

**Aris Mahasiripan* and Somnuk Tangtermsirikul**
School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, Rangsit Campus , Khlong Nueng , Khlong Luang , Pathumthani 12120 Thailand

**Pakawat Sancharoen**
Construction and Maintenance Technology Research Center, Sirindhorn International Institute of Technology, Thammasat University Rangsit Campus , Khlong Nueng , Khlong Luang , Pathumthani 12120 Thailand

## Abstract

Re-deterioration of corroded RC structures after patching repair is one of the most important problems in marine environment. The different in chloride content, electrical resistivity of material, and environmental condition cause rapid corrosion of reinforcing steels both in original concrete and repaired zones. A sacrificial anode is a possible solution to prevent this problem. The effects of the concrete mix proportion, the types of sacrificial anodes and the level of chloride content in concrete on the effectiveness of corrosion protection of reinforcing steels by sacrificial anodes were studied. Ordinary Portland cement (OPC) type 1 was used as a binder with water to binder ratios of 0.4, 0.5 and 0.6. Zinc alloy and Aluminum alloy were used as sacrificial anodes to study their effectiveness with respect to both the current densities distribution and the electrical potential of steel surface at different distances from the location of the sacrificial anodes. The results showed that the water to binder ratio did not affect the performance of sacrificial anodes significantly due to the wet and high chloride content of concrete. The results can be used for preparing a guideline to design the sacrificial anode system to prevent corrosion of reinforcing steels. The factor to be considered include the service life, the required weight of anode and the location of the installation based on service conditions of the RC structure.

**Keywords:** Corrosion; Cathodic Protection; Sacrificial anode; Reinforcing Steel; Repair; Maintenance.

## 1. Introduction

Currently, steels are widely used to build many structures such as pipelines and marine structures including ships, submarines and offshore structures. These structures are normally located in the soil and seawater. So they are rapidly deteriorated by corrosion. Corrosion is a major problem affecting the safety and serviceability of the structures because it causes a reduction of the sectional area of the steel members. Consequently, consideration of corrosion control methods is essential to maintain the serviceability of the structures. There are two

***Correspondence** : mahasiripana@gmail.com

protection mechanisms to control steel corrosion such as corrosion potential ($E_{corr}$) and corrosion current density ($I_{corr}$) [1].

Cathodic protection technique is not widely used in Thailand especially in reinforced concrete structures because of its complication both in design and in application. Normally, an RC structure is protected from steel corrosion by using dense concrete, thick concrete cover or surface coating. However, the RC structure can still be damaged the long run especially in the marine environment. Sacrificial anodes can be used to solve this problem [1] because sacrificial anode themselves discharge electrons and corroded to save the reinforcing steels from corroding. There are two criteria for evaluating performance of sacrificial anodes. One is current requirement and another is based on protective potential [2]. It is essential to study the corrosion protection behaviour of sacrificial anodes to protect RC structures in Thailand. Zinc anode is the most widely used as sacrificial anode material in RC structure. However, a problem regarding to its oxide film was found [3]. To solve this problem, some researchers have tried coating a high alkalinity or a high chloride content around zinc anode [4]. Other type of anodes such as aluminium and magnesium anodes that were used in RC structures [5]. However, their performance in different concrete mix proportion has not been reported. The goal of this study is to determine performance of different types of sacrificial anodes in different concrete mix proportions to prevent corrosion of reinforcing steel [6].

## 2. Materials and Methods

### 2.1 Materials

The sacrificial anodes used in this study, were Aluminium alloy anode manufactured according to the MIL-DTL-24779B-2009 standard [7] and Zinc alloy anode manufactured according to ASTM B418 [8]. The zinc alloy anode had some problems with its oxide film that affect its efficiency [6]. Therefore, one set of zinc alloy anode was coated with high alkaline activated mortar in which Lithium hydroxide was mixed. It means that sacrificial anodes became aluminium alloy (Al) sacrificial anode, zinc alloy (Zn) sacrificial anode and alkaline-activated zinc sacrificial anode as shown in Figure 1.

(a)

(b)

(c)

**Fig.1.** Sacrificial anodes
a) Al anode b) Zn anode c) Alkaline-activated zinc anode.

Reinforcing steel acting as a cathode material was a carbon steel of grade SD40 with 12 mm in diameter and 14 cm in length. Each reinforcing steel was coated on both ends by 3 cm in length as shown in Figure 2.

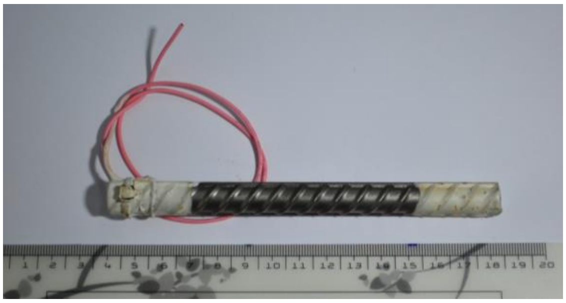


**Fig.2.** Steel surface before testing.

Ordinary Portland Cement (OPC) type I according to ASTM C150 [9] was used as a binder in this study. Natural river sand and crushed limestone were used as fine and coarse aggregates, respectively.

## 2.2 Specimen preparation

### 2.2.1 Mix proportion

The concrete specimens for this study were prepared by varying 3 mix concrete proportions as 0.4OPC, 0.5OPC and 0.6OPC. The mix proportions of concrete are shown in Table 1. Chloride ion was mixed into the mixing water in term of Sodium chloride (NaCl). All concrete mix proportions have the source $Cl^-$ concentration as 0.4% by weight of binder.

**Table 1.** Mix proportions of tested concrete

| Name | Unit content (kg/m$^3$) | | | | |
|---|---|---|---|---|---|
| | **OPC** | **Water** | **Sand** | **Gravel** | **$Cl^-$** |
| **0.4OPC** | 454 | 182 | 720 | 1032 | 18.16 |
| **0.5OPC** | 399 | 199 | 720 | 1032 | 15.96 |
| **0.6OPC** | 355 | 213 | 720 | 1032 | 14.2 |

### 2.2.2 Specimen size

There are two types of concrete specimen shapes. A prisms bar of 10×10 cm in cross section and 1 m in length as shown in Figures 3 and 4 for measuring corrosion, and 10×10 cm cubes for measuring electrical resistivity were used.

Before casting concrete, we installed reinforcing steel bars in the specimen at different distances from the anode as shown in Figure 4. All reinforcing steel bars were externally connected to the sacrificial anode with copper wires. After installing all materials in the specimen, we casted concrete in the mould. Then, the concrete specimens were
cured for 1 week with a piece of wet cloth and a sponge before we started the experiment.
After that, the specimens were continuously covered at the surface with a piece of wet cloth during testing.

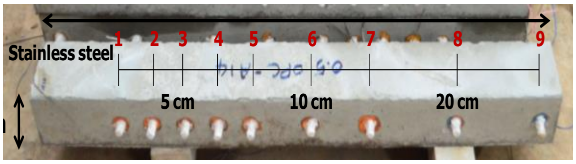



**Fig.3.** Concrete specimen.

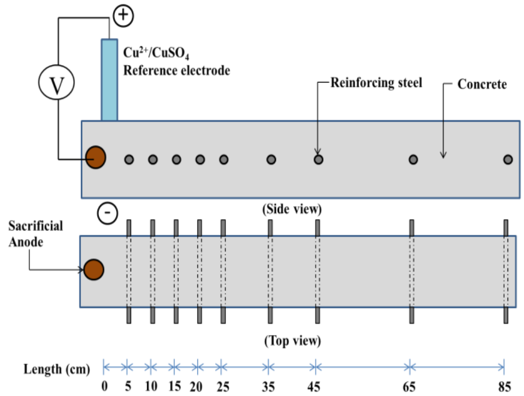



**Fig.4.** Illustration of concrete specimen.

## 2.3 Testing

### 2.3.1 Half-cell potential measurement

Half-cell potential was measured at an anode and all locations of steel bars by a voltmeter and a copper/copper sulfate reference electrode as shown in Figure 4. An example of a half-cell potential measurement is shown in Figure 5. Measurements under three conditions were made. The half-cell potential measurement was conducted following the procedure recommended by ASTM C876 [10]. However, three measuring conditions according to the DNV standard [2] were used to measure the half-cell potential.

When an anode is connected with steel and half-cell potential became stable, a measurement was made. This is called the "ON-potential" measurement condition. During the ON-potential measurement shown in Figure 6. Electrical currents from a sacrificial anode to steel bars were also measured as will be explained later. Then, the half-cell potential was measured 15 minutes after disconnecting the sacrificial anode from the steel. This is called the "INSTANT-OFF potential" condition as shown in Figure 7. Finally, the steel bars were disconnected from the anode then left for 4 hours, then their half-cell potential were measured. This is called the "OFF potential" condition as shown in Figure 8.

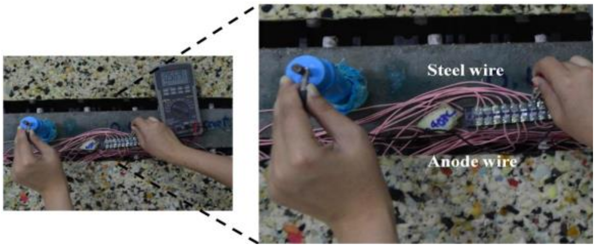



**Fig.5.** Half-cell potential measurement.

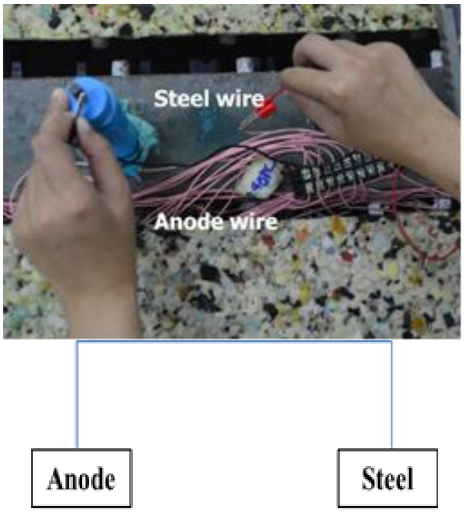



**Fig.6.** On potential measurement.

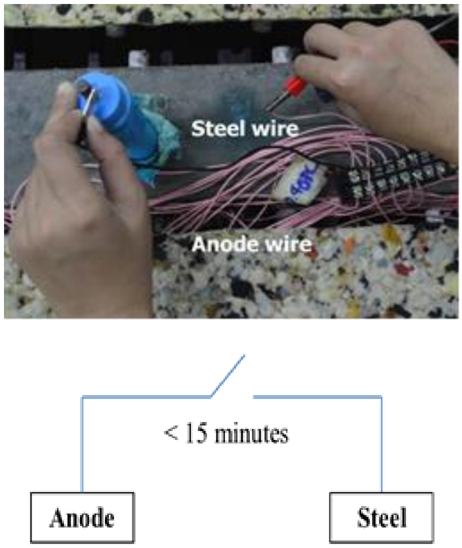



**Fig.7.** Instant off potential measurement.

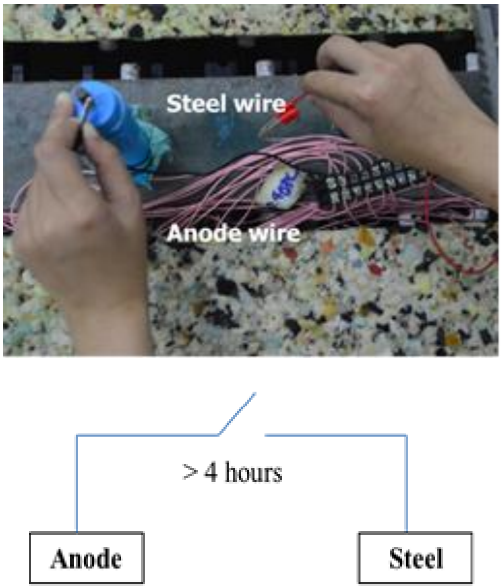



**Fig.8.** Off potential measurement

#### 2.3.2 Sacrificial anode current density

The sacrificial anode current density flow between an anode and a protected steel wire was calculated by using Ohm's law by measuring the voltage across the external electrical resistor connected between the steel and the anode as shown in Figure 9. The measuring procedure was adapted from ASTM G109 [11].

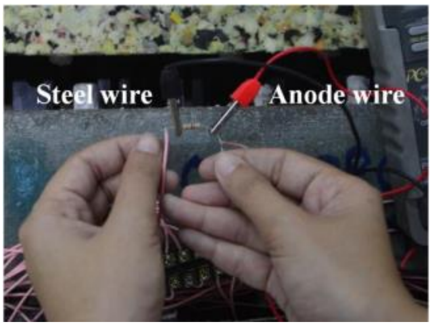



**Fig.9.** The measurement of the current density flow from anode to a cathode

#### 2.3.3Resistivity measurement

The electrical resistivity of the prism bars and the cubes were measured with a four-probe instrument. Resistivity was measured at two sides of the specimen, the anode side and the other end of the specimen as shown in Figure 10. The measurement of the electrical resistivity of the concrete was taken according to ASTM C1202 [12].

**Fig.10.** Resistivity measurement

## 3. Results and Discussion

### 3.1 Half-cell potential

Sacrificial anode cathodic protection acceptance criteria to protect reinforcing steel from corrosion are shown in Table 2. Test method 3, of which the decay shift potential of steel between the instant-off and the off potentials was more than 100 mV, was considered for RC structures.

**Table 2.** Criteria of half-cell potential to protect corrosion [1].

| Test method | Criteria value (Potential versus $Cu/CuSO_4$) |
|---|---|
| **1** On potential | Potential of steel is more negative than 850 mV |
| **2** Instant-off potential | Potential of steel is more negative than 850 mV of polarized potential |
| **3** Off potential | Decay shift of potential of steel between instant-off and off condition is more than 100 mV |

Figures 12, 13 and 14 show the effects of the types of sacrificial anode, Al, Zn and
alkaline-activated Zn anodes respectively, to prevent corrosion of reinforcing steel from corroding.

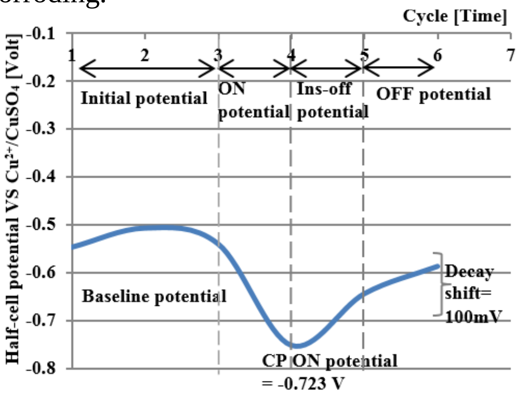



**Fig.11.** Examples of the result of the half-cell potentials measured at different stages.

As shown in Figure 11, the first and the third measurement were initial half-cell potential values of the steel wires before all locations of steel bars were connected with the anode. The fourth measurement was the "on potential" of steel wires after all locations of steel bars were connected with the anode for 1 week.The fifth measurement was the "instant-off potential" of steel wires after all locations of steel bars were disconnected from the anode for 15 minutes.The sixth measurement was the "off potential" of steel wires after all locations of steel bars disconnected from the anode for 4 hours.

As shown in Figures 12-14, all of the on potentials were more than 850 mV, which means that the steel wires were not protected from corrosion based on the test methods 1 and 2 as shown in Table 2. However, based on the test method 3, most of the steel wires were protected from corrosion except for the steel at 85 cm distance from the Zn anode.

Steel wires at shorter distances from the anode had lower potentials compared to those at longer distances due to the effect of the concrete electrical resistivity.

As shown in Figure 12, specimen with aluminium alloy anode had on potential more negative than other anodes because the natural potential of aluminium is lower than that of zinc.

When a zinc anode was used as a sacrificial anode as shown in Figure 13, the potentials of the reinforcing steel wires were more than when aluminium alloy was used. Figure 9 shows that steel at 5 cm from the anode was protected from corrosion. But, the steel at 85 was too far from the anode causing a decay shift between the instant-off potential and the off potential of less than 100 mV. This result indicates that a zinc sacrificial anode cannot protect steel at the distance of 85 cm from the anode.

Figure 14 shows that the half-cell potential of an alkaline-activated zinc anode yields a more stable driving anode potential that is lower than that of zinc without alkaline-activated mortar. This result shows that alkaline-activated mortar increases the driving potentials of zinc anodes because the oxide of zinc can be dissolved on its surface. So zinc coated anode can discharge potential to protect reinforcing steel better than that without coating.

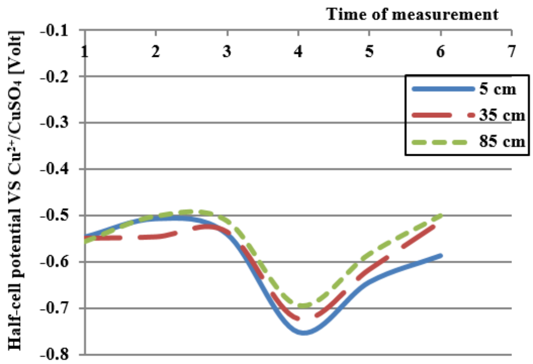



**Fig.12.** Half-cell potential result of 0.5OPC with Al sacrificial anode.

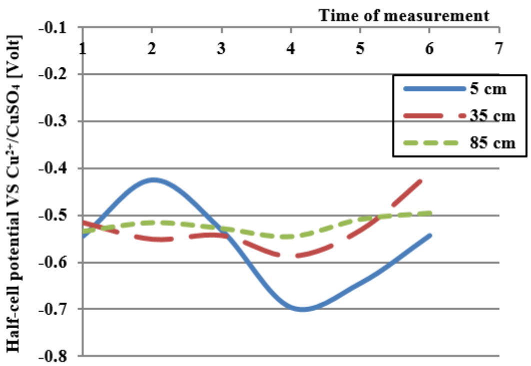



**Fig.13.** Half-cell potential result of 0.5OPC with Zn sacrificial anode.

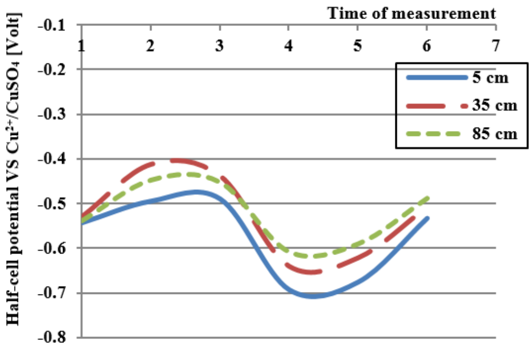



**Fig.14.** Half-cell potential result of 0.5OPC with alkaline-activated Zn sacrificial anode.

The results of 0.4OPC, 0.5OPC and 0.6OPC with aluminium alloy anodes are shown in Figure 15. The results of other water to binder ratios show a similar trend as that of 0.5OPC. As all specimens were kept wet and chloride was mixed in the concrete, the electrical resistivity of concrete did not vary much, as shown in Figure 16. Thus, the aluminium alloy anode can polarize the steel effectively even at the distance of 85 cm as shown in Figure 15.

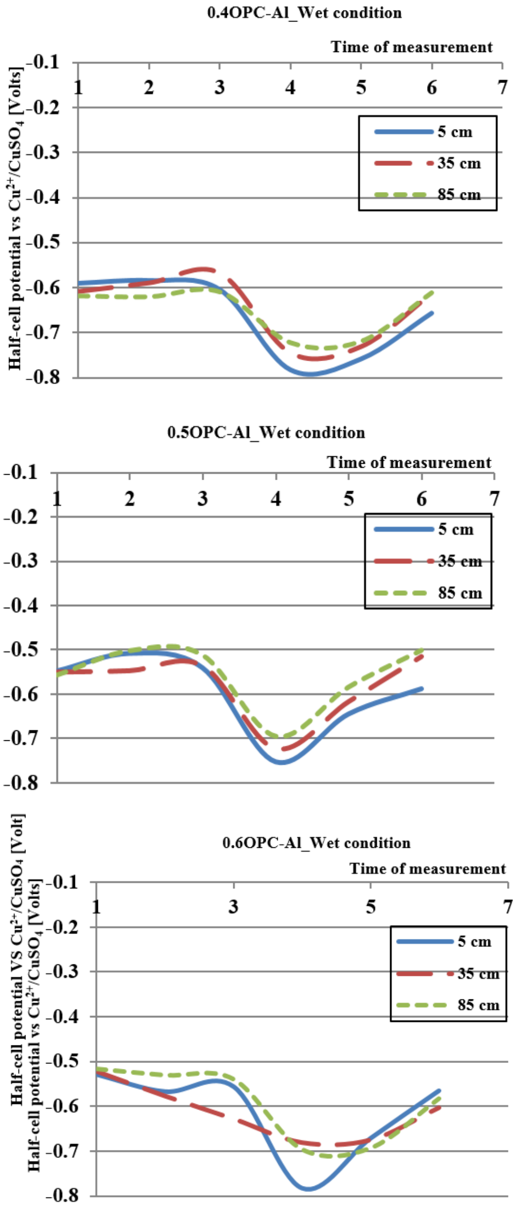



**Fig.15.**Half-cell potential of 0.4OPC, 0.5OPC and 0.6OPC with aluminium alloy anode.

### 3.2 Resistivity of concrete

Figure 16 shows the resistivity of concrete with water to binder ratios of 0.4, 0.5 and 0.6. In wet condition and high chloride content, the resistivity of concrete with different water to binder ratio did not vary much. Overall the resistivity of all samples was around 4-4.5 Ω·cm.

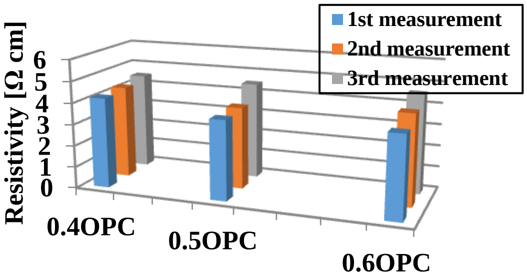



**Fig.16.** Resistivity of concrete specimens tested with four probes.

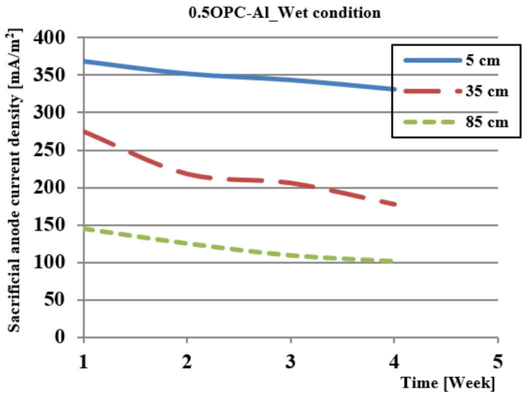
### 3.3 Current density from anode in different environments

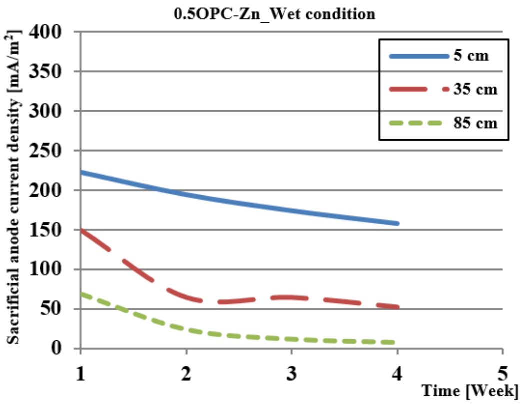
The electrical current density from the anode to cathode was calculated using Ohm's law to evaluate the performance of sacrificial cathodic protection. Table 3 shows the requirement of the current density to prevent corrosion of reinforcing steel. In the case of high chloride level and wet condition, a current density of 30-50 mA/$m^2$ is required.

**Table 3.** Current density requirement to protect reinforcing in concrete [13].

| Environment surrounding steel reinforcement | Current density (mA/$m^2$) |
|---|---|
| No corrosion | 1-3 |
| Chloride present and dry | 3-7 |
| Chloride present and wet | 8-20 |
| High chloride level | 30-50 |

As shown in Figure 17, the aluminium sacrificial anode gave the highest current density to protect reinforcing steel in concrete than the zinc anode and alkaline-activated zinc anode at all distances. But, the zinc anode with alkaline-activated mortar had a significantly improved current density compared to the zinc anode. From the results, steel at longer distances from anode showed lower current density flows from the anodes. However, all anodes in 0.5OPC can prevent corrosion of reinforcing steel based on current density requirement criteria, except for the steel specimen at 85 cm of distance from the zinc anode. This result is similar to the result of HCP. Therefore, both criteria are in agreement.



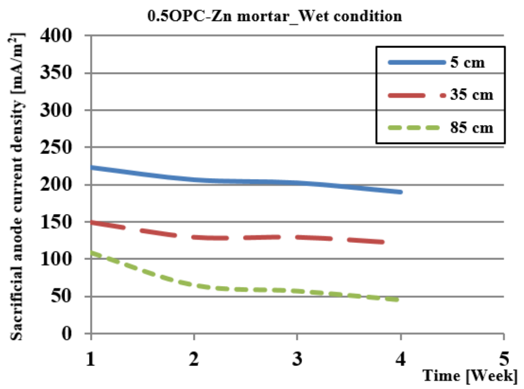
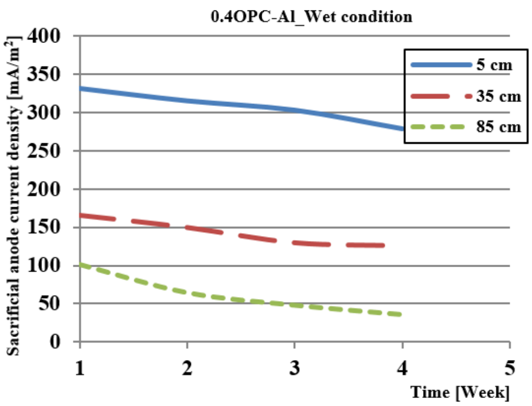
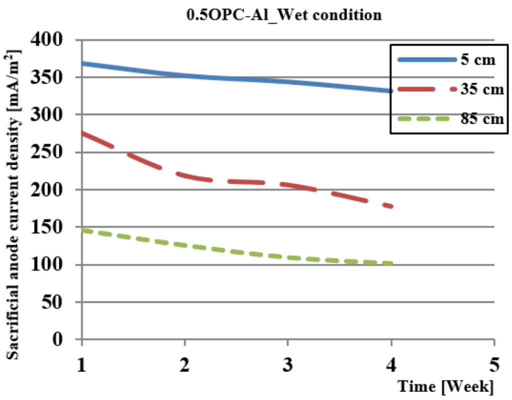




**Fig.17.** Sacrificial anode current density of 0.5OPC.

Shown in Figure 18 are the current density results from concrete specimens with different water to binder ratios, using aluminum anode. The results show that at longer distances from the anode, the current density decreased due to the higher cumulative electrical resistance between the sacrificial anode and reinforcing steel.

The water to binder ratio directly affects the current density from anode. When the water to binder ratio increased, from 0.4OPC to 0.5OPC and 0.6, sacrificial anode current density increased especially at 85 cm of steel position. As shown, Al anode can protect steel at all positions even at lower water to binder concrete in wet and high chloride condition.



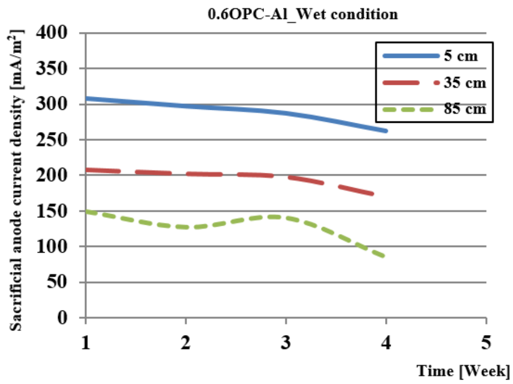




**Fig.18.** Sacrificial anode current density of 0.4OPC, 0.5OPC and 0.6OPC with aluminium alloy anode.

### 3.4 Protective length of sacrificial anode

The protective lengths of sacrificial anode were summarized in Table 4. A protective length is the maximum distance from sacrificial anode that a reinforcing steel bars was still protected from corrosion based on the current density requirements criteria. As shown, most of sacrificial anode materials can protect up to 85 cm from anode in wet and high chloride content concrete except for the zinc anode in 0.4OPC and 0.5OPC.

**Table 4.** Protective length of sacrificial anode.

| No. | Designation | Sacrificial anode length (cm) | | |
|---|---|---|---|---|
| | | Al | Zn | Zn mortar |
| 1 | 0.4OPC | 85 | 35 | 85 |
| 2 | 0.5OPC | 85 | 35 | 85 |
| 3 | 0.6OPC | 85 | 85 | 85 |

## 4. Conclusion

In this study, the effectiveness of sacrificial anodes to prevent corrosion of steel in wet condition was evaluated by measuring the half-cell potential (HCP), the corrosion current density and the concrete resistivity by varying testing parameters such as the water to binder ratio (w/b) and the sacrificial anode materials.

It was found from the results that the water to binder ratio did not significantly affect the effectiveness of sacrificial anodes in wet concrete and high chloride content condition because the concrete had similar levels of electrical resistivity.

From the HCP results and the sacrificial anode current density results, aluminium anodes can polarize the potential of steel to more negative values than the two other sacrificial anodes. Thus, aluminium anodes are the best to prevent corrosion of steel in wet concrete condition at least up to the distance of 85 cm.

Performance of zinc anodes was improved significantly by coating its surface with high alkaline-activated mortar.

## 5. Acknowledgement

The sacrificial anode materials used in this study were provided by Thai Naval Dockyard, Royal Thai Navy, Dr.Pinai Mungsantisuk and Dr.Swieng Thuanboon. Also we would like to thank COE program of Thammasat University.

## 6. References

[1] Bushman J.B., Galvanic anode cathodic protection system design. *Principal corrosion engineer*. Medina. Ohio, USA.

[2] DNV-RP-B401, 2010. Cathodic protection design. *Recommended practice of DET NORSKE VERITAS*.

[3] Oladis T., Yolanda H., Angélica V.M., Torres A., Barrios F., Montero P., Oidor-Sanlinas P. and Montero J.R., 2008. Environmental influence on point anodes performance in reinforced concrete. *Construction and Building Materials*. Vol. 22 (494-503).

[4] Cramer, S.D., Covino Jr., B.S., Bullard, S.J., Holcomb, G.R., Russell, J.H., Nelson, F.J., Laylor, H.M. and Soltesz, S.M., 2002. Corrosion prevention and remediation strategies for reinforced concrete coastal bridge. *Cement & Concrete Composites*. Vol.24 (101-117).

[5] Covino, B.S., Cramer, S.D., Bullard, S.J., Holcomb, G.R., Russell, J.H. and Collins, W.K. 2002. Performance of zinc anodes for cathodic protection of reinforced concrete bridges. *Final report of Albany Research Center*. March

[6] Wang, K., Helene, P.R.L. and Monterio, P.J.M., 2006. Potential use of zinc in the repair of corroded reinforced concrete. *Cement & Concrete Composites*. Vol.28 (707-715).

[7] MIL-DTL-24779B, 2009. Anodes, sacrificial aluminum alloy. *Detail Specification*.

[8] ASTM B418, 2006. Standard specification for cast and wrought galvanic zinc anodes. *Annual Book of ASTM Standard*.

[9] ASTM C150, 2007. Standard specification for Portland cement. *Annual Book of ASTM Standard*.

[10] ASTM C876-91, 2006. Standard test method for half-cell potentials of uncoated reinforcing steel in concrete. *Annual Book of ASTM Standard*, Vol. 03.02

[11] ASTM G109, 2007. Standard test method for determining effects of chemical admixtures on corrosion of embedded steel reinforcement in concrete exposed to chloride environments. *Annual Book of ASTM Standard*.

[12] ASTM C1202-97, 1997. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. Annual Book of ASTM Standards, Vol. 15.05.

[13] Concrete Society Technical Report No 37, 1991. Model specification for cathodic protection of reinforced concrete. *The Concrete Society*, Slough, U.K.