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Cathodic Protection Range of the Embedded Sacrificial Zinc Anode for RC Member Deteriorated by Carbonation and Mixed Chloride

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Abstract

Much is left unknown about applicable conditions of the method or quantification of the cathodic protection range. In particular, little has been studied about how the range or effect of cathodic protection is influenced by such factors as the thickness of reinforcing bars (rebars) to be protected, combined deterioration by carbonation and mixed chloride, amount of chloride ions and carbonation depth. This study experimentally evaluated the effect of differences in the chloride ion content in concrete, the carbonation depth or the rebar thickness on the cathodic protection range of the embedded sacrificial anode method. The results of the experiment were that the smaller the carbonation depth, the amount of chloride ions or the rebar thickness, the larger the amount of depolarization of the rebars in the concrete to be protected was. That is, for corrosion protection of rebars near patch repair areas embedded with sacrificial anodes, it would be appropriate to make the steel surface area of components smaller and the salt damage environment less corrosive.

1. Introduction

In corrosion protection of reinforcing bars (rebars) near a patch repair area, controlling microcell corrosion, not only macrocell corrosion, is the key to ensuring long-term durability. Based on the idea, this study has focused on the embedded sacrificial anode method where zinc is embedded in a patch repair area as a sacrificial anode material. This method is good in terms of construction efficiency as zinc is installed where concrete is removed for patch repair. In the past study, the cathodic protection effect of sacrificial anode decreases when sacrificial anode is embedded in patch repair material of high resistivity, and also embedded away from the boundary between the patch repair and concrete sections (Yamaguchi et al. 2009). When the chloride ion content in the concrete is large, the cathodic current tends to flow the rebar near the sacrificial anode intensively (Matsukubo et al. 2004). In addition, the applicability of sacrificial anode to the concrete structure with deterioration caused by chloride ion was inspected (Sergi 2009).

However, much is left unknown about applicable conditions of the method or quantification of the cathodic protection range. In particular, little has been studied about how the range or effect of cathodic protection is influenced by such factors as the thickness of rebars (amount of steel) to be protected, combined deterioration by carbonation and mixed chloride, amount of chloride ions and carbonation depth.

This study experimentally evaluated the effect of differences in the chloride ion content in concrete, the carbonation depth or the rebar thickness on the cathodic protection range of the embedded sacrificial anode method.

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2. Overview of the experiment

Using specimens prepared with discontinuous rebars, an experiment was carried out to evaluate how the cathodic protection range of the embedded sacrificial anode method would be influenced by the difference in chloride ion content in the concrete, carbonation depth or rebar thickness. Discontinuous rebars were prepared in reference to the study of the past (Nagataki et al. 1996).

2.1 Specimens

Figure 1 shows the outline of the specimens. Each specimen was a rectangular column of 100×100×800 mm partially having an artificial patch repair section. A series of discontinuous round bars were placed as rebars with a concrete cover depth of 25 mm. Lead wires were used for electrical connection between the sacrificial anode and a discontinuous rebar and that between the adjacent dis-
continuous rebars, so that short-circuiting or isolation was made possible. As shown in the side view in Fig. 1, the discontinuous rebars were numbered from (1) to (5) from left to right. The water-cement ratio of the concrete used was 70%, it was larger than usual as considering to deteriorate at an early stage. The patch repair material was a commercial product of polymer-cement mortar (PCM) commonly used for actual repair work. The PCM was prepared by premixing cement, sand, polymer, admixture and other components and adding 1.1 kg of a liquid mainly consisting of SBR-based synthetic rubber latex and 2.25 kg of water to 25 kg of the premixed powder. Figure 2 shows the sacrificial anode used in the experiment. Its dimensions were 45 mm wide, 140 mm long and 13 mm thick. The zinc was covered with a high pH backfill material that consisted mainly of lithium hydroxide, in expectation of less formation of oxidized film after the anode reaction. Table 1 shows the main materials used, and Table 2 shows the standard mix design of the concrete.

### 2.2 Test factors

Table 3 shows a list of the specimens. Seven different types were prepared, with the chloride ion content in the concrete, carbonation depth and rebar thickness (diameter) varied as the test factors. As for the chloride ion content in the concrete, sodium chloride (NaCl) was added to replace fine aggregate partially, thereby simulating the internal salt damage from sea sand. The stan-

![Fig. 2 Sacrificial anode material.](image)

![Fig. 1 Test specimen.](image)
standard chloride ion content was set to 3 kg/m³ (equivalent to 4.9 kg/m² of NaCl) based on a previous study (Aramaki 2006), and a highly corrosive environment was represented with a chloride ion content of 9 kg/m³ (equivalent to 14.8 kg/m² of NaCl). In case of chloride ion content of 9 kg/m³, slump and air almost became the target value. However, in case of chloride ion content of 3 kg/m³, it was a data smaller than target value with slump and air. Two values were adopted for carbonation depth, assuming combined deterioration by carbonation and mixed chloride: 10 mm to obtain a carbonation residual of 15 mm (Tottori et al. 2005) where the number of structures with the degree of rebar corrosion reaching the level of IIa or IIb was considered to gradually increase; and 25 mm to obtain a carbonation residual of 0 mm as a very highly corrosive environment where initially-contained chlorides would migrate to and concentrate at around rebars. The rebar thickness was 28 mm as the standard, with 19 mm and 13 mm added for comparative purposes. The reason for choosing 28 mm as the standard was that the value was practically equivalent to the area of steel per unit concrete surface area in common intermediate slabs of rigid-frame reinforced concrete (RC) viaducts on the Sanyo Shinkansen bullet train system.

Figure 3 shows the relationship between carbonation and the amount of chloride ions with the measurement results on the specimens with a chloride ion content of 9 kg/m³. Migration and concentration of chloride ions occurred in the depth direction, with the maximum value found at the carbonation front.

2.3 Preparation and curing of the specimens
The specimens were prepared as follows. Concrete was first placed in the dimensions of 100×100×600 mm for the section of discontinuous rebars (2) to (5). The mold was removed the following day, and the concrete specimens were wet cloth cured in a chamber controlled to 20°C until 28 days of age. On the specimens not for accelerated carbonation, a sacrificial anode was fixed to discontinuous rebar (1) in the patch repair section after the completion of curing, and PCM was placed in the dimensions of 100×100×200 mm. The specimens to be subjected to accelerated carbonation were wrapped with aluminum foil tape for protection after the completion of curing, except for the concrete cover surfaces, and allowed to stand still in an accelerated carbonation tank until the carbonation depth was 10 mm or 25 mm. The accelerated carbonation test was performed in compliance with JIS A 1153:2003 - Method of Accelerated Carbonation Test for Concrete. The degree of carbonation was determined by spraying 1% phenolphthalein solution to the test pieces which were cut out of the control specimens prepared at the same time as the specimens shown in Fig. 1. When the desired carbonation depth was reached, the specimens were removed from the tank, and PCM was placed in the same manner as on the non-carbonated specimens. With this, date of PCM placement varied depending on the degree of carbonation: at a concrete age of 73 days for the specimens with a carbonation depth of 10 mm; and at a concrete age of 129 days for the specimens with a carbonation depth of 25 mm. The sacrificial anode was short-circuited to rebar (1) immediately after the placement of PCM.

2.4 Measurement items
Potentials of each rebar and the sacrificial anode were measured immediately after isolation from the sacrificial anode (Eio and Eaito, respectively) and then 24 hours after isolation from the sacrificial anode (Eof and Eaofof, respectively). Other measurement items include the amount of cathodic current flowing to and from the individual discontinuous rebars, polarization resistance of each discontinuous rebar, concrete resistance and anodic polarization curve of the sacrificial anode. Potential measurements of the rebars and the sacrificial anode were taken on the side surface of each specimen by using saturated copper sulfate electrodes (CSE). The amount of depolarization in each rebar was obtained as a difference between Eof and Eio. The amount of cathodic current was measured by using a zero-resistance ammeter, and the result was divided with the surface area of the discontinuous rebar to determine the current density. The polarization resistance was determined by applying a voltage of 10 mV at two different frequencies, 10 Hz and 20 MHz, calculating the apparent polarization resistance from the AC impedance values measured at the two frequencies, and multiplying the result with the rebar area. A duplex electrode sensor was used for the counter electrode. The concrete specific resistance was calculated from the concrete resistance obtained by the two-frequency AC impedance measurement. The anodic polarization test on the sacrificial anode was performed after the measurement of Eof. With the lead wires between the discontinuous rebars left connected, anode current was applied to the sacrificial anode in increments (up to 1.0 mA) by using a potentiogalvanostat, and Eaito was measured after holding the current flow for 15 minutes. The test period was about 6 months. The ambient temperature in the environment where the specimens...
were placed, as well as that during the measurements, was kept to 20°C.

3. Results and discussion

3.1 Cathodic current distribution

Figure 4 shows the change over time in the amount of cathodic current flowing from the sacrificial anode to discontinuous rebar (1) and that in the amount of cathodic current flowing from discontinuous rebar (1) in the patch repair section to discontinuous rebar (2) in the adjacent concrete. In the non-carbonated specimens, ZN03D28, ZN03D19 and ZN03D13, the amount of cathodic current flowing from the sacrificial anode to rebar (1) was found to be large in the early stage and gradually decreasing thereafter. In the artificially carbonated specimens, ZN03C10, ZN03C25, ZN09C10 and ZN09C25, the amount of current from the sacrificial anode to rebar (1) showed no significant fluctuation from the start of the current flow, resulting in no major change until the end of the test period. The amount of cathodic current flowing between rebars (1) and (2) generally decreased with the lapse of time from the start of the current flow in all specimens, with larger values shown by the specimens with lower chloride ion contents or smaller carbonation depths.

Figure 5 shows the change over time in the concrete specific resistance of ZN03C10, ZN03C25, ZN09C10, ZN09C25 and ZN03D28, which were specimens with a rebar thickness of 28 mm. The concrete specific resistance shown here is the mean value of the measurements on the discontinuous rebars in the concrete section of each specimen. Among ZN03D28 (0 mm carbonation depth), ZN03C10 (10 mm carbonation depth) and ZN03C25 (25 mm carbonation depth) which had a chloride ion content of 3 kg/m³, those with a larger carbonation depth showed a higher concrete specific resistance. These specimens were different in the age of concrete when the patch repair material was placed, which would suggest influence of the progress of cement hydration reactions. However, as shown in the diagram, the tendency of a higher concrete specific resistance in the specimens with a larger carbonation depth could be found also at the same concrete age. From these findings, carbonation and resultant microstructure densification (Nihei et al. 2003) could have also contributed to the increase in the concrete specific resistance. It is likely that, in the specimens with advanced carbonation, the increased concrete specific resistance has prevented the amount of cathodic current from being distributed to farther locations. In the specimens with the higher chloride ion content, 9 kg/m³, the amount of cathodic current flowing to the rebars in the concrete was found to be small, despite their low concrete specific resistance.

Figure 6 shows the polarization resistance of discontinuous rebar (2) in the concrete section, and Fig. 7
shows the change over time in the specific resistance of the patch repair section where the sacrificial anode was embedded. The polarization resistance shown in Fig. 6 is the mean values during the test period. As shown in Fig. 6, the larger the carbonation depth, or the larger the amount of chloride ions, the smaller the polarization resistance was, and, thus, the higher the corrosion rate of the rebars was. It was shown in Fig. 7 that the specific resistance of the patch repair section increased with time until starting to decrease after 100 days of current flow, and that the values were about up to 10 times the specific resistance of the concrete section. The cathodic current density in the galvanic anode method is generally thought to change according to the corrosion rate of rebar. The concentration of the cathodic current flow found in this study at the rebar in the patch repair section closest to the sacrificial anode was likely due to the extremely higher specific resistance of the patch repair section embedded with the sacrificial anode than that of the concrete section. This was also clear from the distribution of the cathodic current density to be discussed later.

Figure 8 shows the change over time in the amounts of cathodic current flowing to individual discontinuous rebar in the concrete for specimens ZN03D28 (28 mm rebar), ZN03D19 (19 mm rebar) and ZN03D13 (13 mm rebar) which were different only in the rebar thickness. The closer to the sacrificial anode, the larger the amount of current flowing to a discontinuous rebar was, with a tendency of decrease with time. Yet, the cathodic current was found to have reached all rebars. The same-numbered discontinuous rebar showed similar current values, with no major difference between the specimens.

Figure 9 shows the distribution of the cathodic current density in each specimen after 14 days of current flow. Since the amount of incoming current was similar between the same-numbered discontinuous rebar, the specimens with a smaller rebar thickness showed a larger cathodic current density in the same-numbered discontinuous rebar. This allows to consider that, the smaller the rebar thickness, the larger the cathodic current density at remote locations from the sacrificial anode is, meaning a larger cathodic protection range of the embedded sacrificial anode method. In addition, it is further suggested that an increased number of sacrificial anodes need to be embedded when the rebar thickness, or the amount of steel to be protected, is large.

Figure 10 shows the change over time in the cathodic current density flowing to individual discontinuous rebar in ZN03C10, ZN03C25, ZN09C10 and ZN09C25, the specimens with the same rebar thickness but different in the chloride ion content in the concrete and the carbonation depth. Here, the locations with negative cathodic current density values show the discontinuous rebar with a significant anode current that behave as macro-anodes. The reason why positive current density values appeared beyond the locations with negative values, farther from the sacrificial anode, was considered to be the formation of macro-cathodes and macro-anodes among the discontinuous rebar in the concrete. Focusing on the boundary between the patch repair and concrete sections in Fig. 10, it was found that the cathodic current density gradually decreased in discontinuous rebar (2) in the concrete, while gradually increasing in discontinuous rebar (1) in the patch repair section. Exceptions were discontinuous rebar (1) of ZN03C10 and ZN09C25 in which the current density decreased after reached the maximum level at 56 days of current flow. This will be discussed later in Section 3.4.
3.2 Depolarization

Figure 11 shows the change in the amount of depolarization of each specimen over time. The amount of depolarization was large in discontinuous rebar (1) in the patch repair section and became smaller in the discontinuous rebars in the concrete which were the intended target of corrosion protection. This tendency of decrease over time was consistent with the aforementioned behavior of the cathodic current density which increased in discontinuous rebar (1) in the patch repair section and decreased in the rebars in the concrete. Focusing on the test factors, the smaller the carbonation depth, the amount of chloride ions or the rebar thickness, the larger the amount of depolarization was found to be. This indicated that, the smaller the carbonation depth or the amount of chloride ions, the larger the polarization resistance of rebars would be, causing cathodic polarization at a smaller current density. The influence of the rebar thickness was as mentioned in the above section: the smaller the rebar thickness, the larger the cathodic current densities at farther locations were, causing the amount of depolarization to be large.

Among the artificially carbonated specimens, ZN03C10 with a chloride ion content of 3 kg/m$^3$ in the concrete and a carbonation depth of 10 mm showed a significantly large amount of depolarization as compared to other specimens during the test period. This will be discussed in Section 3.3 from the viewpoint of polarization behavior of the rebars after 56 days of current flow.

3.3 Rebar potential

Figure 12 shows the distributions of E$\text{io}$, E$\text{of}$ (polarization), E$\text{of}$ (depolarization) and E$\text{ao}$ of the artificially carbonated specimens after 56 days of current flow. Here, E$\text{of}$ (polarization) is the half-cell potential measured with the discontinuous rebars kept short-circuited, and E$\text{of}$ (depolarization) is the half-cell potential measured with the discontinuous rebars kept isolated. The diagram also shows the macro-cathode and macro-anode locations near the patch repair section determined from the potential difference between E$\text{of}$ (polarization) and E$\text{of}$ (depolarization). In ZN03C10, the macrocell was likely to have been formed between discontinuous rebars (2) and (3) in the concrete, not at the boundary between the patch repair and concrete sections. In the other specimens it was likely that the patch repair section behaved as a macro-cathode, while discontinuous rebar (2) in the adjacent concrete behaved as a macro-anode. E$\text{of}$ (depolarization) and E$\text{of}$ (polarization) in each macrocell region are considered to be the start and end points, respectively, of the polarization behavior during the macrocell formation. Figure 13 shows the schematic diagram (PWR1 2009) of macrocell corrosion expressed with the polarization curves. Here, points A and C represent E$\text{of}$ (depolarization) and E$\text{of}$ (polarization) of the macro-anode, respectively, and points B and D represent E$\text{of}$ (depolarization) and E$\text{of}$ (polarization) of the macro-cathode, respectively. In Fig. 12, the specimen with a large amount of polarization in the macro-anode rebar was ZN03C10 in which a relatively large amount of depolarization was obtained. It is likely that the amount...
of depolarization increases when the potential of a rebar to be protected becomes very noble due to polarization caused by the formation of a macrocell.

**Figure 14** shows the distributions of $E_{i0}$ and $E_{o}$ of each specimen after 56 days of current flow. The smaller the amount of chloride ions, or the smaller the carbonation depth, the more noble the $E_{i0}$ and $E_{o}$ of the rebars in the concrete became. ZN03C10 exhibited a characteristic upward convex shape where the half-cell potentials of the rebars in the concrete became more noble than that of the rebar in the patch repair section because of the relatively large polarization in the anode region. As described in **Fig. 15**, the amount of depolarization is expected to be large when the distribution of half-cell potential near a patch repair area has a shape of this type. The concentrated flow of cathodic current to the patch repair section can be explained as follows. Embedding a sacrificial anode results in contact of different metals,
Fig. 12 Distribution of $E_{io}$, $E_{op}$ and $E_{ap}$.

Fig. 13 Schematic diagram of macrocell corrosion expressed with polarization curve (PWRI 2009), with edits by the authors.
which leads to formation of a macrocell between the sacrificial anode and a rebar in the patch repair area. The current generated is thought to be dependent on potential difference and resistance. Discontinuous rebar (1) in the patch repair section was located close to the sacrificial anode and had the largest potential difference, which was likely to be the cause of the concentration of the cathodic current. As for the concern of possible macrocell corrosion after patch repair, rebars in the patch repair area are protected by those in the adjacent concrete that serve as sacrificial anodes. The protection current supplied to the patch repair area can even result in excessive corrosion protection. Consequently, for corrosion protection of rebars near patch repair areas embedded with sacrificial anodes, it would be appropriate to make the steel surface area (rebar thickness) of components smaller and the salt damage environment less corrosive.

### 3.4 Anodic polarization characteristics of the sacrificial anode

**Figure 16** shows the relationship between the amount of cathodic current generated from the sacrificial anode and \( E_{aof} \). The smaller the amount of cathodic current, the more noble \( E_{aof} \) was. That is, with the decrease in the performance of the sacrificial anode, the anodic polarization resistance of the sacrificial anode increases, making \( E_{aof} \) more noble. **Figure 17** shows the anodic polarization curves of the sacrificial anodes measured at the end of the test period. The figure also shows a polarization curve of an unused sacrificial anode exposed to two weeks of indoor air curing after placement of the patch repair material, without being short-circuited to a rebar. The figures in parentheses shown after the specimens are the measured values of the amount of cathodic current generated from the sacrificial anode at the end of the test period. It was found that the anodic polarization resistance of the sacrificial anodes increased through the six months of current flow. The polarization curves of ZN03C10 and ZN09C25, which had smaller amounts of cathodic current, exhibited larger gradients at lower current density stages. In these specimens, the current density flowing to the discontinuous rebar in each patch repair section was found to decrease after 56 days of current flow. It is possible that increase in polarization resistance due to oxidation of zinc has contributed to the decrease in the amount of cathodic current.

**Figure 18** shows the change in \( E_{aof} \) over time. ZN03C10 and ZN09C25 exhibited more noble \( E_{aof} \) values at the end of the 6 months of current flow.
the test period, which was consistent with their smaller values for the amount of cathodic current as found in Fig. 4 shown above.

In light of all the above findings, it will be possible to quantify the decrease in the sacrificial anode performance by using the potential and anodic polarization curves of sacrificial anodes. On the other hand, while sacrificial anodes reduce their performance as they continue to work, the continuous flow of current increases the anodic polarization resistance of the rebars, possibly decreasing the current density necessary for corrosion protection. That is, for proper evaluation of the cathodic protection effect, it is necessary to evaluate the amount of depolarization of rebars as well as the decrease in the sacrificial anode performance.

4. Conclusions

This study investigated corrosion protection of rebars near a patch repair area, focusing on the embedded sacrificial anode method that used zinc embedded in a patch repair area as a sacrificial anode material. Experimental evaluation was carried out to find how the differences in the chloride ion content in concrete near a patch repair area, the carbonation depth or the rebar thickness would influence the cathodic protection range of the embedded sacrificial anode method. The major findings of this study are as follows:

1) The amount of cathodic current flowing from the sacrificial anode to the rebars in the concrete was relatively large in the early stage but then decreased due to the over-time increase in specific resistances of the patch repair material and the concrete.

2) The specific resistance of the patch repair material was larger than that of the concrete, which resulted in a concentrated flow of cathodic current to the rebar in the patch repair section located the closest to the sacrificial anode.

3) If the cathodic current flow does not reach remote locations from the sacrificial anode, a macrocell may be formed between the rebars in the concrete.

4) The smaller the carbonation depth, the amount of chloride ions or the rebar thickness, the larger the amount of depolarization of the rebars in the concrete to be protected was. That is, for corrosion protection of rebars near patch repair areas embedded with sacrificial anodes, it would be appropriate to make the steel surface area (rebar thickness) of components smaller and the salt damage environment less corrosive.

5) The embedded sacrificial anode method was capable of controlling macrocell corrosion occurring in the early stage after patch repair and also had the effect of microcell cathodic protection. However, the cathodic protection effect on the rebars decreased when the chloride ion content in the concrete was large.

6) It is possible to quantify the decrease in the sacrificial anode performance by using the potential and anodic polarization curves of sacrificial anodes. On the other hand, the continuous flow of current increases the anodic polarization resistance of the rebars, decreasing the current density necessary for corrosion protection. Therefore, it is also necessary to evaluate the amount of depolarization of the rebars.

The cathodic protection effect of the embedded sacrificial anode method has been demonstrated by test construction on intermediate slabs of an RC rigid frame viaduct with combined deterioration by carbonation and mixed chloride (Yoshida et al. 2020).

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