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Application of sacrificial anode cathodic protection for partially repaired RC beams damaged by corrosion

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ABSTRACT

In this study, patch repair and sacrificial anode cathodic protection (SACP) techniques were applied to 44-year-old RC beams in which steel bars were corroded severely in order to extend the service life of beams. In the first repair stage, polymer modified mortar was used to replace the existing concrete after the installation of embeddable sacrificial anodes along with the un-rusted rebar. The polarization effect demonstrated that the protection area limited in the patch repair section due to the electrochemical incompatibility between the new material and the existing concrete. Disconnecting the sacrificial anodes during a year is applied for observing rebar condition during the absence of current supply in patch repair system as second repair stage. It indicates that the rebars in the patch repair area have remained passive with no corrosion sign. It shows that polymer modified mortar has a persistent protective effect in the absence of cathodic protection. In order to enlarge the protection area, additional sacrificial anodes were inserted in the existing concrete as the third stage. From 12-month observation, application of sacrificial anodes both in the patch and non-patch repair concrete is sufficient to provide negative potential shift with an optimum distance of 400 mm for each anode in order to achieve 100 mV depolarization. The polarization of rebar in patch repair is limited to 200 mm from the boundary.

INTRODUCTION

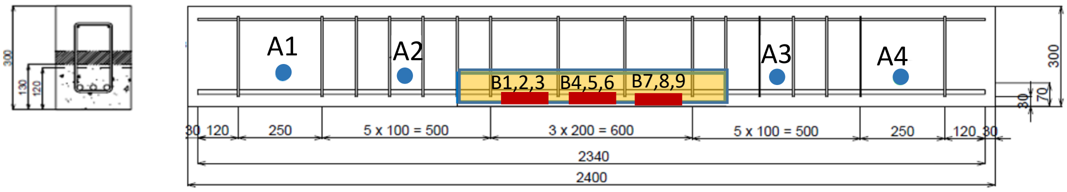
Chloride-induced corrosion is one of the most common deterioration mechanism in reinforced concrete (RC) structures exposed to the marine environment. The penetration of chloride ion concentration into concrete activates the corrosion of rebar by destructing the passivity film when the chloride ion concentration at the rebar surface reaches a critical value (Glass and Buenfeld, 1997). Whenever the threshold amount of the chloride ions reaches the surface of rebar, along with enough oxygen and moisture, steel corrosion may result in concrete cracking and spalling of the cover concrete when expansive stress exceeds the tensile strength of concrete; reduction of steel reinforcement cross-section may lead to structural failure. As a result, the corrosion of reinforcement adversely affects the safety and the serviceability of concrete structures and hence shortens the service life (Song, et al., 2007).

In the last decades, several electrochemical repair techniques were developed for offering chloride-induced corrosion, and sacrificial anodes have been used to limit the extent of concrete replacement and extend the service life of patch repairs to corrosion damaged RC structures (NACE, 2005). In this study, patch repair method and sacrificial anode cathodic protection were demonstrated for accomplishing severely damaged RC beams aged 44-year-old exposed to the actual marine environment. The decision to apply sacrificial anode cathodic protection and patch repair method to the particular structures can be in many cases based on the results of a preliminary investigation that shows some high levels of chloride contamination, corrosion possibility of rebars, and damage appearance in some part of the structures (Cheaitami, 2000).

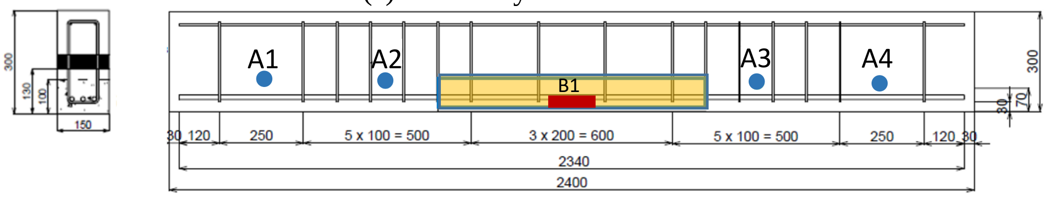
EXPERIMENTAL PROGRAM

Specimen design. Two RC beams which were 44 years old having a length of 2400 mm were used for this experiment notated as RC-1 and RC-2 with a concrete cover thickness of 50 mm and 30 mm. The cross-sectional area of RC-1 and RC-2 are 200 × 300 mm and 150 × 300 mm, respectively. Both of specimens were exposed in the natural marine environment in the first 20 years, then it kept in dry condition at PARI (Port and Airport Research Institute), Yokosuka, Japan until 35-year (Hamada, et al., 1998 and Yokota, et al., 1999), and the beams were moved and stored at outside exposure field in Kyushu University (2010-2016). During the repair process, the specimens were kept in air condition in a laboratory. The detail of specimen design is illustrated in Figure 1(a) and 1(b) whereas Figure 1(c) shows the setting position of 9 anodes and 1 anode in patch repair of RC-1 and RC-2, respectively.

Materials. Ordinary Portland Cement (OPC) was used as a binder of the existing concrete. The compressive strength and elastic modulus after 40 years were 30.0 MPa and 29.0 GPa, respectively. The deformed steel bars with a diameter of 13 mm and yield strength of 363 MPa were used as tensile rebar, and round steel bars of 6 mm in diameter were used as compressive rebar. Stirrups with a space of 100 mm were applied in the specimens. The polymer modified mortar with a compressive strength of 40.5 MPa and a bending strength of 8.6 MPa at 28 days (Figure 2(a)) was fabricated as replacement material in patch repair section after application of EVA (Vinyl Acetate / Ethylene) copolymer emulsion as adhesive material coating agent (Figure 2(b)) between existing concrete and new patch repair material. Two types of sacrificial anodes, Type A and Type B (Figure 2(c) and 2(d)), were used to protect rebars in the patch and non-patch repair. The anode type selection is based on the available space where it will be embedded. Anode Type B with thickness, width, and length of 13 mm, 45 mm, and 140 mm, respectively, was chosen to apply for the patch repair while cylindrical ribbed sacrificial anode with the diameter of 30 mm and length of 130 mm was inserted in the existing concrete. These anodes were made of zinc coated with a porous mortar which has a lithium monohydrated solution to maintain zinc corrosion activation. This lithium base solution keeps the zinc surroundings humid and the efficiency of the system is told to be constant during its lifetime (Rincon, 2008).



(a) Geometry of RC-1



(b) Geometry of RC-2

(c) Anode Type B setting position

Remark:

● Anode type A   ▬ Anode type B   ▭ Patch repair area

Figure 1. Specimen design and setting position of anode Type B

(a) Polymer modified mortar

(b) Coating agent

(c) Anode Type A

(d) Anode Type B

Figure 2. Materials for the repair process

Repair sequences. The repair techniques and the expected result of each stage during three years of the investigation in this study were described in Table 1.

Table 1. The details of repair techniques

Stage	Method	Duration	Expected Results
I	Patch repair and sacrificial anodes (Type B) were applied in the middle tensile rebar part.	200 days	Protected condition on the patch repair section by replacement of chloride contaminated into chloride free concrete and current flow generated from sacrificial anode to rebar.
II	Sacrificial anodes Type B were disconnected.	1 year	Protection condition was expected by the durability of new patch repair material only.
III	Additional sacrificial anodes Type A were installed in the existing concrete.	1 year	In order to protect all of the cross-sectional specimens, additional sacrificial anodes were embedded in the non-patch repair part.

Measurement methods. Half-cell potential test of rebars according to ASTM C876-15(2015) was conducted by a saturated calomel electrode (SCE) and high impedance voltmeter on grid points of 50 mm spacing after one hour of pre-wetting. The reference electrode was connected to the negative terminal and the reinforcing bar to the positive terminal of the voltmeter. On-potential (E_{on}) of rebar and the anode was measured under sacrificial anode cathodic protection. Instant-off potential (E_{off}) was checked immediately after disconnection, and the rest potential (E_{corr}) was measured at 24 hours after the disconnection.

RESULT AND DISCUSSION

Preliminary investigation. The defective appearance of the beams including crack and rust stain after 44-years exposure are shown in Figure 3. Figure 4(a) and 4(b) depicted the initial half-cell potential of rebars, crack pattern and maximum crack width on the concrete surface. In both of beams, several longitudinal and transversal cracks in the tensile area are observed. The longitudinal cracks are coincident with the position of tensile rebar with a maximum width of 1.9 mm and 2.2 mm for RC-1 and RC-2, respectively. The transversal cracks concentrated in the middle span were initiated from bending stress of the beams of stirrups corrosion. No concrete spalling is observed in both of beams. In RC-1, 77% area is categorized as corrosion region and 23% area is classified as uncertainty region based on ASTM C 876 whereas 94% area of RC-2 is in corrosion condition and 6% is in uncertainty condition. The average of total chloride ion concentration in the surrounding of rebar is 4.65 kg/m^3 in RC-1 and 4.75 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"). Based on JSCE standard specifications for concrete structures – 2001 "Maintenance" 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.

Figure 3. The appearance of specimens

Polarization effect of sacrificial anodes in patch repair. In Stage I, the sacrificial anodes Type B was inserted in the patch repair part. The polarization effect of sacrificial anodes was shown in Figure 5, 6, and 7. From the depolarization test value in Figure 7, the polarization effect of anode only occurred in patch repair section, and it cannot reach to the existing concrete due to electrochemical incompatibility between two different concrete resistivity. In RC-1, all area in patch repair section is in protection condition, while only in the radius of 200 mm away from anode position is in protection condition for RC-2. It indicated that the number of anodes effect on the protection area and the optimum distance of every anode type B is 400 mm.

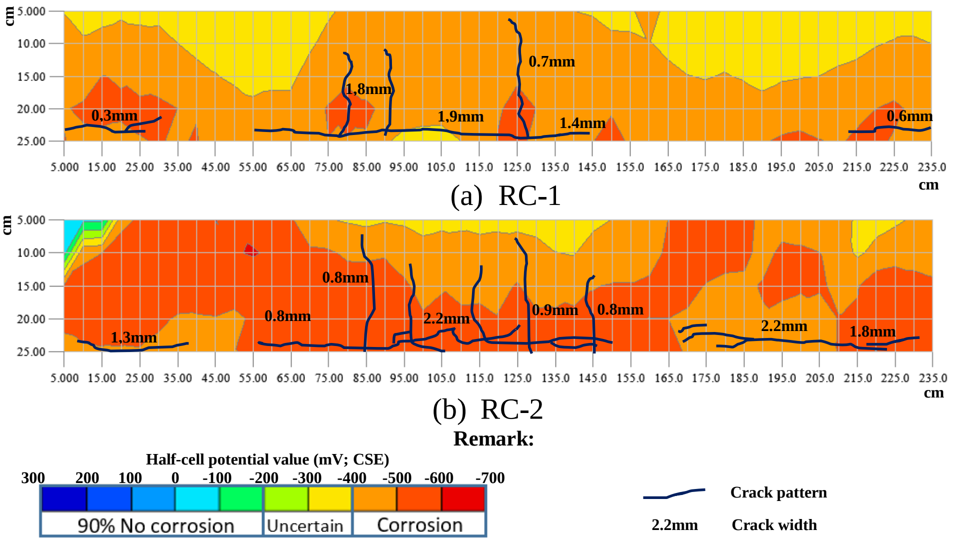


Figure 4. Initial half-cell potential and crack pattern, (a) RC-1 and (b) RC-2

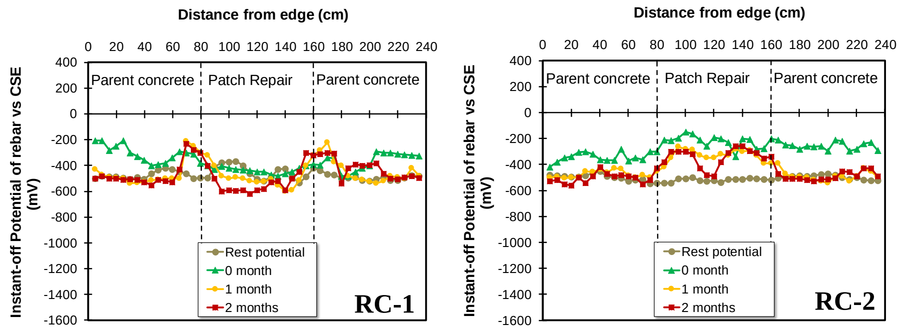


Figure 5. The instant-off potential of rebar due to sacrificial anodes Type B

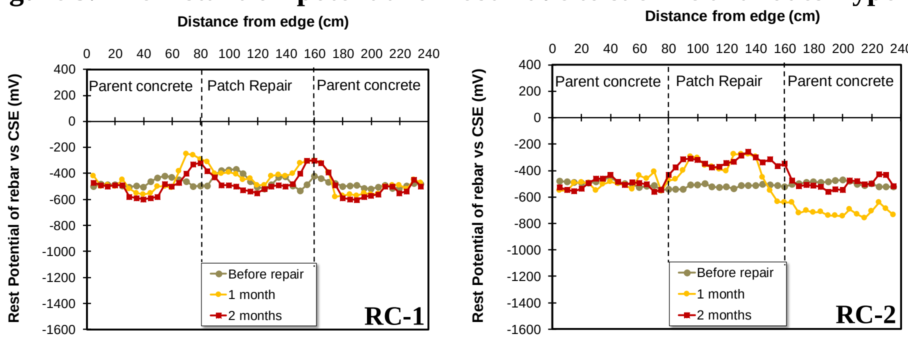


Figure 6. Rest potential of rebar due to sacrificial anodes Type B

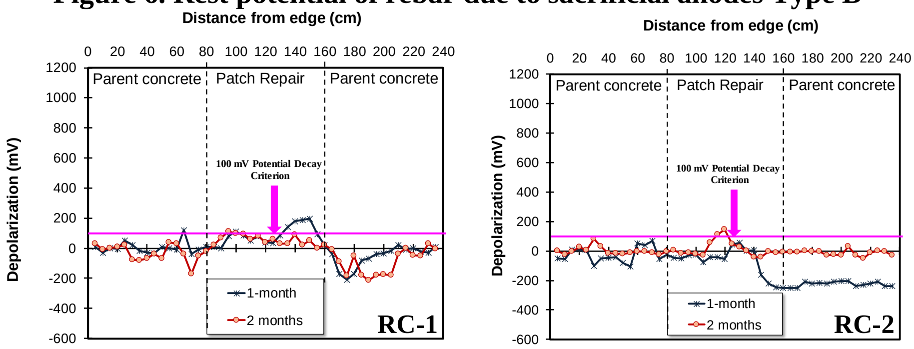


Figure 7. Depolarization test value of rebar due to sacrificial anodes Type B

Disconnection of sacrificial anodes in patch repair. After 200 days connection, anodes were disconnected almost for one-year (Stage II). The rest potential of rebar at the end of the Stage II period was shown in Figure 8. Both in RC-1 and RC-2, the protection due to the application of sacrificial anodes type A is remain only in the patch repair area. After one year with no anodes connection, the rest potential value of patch repair section is in 90% no corrosion probability. It may because the effectiveness of polymer modified mortar as a new replacement material without chloride contamination. The corrosion probability of rebar on RC1 and RC-2 was decreased from 77% (initial condition) to 75% and from 94% to 60%, respectively.

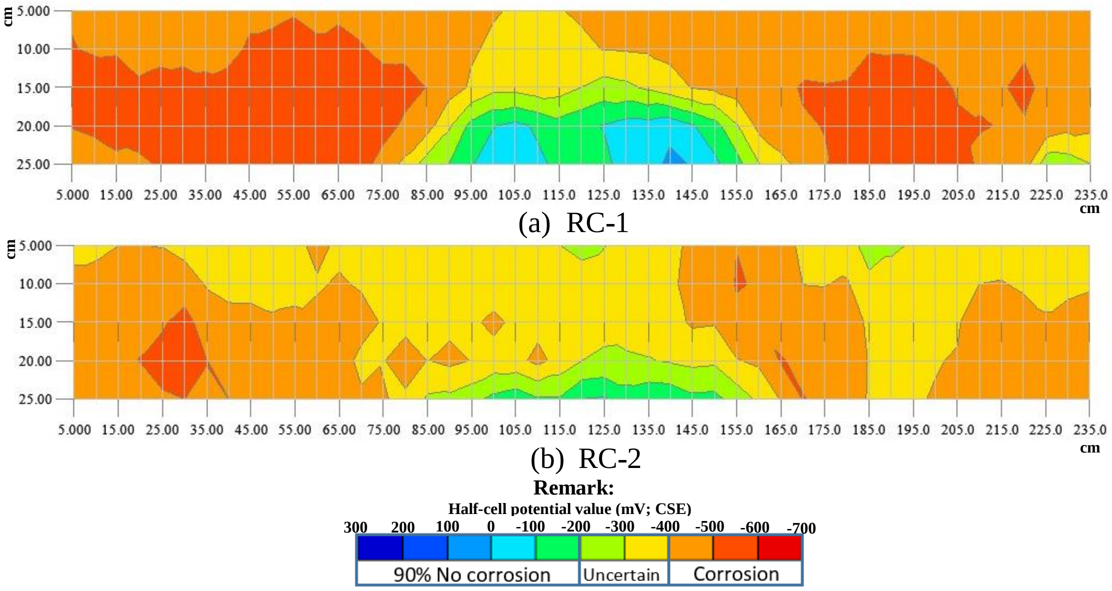


Figure 8. Rest potential and crack pattern, (a) RC-1 and (b) RC-2

Polarization effects of sacrificial anodes in the patch and non-patch repair. Additional sacrificial anodes type B were installed at both sides of existing concrete in order to protect its area (Stage III). The protective current density of sacrificial anodes is presented in Figure 9. It showed that the protective current density tends to fall with time as the anode is consumed. As a result, sacrificial anodes cathodic protection is not generally achieved by sustaining an adequate level of steel polarization, as in the case for other electrochemical treatments (Glass and Christodoulou, 2012). Even though the protective current flow of these specimens decreased until less than the minimum design limit of cathodic protection based on BS EN ISO 12696 after 6-months of repair period, and it still polarized the rebar more than 100 mV.

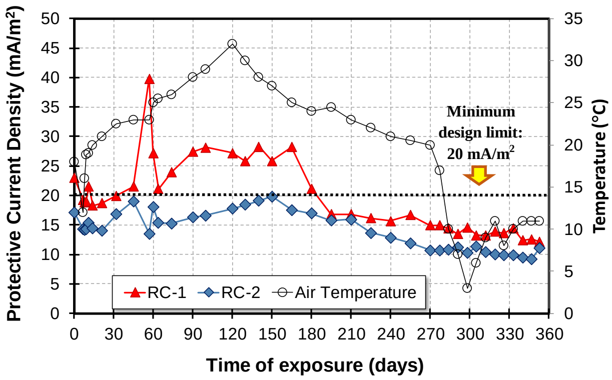


Figure 9. The protective current density of sacrificial anodes Type B in RC-1 and RC-2

The instant-off potential, rest potential, and depolarization test value of tensile rebar in this period until one-year observation were shown in Figure 10, 11, and 12. The instant-off potential of rebar was check immediately after the disconnection of sacrificial anodes and rebar. The half-cell potential of rebar after 24-hour of off-condition is described as rest potential. The different potential value between instant-off potential and rest potential is defined as depolarization test value, a parameter to categorize the effectiveness of cathodic protection. 100 mV potential decay, the common criterion is used to evaluate the performance of sacrificial anode cathodic protection. A fall in potential was observed for all specimens following the application of additional sacrificial anodes type B. This indicates the additional anodes polarising the rebar to more negative potential than 750 mV vs CSE. In this case, the potential shift is almost limited to the distance of approximately 200 mm away from the anodes position. It indicates that the optimum distance of anode type B is 400 mm.

The 24-h decay or depolarization test value from instant-off potential was monitored monthly after sacrificial anodes switch off. Both of specimens showed similar behavior and satisfied the 100 mV decay since 3-months of connection. It indicates that the protection is achieved within 3-months. It is consistent with the age and condition of rebars, with no long term corrosion existing, unlike in real marine RC structures, where a longer passivation period would be expected. At the conclusion of the trial instant-off potentials were recorded. As would be expected, both of specimens demonstrated a drop less negative potentials, with all achieving a potential decay at least 100 mV, satisfying the potential decay criterion. Rest potential of rebar in all cross-sectional beams were slightly more positive compared to before repair period. This can be attributed to the generation of hydroxyl ions at the steel bar/ cement interface and repulsion of chloride ion from the vicinity of the rebar due to the application of sacrificial anodes. These secondary effects of cathodic protection cause re-passivation effects of the rebar and move the rest potential to a more positive value (Glass and Chadwick, 1994).

Figure 13 and 14 presented the rest potential and protection area of beams at the end of the test. It showed that there was no significant change of rest potentials in patch repair section at the end of the test. Moreover, the protection improvement was shown in existing concrete due to the protective current flow of sacrificial anodes installation. The rest potential of rebar in existing concrete in RC-1 was more negative (-300 ~ -400 mV vs CSE) than RC-2 (-200 ~ -300 mV). It may due to the reinforcing density of RC-1 is lower than RC-2.

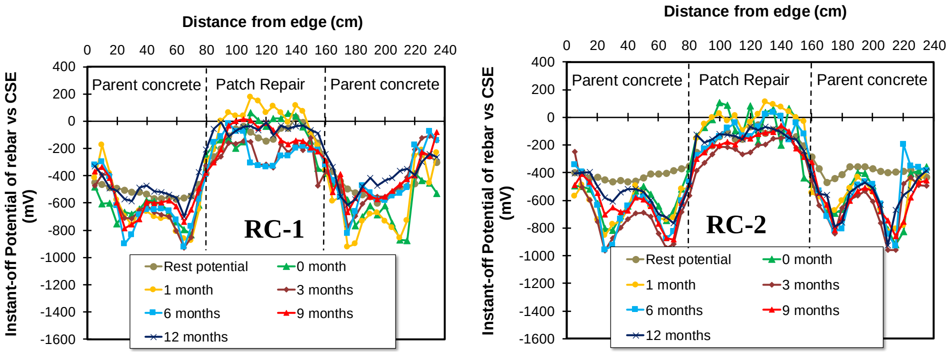


Figure 10. The instant-off potential of tensile rebar in RC-1 and RC-2

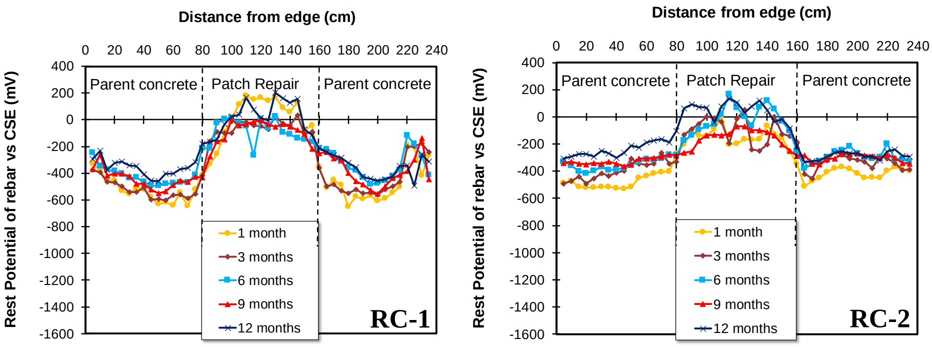


Figure 11. Rest potential of tensile rebar in RC-1 and RC-2

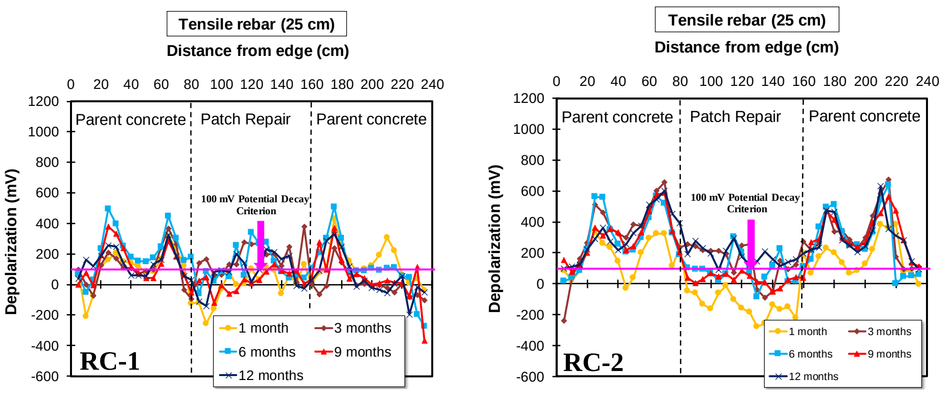
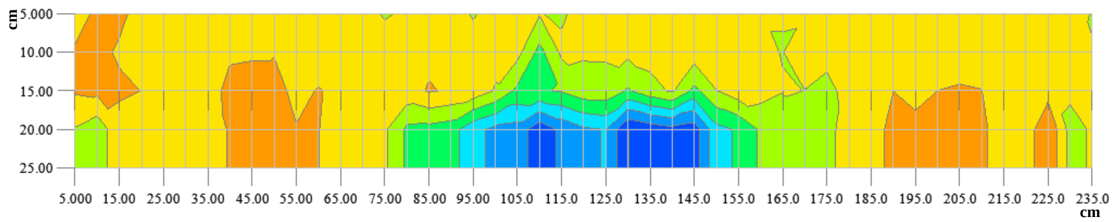
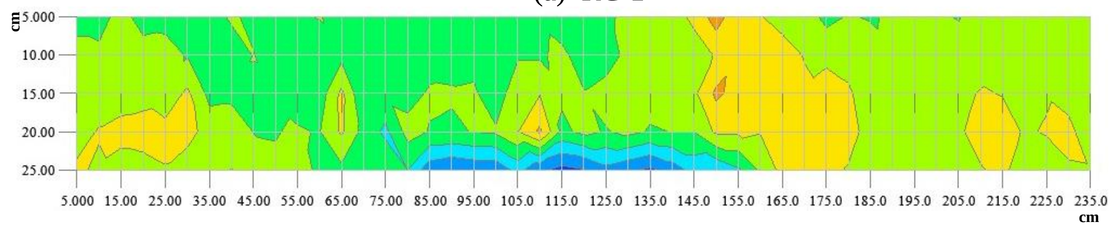


Figure 12. Depolarization test value of tensile rebar in RC-1 and RC-2



(a) RC-1



(b) RC-2

Remark:

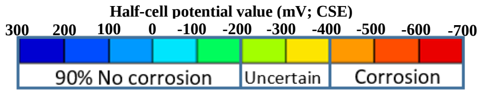
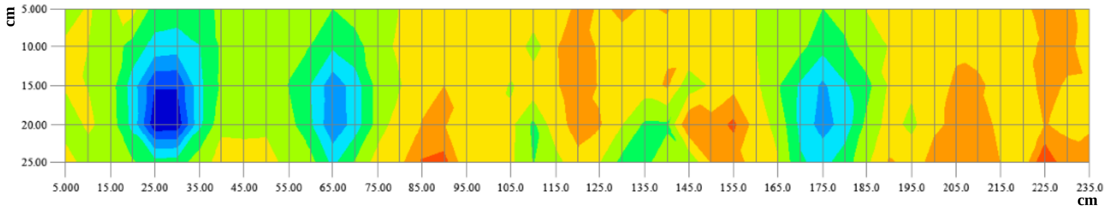
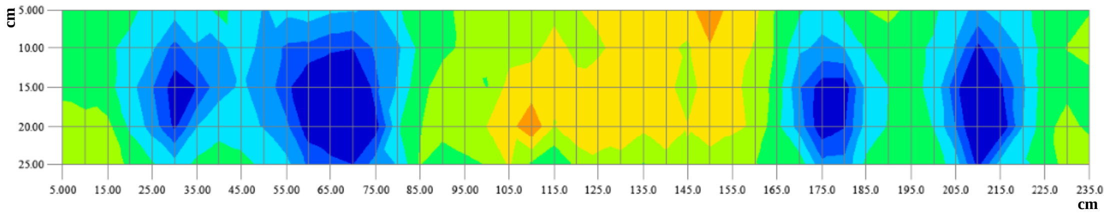


Figure 13. Rest potential at the end of the test, (a) RC-1 and (b) RC-2



(a) RC-1



(b) RC-2

Remark:

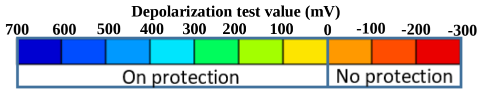


Figure 14. Protected area at the end of the test, (a) RC-1 and (b) RC-2

CONCLUSION

From this study, several conclusions are drawn as follows,

1. Application of sacrificial anodes in the patch repair material is sufficient to polarize the rebar to the noble value even though its protection cannot reach the existing concrete due to electrochemical incompatibility.
2. After a year with no sacrificial anode cathodic protection, the rebars in polymer modified mortar have remained passive with no corrosion sign. This indicated that polymer modified mortar has a persistent protective effect in the absence of cathodic protection.
3. Application of sacrificial anodes both in non-patch and patch repair concrete is effective to provide negative potential shift with an optimum distance of 400 mm in order to achieve 100 mV depolarization.

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