Corrosion Mitigation of Steel Rebars Using Galvanic Anode Materials for Salt-deteriorated RC Slabs in Snowy Regions

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Abstract**—Early detection, timely maintenance, and recovery works can enhance the lifetime of a structure and prevent overall failure, guaranteeing its structural safety and serviceability with minimum cost. In snowy regions of Japan, reinforced concrete slab decks are experiencing early deterioration caused by salt damage owing to the penetration of the chloride ion contained in the anti-freezing agent into the interior of the concrete. Because the deteriorated parts are locally and scattered, repair and maintenance by access from the bridge surface are difficult. Therefore, the efficient maintenance works on bridges degraded by salt damage are required. With the aim of contributing to efficient structural health monitoring approaches, the authors propose a steel corrosion mitigation method by constructing an easily detachable sacrificial anode from the lower surface of a bridge. Based on the obtained results, this study first describes the proposed corrosion mitigation method, then outlines an actual case study performed on an actual bridge to clarify the corrosion mitigation effect. In addition, the process of construction, maintenance, and management of the proposed method are introduced.**

Index Terms**—anti-freezing agent, reinforced concrete deck slab, sacrificial anode, corrosion mitigation, salt damage**

I. Introduction

In the Hokuriku district, a snowy coastal region on the East side of Japan, where a lot of anti-freezing agents (NaCl) has been sprayed during winter, salt damage, alkali-silica reaction (ASR), and frost damage cause early severe degradation of the bridges without warning [1–6]. The influence of overloaded vehicles is also a safety concern. Therefore, fatigue damage due to repetitively running of large vehicles and deterioration due to environmental conditions in the area are primary causes of the degradation of the reinforced concrete (RC) slab decks which are currently maintained and managed. Although fatigue was considered as one of the main causes of deterioration of the RC deck of the urban bridges, fatigue damage was unlikely to be the main cause of the deteriorations of the local road bridges because of the small traffic volume per day. The first large-scale renewal and repair project replacing all RC slabs of the region was completed at two highway bridges in November 2016. Because of the current budget constraint, the replacement work of all deteriorated deck slabs in the Hokuriku district is still unclear. Therefore, the large-scale renewal and repair projects require economical and rational countermeasures that fully consider the regional characteristics of the region. Under such a regional condition, how to take appropriate countermeasures have become urgent issues. Accordingly, developing efficient and reliable countermeasures against salt damage for road bridge RC slabs constructed in snowy cold areas is a topic that has gained notable attention in the literature in recent years.

Salt damage deterioration due to spraying of the anti-freezing agent is a phenomenon in which water containing salt is permeated into the interior and causes corrosion of the steel material on the upper surface of the slab deck. After an acceleration period in which cracking due to corrosion expansion appears, grows and then spreads out in different directions, the partial peeling and

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spalling of concrete mark the start of the deterioration period of the slab deck [7]. Such deterioration is not caused over the entire surface of the slab but is characterized as being partially and scattered. Countermeasures against salt damage include the section restoration method accompanied by traffic regulation, the partial replacement method and updating to a precast prestressed concrete slab. However, the cost may significantly increase as a result of re-degradation owing to the acceleration of macrocell corrosion, and long-term traffic regulation. Many studies on the technical methods which are used to solve the problem of corrosion and reduce its effects have attracted considerable interest in technical literature and have been investigated using different approaches such as coatings and linings [8,9], anodic and cathodic protection [10–12], use of inhibitors [13–15], and material selection and design improvement [16–18].

With regard to the coatings and linings approach, Velivasakis et al. proposed nondestructive, electrochemical treatments to prevent corrosion in chloride-contaminated and carbonated concrete by attaching a steel or titanium mesh electrode to the objective structure [8]. The process actually removes chloride ions from the contaminated concrete by the principle of ion migration while at the same time raising the pH of the carbonated concrete through electro-osmosis. In 2009, Chen et al. developed a test rig to study the effect of cathodic protection on corrosion of pipeline steel in the crevice area under disbonded coating through the measurements of local potential, solution pH and dissolved oxygen concentration. It was perceived that in the early stage of corrosion of steel, because of the geometrical limitation, the cathodic protection could not reach the crevice bottom to protect steel from corrosion [10]. For the use of inhibitors, the efficiency of inhibitors has been evaluated under varying chloride and temperature by Khaled A. Alawi Al-Sodani et al. in 2018 [13]. In particular, the performance of five corrosion inhibitors in mitigating the corrosion rate of mild steel immersed in the test concrete pore solution with three levels of chloride contamination (1000, 1500 and 2000 mg/L) and three exposure temperatures (25, 40 and 55 ℃) was studied by the potentiodynamic polarization technique. The results showed that all the investigated inhibitors were effective in minimizing in decreasing the corrosion current density, both at high temperature and high chloride concentration. In another study worth mentioning, Lee et al. studied the effect of sodium hexametaphosphate along with sodium benzoate and benzotriazole to mitigate the corrosion of steel rebars in aggressive solution [14]. They reported that the inhibitor has passivity properties on steel surface due to anodic adsorption on steel surface and enhances the corrosion resistance properties. Besides, the durability of concrete is also improved by the addition of supplementary cementitious materials and/or chemical agents to concrete mixtures such as concrete with marble and granite waste dust [16], concrete mixes with masonry chips as coarse aggregate [17]. A recent study of Abd El Fattah et al., reinforced concrete blocks made from eight mixes, containing different cement types, admixtures, and corrosion inhibitors, were subjected to the twelve-month exposure test in an aggressive marine environment with high-temperature, high humidity, and high salinity variation [18]. Their results proved that corrosion inhibitors showed better effectiveness with cover depth increase. Moreover, fly ash and slag cement provided the best performance of corrosion mitigation.

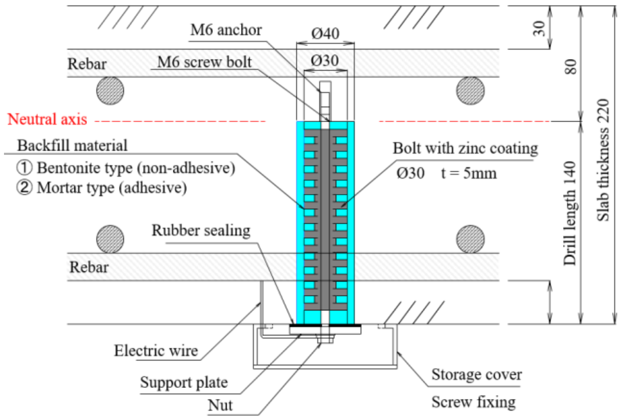


Figure 1. Outline of corrosion mitigation method (unit: mm)

With the aim of contributing to efficient countermeasures against salt damage, the authors propose a steel corrosion mitigation method by constructing an easily detachable sacrificial anode from the lower surface of a bridge. The electrochemical repairing method which electrochemically suppresses steel corrosion includes desalination method, cathodic protection methods such as using an external power supply or sacrificial anode method. Because the desalination method reduces mainly chloride ions around the steel material located in the concrete surface layer, construction from the upper and lower surfaces of the deck and long-term traffic regulation are required, and this results in high cost. On the other hand, although the external power source type electric corrosion prevention method can prevent corrosion of the steel material on the upper surface of the slab by construction from the lower slab surface, a large amount of anode material, large protection current are required. Furthermore, because of the leakage from the upper surface of the slab, the uniform distribution of the anticorrosive current is affected, so that a good anticorrosion effect cannot be expected [19]. However, although the sacrificial anode method electrochemical corrosion method can exert the corrosion inhibiting effect without being affected by water leakage [19], there is no bath voltage enough to pass the corrosion prevention current to the steel material on the upper surface of the deck from the lower surface of the deck. Therefore, in consideration with the leveling of the maintenance cost of the deck, the repair method using the newly developed sacrificial anodic material is not an electric corrosion prevention method that completely suppresses corrosion of steel. The steel corrosion mitigation construction method is adopted from the viewpoint that the corrosion mitigation will be ensured, and the cost can be reduced by extending the lifetime by about 10 to 20 years until the renewal of the deck slab. The proposed approach has a feature that the sacrificial anode system is capable of suppressing the corrosion of the steel material on the upper surface even though the construction from the lower surface of the slab, and can be easily replaced when no longer functional guarantee. At the laboratory level, the effectiveness of the proposed method was confirmed with respect to a removal slab specimen degraded by salt damage [19, 20]. The purpose of this work is to apply this method to actual structures under severe salt damage environment constructed in a snowy region and to examine the workability and its feasibility.

II. Development of Corrosion Mitigation Method by Galvanic Anode Material

A. Outline of Construction Method

The construction method was developed with the following keywords:

- Construction from the lower surface of the deck,
- The anode system is not affected by leakage from the upper surface of the deck,
- Each current-carrying anode material is independently energized,
- Maintenance of the presence or absence of energization of the representative current-carrying anode material,
- Easy replacement of galvanic anode material.

A schematic diagram of the developed corrosion mitigation method is shown in Fig. 1. This construction method consists of an anchor, a current-carrying anode material, a backfill material, a holding plate, and a storage cover. The anchor is aimed at fixing the sacrificial anode material inside the drill hole with a diameter of 40 mm. In addition, zinc plates of 30mm in diameter and 5mm in thickness are connected by a long screw bolt with anticorrosive zinc coating and act as a galvanic anode. The bolt length matches the depth at which the depth of the drill hole is equal to or less than the neutral axis of the deck slab.

In this work, two kinds of backfill materials were prepared, one consisting of bentonite mixed with LiOH and a special sponge containing LiOH aqueous solution (bentonite type), and the other one was mortar material mixed with LiOH (mortar type). The storage cover, which has high water retention performance, is intended to protect the galvanic anode material and store the measurement terminal with or without the energization.

B. Effectiveness of the Proposed Method

The 100-mV depolarization criterion [21] has been widely adopted as an anticorrosion criterion for the electrical corrosion prevention method [22–24]. When the galvanic anode method is adopted as the prevention method, it is necessary to adopt the same protection criteria. However, considering the life cycle time of the deck slab, the construction cost can be reduced by lowering the corrosion mitigation level in consideration with the anticorrosive effect of the prevention method.

The ratio of the anticorrosive effect at each amount of depolarization level to the anticorrosive effect at the 100-mV depolarization criterion is defined as the corrosion protection rate and the results of previous studied [25–27] are summarized in Table I. Although the protection rate differs depending on the test conditions, it was about 0.9 at the depolarization amount of 25 mV, and ~0.9 or more at the recovered amount of 50 mV. Therefore, the corrosion protection rate is assumed to be sufficient without considering the depolarization amount of 100 mV. This simplifying assumption was confirmed by Yoshida and colleagues [28], who also proposed that it was only necessary to secure a 50-mV depolarization amount when utilizing the galvanic anode method in a mild environment in consideration with the life-cycle cost of the structure. Therefore, in this paper, with reference to previous research results and Yoshida's proposal [28], it was assumed that the corrosion of steel material is relieved when the depolarization amount over 50 mV is recognized.

TABLE I. Corrosion Protection Rate of Previous Studies

Researcher	Test conditions			Corrosion protection rate (*)	
	Cl^- (kg/m^3)	Environment	Test period (days)	Depolarization amount 25 mV	Depolarization amount 50 mV
Chiba et al. [25]	–	Wet and dry repetition	534		0.99
Otani et al. [26]	2, 5, 10	Constant temperature and humidity	250	0.86–0.92	0.92–0.97
JCI [27]	7.5	Wet and dry repetition, dry, wet	400	–	Wet and dry repetition: 0.84; Dry or wet: 0.88

(*) Corrosion protection rate: The ratio of the anticorrosive effect at each amount of depolarization level to the anticorrosive effect at the 100-mV depolarization criterion.

III. Application to Actual Structure

A. *Outline of Structure*

Located in the Hokuriku district, the objective bridge of this study is a part of the elevated line of a highway. As can be seen in Fig. 2, the bridge is a composite bridge with a slab thickness of 220 mm and four main steel girders. Forty years have passed since the bridge was started in 1978 as a part of the important route which has a volume of traffic of 27000 vehicles per day and connects the East and West sides of the Kanazawa city.

Figure 2. Condition of the target structure

B. *Deterioration Situations*

The test range was set to about 20 m^2 covering a slab across the middle sway bracing and between the G2 and G3 main girders. Although cracks due to fatigue were not observed on the deck slab of the test range, white precipitates were scattered as shown in Figs. 3 and 4. Two cylindrical concrete specimens were sampled from the areas with white precipitates and healthy places without white precipitates, respectively, and then were subjected to the salinity analysis. The samples were sliced in 10-mm pitch. Then, the total chloride ion content was determined by a potentiometric titration method, and the chloride ion concentration distribution is shown in Fig. 5. Because the sprayed anti-freezing agent penetrated into concrete together with road surface water, the chloride ion amount tended to increase as the distance from the lower surface of the deck increased. Also, the amount of chloride ion in the white precipitate generation part tended to be larger than that in the healthy place. The figure shows that the chloride ion concentration at the position of the reinforcing bar on the lower surface of the deck was as small as ~0.3 to 0.5 kg/m^3. In addition, the measured results did not exceed the limit value 1.2 kg/m^3 of steel corrosion occurrence, which could be determined from the proposed formulas (-3.0 (W/C) + 3.4; estimated W/C: 55%–60%) by the Standard Specification for Concrete Structures of Japan [29]. However, based on the chloride ion amount distribution, the position of the reinforcing bar on the upper surface of the slab at the areas with white precipitates exceeded 1.2 kg/m^3, possibly corrosion of steel material was thereby considerably high.

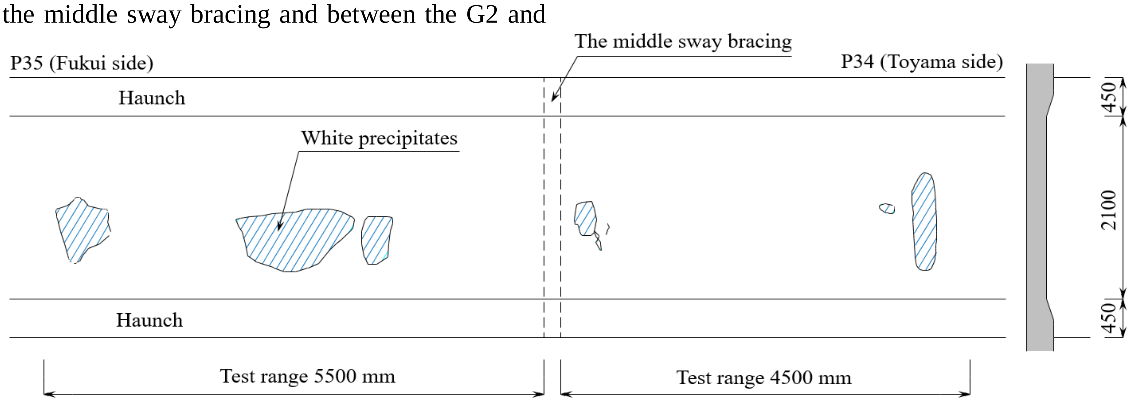


Figure 3. Test range (unit: mm)

Fig. 6 shows the distribution of the natural potential of the reinforcing bars on the lower surface of the deck. Specifically, the rebar potential in this study is expressed based on a silver-silver chloride reference electrode (or SSE) and categorized based on the ASTM C876 standard [30, 31]. The ASTM C876 standard is an empiric-based protocol of potential measurements used as a guideline for reinforcement corrosion monitoring. It relies on the relationship between the rebar corrosion potential converted to the silver-silver chloride equivalent potential and the probability of corrosion as follows. As shown in Fig. 6, $E > -80$ mV$_{SSE}$ indicates no corrosion with a probability of 90% or more (blue). For $E < -230$ mV$_{SSE}$, there is corrosion with the probability of more than 90% (red), whilst values falling between these limits are assimilated to an uncertain probability (yellow). In addition, the areas with white precipitates are simultaneously shown in the figure. As the results, the potential of the rebars in the white precipitate generation part was lower than that measured at the healthy place and tended to be classified as the uncertain category. The cause of this tendency is presumed that the amount of chloride ions and water tended to be significant in the concrete at the white precipitate locations. From the above results of the natural electrode potential and the chloride analysis, the slab within the test range was estimated to be in a period of transition from the corrosion incubation to the stage of development.

C. Construction Method of the Proposed Sacrificial Anode Material

Fig. 7 describes the construction procedure of the proposed sacrificial anode method.

1) Preliminary survey • marking work

Nondestructively investigate the position of the reinforcing bar using a radar device and mark the position of the rebar, the positions of the galvanic anode material and the monitoring sensor installation.

Figure 4. Status of the deck

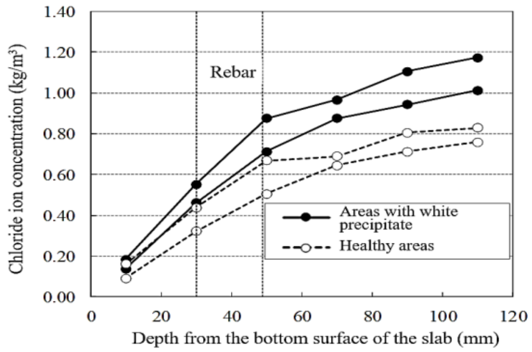


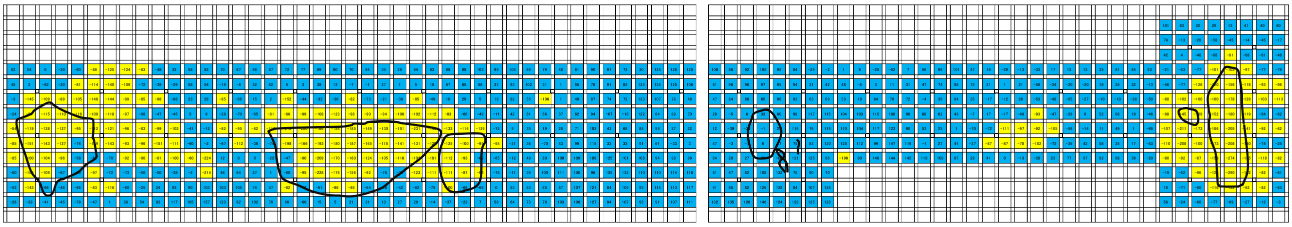
Figure 5. Chloride ion analysis result

2) Core drilling work

Drill the concrete cylinder samples with a diameter of 40 mm to provide places for the galvanic anode installation.

3) Sacrificial anode installation work

Place the anchor at the deepest part of the drilled hole, and fix the anode material (see Fig. 8) to the anchor. When non-stick-type backfill material is used, as shown in Fig. 9, bentonite is previously attached to the galvanic anode material and then the anode is inserted into the hole. On the other hand, when the mortar type is used, after fixing the galvanic anode material to the hole, mortar is injected after the packing installation as shown in Figs. 10 and 11.



Rest potential (E) mV_{SSE}	Possibility of rebar corrosion protection
- 80 < E	No corrosion with a probability of 90% or more
- 230 < E ≤ -80	Uncertain
E ≤ - 230	Corrosion with a probability of 90% or more

Figure 6. Natural potential distribution of rebars on the lower surface of the deck

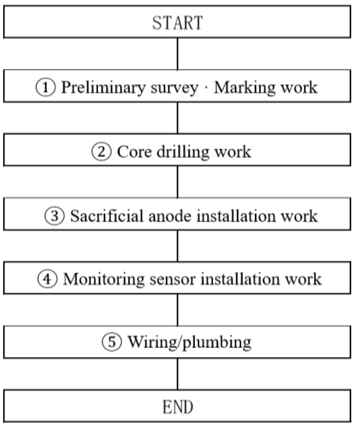


Figure 7. Construction flow chart

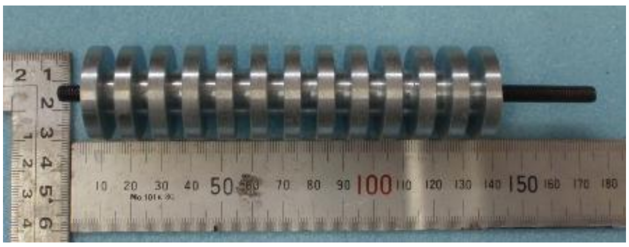


Figure 8. Galvanic anode material

After the installation work, the anode was connected with a wire and was then separately connected with a wire connected to the reinforcing bar of the slab.

4) Monitoring sensor installation work

As shown in Figs. 12 and 13, titanium wire sensors [32] (TW sensor) were embedded in concrete and utilized as monitoring sensors to measure the potential of the rebar.

5) Wiring/plumbing

After the sensor installation, the electric wires used to connect the galvanic anodes are installed, then they are set into the protective conduit system. Moreover, the exposed parts of the anodes are also protected by protective boxes. Finally, the electric wires, the galvanic anodes, and the TW sensors are connected to a control box. The proposed sacrificial anode system after the installation work is shown in Fig. 14.

D. Installation and Measurement Items of Sacrificial Anode Material and Monitoring Sensor

The installation interval of the sacrificial anode material is influenced by the amount of reinforcing bar, the degree of corrosion of rebar, and resistance of concrete. Indeed, the applicability of the sacrificial anode material to the slab has been gradually investigated by indoor experiments with small specimens [19], exposure tests with large specimens [33], and verification tests with removed floor slabs [20]. From the previous results, the installation interval of the anode capable of securing the depolarization amount of about 50 mV, which is a measure of the steel corrosion mitigation in this study, was approximately 400 mm. In this test work, considering the spacing of the rebars, the installation interval of the anodes was selected as ~500 mm in the direction of the bridge axis and as ~450 mm in the direction perpendicular to the bridge axis. As an advantage of the repairing method using the sacrificial anode material, there is no need to install the anodes on the entire surface of the deck, and it is only necessary to install them on the deteriorated part and its surroundings. From the viewpoint of the above-mentioned advantages, only the white precipitate generation areas shown Fig. 3 and its surroundings require the anode system. However, the galvanic anodes were also installed at the healthy section in this study. The installation positions are shown in Fig. 15.

Figure 9. Bentonite-type backfill material

Figure 10. Installation of packing

Figure 11. Injection of mortar material

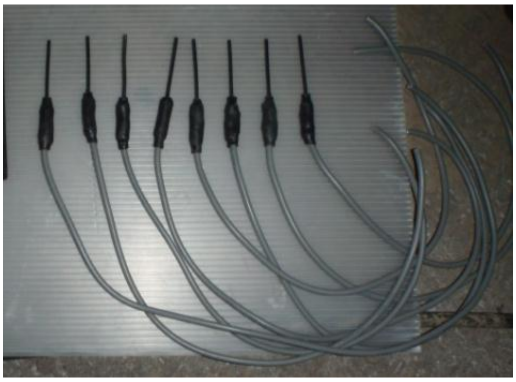


Figure 12. TW sensor

Figure 13. Installation of TW sensor

Figure 14. The proposed corrosion mitigation system

In order to evaluate the performance of the proposed method, the potential of the rebar was measured using the TW sensors and the portable reference electrode. Fig. 15 shows the measurement positions. Specifically, the TW sensors WR1 and WR2 measured the potential of the reinforcing bar in a sound place observed on the lower surface of the deck, while the potentials from areas with white precipitate were extracted from the measurement data of the sensors WR3 and WR4. In addition, the amount of current generated by the galvanic anode materials AN1 ~ AN4 was also analyzed to verify the effects of the variation in ambient temperature, the type of backfill materials and the severity of salt damage on the measured data.

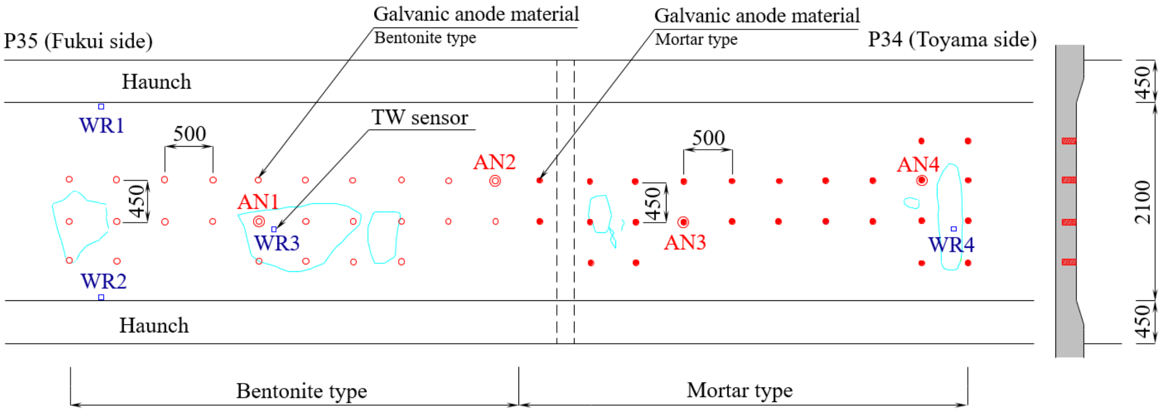


Figure 15. Installation positions of galvanic anode material and TW sensor (unit: mm)

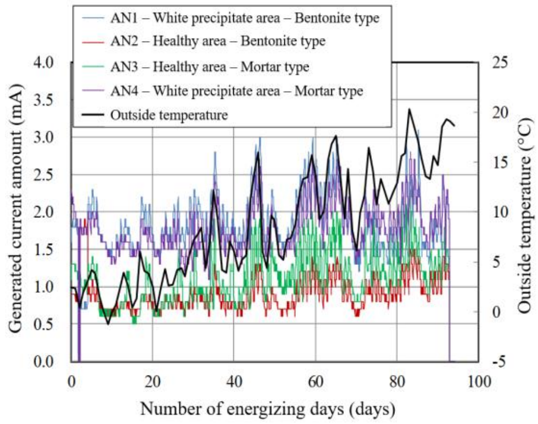


Figure 16. Variation in the amount of current generated by the galvanic anode material

E. Trend of Current, Potential, and Corrosion Mitigation

Fig. 16 shows the variation in the amount of current generated by the galvanic anode material over time. In particular, the amount of electric currents generated by the anode materials installed at the areas with white precipitates (AN1 and AN4 positions) tended to be larger than those obtained from the sound places (AN2 and AN3 positions), and both tended to increase and decrease repeatedly with the change of the ambient temperature. This is a characteristic of the sacrificial anode material that generates a large protective current for suppressing the high corrosion rate.

Although a comparison was also conducted on the two kinds of backfill materials, the outcomes showed that there was no apparent difference in the amount of current generated by the galvanic anode materials utilizing the mortar-type or bentonite-type backfill materials, as shown in Fig. 16. Specifically, there was a marginal difference in the amount of current obtained from the areas with white precipitates (AN1 and AN4 positions). Regarding the anode material installed at the sound areas, the amount of current produced by the anode using the mortar type (AN3 position) was relatively higher than that of the bentonite type (AN2 position).

In addition, Fig. 17 shows the distribution of the depolarization amount of the reinforcing bars on the lower surface of the deck one week after the start of energization from the galvanic anode system.

The distribution of the depolarization amount was estimated from the potentials obtained by the portable reference electrode. Regarding the steel depolarization, after an instant-off potential measurement, the anode was left disconnected and remain so while the potentials were measured again after 24 hours of the disconnection. The anode was reconnected afterward. Here, the depolarization amount indicates the difference between the electric potential right after cutting off the occurred electric current (instant-off potential) and the potential after 24 hours of the disconnection (24-hour-off potential). Since the ambient temperature is low and the corrosion reaction of the steel material is suppressed at the beginning of energization, the tendency of the recovered potential amount tends to be decreased. Although the depolarization amount near the anode material is 100 mV or more, as the distance increases, it tends to be slightly smaller than 50 mV. Therefore, there were places which did not satisfy the criteria of corrosion mitigation considered in this paper.

Table II shows the results of measuring the potential after 92 days of energization using the TW sensors. The potential of the rebar in the measurement position WR1 was -80 mV which was almost the same as the potential level indicating no corrosion with a probability of 90% or more as mentioned in Fig. 6. However, at the position WR2, the potential of the rebar was estimated at a slightly lower value than the safety level, which was -112 mV compared to -80 mV. Regarding the positions WR3, WR4, the depolarization amount was estimated at 33 mV, 42 mV for the upper rebars, and at 33 mV, 37 mV for the lower rebars, respectively. Because the results obtained after 92 days at the position WR3 and WR4 by TW sensors are similar to the results obtained after 7 days of installation, which was approximate ~40 mV, it seems that the polarization of the steel material was not advanced due to the current generated from the sacrificial anode.

Moreover, if the potential after 24 hours of the cut-off energization, which is considered to have no influence of the current generated from the galvanic anode material, is regarded as a natural potential, the natural potentials of the upper rebar in WR3 and WR4 positions were -277 mV, -315 mV, and that of the bottom rebar were -270 mV, -250 mV, respectively. From the ASTM standard [30, 31], the above results were classified into corrosion categories with a probability of 90% or more. Compared with the natural potential of the lower rebar shown in Fig. 6 in the same measurement position, the results obtained from WR3 and WR4 positions differed by about 20 mV ~ 50 mV. One of the possible reasons for the difference is that the electric potential measured by the portable matching electrode shown in Fig. 6 might be influenced by the water content ratio in concrete, and thereby leading to the overestimation of the measured potential. The results of visual observation of the lower rebar in the vicinity of both measurement positions are shown in Fig. 18. From Fig. 18, slight corrosion was confirmed, and it is consistent with the natural potential measurement result.

From now on, the depolarization amount, the amount of current and the potential will continue to be monitored to verify the effect of the proposed corrosion mitigation method.

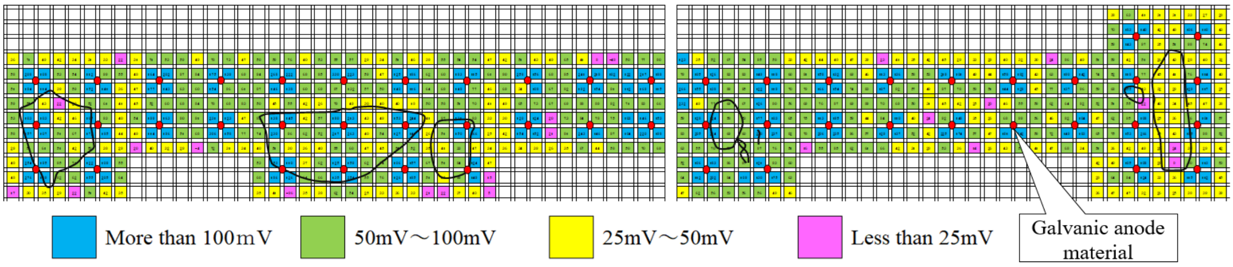


Figure 17. Distribution of the depolarization amount

TABLE II. REBAR POTENTIAL OF TW SENSOR AFTER 92 DAYS OF ENERGIZATION

Titanium wire sensor No.	Rebar position	Types of electric potential	Measured value (mV_{SSE})
WR1	Upper layer	Natural potential	-80
WR2	Lower layer	Natural potential	-112
WR3	Upper layer	Instant-off potential	-310
		24-hour-off potential	-277
		Depolarization amount	33
	Lower layer	Instant-off potential	-303
		24-hour-off potential	-270
		Depolarization amount	33
WR4	Upper layer	Instant-off potential	-357
		24-hour-off potential	-315
		Depolarization amount	42
	Lower layer	Instant-off potential	-287
		24-hour-off potential	-250
		Depolarization amount	37

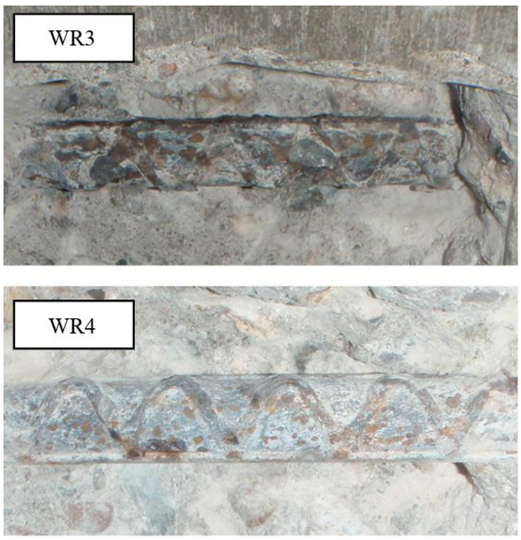


Figure 18. Corrosion condition of rebar of white precipitated part

IV. Conclusions

In this study, the practicality and effectiveness of the corrosion mitigation method using the galvanic anode material were verified by applying the proposed approach on an actual bridge, and then conducting long-term monitoring the variation in the depolarization amount, the amount of current and the potential of the reinforcing bars. The results obtained by this work can be summarized as follows:

The deck slab within the test range was estimated to be in a period of transition from the corrosion incubation to the stage of development.

It was possible to successfully carry out the construction of the galvanic anode system smoothly from the lower surface of the deck slab of the highway bridge that is in service.

The amount of electric currents generated by the anode materials installed at the areas with white precipitates tended to be larger than those obtained from the sound places, and both tended to increase and decrease repeatedly with the change of the ambient temperature.

There was an insignificant difference in the amount of current produced by the galvanic anode materials utilizing the mortar-type or bentonite-type materials.

The potential of the lower rebar at the position of white precipitates provided lower results than in other places. In addition, the potential of the upper rebar at the same position showed a tendency to be lower than that at the lower position.

As a result of installing the galvanic anode material at intervals of approximately 450 ~ 500 mm, in the vicinity of the anode material, a recovered potential amount of about 50 mV or more was secured, which resulted in satisfying the criteria for corrosion mitigation.

Because the results obtained after 92 days at the position WR3 and WR4 by TW sensors are similar to the results obtained after 7 days of installation, the polarization of the steel material was not advanced due to the current generated from the sacrificial anode.

From the results of visual observation of the lower rebar, slight corrosion was confirmed, and it is consistent with the natural potential measurement result.

This study is considered to be preliminary in reference to the use of a novel corrosion mitigation approach for the actual structure. Further research is needed on the subject. Regarding long-term prospects, further research should be carried out to apply this approach extensively in practical cases. Regarding the target structure in this study, long-term monitoring of the variation in the depolarization amount, the amount of current and the potential, and the effects of temperature and humidity on the above-measured data will continue to proceed to verify the effect of the proposed corrosion mitigation method.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors conducted research, analyzed the data and wrote the paper. All authors had approved the final version.

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References

[1] T. Katayama, M. Tagami, Y. Sarai, S. Izumi, and T. Hira, "Alkali-aggregate reaction under the influence of deicing salts in the Hokuriku district, Japan," *Materials Characterization*, vol. 53, no. 2–4, pp. 105–122, 2004.

[2] K. Torii, T. Daidai, H. Yamato, and T. Hirano, "Database on reactive aggregates and ASR-affected structures in Ishikawa prefecture," in *Proc. the Japan Concrete Institute*, vol. 30, no. 1, pp. 1017–1022, 2008.

[3] N. Arima, S. Fukada, M. T. Ha, M. Moriyama, and T. Miyashita, "Structural damage identification based on non-destructive and destructive investigation of PCT girder removed due to salt damage," presented at the Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International Symposium on Life-Cycle Engineering, Delft, The Netherlands, October 16-19, 2016.

[4] T. M. Ha, S. Fukada, and K. Torii, "Effects of fly ash on mechanical properties of PC girder using reactive andesite aggregates," *Journal of Advanced Concrete Technology*, vol. 15, pp. 579–594, 2017.

[5] T. Maeshima, Y. Koda, I. Iwaki, H. Naito, R. Kishira, Y. Suzuki, K. Ohta, and M. Suzuki, "Influence of alkali silica reaction on fatigue resistance of RC bridge deck," *Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures)*, vol. 72, no. 2, pp. 126–145, 2016.

[6] Y. Ishikawa, Y. Adachi, M. Aoyama, and M. Nagai, "Characteristic and structural assessment of damaged RC decks by chloride corrosion of reinforcing bar and fatigue," *Kozo Kogaku Ronbunshu. A (Journal of Structural Engineering. A)*, vol. 57A, pp. 1263–1272, 2011.

[7] Maintenance manual of road bridge deck, Japan Society of Civil Engineers, 2016.

[8] E. E. Velivasakis, S. K. Henriksen, and D. Whitmore, "Chloride Extraction and Realkalization of Reinforced Concrete Stop Steel Corrosion," *Journal of Performance of Constructed Facilities*, 1998.

[9] M. Balonis, G. Sant, and O. Burkan Isgor, "Mitigating steel corrosion in reinforced concrete using functional coatings, corrosion inhibitors, and atomistic simulations," *Cement and Concrete Composites*, in press, 2018.

[10] X. Chen, X. G. Li, C. W. Du, and Y. F. Cheng, "Effect of cathodic protection on corrosion of pipeline steel under disbonded coating," *Corrosion Science*, vol. 51, no. 9, pp. 2242–2245, 2009.

[11] J. Carmona Calero, M. A. Climent Llorca, and P. Garcés Terradillos, "Influence of different ways of chloride contamination on the efficiency of cathodic protection applied on structural reinforced concrete elements," *Journal of Electroanalytical Chemistry*, vol. 793, pp. 8–17, 2017.

[12] E. Q. Zhang, Z. Abbas, and L. Tang, "Predicting degradation of the anode–concrete interface for impressed current cathodic protection in concrete," *Construction and Building Materials*, vol. 185, pp. 57–68, 2018.

[13] K. A. A. Al-Sodani, O. S. B. Al-Amoudi, M. Maslehuddin, and M. Shameem, "Efficiency of corrosion inhibitors in mitigating corrosion of steel under elevated temperature and chloride concentration," *Construction and Building Materials*, vol. 163, pp. 97–112, 2018.

[14] H. S. Lee, H. M. Yang, J. K. Singh, S. K. Prasad, and B. Yoo, "Corrosion mitigation of steel rebars in chloride contaminated

concrete pore solution using inhibitor: An electrochemical investigation," *Construction and Building Materials*, vol. 173, pp. 443–451, 2018.

[15] E. Chajduk and A. Bojanowska-Czajka, "Corrosion mitigation in coolant systems in nuclear power plants," *Progress in Nuclear Energy*, vol. 88, pp. 1–9, 2016.

[16] S. Ghorbani, I. Taji, M. Tavakkolizadeh, A. Davodi, and J. de Brito, "Improving corrosion resistance of steel rebars in concrete with marble and granite waste dust as partial cement replacement," *Construction and Building Materials*, vol. 185, pp. 110–119, 2018.

[17] T. Manzur, B. Baten, M. J. Hasan, H. Akter, A. Tahsin, and K. M. A. Hossain, "Corrosion behavior of concrete mixes with masonry chips as coarse aggregate," *Construction and Building Materials*, vol. 185, pp. 20–29, 2018.

[18] A. Abd El Fattah, I. Al-Duais, K. Riding, and M. Thomas, "Field evaluation of corrosion mitigation on reinforced concrete in marine exposure conditions," *Construction and Building Materials*, vol. 165, pp. 663–674, 2018.

[19] S. Ura, T. Kamotani, K. Ishii, and K. Torii, "Development of galvanic anode system for easy replacement against RC slabs deteriorated by chloride attack and investigation on current flow characteristics," in *Proc. the Japan Concrete Institute*, vol. 39, no. 1, pp. 673–678, 2017.

[20] H. Kameda, T. Aoyama, K. Ishii, and K. Torii, "Study on corrosion mitigation measures of steel using electrodeposited anode construction to reinforced concrete slab with removal of salt damage," in *Proc. the Japan Concrete Institute*, vol. 40, no. 1, pp. 753–758, 2018.

[21] Standard Practice Control of External Corrosion on Underground or Submerged Metallic Piping Systems, NACE International, 2013.

[22] J. A. Beavers and K. C. Garrity, "100 mV polarization criterion and external SCC of underground pipelines," presented at Corrosion 2001, Houston, Texas, March 11-16, 2001.

[23] M. Funahashi and J. B. Bushman, "Technical review of 100 mV polarization shift criterion for reinforcing steel in concrete," *Corrosion*, vol. 47, no. 5, pp. 376–386, 1991.

[24] A. Araujo, Z. Panossian, and Z. Lourenço, "Cathodic protection for concrete structures," *Ibracon Structures and Materials Journal*, vol. 6, no. 2, pp. 178–193, 2013.

[25] T. Chiba, H. Seki, M. Abe, and K. Ishii, "Verification of corrosion protection standard for reinforcing bar in concrete," in *Proc. the symposium on repairing method of concrete structure and electric corrosion prevention*, pp. 33–38, 1994.

[26] S. Otani, A. C. Muhammad, D. Yamamoto, and H. Hamada, "Fundamental study on depolarization value and protection effects of steel in concrete under cathodic protection," *Concrete Research and Technology*, vol. 28, pp. 25–33, 2017.

[27] *Electrochemical Protection Method for Concrete Structures*, Research Committee Report, Japan Concrete Institute, 1994, pp. 140–159.

[28] T. Yoshida, "Study on maintenance of reinforced concrete structure by galvanic anode method," Ph.D. dissertation, Kyoto University, 2015.

[29] Standard Specifications for Concrete Structures: Design Code. Concrete Committee, Japan Society of Civil Engineers, 2012.

[30] Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete, ASTM C 876-91, 2015.

[31] R. Koyama, T. Yajima, T. Uomoto, and T. Hoshino, "Prediction of steel corrosion portion and area by natural potential measurement," *Doboku Gakkai Ronbunshu*, vol. 1996, no. 550, pp. 13–22, 1996.

[32] H. Kameda, T. Aoyama, K. Ishii, and K. Torii, "Experimental study on measurement of rebar with titanium wire sensor," in *Proc. the Symposium on Developments in Prestressed Concrete*, 2018.

[33] H. Kameda, T. Aoyama, K. Ishii, and K. Torii, "Applicability of the electrochemical repair method on the salt damage deteriorated RC Slab Structure," in *Proc. the Concrete Structure Scenarios*, JSMS, vol. 453–458, 2018.

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