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COMBINATION OF IMPRESSED CURRENT AND SACRIFICIAL ANODE CATHODIC PREVENTION TO IMPROVE CORROSION PREVENTION SYSTEM IN REINFORCED CONCRETE

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ABSTRACT

In this study, effectiveness of impressed current cathodic prevention (ICCP) and sacrificial anode cathodic prevention (SACP) in corrosion prevention of rebar in reinforced concrete (RC) is compared. Firstly, SACP method is applied in chloride-contaminated specimens which are kept in air curing condition for 150 days, then changed to dry/wet cycle NaCl solution cycle condition. Result shows that extremely high initial protective current, then decreased drastically until being stabilized. The depolarization value increases in dry/wet cycle condition than air condition. Secondly, ICCP method is applied with different protective current density, where corrosion of the steel bars were accelerated beforehand. Result shows that higher current density provides higher depolarization value. However, even smaller current density still able to reach 100 mV criterion after 56 days of test period. Based on both results, ICCP and SACP were combined as "hybrid system" to extend the service life of SACP. Initial current consumption was controlled in ICCP stage before changing to SACP stage. Result shows that on potential value increases gradually in ICCP stage and stabilizes after changing to SACP stage, while depolarization value in SACP stage shows more stabilized value compared to the value in SACP only.

Keywords: Reinforced Concrete, Corrosion Prevention, Cathodic Prevention, Impressed Current, Sacrificial Anode, Protective Current Density

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1. INTRODUCTION

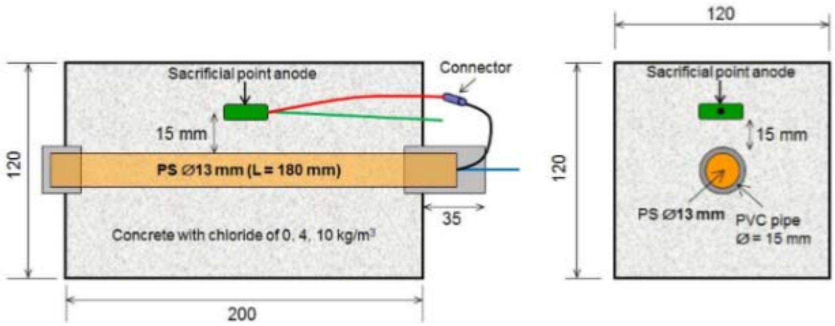
1.1. Research background

Cathodic prevention is one of the prevention methods applied in reinforced concrete structures in order to prevent the structures from deterioration. Electrons that flows between embedded anode and rebar will produce protective current to protect the passivity film of rebar from breaking [1]. There are two cathodic prevention methods; sacrificial anode and impressed current cathodic prevention. Sacrificial anode cathodic prevention (SACP) is a low cost and easy method to apply. However, its excessively high initial protective current flow cannot be controlled manually, which reduces its service life [2]. On the other hand, impressed current cathodic prevention (ICCP) allows the engineer to control protective current manually. However, it consumes higher cost than SACP due to its continuous current supply. The purpose of this research is to improve cathodic prevention method in SACP by combining the ICCP to control its initial protective current flow while monitoring its effectiveness.

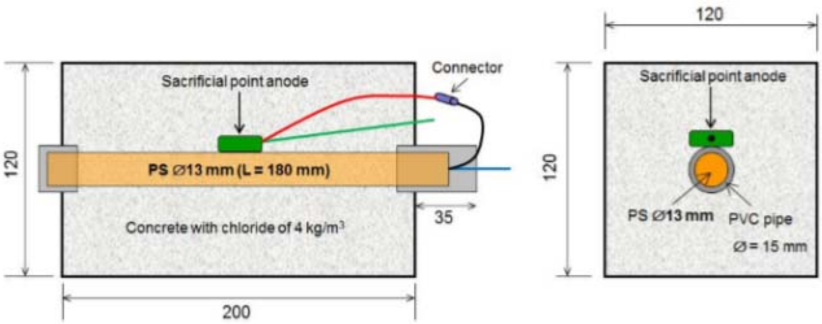
1.2. Sacrificial anode cathodic prevention

SACP is a simple method by connecting a metal that is easier to corrode than the metal to be protected to act as sacrificial anode. This phenomenon occurs due to protective current which flows when both metals have different natural potential value are connected. Protective current flows from anode, metal which has lower natural potential, to cathode, which makes the anode corrodes and acts as a sacrificial metal. [1]

In previous study, SACP was applied in chloride-contaminated specimens with cross-sectional area of 120 x 120 mm and length of 200 mm [2]. Specimens are divided into two types, which are specimens with a gap of 15 mm between sacrificial anode and rebar, and specimen without gap (**Figure 1.**). One specimen without gap between the anode and the steel bar has chloride contamination of 4 kg/m^3, while three specimens with gap has chloride contamination of 0, 4, 10 kg/m^3 respectively. The specimens were kept in air curing for 150 days before changed to dry/wet cycle of 3% NaCl solution to recreate marine environment. As shown in **Figure 2.** below, an extremely high initial protective current density in SACP was measured when the anode and rebar is connected in early stage, before drastically decreased and stabilized [2]. One of the reasons may be due to high resistivity of concrete, which decrease the current output of the sacrificial anode to the steel bars [3].



(a) specimen with gap between sacrificial anode and steel bar



(b) specimen without gap between sacrificial anode and steel bar

Figure 1. Specimen design of previous experiment [2]

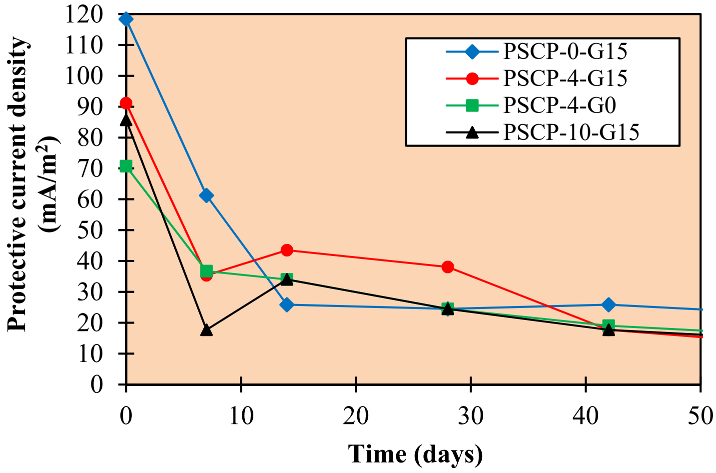


Figure 2. Protective current density. [2]

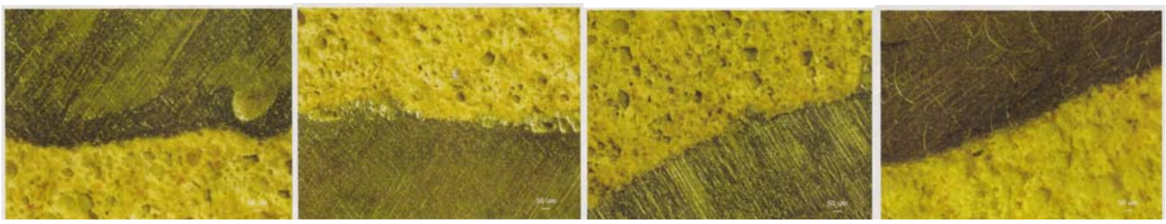
Notation :

PSCP : Plain steel bar with sacrificial anode

0, 4, 10 : Chloride contamination content is 0 kg/m^3, 4 kg/m^3, 10 kg/m^3 respectively

G0, G15 : Gap between steel bar and sacrificial anode is 0 mm, 15 mm

Microscopic photo was taken for visual observation of sacrificial anode (**Figure 3.**) after 50 days of protection. Based on **Figure 3.** (a), it was observed that the surface of zinc anode corroded the most in specimen PSCP-0-G15, which has the highest protective current density compared to other specimens. From this observation result, it can be assumed that protective current flow consumption affects the service life of sacrificial anode. Therefore, high protective current is assumed to reduce the lifetime of sacrificial anode. Moreover, in sacrificial anode system, current output tends to fall with time as the anode is consumed. As a result, sacrificial anode protection is not generally achieved by sustaining an adequate level of steel polarization [4].



(a) (b) (c) (d)

Figure 3. Microscopic photo observation of sacrificial anode.
(a) PSCP-0-G15 (b) PSCP-4-G15 (c) PSCP-4-G0 (d) PSCP-10-G15

1.3. Impressed current cathodic prevention

ICCP has a merit to be able to control current supply manually, hence to control protective current density between anode and rebar. In previous research, ICCP was applied to rebar in chloride contaminated specimens with different amount of protective current supply [2]. From the result shown in **Figure 4.**, depolarization value of rebar increased as protective current density increases. Even so, the values are capable to reach criterion 100 mV even for with lower current density supplied to the rebar after connection time passed as the value increased by time [2, 5].

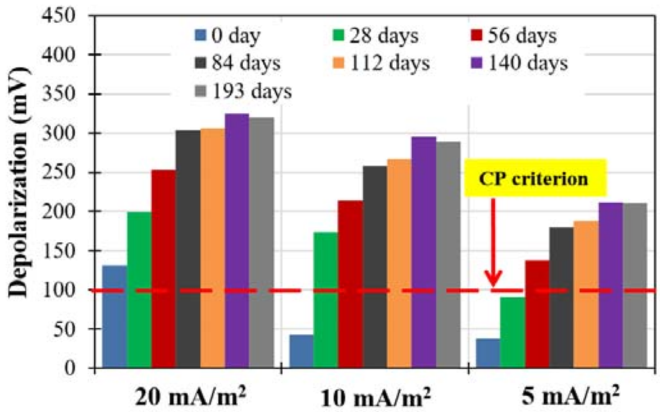


Figure 4. Depolarization value of rebar with different protective current density supply. [2]

1.4. Research objective

As mentioned in **1.2.**, high protective current consumption reduces the lifetime of sacrificial anodes. The lifetime of sacrificial anode is assumed to be extended by controlling and reduction of the initial protective current consumption. Based on both previous researchers' results stated in **1.2**. and **1.3.**, both ICCP and SACP are combined, named "hybrid system" cathodic prevention, which is to be introduced in this paper.

The aim of this research is to control the initial protective current density to the rebar by applying ICCP, in order to extend the lifetime of sacrificial anode in SACP while monitoring the effectiveness of this hybrid system to prevent rebar corrosion in chloride contaminated RC specimens.

2. EXPERIMENTAL PROGRAMS

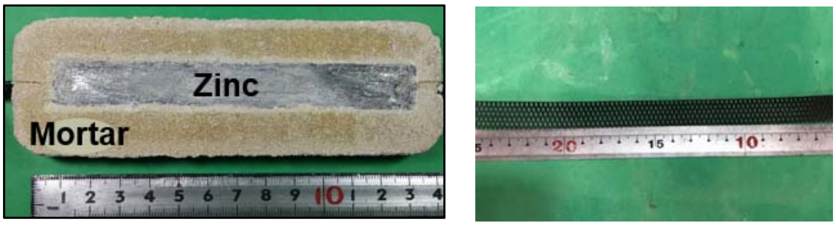
2.1. Materials

Ordinary Portland cement was used as binder and tap water (temperature 20±2°C) was used as a mixing water. Crushed stones with diameter of 5 - 10 mm coarse aggregate with density of 2.91 g/cm^3 and washed sea sand with density of 2.58 g/cm^3 and water absorption of 1.72% was used as fine aggregate. Both aggregate types were prepared in surface-saturated condition (SSD) before mixing process. NaCl was used to contaminate the concrete specimens in order to accelerate corrosion of steel bar. Air entrained water reducing (AEWR) agent and air entrained (AE) agent were used as admixtures in the concrete. All materials properties are summarized in **Table 1.** below. Steel bar with diameter of 19 mm and PVC pipe was used to cover both ends steel bar to prevent penetration of air and water from both ends of steel bar.

F-type zinc sacrificial anode with cross-section of 40 mm x 13 mm and length of 140 mm, provided by Denka Co. Ltd. was used as sacrificial anode (Shown in **Figure 5.** (a)). Titanium ribbon mesh with dimension of 190 mm x 13 mm and thickness of 1 mm was used (**Figure 5.** (b)) as anode for ICCP.

Table 1. Properties of material [6]

Component	Physical properties	
Ordinary Portland cement	Density, g/cm^3	3.16
Fine aggregate	Density, g/cm^3 (SSD condition)	2.58
	Water absorption (%)	1.72
	Fineness modulus	2.77
Coarse aggregate	Density, g/cm^3	2.91
AEWR	Polycarboxylate ether-based	
AE agent	Alkylcarboxylic	



(a) (b)

Figure 5. Metals that act as anode in specimens (a) Zinc sacrificial anode (b) Titanium ribbon mesh.

2.2. Mix proportion

A concrete mix proportion as shown in **Table 2.** was used for specimen casting. Water-cement ratio of 55%. Chloride content of 5 kg/m^3 to accelerate corrosion process of rebar. AEWR and AE was used as admixture to increase the concrete workability when handling it in fresh condition while keeping the concrete quality when hardened.

Table 2. Mix proportions of specimens [6]

Material	W/C	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	NaCl (kg/m^3)	AEWR (kg/m^3)	AE (mL/m^3)
Properties	55%	190	345	841	956	5	1.08	1036

2.3. Specimen design

Four specimens with dimension of 120 mm x 120 mm x 200 mm and cover depth of 50 mm were prepared for this study. Each specimens has a steel bar with an approximate length of 230 mm, however the length area that was in contact with concrete is approximately 190 mm.

Specifications of each specimens are stated as in **Table 3**. In Specimen 1, ICCP is applied where rebar and titanium ribbon mesh, which acted as its anode, was connected to a current supplier. In Specimen 2, SACP is used as cathodic prevention method and rebar is connected to a zinc sacrificial anode. In Specimen 3, hybrid system cathodic prevention introduced in this paper is applied, where rebar is connected to impressed current for the first 25 days, then switched to sacrificial anode. Specimen 4 were prepared to observe the corrosion condition of rebar when no protection was applied. However, both titanium ribbon mesh and zinc sacrificial anode were embedded as preparation for future work.

Table 3. Specimen specification

Specimen number	Cathodic prevention type	Anode type
1	Impressed current	Zinc sacrificial anode
2	Sacrificial anode	Titanium ribbon mesh
3	Hybrid system	Titanium ribbon mesh and zinc sacrificial anode
4	No protection	Titanium ribbon mesh and zinc sacrificial anode

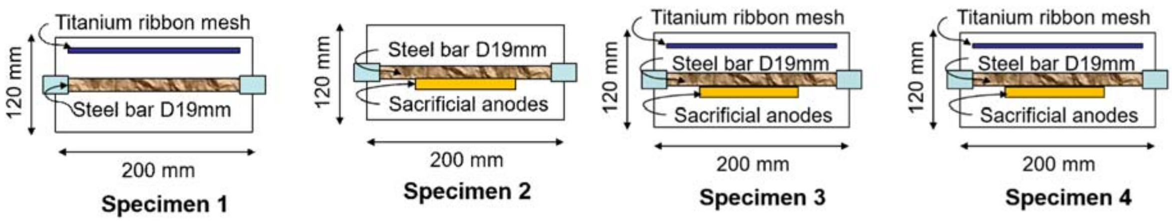


Figure 6. Specimen design.

2.4. Exposure conditions

After casting process was completed, the specimens were wrapped in moist paper towel and sealed by plastic wrap for 14 days of curing period in a room with temperature kept at 20±2°C. After that, the specimens were exposed in air condition of laboratory with temperature of 20±2°C for about 200 days.

2.5. Measurement method

2.5.1. Protective current flow

Protective current flow to the rebar is measured when rebar and anode is connected by using multi-meter. For Specimen 1, protective current density is read directly from galvanostat.

(a) (b)

Figure 7. Measuring apparatus used; (a) Galvanostat (b) multi-meter and CSE reference electrode.

2.5.2. Potential measurement

Potential of rebar during on potential, instant-off potential and rest potential was monitored by measuring of rebar by using half-cell potential measurement method. On potential is potential value that is measured during when anode and rebar are connected, which shows the potential value of rebar when under protection. Instant-off potential is potential value taken when the connection was interrupted or disconnected within one second. Rest potential was measured when 24 hours after the connection was disconnected. The difference between instant off potential and rest potential of rebar is called depolarization. Depolarization was used to evaluate the effectiveness of the prevention method. The prevention method is fully effective when the depolarization of rebar exceeds 100 mV depolarization criterion [5].

Saturated calomel electrode (SCE) was used as reference electrode, then measured values were converted to values when copper-copper (II) sulphate electrode (CSE) was used in 25°C environment. Corrosion condition of rebar during rest potential was evaluated based on the ASTM C 876-91 standard [7].

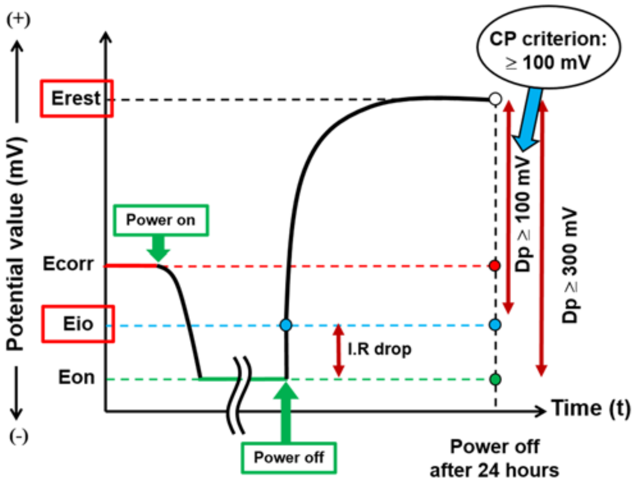


Figure 8. Potential measurement items

2.5.3. *Grade passivity and oxygen permeability*

Passivity refers to the loss of chemical reactivity experienced by certain metals and alloys under particular environmental conditions. The insoluble oxide film prevents oxygen from reaching the steel thereby effectively inhibiting the electrochemical process of corrosion [8]. Anodic polarization curve (APC) is related to the passivity condition of steel bar. When the current density becomes larger, the grade passivity film of steel bar becomes worse. Cathodic polarization curve is related to the diffusion of oxygen. When the current density becomes larger, the level of oxygen diffusion becomes larger [9]. The specimens were immersed in tap water, and two electrodes (counter and reference electrodes) were arranged and connected with the instrument in the solution. Standard calomel electrode and stainless steel electrode were used as reference electrode and counter electrode respectively. Rest potential of rebar gradually shifted to +700 mV for APC and -700 mV for CPC with a scan speed of 50 mV/min by potentiostat. The maximum current density obtained from APC was used to judge passivity grade [10].

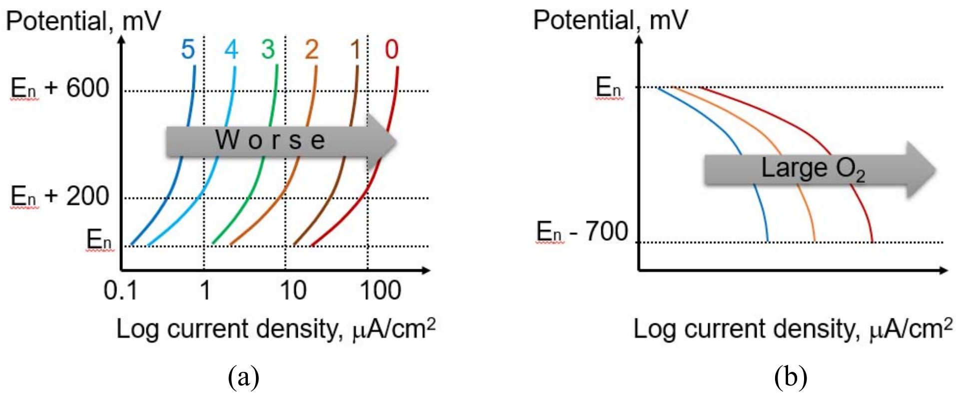


Figure 9. Evaluation of polarization curve; (a) grade passivity from anodic polarization curve, (b) oxygen supply from cathodic polarization curve [10]

3. RESULTS

3.1. Protective current density

Specimen 1 and 3 started with the same current flow by impressed current with current flow of 1200 µA, then reduced every 100 µA to 200 µA until the current supply reached 250 µA on the day 25. For Specimen 1, the value was kept constant until the end of monitoring period, while for Specimen 3, the value was kept constant until day 29, when the prevention method was switched to SACP. On potential of rebar in Specimen 3 was then measured using multi-meter.

As shown in **Figure 10.** below, in Specimen 3, after switched to SACP on the day 29, the protective current density stabilized and slightly increased from 250 µA to 326 µA until 82 days of observation. The value then dropped about half of the previous measured value, which was 93 µA on the day 95. The value stabilized again until on the day 166, the value dropped to 50 µA.

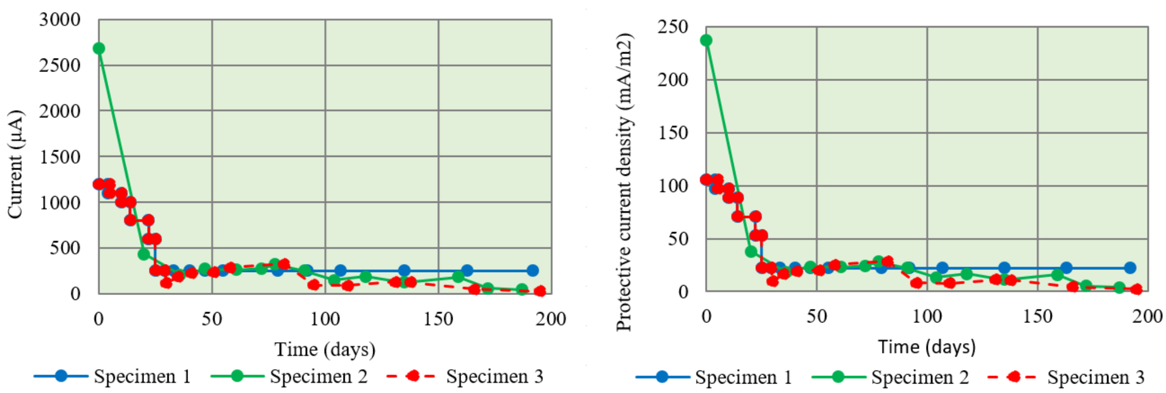


Figure 10. Protective current flow and protective current density measurement.

3.2. Potential measurements

3.2.1. On potential measurement

On potential of rebar measurement result is summarized in **Figure 11.** On potential value of rebar in Specimen 1 gradually increases, as the protective current supplied was decreased. However the value slowly decreases even though the current flow amount was kept constant after 25 days of connection.

On the other hand, on potential value in Specimen 2 shows a very low initial value, which is -1077 mV. The value then suddenly shifted to a more positive value on day 2 of connection, which is -283 mV, before value drops to -485 mV. This large potential shift is caused by the difference in value drop of protective current between rebar and sacrificial anode. The value then stabilized in a range from -485 mV to -216 mV.

In Specimen 3, on potential value gradually increases as protective current density is decreased. After switching from ICCP to SACP, the value abruptly increased to -209 mV on the day 41, however it stabilized around -400 mV until 138 days, the value again increased to -215 mV on the day 166 before returning to around -400mV.

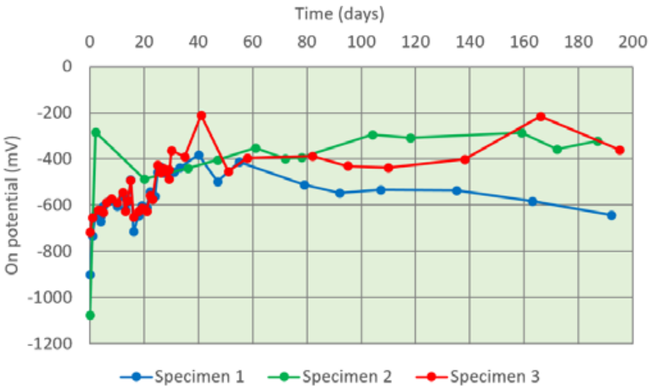


Figure 11. On potential measurement result

3.2.2. Rest potential

Measured rest potential value indicates the corrosion condition of rebar surface, and the evaluation standard is based on ASTM C 876-91 standard. In Specimen 1, rest potential values did not show a large difference between each measurement, where the value range is only from -209 mV to -153 mV. This shows that there's no corrosion occurred on the rebar surface. Rest potential in Specimen 2 shows an irregular trend, where its rest potential ranges between -208 mV and -69 mV, which indicates "no corrosion" occurred on rebar surface. Meanwhile, rest potential value in Specimen 3 also shows an irregular trend, where the value range is from -275 mV to -98 mV. Rest potential value after 138 days of connection is -275 mV which indicates "uncertain corrosion" condition. However, after the day, it recovered gradually. In Specimen 4, until the day 180, the potential is stable, however, after the day it shows the trend of decreasing.

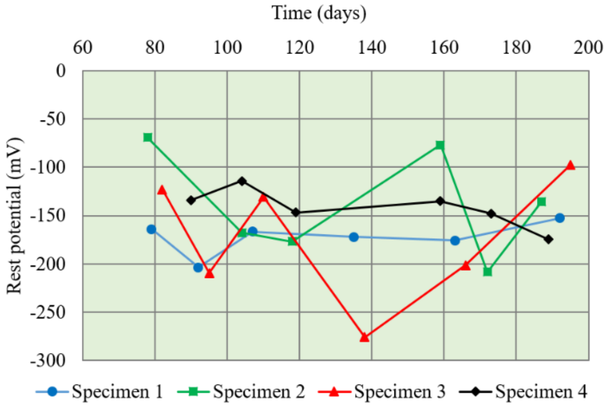


Figure 12. Rest potential of rebar measurement result.

3.2.3. *Depolarization*

Depolarization value of Specimen 1, Specimen 2 and Specimen 3 is presented in **Figure 13.**. Depolarization values of rebar in Specimen 1 are measured after current supply are kept constant, while the values in Specimen 3 are measured after it was switched from ICCP to SACP. Depolarization in all three Specimens exceeds 100 mV, which satisfies the depolarization criterion of rebar. Depolarization value in Specimen 1 increases even by time even after the current supply to the rebar are kept constant. The value in Specimen 3 increased until day 110, however dropped abruptly until day 166 to 11 mV. One reason is assumed that there was interruption error between the connections during measurement. The value increased again on the day 195.

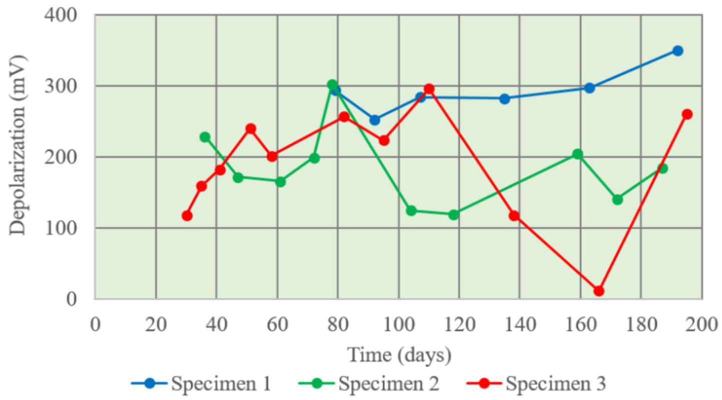


Figure 13. Depolarization value of rebar in each specimens.

3.2.4. *Grade passivity and oxygen permeability*

APC and CPC results of rebar in all specimens are as shown in **Figure 14.**. The decreasing current density from APC result indicates that the passivity film of rebar in each specimen is improved, while the decreasing of current density from CPC indicates that the level of oxygen diffusion becomes smaller throughout the monitoring period. APC of rebar in Specimen 1 and 3 indicates passivity of Grade 5, which indicates excellent passivity film exist surrounding the rebar surface. On the other hand, APC in Specimen 2 and 4 indicates passivity of Grade 4, which indicates a certain of passivity exists.

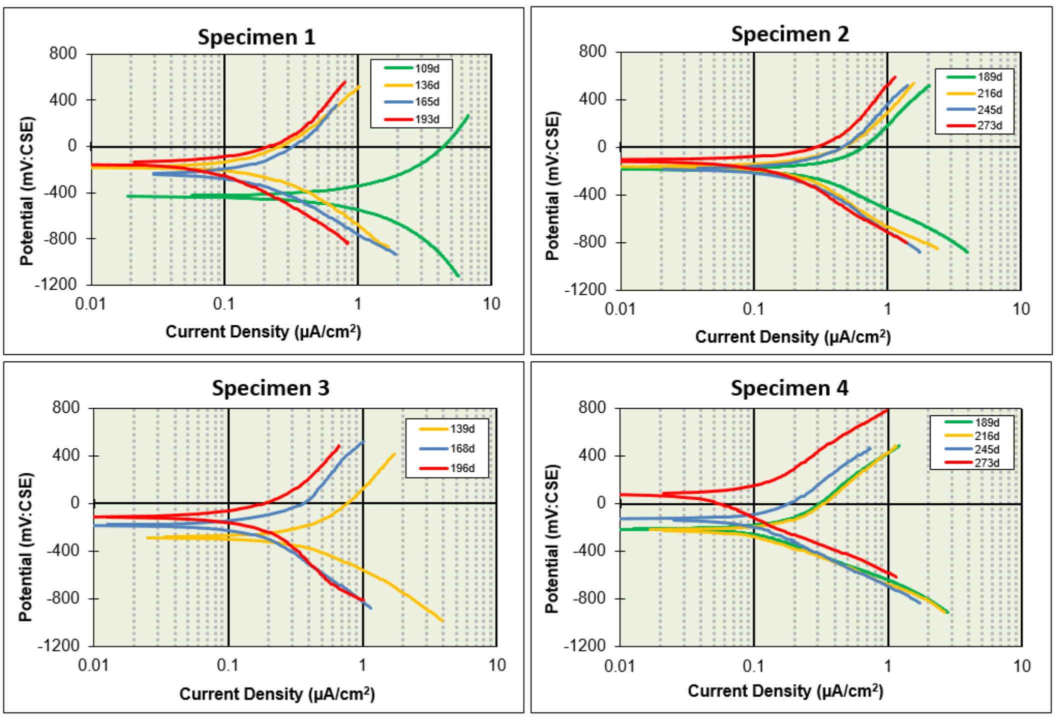


Figure 14. Anodic and cathodic polarization curve of rebar in each specimens.

4. DISCUSSION

This experiment aims to control the initial current density in SACP by ICCP while monitoring its performance to prevent corrosion in rebar.

On potential of Specimen 1 and Specimen 3 shows a similar pattern in the first 29 days, as the value protective current supplied to Specimen 3 was controlled by ICCP same to the value in Specimen 1. On potential in both specimen increased until both protective current density were kept constant. After Specimen 3 was switched to SACP, the protective current in the specimen stabilized as the protective current value in Specimen 2, which SACP was applied. The protective current value however decreased after 95 days of connection, but still capable to achieve 100 mV criterion to show the effectiveness of the prevention method.

Moreover, on potential value in the hybrid specimen stabilized approximately -400 mV as the protective current stabilized. The on potential values also show the same trend as on potential in Specimen 2. This shows that the switching from ICCP to SACP in Specimen 3 is successful.

Based on **Figure 14.**, passivity grade of Specimen 3, which hybrid system was applied as prevention system, has improved from Grade 4 to Grade 5 which shows that the passivity film improved as a result of the prevention system applied. Compared to passivity grade of rebar in Specimen 4 (**Figure 14.**), which was not connected to any prevention method, it indicates that the passivity film of rebar starts to break, however corrosion is not yet initiate based on **Figure 12.**.

5. CONCLUSIONS

Conclusion of this research is based on the results of Specimen 3, which hybrid system was applied. Protective current in the specimen stabilized together with on potential value of rebar after switched to SACP from ICCP. These two results indicates that the switching from ICCP to SACP is successful. The depolarization of rebar satisfies the 100 mV criterion. The improvement of passivity grade of rebar in the specimen also shows that the hybrid system is effective to be applied for prevention method.

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