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PARTIALLY REPAIR METHOD OF DETERIORATED RC BEAMS BY SACRIFICIAL ANODE CATHODIC PROTECTION AND CORROSION INHIBITOR

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ABSTRACT

Patch repair of deteriorating concrete, which mainly involves the replacement of chloride-contaminated concrete with the fresh alkaline patch concrete is a common intervention to rehabilitate the defecting reinforced concrete (RC) structure while the concrete replacement of this process is expensive. Application of curative corrosion inhibitor directly on the surface of corroding rebar before new patch material casting is recommended as easy to use approach for new corrosion attack. Sacrificial anodes have been used to limit the extension of concrete replacement and extend the service life of patch repair to RC member. This study focuses on the utilization of sacrificial anode cathodic protection arrangement and corrosion inhibitor in partially repair RC beams. Two specimens of 44-years of serious chloride-induced corrosion condition having a length of 2400 mm and 200x300 mm cross-section were prepared as RC-1 and RC-2. The polymer-modified mortar as the patch repair material was applied to the middle tension area in the dimension of 70x150x800mm. Four cylindrical ribbed sacrificial zinc anodes with 30 mm diameter and 130 mm length installed in the parent concrete by LiOH cementitious coating material. A specially modified epoxy paint as corrosion inhibitor was applied to the tensile steel bar surface of the patch repair section in RC-2. The exposure condition of the specimens was on two-days wet and followed by five-days dry in laboratory air condition until 12-months observation. Depolarization test of rebar by the calomel-saturated electrode (CSE) on the side section of specimen's surface, the current density of sacrificial zinc anodes and rebar, anodic-cathodic polarization curve are measured regularly until 12-months observation as the performance evaluation was presented in this paper. The sacrificial zinc anode tested in this research affects polarizing the potential of rebar in the deteriorated RC member. However, the high polarization is limited to 15 cm away from 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. The application of corrosion inhibitor in the rebar surface of patch repair part may extend the polarization effect of anodes and significantly increase the polarization distance until two times.

Keywords: Corrosion inhibitor, sacrificial anode, patch repair, chloride-induced corrosion.

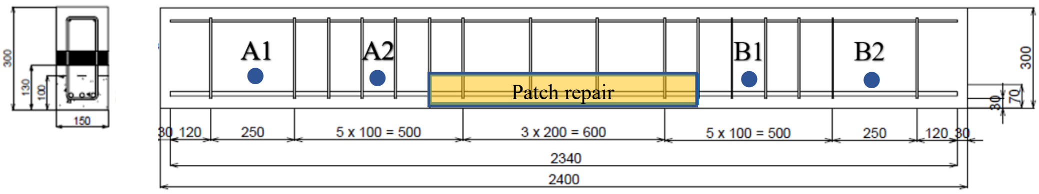
1. INTRODUCTION

Patch repair of deteriorating concrete is a common intervention to rehabilitate defecting reinforced concrete (RC) structure. Some standards suggest that the section that shows chloride concentration greater than 0.3 percent by weight of cement and half-cell potential value less than -350 mV should be removed [1]. Concrete replacement on this case can be costly [2]. Sacrificial anodes have been used to limit the extent of concrete replacement and extend the service life of patch repair to RC member. They respond to the changes in the environmental conditions they are exposed to [2,3,4]. Such an effect will be more dominant in parent concrete that has a residual level of chloride contamination as opposed to non-contaminated repair concrete or mortar [5]. Another practiced method for control of steel corrosion in concrete is the use of corrosion inhibitor. The curative and preventive treatments can be distinguished depending on the mode of the inhibitor application. The curative treatment consists of the application of corrosion inhibitors directly on the surface of exploited and corroding reinforced concrete structures. The preventive treatment consists in the introduction of corrosion inhibitors within mixing water to the fresh concrete. The curative corrosion inhibitor was chosen in this study as easy to use approach for application in the steel bar surface of the patch repair part [6]. This study analyzed the performance of sacrificial anodes installed within the parent concrete as opposed to the previous approach of placing sacrificial anodes within the patch repair section itself and the effect of the application of rust inhibitor in patch repair section after one-year exposure are presented. The anodes were monitored to assess their performance, and the results provide a better understanding of the corrosion mechanism in the patch and non-patch repair section and the suitable improved repair method.

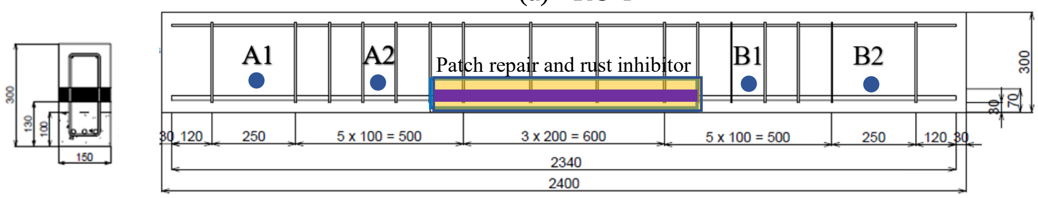
2. EXPERIMENTAL PROGRAMS

2.1 Specimen design

Two identical RC beams (RC-1 and RC-2) were used for this study having a length 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 Fig. 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 30.0 MPa and 29.0 GPa, respectively [7]. The deformed steel bar with a diameter of 13 mm and yield strength of 363 MPa [6] was used as 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 (Fig. 2(a)) 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 rust removal using an EVA (Vinyl Acetate / Ethylene) copolymer emulsion as adhesive material coating agent (Fig. 2(b)) between parent concrete and patch repair mortar. Cylindrical ribbed sacrificial zinc anode (Fig. 2(c)) 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 (Fig. 2(d)) was used to cover the anodes after settling position in the hole. Modified epoxy paint (Fig. 2(e)) was applied to the un-rusted tensile steel bar surface in the patch repair section of the RC-2 as a corrosion inhibitor before casting new patch repair material.

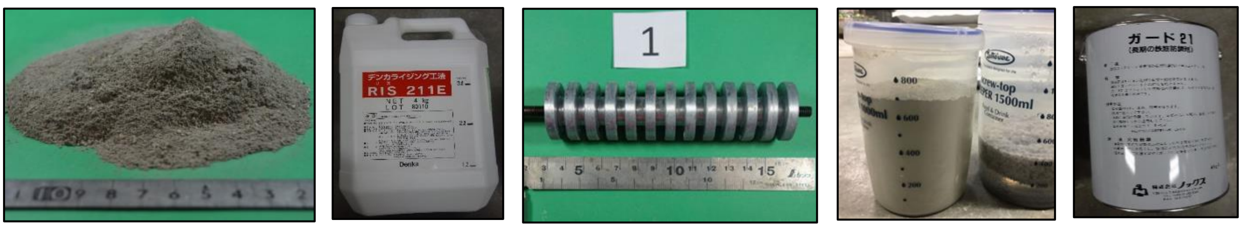


(a) RC-1



(b) RC-2

Fig. 1 Specimen design (a) RC-1 and (b) RC-2



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

Fig. 2 Materials for repair (a) polymer modified mortar, (b) coating agent, (c) cylindrical ribbed sacrificial zinc anode, (d) Cementitious anode coating material mixed with LiOH, and (e) rust inhibitor

2.2 Testing method

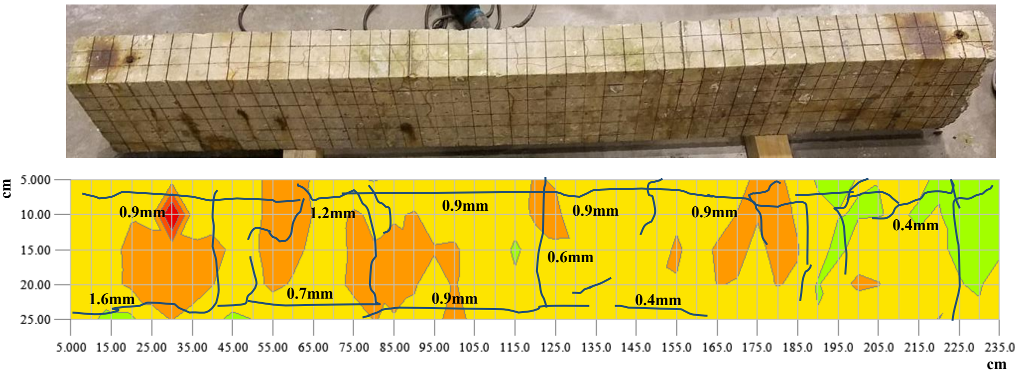
To evaluate the polarization of rebar, half-cell potential test of rebar according to ASTM C876-91 (1999) was conducted by the calomel-saturated electrode (CSE) and high impedance multimeter (voltmeter setting) on every 50 mm square grid at the compressive and tensile rebar position after one hour of pre-wetting. On potential (E_{on}) of rebar and the anode are measured under sacrificial anode cathodic protection. Instant-off potential (E_{iof}) is checked immediately after disconnection, and the rest potential (E_{corr}) is measured at 24 hours after interruption of the steel bar and the anode. The corrosion current density is measured by using silver/silver chloride electrode (SSE) and portable corrosion meter. Potentiostat, functiostat, and data logger are used for assessment of passivity grade of rebar with anodic and cathodic polarization curve method.

3. RESULTS AND DISCUSSION

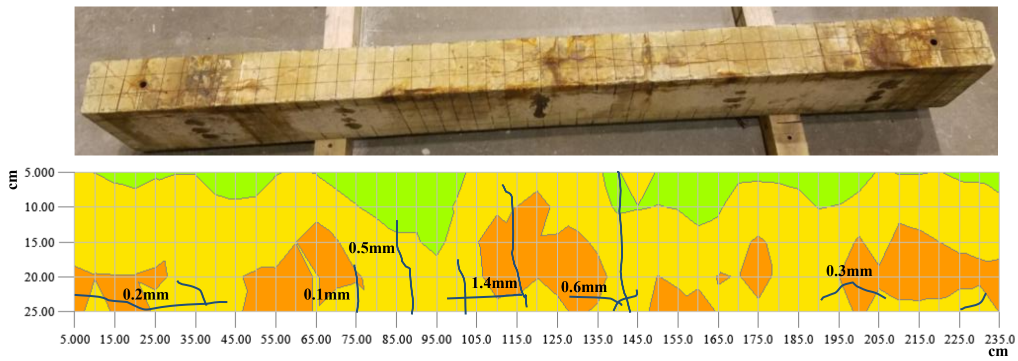
3.1 Preliminary Investigation

The crack pattern, crack width, and initial corrosion map on the concrete surface after 44-years of exposure are presented in Figure 3. RC-1 shows more serious crack appearance than RC-2. Many longitudinal and transversal cracks both in the tensile and compressive area are observed in RC-1. The maximum crack width 2.2 mm of the longitudinal cracks is recognized in the tensile part and 1.3 mm in the compressive part. The transversal cracks have coincided in the position of the stirrup with a maximum width of 0.6 mm. In RC-2, longitudinal cracks only occur in a tensile area with a maximum width of 1.5 mm. Transversal cracks concentrated on the middle span of the tensile area were initiated from the pre-cracking or due to stirrups corrosion [7,8]. No concrete spalling is observed in both beams.

Identical initial corrosion condition of both of beams is recorded. In RC-1, 20% area is categorized as corrosion region and 73% is classified as uncertainty region based on ASTM C 876 whereas 21% area of RC-2 is in corrosion condition and 11% is in uncertainty region.



(a) RC-1



(b) RC-2

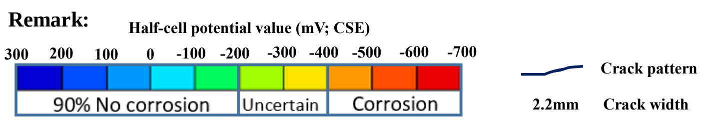


Fig. 3 The appearance of beams and initial corrosion condition

The average of total chloride ion concentration in the surrounding of rebar is 6.05 kg/m^3 in RC-1 and 3.08 kg/m^3 in RC-2. These values are higher than the chloride ion threshold initiating corrosion of 1.2 kg/m^3 (JSCE standard specification for concrete structures – 2007 "Design") [9]. Based on JSCE standard specifications for concrete structures – 2001 "Maintenance" [10] Table C14.3.5.1 Grades of appearance and deterioration of structures, these specimens were categorized as Grade II-1 (former acceleration stage) where corrosion-induced cracking and rust appearance are observed. The intervention methods such as surface coating, patching, cathodic protection, and electrochemical desalination are required to extend the service life of members.

3.2 Polarization effect of anodes

After 28 days of patch repair fabrication and anodes installation, the sacrificial anodes were connected to the steel bar. The time dependency of protective current density generated by sacrificial anodes and air temperature during one-year observation was provided at Fig. 3 whereas one-month observation data was presented in the previous study [7]. It shows that both of RC-1 and RC-2 have anodic current density exceed the minimum design limit of cathodic protection more than 10 mA/m^2 as specified in EN 12696 [11]. In the first 150 days, RC-1 shows higher protective current density than RC-2. It may be due to the difference of initial corrosion and cracking condition indicated by higher total chloride ion concentration in RC-1 (6.05 kg/m^3) than in RC-2 (3.08 kg/m^3). Besides, the number of the crack of RC-1 is more than RC-2. This condition reveals that the current flow of sacrificial anodes change the environmental condition around steel bar into stable until 150 days and after that, the current density of both beams become almost same and slightly decrease time dependency.

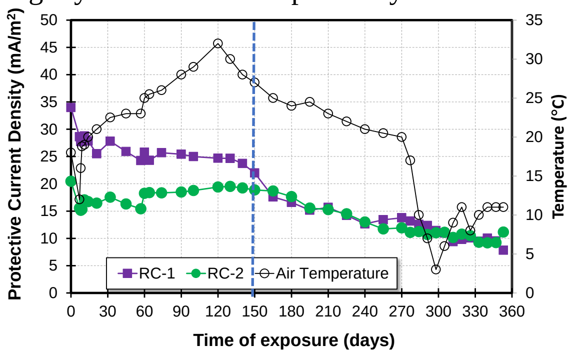


Fig. 3. Protected current density generated by sacrificial anodes

In order to access the performance of sacrificial anode cathodic protection, the potential of rebar and sacrificial anodes during connection (on potential), immediately after disconnection (instant-off potential), and half-cell potential after 24-hours of disconnection (rest potential) were recorded. The obtained on and instant-off potential values of all sacrificial anodes in RC-1 and RC-2 are -1400 mV~-1000 mV during 0 day until 120 days and it shifted to noble value around -1000 mV~-600 mV in 353 days whereas the rest potential of anodes is around -1400 mV ~ -1000 mV.

The polarization effects of tensile rebar afforded by the distance of the sacrificial anode away from the edge of the beams are shown in Fig 4 and 5. On and instant-off potential of rebar shows that the sacrificial anodes affected the potentials to a distance of approximately 200 mm from the anode position until one-year of observation. The time-dependent trends monitored in Fig. 4 and 5 were attributed to changes in the weather conditions. The rest potential of rebars are shown in Fig. 6. It showed that the time dependency of rest potential of rebar shifted to noble value in RC-2. However, it was not significantly changed in RC-1.

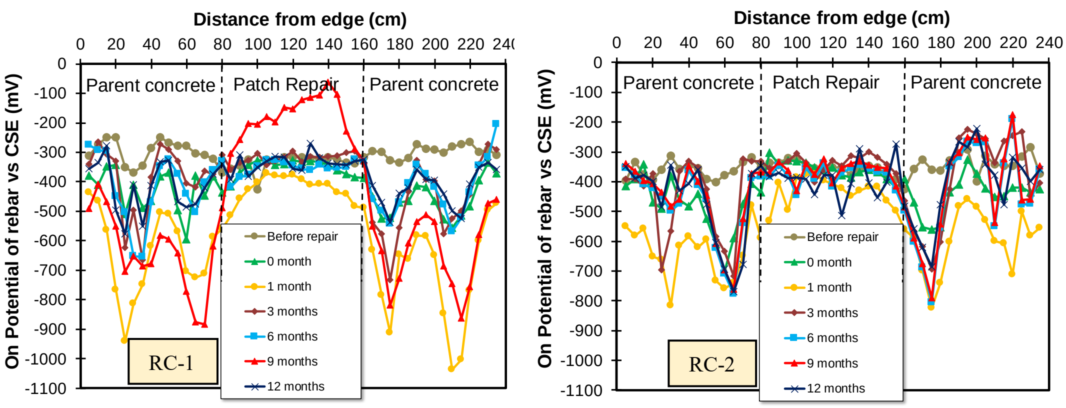


Fig. 4. On potential of tensile rebar

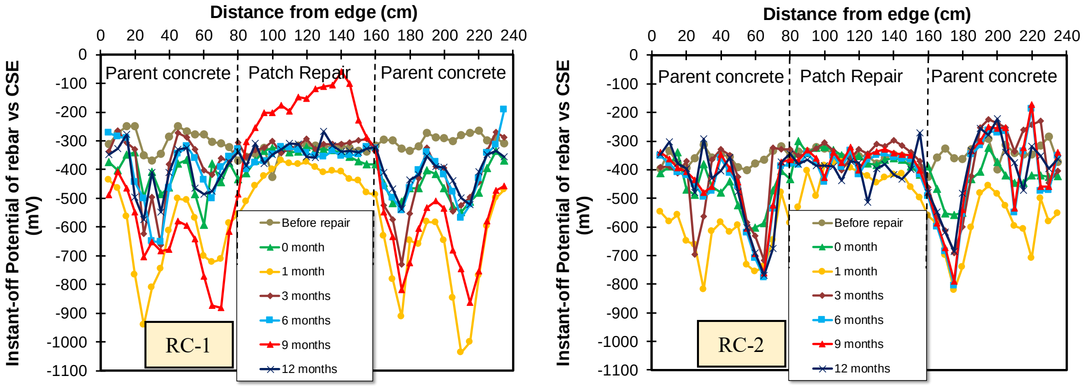


Fig. 5. Instant-off potential of tensile rebar

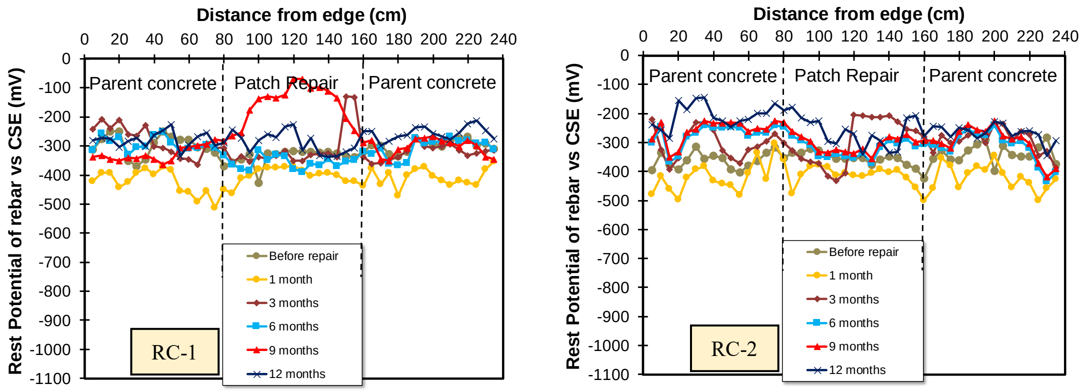


Fig. 6. Rest potential of tensile rebar

Depolarization test of rebar was checked at 24 hours after the disconnection of sacrificial anodes. It was calculated by the difference value between instant-off and rest potential. Normally, the potential decay criterion of 100 mV is adopted for assessing the performance of cathodic protection. Fig. 7 presents the depolarization test value after 1, 3, 6, 9, and 12 months of exposure. It shows that the depolarization test value of rebar in parent concrete of both specimens can exceed 100 mV. It indicated that sacrificial anodes are effective to stop corrosion in chloride contaminated concrete. However, the depolarization is limited in patch repair due to the difference in material properties between the patch and non-patch repair. The application of corrosion inhibitor in RC-2 demonstrated higher depolarization than in RC-1. There was no significant effect of corrosion inhibitor in the early age of repair but it gradually increased time-dependently. After 12 months of rehabilitation, the depolarization test value of rebar in patch repair with corrosion inhibitor can reach 100 mv.

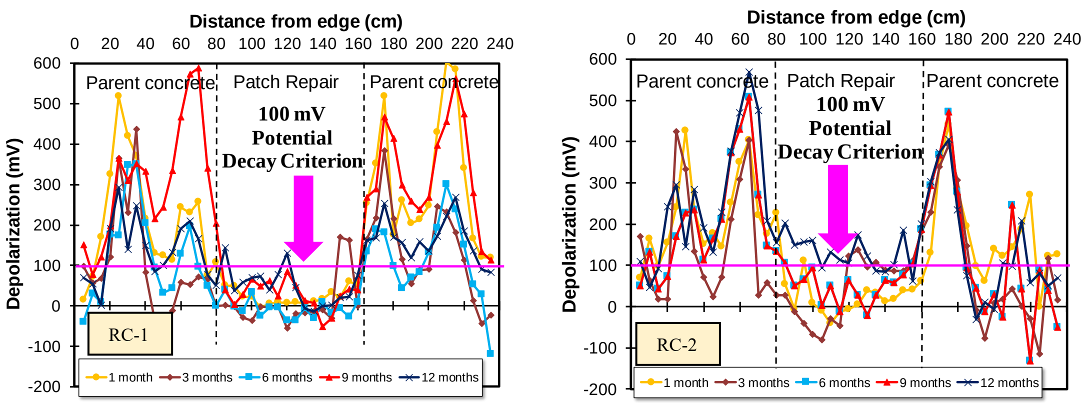


Fig. 7. Depolarization test value of tensile rebar

3.3 Corrosion Current density

The monitoring of corrosion current density of rebar in non-patch repair, patch repair, and boundary of a repair part is shown in Fig. 8. The passivity limit is generally defined as a corrosion current density of 0.1 μA/cm^2[12].

The initial condition of the rebar of both specimens is active corrosion indicated by corrosion current density that exceeded the passivity limit of 0.1 μA/cm^2. After the repair methods were applied, the corrosion rate was significantly decreased. In the 12-month, it was the passive condition. It indicates that the repair strategy of patch repair and corrosion inhibitor is sufficient to suppress corrosion.

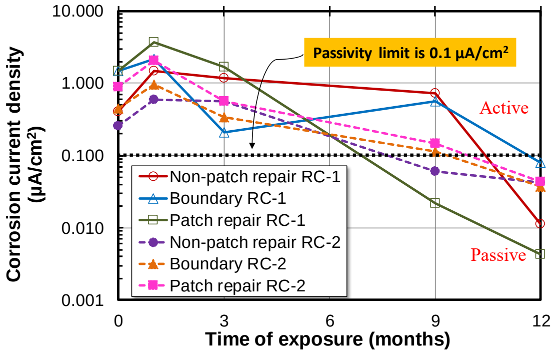


Fig. 8 Corrosion current density

3.4 Polarization curve (grade of passivity)

The passivity degree of rebar is one indicator to understand the performance of the repair method. A systematic way to evaluate the passivity degree of rebar provided by rebar can be presented by using the grading criteria for passivity [13]. The criteria were based on the behavior of the anodic polarization curves of rebar. The degree of passivity was presented as different grades depending on how the current densities behaved between +200 mV and +600 mV (vs. SCE) potential on the anodic polarization curve. When the anodic curve towards lower current density region, the passivity degree of rebar tends to a better condition. Another corrosion performance parameter is the concentration of oxygen in the corrosion process, especially illustrating the reduction in oxygen content shifts the cathodic curve to lower current densities over a wide range of potentials. The Anodic and cathodic polarization curve time dependency of tensile rebars in parent concrete, patch repair, and the boundary between parent concrete and patch repair at 400 mm, 1200 mm, and 800 mm from the edge were depicted in Fig. 9.

Generally, the maximum current density of rebars was decreased in both of two repaired specimens. At the end of the test, the passivity condition was categorized as grade 3 (current density are between 1 and 10 μA/m^2), which indicates a certain degree of passivity exist. During 12-months of exposure, RC-2 (specimen with a corrosion inhibitor in patch repair) demonstrated better performance indicated by greater shift of anodic polarization curve than RC-1 (specimen without corrosion inhibitor). It shows that the application of corrosion inhibitor in patch repair part of RC-2 delivers the polarization effect of sacrificial anodes from parent concrete to patch repair section.

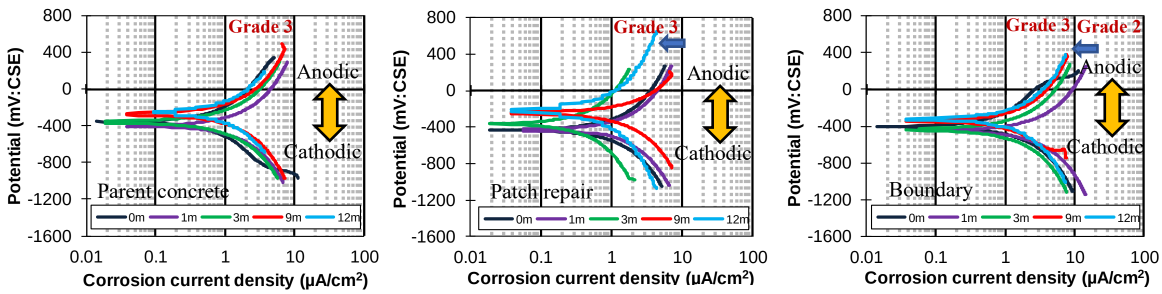


Fig. 9 Anodic and cathodic of tensile rebar in RC-1

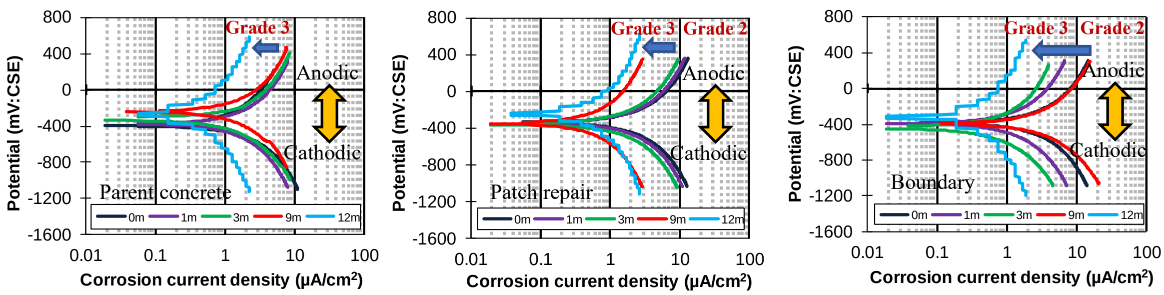


Fig. 9 Anodic and cathodic of tensile rebar in RC-2

3.5 Discussion

This study investigated the performance of sacrificial anodes installed in parent concrete on two identical RC beams damaged by corrosion and corrosion inhibitor applied for rebar surface in patch repair section in one of the specimens. Monitoring was performed by close interval relative potential mapping in the concrete surface to verify that sacrificial anodes were still active, and at staged distances away from the position of the anode to assess the polarization effect afforded by the sacrificial anodes to the steel in the parent concrete and patch repair.

The performance monitoring data indicates that the sacrificial anodes affected rebar potentials concentrically in parent concrete at a distance away from the position of the anodes. The corrosion and protection mapping of the specimens were presented in Fig. 10. The rest potential as corrosion mapping shows that RC-2 performs better potential recovery since 1-month of repair. Protection mapping specified by depolarization test value also reveals the same trend. For RC-1, with patch repair only, the polarization effect was to a distance of approximately 15 cm away from the position of the anodes. For RC-2, with corrosion inhibitor in patch repair, the polarization effect afforded was increased to approximately 30 cm from anodes position. It indicates that sacrificial anodes have limitations, and the existence of corrosion inhibitor extends the polarization of rebar.

An alternative performance criterion, to that of 100 mV potential decay, may be adopted for assessing the performance of sacrificial anodes system utilizing potential mapping to obtain the spatial variations. Sacrificial anodes in parent concrete should demonstrate that it affords a dominant influence on the rebar potentials away from the position of the anode that is at least equal to half the spacing between anodes position. This alternative criterion is also in line with the work of previous researcher works [5, 14].

Standard for structural repairs as BS EN 1504 [15] confirms that patch repair materials such as polymer modified mortar did not affect the performance of sacrificial anodes installed in parent concrete around of repair, although it is not generally considered suitable for together usage with sacrificial anodes due to its high resistivity [11]. In contrary, such materials will improve the quality and longevity of the repair it self, and due to its higher resistivity will preferentially direct current from sacrificial anodes to rebar in parent concrete, which is considered to be at higher risk [14].

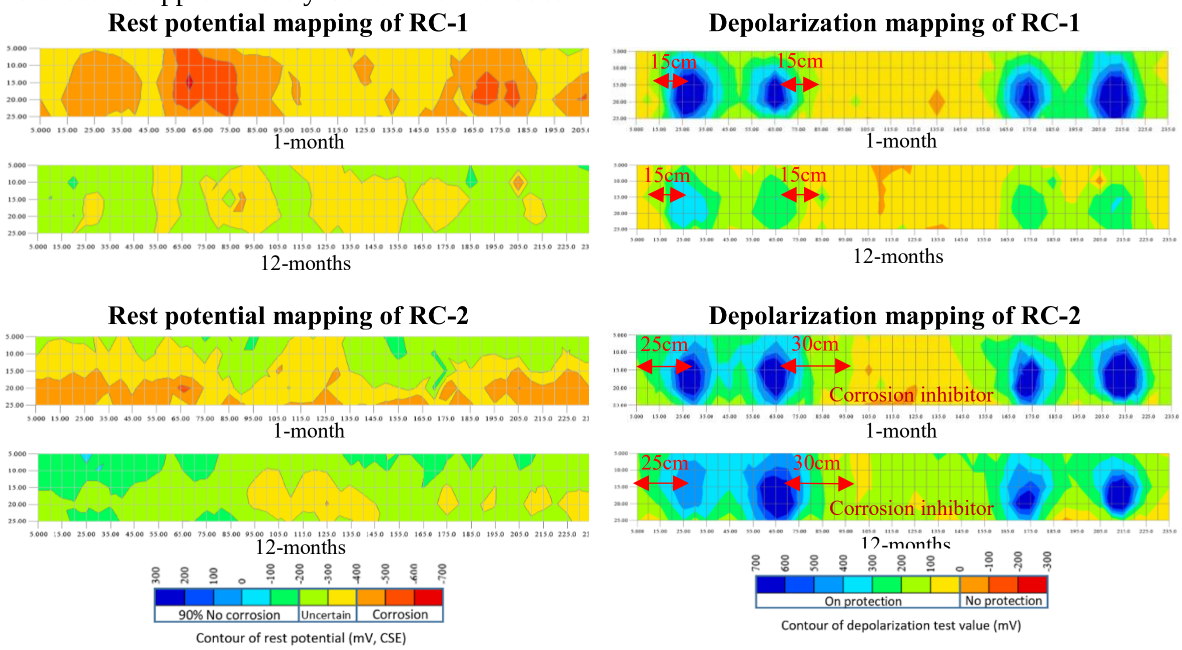


Fig. 10. Rest potential and depolarization mapping on 1-month and 12-months

5. CONCLUSIONS

The results indicate that:

1. The sacrificial zinc anode tested in this research affects polarizing the potential of rebar in the RC member damaged by corrosion. 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.

2. The application of corrosion inhibitor in the rebar surface of patch repair part extends the polarization distance significantly until two times.
3. An alternative performance criterion, to that of 100 mV potential decay, maybe adopt for assessing the performance of sacrificial anodes, the sacrificial anodes in parent concrete should demonstrate that it affords a dominant influence on the rebar potentials away from the position of the anode that is at least equal to half the spacing between anodes.

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