Influence of Rust Removal Process on The Effectiveness of Sacrificial Anode Cathodic Protection in Repair Concrete

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Abstract. The accumulation of corrosion product on the steel surface may cause eventual failure to deliver of ionic current protection from sacrificial anode cathodic protection. The effect of cleaning of deteriorated steel bar before cathodic protection application is studied in this paper. Two specimens having a length of 580 mm and 150x100 mm of the cross-sectional area with deteriorated reinforcing bar and half-part of chloride contaminated concrete were fabricated to simulate the repair process. Two corroded reinforcing bar with the same surface condition (ø 13mm) were embedded in concrete parallel to each other with the intermediary distance of 40 mm and the cover depth of 30 mm in the bottom surface of the specimen. In the first specimen, rust on the steel bar surface in the repair section was removed. Discrete sacrificial zinc anode is connected to one steel bar in the repair section. During three-years observation, the specimens were exposed to several conditions: 20°C air curing, dry-wet cycle, dry laboratory air, and wet condition, respectively. Potential of both rebar and the sacrificial anode was monitored to understand the performance of the cathodic protection system. The result indicates that rust removal process of steel bar surface in repair concrete part is the most desirable initial condition when the sacrificial anode is applied on it to protect corroded steel bar in new and existing concrete.

Keywords: rust removal of reinforcing bar, sacrificial anode cathodic protection, repair concrete

1. Introduction
The corrosion experiencing section maybe patch-repaired by removing the chloride-contaminated concrete and replacing it with chloride-free concrete. As a result, the previous active steel in the patch becomes passive, and corrosion stops. However, that transition to the passive condition also elevates the potential of the steel in the patch from its former highly negative value to one that can be several hundred mV more positive, removing the natural cathodic prevention effect initially in place [1, 2]. The lower value of chloride threshold in the surrounding zone then may be less than the existing local chloride concentration, and active corrosion could promptly start [3]. This detrimental consequence is called macro-cell corrosion around the repaired patch [4]. In this case, prevention may be restored by applying a sacrificial anode in the repair section. The anode takes up the function of the previous corroded rebar and prevents re-deterioration due to corrosion starting both in repaired patch area and the boundary.
The sacrificial anode is commercially available for casting in patch repairs, for intended purposes of forestalling the macro-cell corrosion effect [5, 6]. On a practical, reinstating corrosion protection in concrete using sacrificial anode cathodic protection in the repaired patch does not require perfect repairs; only physical damages need to be repaired, without the need to remove a lot of chloride-contaminated concrete and without the need to perfect rust cleaning of steel. The variability appears when evaluation of anode in such cases stems from the current demand by the rebar assembly, which may be sustained at high levels for long periods of time, or drop rapidly in the early life of the test depending on the initial condition of the steel surface, small variations in the pore water composition, or concrete moisture [7, 8]. In the application of sacrificial anode cathodic protection in repaired patch concrete, accumulation of corrosion product in reinforcing bar surface may impede the passage of ionic current or even promote passivation of the anode surface causing fail to deliver protection [9, 10].

Regarding the cleaning of steel bar before application of sacrificial anodes, the effect of rust removal on deteriorated reinforced concrete structures before anodes application in repair section has not been clearly reported. In this paper, the influence of rust removal of steel bar surface on the performance of the sacrificial anode in repaired RC member during three-year observation is presented.

2. Experimental program

2.1. Materials

Ordinary Portland Cement (OPC) was used as a binder, and tap water (temperature 20±2°C) was used as mixing water. Washed sea sand passing a 5 mm sieve with a density of 2.58 g/cm³ and water absorption of 1.72 %, which was less than 3.5% as stated in JIS standard, was used as fine aggregate. Meanwhile, crushed stone with a maximum size of 10 mm was used as coarse aggregate. All aggregates were prepared under surface-saturated dry condition. The ratio of fine aggregate to total aggregate volume (s/a) was 0.47. The properties of aggregates and admixtures are shown in Table 1. Moreover, a galvanic anode made of zinc as the main material was used as the sacrificial anode. The dimension is 140 mm in length, 45 mm in depth and 13 mm in width, as shown in Figure 1.

Table 1. Properties of materials [10, 11, 12].

| Component | Physical properties |
|-----------|---------------------|
| Ordinary Portland Cement | Density, g/cm³ 3.16 |
| Fine Aggregate | Density, g/cm³ 2.58 (SSD Condition) |
| | Water absorption (%) 1.72 |
| | Fineness modulus 2.77 |
| Coarse aggregate | Density, g/cm³ 2.91 |
| AEWR agent | Polycarboxylate ether-based |
| AE agent | Alkylcarboxylic type |

Figure 1. Sacrificial anode installed on the rebar [10, 11].
In this research, 20-year-old deteriorated reinforcing bars with a diameter of 13 mm were used, as shown in Figure 2. These steel bars were taken from the specimens exposed in severe chloride environment with high temperature for 20 years. For the non-rusted condition, the deteriorated rebar was immersed in 10% (weight percentage) di-ammonium hydrogen citrate solution for 24 hours, and the rust was removed by using a steel wire brush. At both ends of each rebar, a 30 cm lead wire was screwed.

![Before immersion](image1.png) ![After immersion](image2.png)

**Figure 2.** A 20-year-old deteriorated reinforcing bar.

### 2.2. Mix proportion

A concrete mix with water to cement (w/c) ratio of 0.45 was used for specimens. Air-entraining agent and water-reducing admixture were added to the cement mass to obtain the slump and air content in all concrete mixes in the range of 10±2.5 cm and 4.5±1%, respectively. There were two types of concrete mix proportions used for each specimen: existing concrete (chloride-contaminated) and patch repair concrete (chloride-free). Pure sodium chloride (NaCl) as the source of chloride ions were added around 10 kg/m$^3$ during mixing into the existing concrete to accelerate the corrosion process. Mix proportions of concrete are shown in Table 2.

| Material             | Existing concrete | Repair concrete |
|----------------------|-------------------|-----------------|
| Water-cement ratio (w/c), % | 45            | 45              |
| Sand-aggregate ratio (s/c), %   | 47              | 47              |
| Water, (kg/m$^3$)     | 190              | 190             |
| Cement, (kg/m$^3$)    | 422              | 422             |
| Sand, (kg/m$^3$)      | 766              | 766             |
| Gravel, (kg/m$^3$)    | 970              | 970             |
| Chloride, (kg/m$^3$)  | 10               | 0               |
| Additive              |                   |                 |
| - AE, mL             | 19               | 19              |
| - AE-WR, kg          | 1.34             | 1.34            |

### 2.3. Specimen design

Three specimens, notated as D1 and D2, with the dimensions of 580 mm in length, 150 mm in width and 100 mm in depth were fabricated. Each specimen consisted of two steel bars with a diameter of 13 mm, same surface conditions and positioned parallel to each other with an intermediary distance of 40 mm and a cover thickness of around 30 mm from the bottom surface of the specimen. D1 specimen illustrated rust removal before replacement material application in the repair section, and D2 specimen demonstrated the application of sacrificial anodes and material casting rust removal before. The details of the concrete specimen are depicted in Figure 3. In addition, a sacrificial anode was applied to the repair concrete section.

In order to simulate the repair process, the concrete casting process was in two steps. First, the existing concrete was placed and demoulded after 24 hours. After demoulding, all specimens were subject to 14 days of sealed curing with wet towels and followed by the installation of the sacrificial anode on the steel bar, and new concrete was placed in the repair part. After 24 hours, the specimens were demoulded, followed by masked curing with wet towels for 28 days.
Figure 3. Specimen design.

After 28 days of sealed curing, the sacrificial anode was connected to one of the embedded steel in the patch repair concrete. Adjacent steel element and the sacrificial anode was connected through lead wires to measure the current flow generated by sacrificial anodes. At the end of the steel bar in the repair section, a 30 cm length lead wire was screwed. The connection of wire and steel bar was covered by epoxy resin to avoid the corrosion at the connection. The thickness of the epoxy layer was approximately 10 mm. However, these connectors were temporarily disconnected to measure the instant-off potential, the protective current, and depolarization. The saturated calomel electrode (SCE) is used as a reference electrode for potential measurement in this study.

2.4. Exposure conditions
After the casting of both existing and repair concrete was finished, specimens were subjected to exposure conditions, in the air curing with a temperature of 20±2°C and relative humidity of 60%. This environment was kept for 105 days of exposure time. After that, the specimens were moved to the dry-wet cycle condition. Five days in dry condition was followed by two days of wet cycle involved immersion in a 3% NaCl solution up to 140 days; hence, one cycle corresponded to seven days. Measurements were taken weekly at the end of the wet cycle. Then, the specimen was stored in dry laboratory air condition up to 1000 days before moved to wet condition until 1260 days.

2.5. Observation method
The potential of rebar in the distance of 10 mm from the boundary between the repaired patch and existing concrete was monitored during on potential, instant-off potential, and rest potential by using half-cell potential measurement. Saturated calomel electrode (SCE) was used as a reference electrode for measurement, and this potential reading was converted to copper/copper sulfate electrode (CSE) in 25°C [8].

3. Results and discussion
3.1. The protective current density of sacrificial anodes
The current density generated by the anodes to the reinforcing bar as a function of exposure time until 1260-days is shown in Figure 4. The current density of all specimens shows the trend to decrease gradually as a function of time in air curing and laboratory air condition. However, the sacrificial anodes became active after the changing of exposure condition to be a wet-dry condition, due to the high moisture content of concrete [10, 11]. In this experiment, no measurement was conducted from 140 days
to 720 days. In this phase, the specimens were kept in dry laboratory condition. The re-starting of measurement was conducted from 721-days. It shows that the increase of current flow generated by anodes was occurred due to the increasing of moisture content in concrete during pre-wetting before measurement.

In this observation, only in the first 140-days (air curing and wet-dry condition) and wet condition, the protective current level was within design limit of cathodic protection between 0.2 – 2.0 µA/cm² as specified in EN 12696 [7]. After the change of the environmental condition to dry laboratory air, the protective current is less than the minimum design limit of cathodic protection. In the viewpoint of the protective current density of anodes, generally, the specimen with rust removal shows higher current density than specimen without removal time dependency.

![Figure 4. Protective current density of the sacrificial anode.](image)

### 3.2. Potential development of rebar and anode

In the case of cathodic protection application, observation of potential development on rebar and anodes was recorded consist of on-potential, instant-off potential, and rest potential. On-potential is observed during the connection of sacrificial anode and rebars. The instant-off potential is measured between 0.1 and 1 second after switching off the protection current of anodes to remove the IR drop of measured potential. Rest potential is checked 24 hours after switching off between sacrificial anode and rebar. The position of these measurements is 50 mm from the interfacial zone to the repair and the existing concrete. Figure 5, 6, and 7 present on-potential, instant-off potential, and rest potential of rebar, respectively. The rest potential of rebar in existing concrete with chloride-contaminated was slightly more negative than in repair part or chloride-free concrete. In specimen D1, the rebar with rust removal connected to sacrificial anode (SCP) in repair concrete shows more negative result than rusted rebar between air curing and dry-wet condition. When the exposure condition is changed to wet-dry cycles, the potential of rebar shifted to the negative direction, and when it is changed to dry laboratory air, the potential of rebar shifted to more positive value. This phenomenon is caused by the change in moisture and oxygen content in the concrete.
The potential of rusted rebar connected to anodes is gradually decreased around -580 mV for repair concrete and approximately -600 mV for existing concrete after 1000-days of exposure in dry air condition. It is more clear when the environmental condition was changed to wet condition, the rest potential of rebars with rust removal in repair section were shifted to be more positive value than rebar in existing concrete. This results express that non-rusted rebar is on better protection than rusted rebar after three years of exposure.

Figure 5. On-potential of rebar protected by sacrificial anode.

Figure 6. Instant-off potential of rebar protected by sacrificial anode.

Figure 7. Rest potential of rebar protected by sacrificial anode.
The half-cell potential of rebar without anodes connection (SNCP) with instant-off potential of rebar protected by anode (SCP) is depicted in Figure 8. After the exposure changed from wet-dry to dry condition, the potential of rebar SNCP-D1 and SNCP D2 are shifted to be more positive due to the absence of water and oxygen on the steel surface. It gradually changed to 90% corrosion condition when it moved to wet condition. Based on ASTM C876-91:1999, the rebar in “corrosion condition” during the dry-wet cycle and wet condition.

Figure 8. Half-cell potential of rebar without anode connection.

Figure 9 (a) and (b) show the rest potential mapping on specimens in dry condition (1000-days) and in wet condition (1200-days). It shows that steel bar protected by sacrificial anode in repair and existing concrete demonstrates similar rest potential condition in dry condition. Meanwhile, the rest potential of steel bar without sacrificial anode connection is greatly affected by chloride contamination. The effect of rust removal process in repair concrete also may be one of the factors to present better condition in the repair section. From the rest potential result in dry and wet condition indicates that higher moisture content in concrete reveals lower rest potential and increases the corrosion probability of rebar both in chloride contaminated and chloride free concrete.

Figure 9. Rest potential mapping of rebar.

The potential development of anodes is shown in Figure 10. During the exposure at air curing from 0-day to 105-days, on-potential and instant-off potential of anodes in all specimens increased gradually to be a positive value. Furthermore, when the environment changed to be a dry-wet condition, the
potential of anodes in all specimens slightly shifted to be more negative again and relatively stable until the end of exposure time. The rest potential shows that in the early age of specimen, the rest potential of anodes is around -1100 mV ~ -900 mV. The anode in D2 specimen shows stable in dry condition but D1 specimens show increasing rest potential in ~400 mV. In the last environmental condition, both D1 and D2 show similar trend of rest potential in around -100 mV. It indicates that the moisture level of concrete affected the potential of the sacrificial anode, which is a similar trend as the potential development of rebars.

3.3. Depolarization test
In this research, depolarization test was carried out by disconnecting the rebar from anodes for 24 hours and calculating the difference value between the instant-off potentials was measured immediately after disconnection of the sacrificial anodes (Eoff), and the potential values were measured after 24 hours (Eoff24h). The 100 mV depolarization value is used as a criterion for evaluating the effectiveness of the cathodic protection system for reinforced concrete structures [7].

Figure 11 illustrates the depolarization value of rebar in repair and existing concrete during exposure time. It can be observed that SCP-D1 (steel bar with rust removal) achieves the 100 mV potential decay criterion until 1000 days during exposure condition of air curing 20°C, wet-dry cycle, and dry laboratory air. Meanwhile, SCP-D2 (steel bar without rust removal) fails to exceed 100 mV since the beginning of exposure time. After the exposure condition is changed to wet condition from 100-days, it was observed that the depolarization of steel bar in repair part is generally in positive value. It means the sacrificial anodes effective to protect steel bar only in repair area.
In this research, the effect of steel bar with and without rust removal in long-term observation with several conditions until 1260 days is still not clear. It may because new corrosion product was generated in both of steel bar. From this evaluation, non-rusted rebar condition in repair concrete (chloride-free) is the most desirable initial condition when the sacrificial anode is applied on it to protect the corroded steel bar in existing concrete (chloride contamination).

4. Conclusion
From the experimental program, several conclusions can be drawn as follows,
1. Potential development of rebar is affected by the steel surface condition and the moisture level of the concrete.
2. The protective current of the sacrificial anode became more active in the humid conditions than in dry conditions, due to the high moisture content in concrete.
3. Based on the 100 mV decay criterion, protective conditions were achieved on the steel bars connected to the sacrificial anode with rust removal as an initial condition until three-years.
4. Corrosion product on steel surface decreases the effectiveness of cathodic protection even though embedded in chloride free concrete because the rust on the steel bar impeded the current flow from anode to the steel bar when sacrificial anode applied on it.
5. Rust removal on steel surface in repair concrete is the most desirable initial condition when the sacrificial anode is applied on it to protect corroded steel bar in existing concrete.
6. In this research, the influence of rust removal process in steel bar surface is not clear during exposure time in several condition until 1260 days. It may because new corrosion product was generated in the steel bar.

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6. References

[1] Pedeferri P 1996 Cathodic Protection and Cathodic Prevention *J. Construction and Building Materials* **10** (5) pp 391-402

[2] Presuel-Moreno F J, Sagues A A, Kranc S C 2005 Steel Activation in Concrete Following Interruption of Long Term Cathodic Polarization *Corrosion, The Journal of Science and Engineering* **61** (6) pp 428-436

[3] Alonso C, Castellote M, and Andrade C 2002 Chloride Threshold Dependence of Pitting Potential of Reinforcement *Electrochimia Acta* **47** (21) pp 3447-3469

[4] Christodoulou C et al. 2008 Evaluation of Galvanic Technologies Available for Bridge Structures (Edinburgh, UK: 12th International Conference Structural Faults and Repair)

[5] Sergi G 2011 Ten-years Result of Galvanic Sacrificial Anodes in Steel Reinforced Concrete *Materials and Corrosion* **62** (2) pp 98-104

[6] Astuti P, Mahasiripan A, Rafdinal R S, Hamada H, Sagawa Y, and Yamamoto D 2018 Potential Development of Sacrificial Anode Cathodic Protection Applied for Severely Damaged RC Beams Aged 44 Years *J. Thailand Concrete Association* **6** (2) pp 24-31

[7] EN 12696 2000 Cathodic Protection of Steel in Concrete *European Standard*

[8] ASTM C 876-95 1999 Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete *West Conshohocken, PA: American Society of Testing and Material*

[9] Dugarte M J, and Sagues A A 2014 Sacrificial Point Anode for cathodic prevention of reinforcing steel in concrete repairs: Part 1 – Polarization Behavior *Corrosion, NACE International* **70** (3) pp 303-317

[10] Rafdinal R S 2015 Life Extension of RC Structure by Cathodic Protection using Sacrificial Anode Embedded in Concrete *Ph.D Dissertation Department of Civil and Structural Engineering Kyushu Univ. Fukuoka Japan*

[11] Rafdinal R S, Hamada H, Sagawa Y, and Yamamoto D 2016 Effectiveness of Steel Surface Conditions on Cathodic Protection by Sacrificial Anode in Concrete *Proceeding of Japan Concrete Institute (JCI) Annual Convention, Chiba, Japan*

[12] Astuti P, Rafdinal R S, Hamada H, Sagawa Y, and Yamamoto D 2018 Time Dependency of Rusted and Non-rusted Rebar Protected by Sacrificial Zinc Anode in Patch Repair Section *Proceeding of Japan Concrete Institute (JCI) Symposium on Electrochemical and Maintenance Engineering, Tokyo, Japan*