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POTENTIAL DEVELOPMENT OF SACRIFICIAL ANODE CATHODIC PROTECTION APPLIED FOR SEVERELY DAMAGED RC BEAMS AGED 44 YEARS

P. Astuti [1,2] R.S. Rafdinal [3] A. Mahasiripan [1] H. Hamada [1] Y. Sagawa [1] D. Yamamoto [1]

[1] Department of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan

[2] Department of Civil Engineering of Universitas Muhammadiyah Yogyakarta, Yogyakarta, Indonesia

[3] P.S. Mitsubishi Construction, Co. Ltd., Tokyo, Japan

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**Corresponding Author,*
Email address: pinta.astuti@doc.kyushu-u.ac.jp

ABSTRACT:

Sacrificial zinc anodes, as one of the cathodic protection repair system, are typically embedded in the patch repair section with high resistance mortar to offer corrosion protection on reinforced concrete (RC) structures. Steel bars within the repair area passivate because of alkalinity of the fresh repair material, the absence of chlorides and the abundance of dissolved oxygen in the pore solution of the freshly mixed concrete or repair mortar. As a result, the rebar potential in the repair rises above the passive steel potential, therefore, in the parent concrete a macro-cell corrosion occurs. This study reviews the performance of sacrificial zinc anodes installed in the parent concrete to protect the rebars from re-deterioration and suppress the incipient ring anode or macro-cell corrosion activities around the boundary between parent concrete and patch repair concrete, from a view of potential development.

Two specimens of 44-year-old severely damaged RC beams having a span of 2400 mm and 200x300 mm cross-section, both suffering from chloride-induced corrosion of the reinforcement are prepared as “RC1” and “RC2” marking. The polymer modified mortar as the material of patch repair section is applied to the middle tension area in the dimension of 70x150x800mm. Four cylindrical sacrificial zinc anodes with 30 mm diameter and 130 mm length installed in the parent concrete by LiOH cementitious coating material. Corrosion inhibitor applied to the tension steel bar surface of the patch repair section in RC2, since the natural macro-cell corrosion was naturally occurred before the repair. Half-cell potential test of rebar by silver/silver chloride reference electrode (SSE) in every 5 cm on the side section of specimen’s surface, and the current density of sacrificial zinc anodes are measured regularly on 0, 7, 14, 21, and 32-days presented in this paper.

The results during the early age of zinc anode embedded in damaged RC beams indicate that sacrificial zinc anode had a profound effect on polarizing the potential of rebar in the parent concrete. The high protection concentrates in the surrounding of anodes in parent concrete and no significant protection of the rebar in patch repair section because of the inherent differences in properties between patch repair material and parent concrete. The rust inhibitor applied in the patch repair is not enough to keep the polarization of rebar in noble values, too. The high resistivity of patch repair material reduced the effectiveness of the sacrificial anodes in parent concrete to protect all cross-section of rebar in RC beam structure.

KEYWORDS: sacrificial zinc anode cathodic protection, potential development, parent concrete

1. Introduction

Protection of rebars due to corrosion in the severely damaged condition is essential to extend the service life of reinforced concrete (RC) structures. However, the long-term performance of RC structures is affected by several factors such as environmental exposure condition, electrochemical reactions, mechanical loading, impact damage, etc. Chloride-induced corrosion of the rebar considered is the main deterioration cause of RC structures [1]. Patch repair on the deteriorated concrete is one of the approaches to rehabilitate the defect of RC structures [3]. This technique is required to apply in the condition of chloride concentration larger than 0.3% by weight of cement and the half-cell potential value more negative than -350 mV, but the concrete replacement will be very difficult and expensive [6], therefore the combination repair method between concrete replacement and sacrificial galvanic anode in non-patch repair section is needed. Sacrificial zinc anodes as one of repair system in the cathodic protection are typically embedded in the patch repair section to offer corrosion protection on the reinforced concrete (RC) structures. The steel bar within the repair area passivates because of the alkalinity of the fresh repair material, the absence of chlorides and the abundance of dissolved oxygen in the pore solution of the freshly mixed concrete or repair mortar. As a result, the rebar potential in the repair rises above the passive steel potential, therefore, in the parent concrete, macro-cell corrosion will occur.

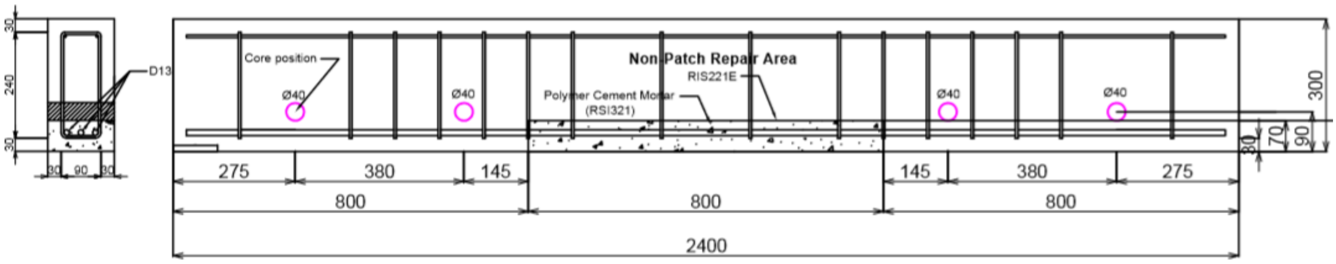
A study on the application of sacrificial zinc anode in severely damaged RC structures is limited at present. In the previous research, Rafdinal [2] observed the application of sacrificial anodes in patch repair section in 42-year-old RC beam structures. The result showed that the protection could not deliver to the parent concrete due to the high electric resistance of patch repair material than old parent concrete. Christodoulou et al. [3, 4] compare the performances of sacrificial anodes installed both within patch repair and parent concrete area in full-scale RC structure. The result indicates that sacrificial anodes installed within parent concrete had a more significant effect on the polarization of rebar around the perimeter of patch repair.

In this study, two 44-year-old RC beams exposed to severe environmental condition (i.e., tidal and splash zone, in marine condition) are prepared and repaired, denoted as “RC1” and “RC2”. Polymer modified mortar applied in the middle part of tension side of the beam as patch repair section and sacrificial anode installed in the non-patch repair section (parent concrete) in both of specimens. Corrosion inhibitor was applied in the tension steel bar surface of RC2 since the natural macro-cell corrosion was occurred in RC2. This study reviews the performance of sacrificial zinc anodes installed in the parent concrete to protect the rebar from re-deterioration and suppress the incipient ring anode or macro-cell corrosion activities around the boundary between parent concrete and patch repair concrete in early age from the viewpoint of potential development.

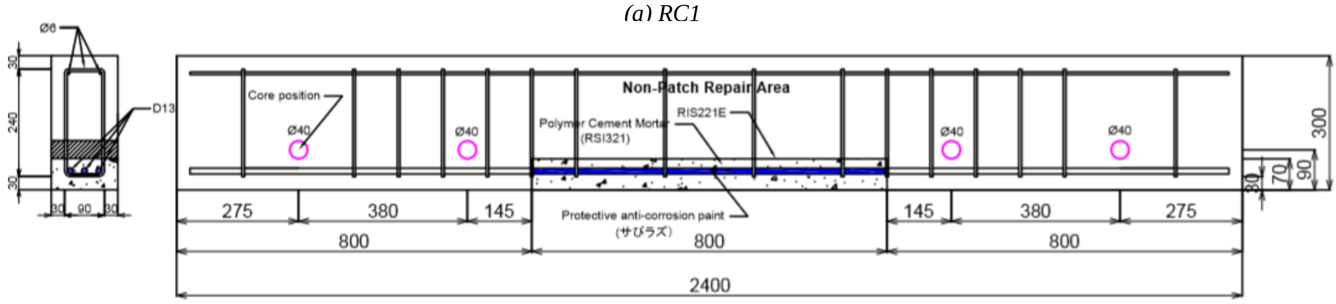
2. Experimental program

2.1 Specimen design

Two identical RC beams (RC1 and RC2) were used for this study having a span of 2400 mm and a cross-sectional area of 150 x 300 mm, with both suffering from chloride-induced corrosion of the reinforcement as shown in Figure 1. Ordinary Portland Cement (OPC) was used as a binder of the parent concrete. The average value of compressive strength and elasticity modulus after corrosion were 30 MPa and 29 GPa, respectively [5]. The deformed steel bar with a diameter of 13 mm and yield strength of 363 MPa [5] was used as a tensile rebar, and non-deformed steel of 6 mm in diameter was used as compressive rebar. Stirrups with a space of 100 mm were embedded in the beam. The polymer modified mortar (Figure 2) was applied in the middle of tension area with the dimension of 70 x 150 x 800 mm after replacing the chloride-contaminated existing concrete by crushing process and using an adhesive material as coating agent between parent concrete and patch repair mortar. Cylindrical sacrificial zinc anode (Figure 3(a)) with a diameter of 30 mm, a length of 139 mm and an approximate weight of 417 grams were installed in pre-drilled holes of 40 mm diameter in parent concrete and cementitious coating material with LiOH (Figure 3(b)) was used to cover the anodes after settling position in the hole. Corrosion inhibitor was applied to the tensile steel bar surface in the patch repair section of the RC2 before casting the patch repair material.



(a) RC1



(b) RC2

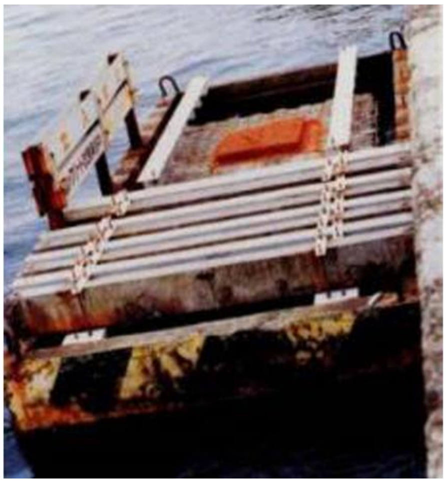
Figure 1 Repaired specimen design (a) RC1 and (b) RC2

Figure 2 Polymer modified cement for mortar

(a)

(b)

Figure 3 (a) Sacrificial Zinc Anode (b) Cementitious anode coating material mixed with LiOH



(a)

(b)

(c)

Figure 4 Exposure condition at (a) Sakata Port (1975-1995)[7], (b) PARI Laboratory (1995-2010), (c) Kyushu University (2010-2018)

2.2 Exposure conditions until 44 years

The two specimens repaired were exposed to the natural marine environment for 20 years (1975-1995) at Sakata Port as shown in Figure 4(a) [5, 7-10], hereinafter Figure 4(b) showed it sheltered from the rain at the Port and Airport Research Institute (PARI) laboratory in Yokosuka, Japan (1995-2010), furthermore the RC beams were moved and stored at the outside exposure field in Kyushu University Ito Campus, Fukuoka, Japan (2010-2018). After the repair process, the specimens were kept for two days' wet condition by tap water followed by the five days' dry condition in the laboratory air.

2.3 Measurement methods

Half-cell potential test of rebar according to ASTM C876-91 (1999) [11] was conducted by silver/silver chloride reference electrode and high impedance multimeter (voltmeter setting) on every 50 mm square grid after one hour of pre-wetting. The reference electrode is connected to the negative terminal and the reinforcing bar to the positive terminal of the multimeter [12]. On-potential (E_{on}) of rebar and the anode are measured under sacrificial anode cathodic protection. Instant-off potential (E_{off}) is checked immediately after disconnection and the rest potential (E_{corr}) is measured at 24 hours after disconnection of steel bar and the anode.

3. Result and discussion

3.1 Cracking map

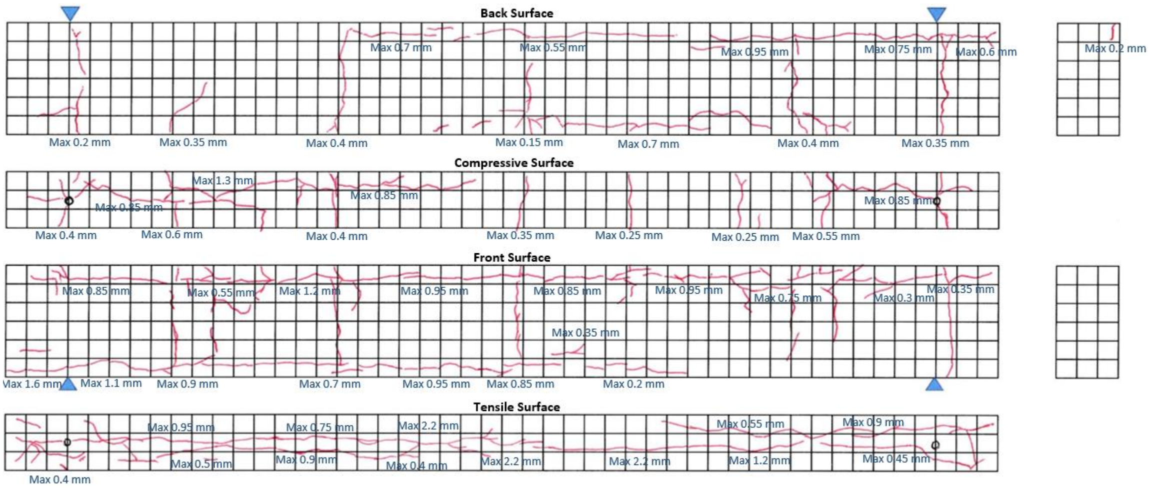
The cracking map after 44-years exposure is shown in Figure 5(a) for RC1 and Figure 5(b) for RC2. In RC1, many longitudinal and transversal cracks both in tensile and compressive area are seen. The longitudinal cracks are coincident with the position of tensile and compressive rebar. The maximum crack width 2.2 mm of longitudinal crack are recognized in the tensile area and 1.3 mm in the compressive area. The transversal cracks are coincided in the stirrups position with the maximum width of 0.55 mm. In RC2, longitudinal cracks are only occurred in a tensile area with the maximum width of 1.5 mm. Transversal cracks concentrated in the middle span of the tensile area were initiated from the pre-cracking or due to stirrups corrosion. No concrete spalling is observed in both RC beams, RC1 and RC2.

3.2 Visual observation of rebar

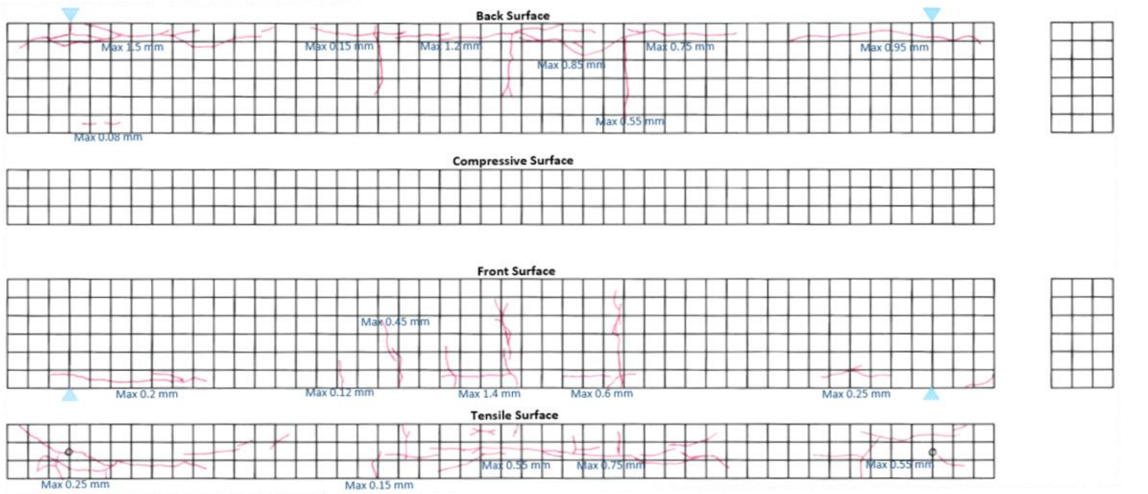
The rebar condition in middle tensile area (patch repair section) was observed before the casting process of polymer modified mortar as shown in Figure 6. In RC1, uniform corrosion occurred in all of rebar surface and there are two points where serious corrosion was recognized at the location of the two concrete cracks at the locations (A) and (B) with 0.70 mm and 0.85 mm crack width, respectively. On the other hand, the different corrosion condition was found in RC2. Pitting corrosion was recognized at the location of (B) and (C). However, the surface condition of steel bar at the location of (A) is good. In this case, it is estimated that the rebar at the section A is the passivated (cathode). Therefore, the galvanic corrosion might occurred between two visibly separated areas. This kind of galvanic corrosion is known as macro-cell corrosion which is due to a non-homogeneity in oxygen supply, crack in the concrete, or localized chloride ion content [13].

3.3 Polarization effect of anodes

This study focuses on the performance of sacrificial zinc anodes to deliver protection current embedded in the parent concrete, especially to the tensile rebar which is the most severely damaged condition. Potential shift of rebar was observed during 32-days after the installation of the anodes. Figure 7 and 8 present the instant-off potential of compressive and tensile rebar, measured at the position of 15 cm and 5 cm vertical distance from the anode position. The polarization of the tensile rebar is larger than that of the compressive rebar due to its closer position to the anode. The polarization is found in the parent concrete, but it is not found in the patch repaired position, because of the inherent differences in properties between patch repair material and parent concrete. In this case, the potential shift is almost limited to the distance of approximately 200 mm away from the anodes position.



(a) RC1

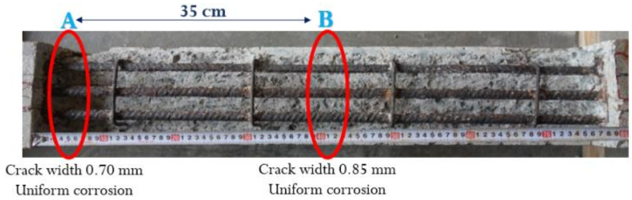


(b) RC2

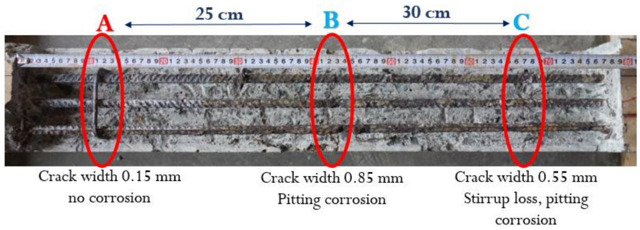
Figure 5 Crack appearance of specimens after 44-years (a) RC1 and (b) RC2

Depolarization test of rebar was done at 24-hours after the disconnection of anode. Normally, potential decay criterion of 100 mV is adopted for assessing the performance of sacrificial zinc anodes. Figure 9 presents the depolarization value after 32-days of the connection. It can be seen that in the RC1, the protection zone was in parent concrete, both of compressive and tensile rebar, but the patch repair area is non-protection zone. Compared to the RC1, depolarization value of RC2 in patch repair section is slightly higher. It may be due to the application of corrosion inhibitor in the tensile rebar. Nevertheless, the corrosion inhibitor applied in the patch repair cannot be evaluated "effective" against the corrosion of rebar at the only 32-days.

Meanwhile, the current density of sacrificial zinc anodes is presented in Figure 10. It shows that both of RC1 and RC2 have anodic current density exceed the minimum design limit of cathodic protection between 2 - 20 mA/m^2 as specified in EN 12696 [14]. The difference between RC1 and RC2 is not clear, but it may be difference in cracking, and corrosion condition. Even though the difference of current density on both of RC beams is high, but the current flow work stable time dependency.



(a) RC1

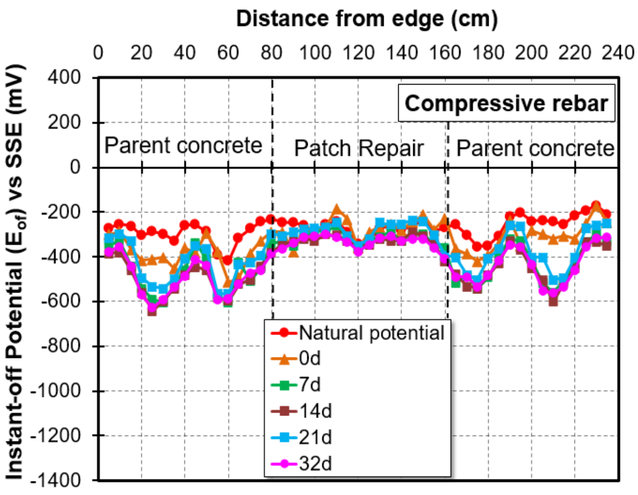


(b) RC2

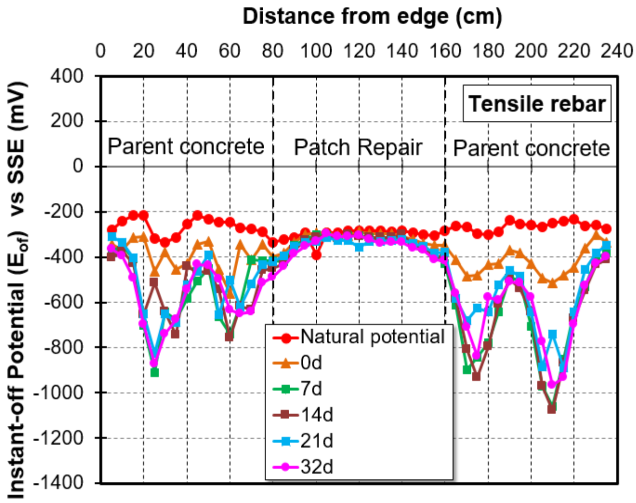
Figure 6 Rebar condition in the middle tensile area of (a) RC1 and (b) RC2

Table 1 Summary of crack condition on RC2

Crack Location	Potential (mV; SSE)	Crack Width (mm)	Total Cross Section Area (mm2)	Visual Condition
A	-262	0.15	352.8	Good
B	-377	0.85	248.1	Pitting
C	-356	0.55	339.3	Pitting

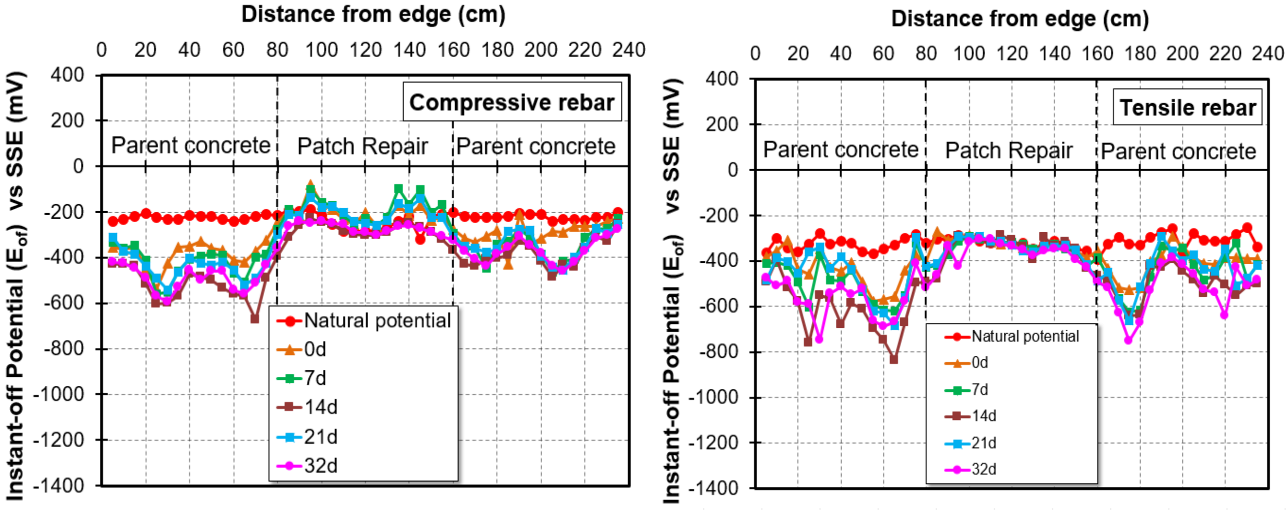


(a)



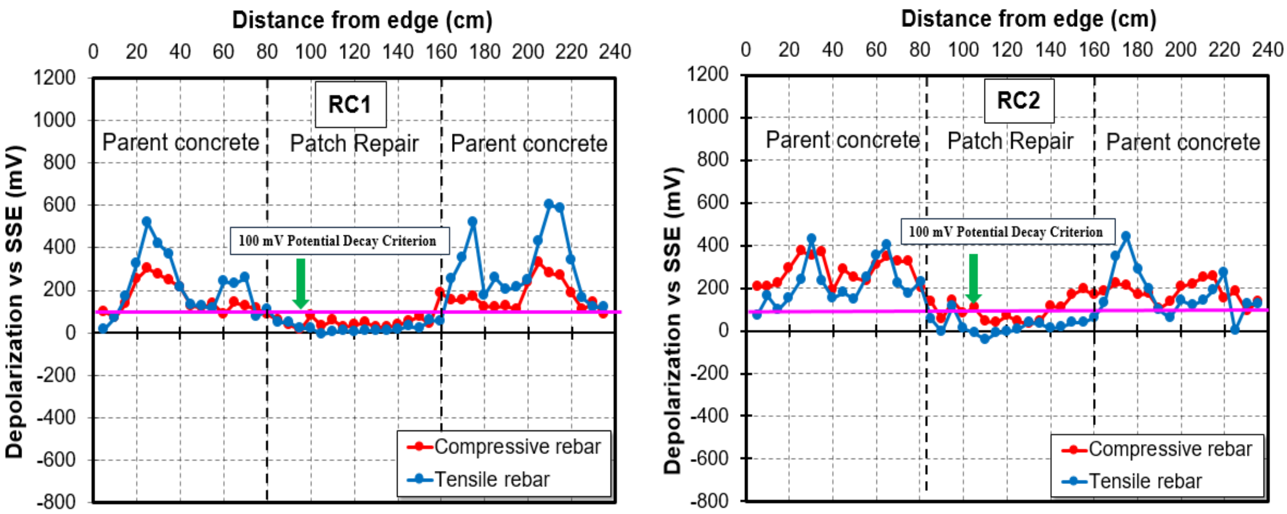
(b)

Figure 7 Natural and instant-off potential of (a) compressive rebar and (b) tensile rebar on RC1



(a) (b)

Figure 8 Natural and instant-off potential of (a) compressive rebar and (b) tensile rebar on RC2



(a) (b)

Figure 9 Depolarization of rebar on (a) RC1 and (b) RC2 at 32 days

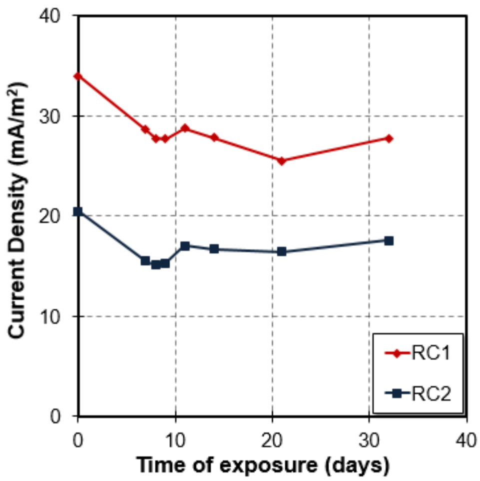


Figure 10 Current density of sacrificial zinc anode

4. Conclusion

The results indicate that:

(1) The sacrificial zinc anode newly developed and tested in this research has an effect on polarizing the potential of rebar in the deteriorated RC member.

(2) However, the high polarization is limited to the surrounding of anodes in parent concrete, not in the patch repair section, due to the inherent differences in the properties of patch repair material and parent concrete.

(3) The effectiveness of the rust inhibitor is still not clear.

(4) The high resistivity of patch repair of modified polymer mortar may reduce the effectiveness of the sacrificial anodes to polarize all of rebar in RC beam structure.

5. Acknowledgments

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