

Corrosion potential of coated steel bar embedded in sea-water mixed mortar

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Abstract. Corrosion of embedded steel bars in concrete structures is the most impactful deterioration case in the world therefore many researchers and engineers are looking for the unknown mechanism related to the occurrence process, the effect of the damaged structures to its capacity and serviceability, and the intervention methods to control the rate of corrosion nowadays. One of the most prevalent liquid materials used in concrete is freshwater. However, the lack of freshwater for basic requirements in certain regions necessitates the adoption of an alternate material. Seawater, abundant in Indonesia, has the ability to substitute freshwater in concrete mixtures. However, its high concentration of chloride ions might raise the risk of corrosion in reinforced concrete structures. The laboratory experiment was proposed to find the empirical test result of the performance of corrosion prevention to the seawater mix RC structures. Three type of cements (PPC, PCC, and PPC-PCC mixture) were used as binder and two type of protection (steel coating and no coating) were applied in this research. One day after specimen casting, it were demolded and cured under water condition until 28 days. After that, the cylindrical and beams specimens were tested and the cubical specimens were exposed to three conditions (air-dry, wet, and dry-wet cycle) until a half-year and the half-cell potential test was conducted periodically every week. Based on the results, it demonstrated that the steel coating is the most suitable corrosion prevention method and PCC is recommended to maintain the corrosion potential stable to be passive.

1 Introduction

Cement, coarse aggregate, fine aggregate, and water serve as cement reagents in a concrete mix. Water used in concrete formulations is typically potable or freshwater. Current trends indicate that freshwater demand is beginning to decline [1-2]. The United Nations and the world's methodological organizations stated at their summit that approximately five billion people would lack drinking water, and that by 2025, half of the human population would live in areas lacking clean water (freshwater). Based on this phenomenon, abundant saltwater has the potential to replace freshwater as a concrete mixing material.

A review of the last 17 years of research on seawater-mixed concrete (2005-2022) is presented. A significant amount of fundamental and applied research has been conducted on this topic, and there is widespread interest in the use of seawater-mixed concrete to reduce concrete freshwater consumption [2]. Seawater-mixed concrete should be used for either unreinforced or non-corrosive reinforced concrete (fiber reinforced polymer or stainless steel)[1, 3]. Seawater's complex effects on hydration processes, concrete microstructure, and

interactions with supplementary cementitious materials are well understood [1]. Seawater and sea sand increase early strength while decreasing later strength, and the pore structure of seawater mixed concrete can form an internal curing effect, which improves later strength [4-8].

Corrosion, on the other hand, is an electrochemical process in which steel in contact with an ion-containing liquid generates a potential difference, causing the reinforcement ions to dissolve to a balanced state and potentially reducing the building's lifespan [9-10]. Generally, there are two types of corrosion, chloride induced corrosion and carbonation induced corrosion. It was once feared that the use of seawater as a mixing water would reduce the durability and resistance of concrete due to chloride induced corrosion. So, several treatments on the steel bar embedded in sea water mixed mortar or concrete was required [10-16]. To prevent corrosion, several efforts have been made, one of which is to provide a protective coating for both the reinforcement and the concrete surface [9, 17]. Corrosion inhibitor paint based by using a magnesium hydroxide layer was used to stabilize the pH of the concrete surface in previous efforts to prevent corrosion

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by providing a protective layer to the concrete surface [18-19]. The study results showed that using a magnesium hydroxide layer could keep the pH of the concrete surface stable, preventing the growth of microorganisms that cause corrosion [20-22]. Furthermore, studies in which layers of organic material were applied to the surface of concrete and reinforcement produced more electropositive results than when no protection was present [22-25]. Several studies have shown that applying a protective layer or coating to the reinforcement or concrete surface improves corrosion resistance compared to not applying a protective layer or coating (non-coating) [3, 20-29].

Based on results by the previous researchers, there is no information about the use of bituminous paint based as the corrosion inhibitor of steel bar in concrete specifically for seawater mixed concrete or mortar. The researcher was done two preliminary works related to the bituminous paint in mortar [11, 30]. In this study, two application methods of inhibitor were done on the steel bar and concrete surfaces with cement type variation (PCC, PPC, and PCC-PPC mixture. The influence of concrete cover thickness, cement type, and exposure condition on the application of inhibitor have also been investigated.

2 Methods

2.1 Materials and specimen design

This study made use of 15 cm x 15 cm x 15 cm cube-shaped mortar specimens with two 12 mm steel bars. The two reinforcements were separated into two mortar cover thickness variations of 3 cm and 5 cm, as shown in Fig. 1. Following that, 27 cube specimens were created and treated as controls with a steel coating, a surface concrete coating, and without a coating (non-coating). This investigation also included 18 mortar cylinder specimens with a 15 cm diameter and a 30 cm height for evaluating compressive strength and split tensile strength, as well as 9 beam specimens with dimensions of 15 cm x 15 cm x 60 cm for testing flexural strength.

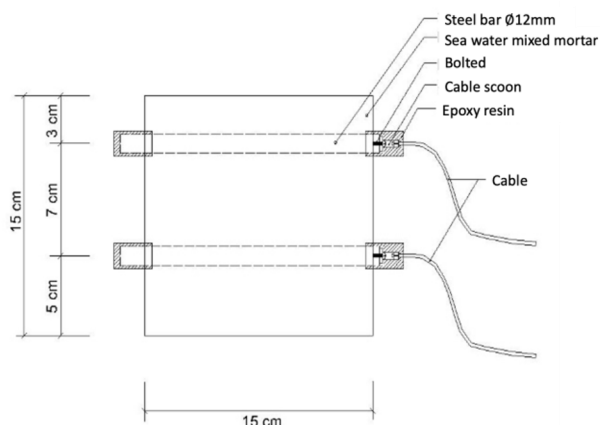


Fig. 1. Specimen design.

After all of the specimens had been molded, they were hardened for 24 hours. The hardened cylinder,

beam, and cube specimens were then removed from the formwork and seawater cured for 28 days. Following the treatment phase, the specimens were exposed to conditions that simulated a corrosive environment in order to accelerate the corrosion process. After curing, cube specimens were exposed to environmental conditions for 28 days. The exposure conditions used in this study were wet, dry, and the dry-wet cycle and it were presented in Fig. 2. There three types of exposure condition are to simulate the real environmental condition of reinforced concrete structures specially in sea water condition.

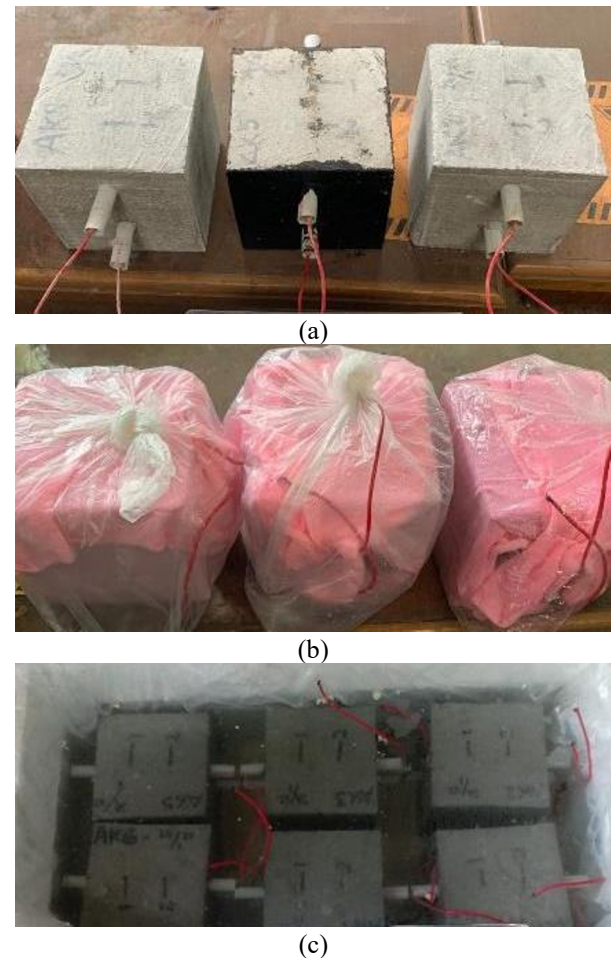


Fig. 2. Exposure conditions of specimens, (a) dry laboratory air condition, (b) wet condition, and (c) dry-wet cycle (5 days in immersed condition and followed by 2 days in dry condition - during wet condition).

Three types of commercially cement, Portland Pozzolan cement (PPC), Portland Composite cement (PPC), and PPC-PPC mixture were used as binders, along with fine aggregate sand from Yogyakarta's Progo River. Pandansimo Beach in Bantul, Yogyakarta, provided the seawater used for mixing. To improve the workability of concrete and bituminous-based anti-corrosion paint for concrete and steel, special superplasticizers were used. For the mixed design of mortar, a water to binder ratio of 0.4 was used in this study. The cement-specific gravity value was 3.15, and the superplasticizer density was 1.06. Table 1 shows the mix design of all specimens. The cement was 100%

PCC, 100%PPC, and 50%PCC50%PPC for each specimen type.

Table 1. Mix design of specimen.

Material	Total
Cement (kg)	554.69
Sand (kg)	1694.067
Water (liters)	225.87
Superplasticizer (liters)	4.24

2.2 Fresh mortar properties test

On fresh mortar, flow table and density tests were performed. The flow table test was used to determine the workability of the mortar. The required initial flow rate, according to SNI 6882:2014, is between 105% and 115%. The flow table test adhered to ASTM C 1437 (2007). The density test was designed to determine the mass unit volume. Fresh mortar was placed in a three-layer cylindrical mold; each layer was stabbed 25 times, and each side of the cylinder was beaten 10 to 15 times to reduce the pores and air bubbles in the mortar (SNI 1973: 2016).

2.3 Corrosion probability test

The half-cell potential measured the corrosion potential of the specimens without causing any damage to the concrete. An electric current was used in this test, along with a Silver-Silver/Chloride reference electrode, or Ag/Ag.Cl (SSE), which was then converted to a Calomel Saturated Electrode (CSE). The half-cell potential test was carried out in accordance with ASTM C876. The scheme for testing the half-cell potential is depicted in Fig. 2. The surface of the specimens was sprayed with water and allowed to dry for 20 to 30 minutes before measuring the half-cell potential. The half-cell potential test was divided into two parts in this study: the curing phase and the exposure conditions. The test was run for 28 days during the treatment period after the specimens were removed from the formworks to compare the potential corrosion values of the specimens with the prevention of a steel coating and the control specimen (non-coating) immersed in seawater. The test under exposure conditions was carried out for 28 days after the curing process was completed. It sought to contrast specimens with a steel coating, a surface concrete coating, and a control specimen (non-coating). Table 2 categorizes corrosion potential values in accordance with ASTM C876-91 (ASTM, 2017). The test scheme was carried out as shown in Fig. 2.

Table 2. Corrosion probability based on ASTM C876.

HCP (mV:CSE)	Probability
$E > -200$	90% no corrosion
$-350 < E < -200$	Corrosion activity cannot be ascertained
$E < -350$	90% corrosion

3 Result and discussion

3.1 Fine aggregate properties

During the fine aggregate physical test on Progo River sand, the grain gradation, water content, specific gravity, and sludge level were all measured. The fine aggregate test was carried out in accordance with the applicable regulations. The fine aggregate test results are shown in Table 3.

Table 3. Fine aggregate test results.

Test type	Result
Grain gradation	Area 2
Fine modulus of grain	2.354
Water content (%)	4
Specific gravity	2.78
Water absorption (%)	2.56
Sludge level (%)	2.5

3.2 Fresh mortar properties

The flow table method was used to perform the mortar workability test, which yielded a value of 112.93%. This result met the required mortar flow value of $110 \pm 5\%$, according to SNI 6882:2014. Following that, a density test on fresh mortar yielded an average value of $2,171.90 \text{ kg/m}^3$ or 2.1719 gr/cm^3 .

3.3 Hardened mortar properties

After a 28-day curing period in seawater, mortar specimens made with seawater and three types of cement (PPC, PCC, and PPC-PCC mixture) as binders were tested for hardened properties. The hardened property test results are shown in Tables 4-6. It were described that the highest compressive strength of those specimens was the mixture of 50% PPC 50%PCC binder (25.76 MPa). The PCC binder performed the highest split tensile and flexural strengths (4.48 MPa and 4.55 MPa, respectively).

Table 4. Hardened properties test results of specimens using PCC as binder.

Test	Reference	Result (MPa)
Compressive strength (MPa)	SNI 1974:2011	22.8
Split tensile strength (MPa)	SNI 2492:2002	5.27
Flexural strength (MPa)	SNI 4154:2014	3.2

Table 5. Hardened properties test results of specimens using PPC as binder.

Test	Reference	Result (MPa)
Compressive strength (MPa)	SNI 1974:2011	24.96
Flexural strength (MPa)	SNI 4154:2014	4.55

Table 6. Hardened properties test results of specimens using 50%PPC 50%PCC mixture as binder.

Test	Reference	Result (MPa)
Compressive strength (MPa)	SNI 1974:2011	25.76
Split tensile strength (MPa)	SNI 2492:2002	4.38
Flexural strength (MPa)	SNI 4154:2014	4.11

3.4 Corrosion potential of steel bar

Following the prevention methods, the half-cell potential test yielded varying corrosion potential values during the curing period and under exposure. Throughout the curing process, the half-cell potential test was performed on coated and uncoated specimens. Fig. 3-5 shows that the corrosion potential values on the specimens with corrosion protection of a steel coating were greater than those on the control specimen (non-coating). The test continued until the 56th day of under exposure after assessing the corrosion potential for 28 days during the treatment phase.

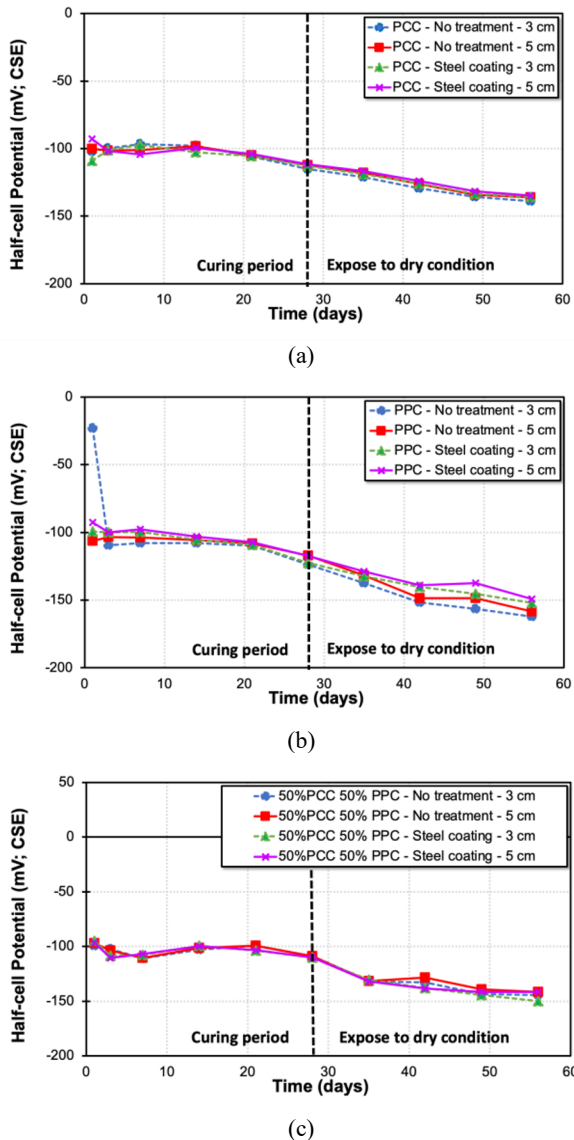


Fig. 3. Half-cell potential of steel bar on the specimens exposed to dry condition (a) PCC binder, (b) PPC binder, dan 50%PPC 50%PCC mixture.

The goal of this test was to see how corrosion prevention with a steel coating and a surface concrete coating affected the corrosion potential values of the specimens. In addition to the two prevention methods, one non-coated specimen was used as a control in this study. The test results revealed that the corrosion potential values of the specimens with a steel coating and a surface concrete coating were superior to the corrosion potential value of the control specimen in all exposure conditions (non-coating).

According to previous research, specimens with a protective layer on the reinforcing steel and surface produced more positive results than unprotected specimens [21-22, 24-25, 27]. Applying the coating directly to the surface of the mortar could cover the pores and cracks on the surface, providing additional protection against moisture and chloride intrusion [18-19, 23-24]. The results of this research were in good agreement to the previous research phenomena.

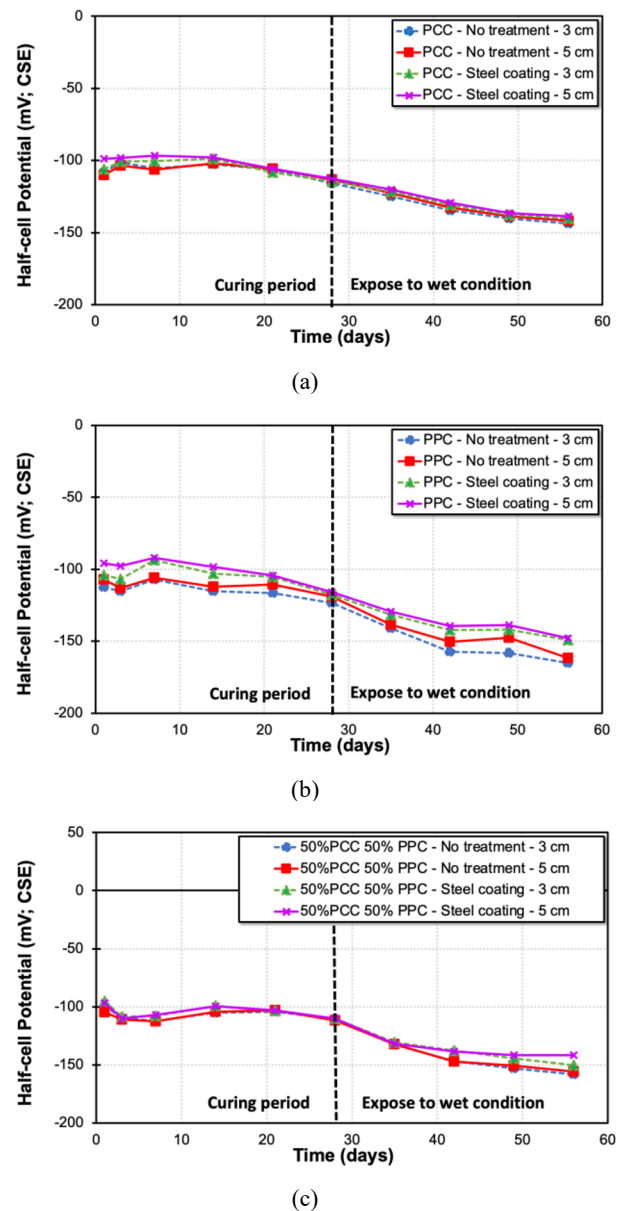


Fig. 4. Half-cell potential of steel bar on the specimens exposed to wet condition (a) PCC binder, (b) PPC binder, dan 50%PPC 50%PCC mixture.

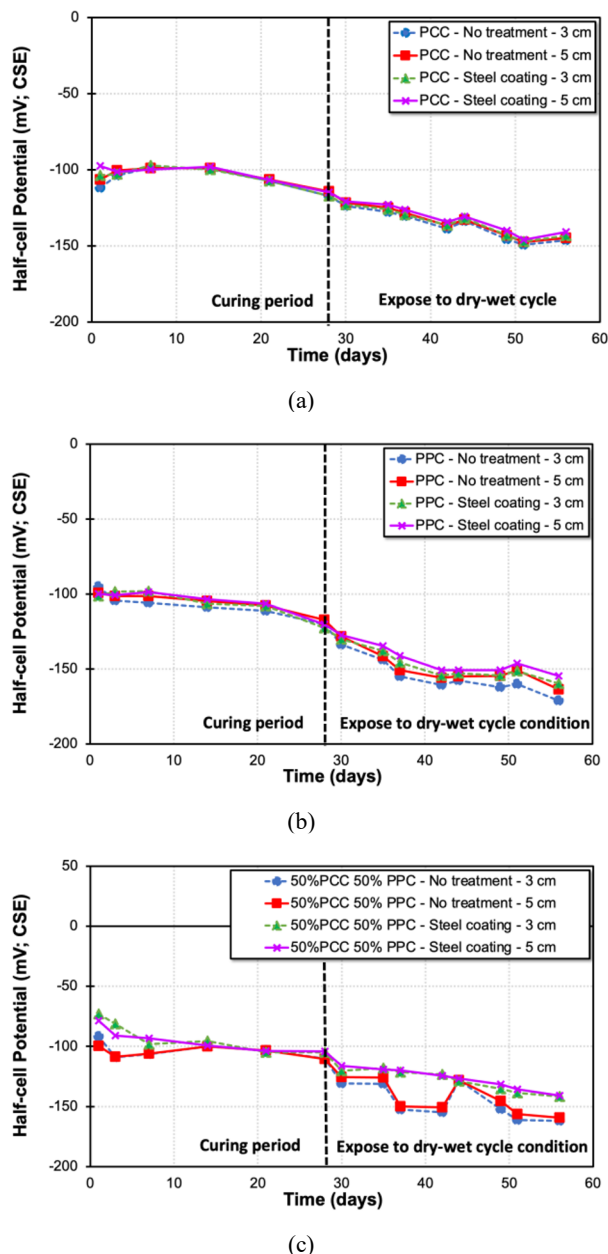


Fig. 5. Half-cell potential of steel bar on the specimens exposed to dry-wet cycle condition (a) PCC binder, (b) PPC binder, dan 50%PCC 50%PPC mixture.

During the curing period, all specimens were typically treated by immersing in the tap water until 28 days. The half-cell potential of steel bar during that period were relatively stable between -130 and -80 mV vs CSE, which is in the 90% no corrosion condition based on ASTM C876. The phenomenon was occurred due to the new steel bar with no corrosion and no extreme exposure condition applied to the specimens. The coating as corrosion prevention method was still no significantly effect to the half-cell potential.

The specimens were exposed to different condition after 28 days of curing period. Based on the data on Fig. 4-5, it was presented that the dry-wet condition was the most impactful condition to initiate corrosion indicated by the slightly lower half-cell potential than another exposure condition. The chloride ions were accumulated rapidly during the wet-dry cycle as tidal zone simulation. The dry condition showed the best situation

to maintain steel bar remained passive without decreasing the half-cell potential value.

In the cover thickness point of view, it could be seen that the 5 cm cover in all specimen types was higher half-cell potential value than the 3cm and it indicated that deeper the cover thickness better corrosion prevention even using coating method. The concrete cover will prevent the chloride intrusion and carbon dioxide diffusion to reach the steel bar surface. The coating was well performed indicated by the higher half-cell potential value than no coating. The bituminous based paint was preventing the corrosion initiation during early age of reinforced concrete.

The concrete material quality also contributed to the corrosion prevention. The compact and high resistivity of material will prevent corrosion. Based on the experimental data, the PCC binder specimens demonstrated the best performance indicated by the higher corrosion potential than another binder type. Composite cement made with 60% OPC + 30% fly ash + 5% limestone powder has higher strength than PPC made with 30% fly ash.

The result of this paper is based on two months exposure condition data only. The long-term observation is required to understand the reliability method.

4 Conclusions

The study's findings revealed that specimens with a steel coating were less likely to corrode than those with a surface concrete coating. This finding held true for the treatment and exposure periods. The corrosion potential value was influenced by the change in mortar cover thickness, with the 5 cm mortar cover thickness exhibiting a higher value than the 3 cm mortar cover thickness for both the treatment and exposure periods. The specimens exposed to a dry-wet cycle (two wet days followed by five dry days) corroded more than the other two conditions. The dry laboratory conditions, on the other hand, produced the least corrosive results. Based on the results, it can be concluded that the steel coating is applicable to corrosion prevention method and PCC is recommended to maintain the corrosion potential stable to be passive.

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