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Investigation of the Effective Range of Cathodic Protection for Concrete Pile Specimens Utilizing Zinc Mesh Anode

Duhyeong Lee and Jin-A Jeong†

Division of Marine System Engineering Korea Maritime & Ocean University, 727 Taejong-ro, Yeongdo-Gu, Busan 49112, South Korea

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A zinc mesh sacrificial anode cathodic protection method is recently being developed to protect the reinforced concrete structure in a marine environment. However, comprehensive information regarding the cathodic protection technology applied to reinforced concrete test specimens utilizing zinc mesh sacrificial anodes remains limited. Particularly, no research has investigated the effective range of sacrificial anode cathodic protection in a reinforced concrete structure regarding the transmission of protection current from zinc mesh sacrificial anode to the reinforced concrete structure, particularly concerning effects of temperature variations. This study examined the distribution of potential and current using a long single rebar and several segment reinforcing bars inside a horizontal beam. Vertical pile specimens were applied with a zinc mesh sacrificial anode to simulate concrete bridges or harbor structures. To check the effect of cathodic protection, cathodic protection potential and current of the reinforced concrete specimens were measured and 100 mV depolarization criterion test was performed. It was confirmed that effect of cathodic protection varied depending on resistivity and temperature. The cathodic protection test of pile specimens revealed that the maximum reachable range of cathodic protection current was 10 cm from the waterline as observed in the experiment.

Keywords: *Concrete, Cathodic protection, Sacrificial anode, Potential, Current*

1. Introduction

Since concrete is strongly alkaline, it forms a protective film called passivity on the surface of the rebar under normal circumstances, so it does not corrode easily. However, in places where corrosive substances such as chloride are present, such as sea bridges and port structures, seawater containing chloride seeps into the porous concrete, destroying the passive tape film and corroding the rebar [1].

In marine environments, the corrosion of reinforced concrete has a substantial impact on the durability of concrete structures. The surface of the splash zone and the tidal zone of seawater is one of the most corrosive parts because it is rich in oxygen and moisture, which are the main factors of corrosion, and it is the most vulnerable part of marine structures as well as bridges and port facilities [2]. Since its introduction in the early 19th century, the cathode protection method has been used as a technology to suppress the corrosion of steel structures in underground and marine environments, and has now become one of the proven methods. Over the past 20 years, cathodic protection technology in the field of concrete has undergone significant advancements, and it has recently been introduced and implemented in many country. Nevertheless, there remain numerous technical challenges to address in the application of the cathodic protection method to heterogeneous concrete structures. In general, cathodic protection technology is broadly classified into two types: impressed current cathodic protection method and sacrificial anode cathodic protection method. Among these two method, the cathodic protection method of concrete structures that are difficult to maintain or manage facilities such as power supplies near the coast is preferred for the sacrificial anode cathodic protection method, which is relatively simple to install and has low cost. Zinc is mainly used as the anode for the cathodic protection method of concrete structures in seawater, and it is mainly applied to the piers of concrete

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†Corresponding author: jina@kmou.ac.kr
Duhyeong Lee: Professor, Jin-A Jeong: Professor

bridges, that is, near the water surface where serious corrosion problems occur in the marine environment. When the sacrificial anode cathodic protection system starts operation after installations, the protection current enters the rebar from the zinc anode through seawater and concrete. There are rare cases of applying sacrificial anodes to reinforced concrete structures, and there have been cases where the cathodic protection effect decreases due to concrete resistivity over time compared to the initial stage of construction.

X. Feng *et al.* conducted a study on the field experience and durability of corrosion prevention of reinforced concrete structures using the sacrificial anode cathodic protection method. In addition, Eric L. *et al.* conducted to assess the performance of cement-based repair mortar in the simulated cathode area in relation to the sacrificial anode method of reinforced concrete structures [3,4].

Sergi. G. *et al.* conducted a study on the electrochemical method monitoring of the cathodic protection method and standard of the cathodic protection method applying zinc sacrificial anode to reinforced concrete structures [5]. On the other hand, Bertolini, L. *et al.* studied the effect of the cathodic protection method using zinc anode on corrosion prevention of reinforced concrete structures, and Caronge, M. A. *et al.* studied the effect of the cathodic protection method using sacrificial point anode for prevention of steel corrosion in cracked concrete structures [6,7].

Cheng M. A. *et al.* solved rebar corrosion in concrete by adding the sacrificial anode in the patch repair section containing zinc sacrificial anodes [8] and, D. Garcia *et al.* conducted a study on the performance and effect of the cathodic protection method applied to reinforced concrete structures with a zinc layer [9].

However, there have been no studies investigating the transmission range of cathodic protection current flowing from the zinc mesh sacrificial anode embedded within the concrete to the reinforced concrete, particularly concerning the effect of temperature variations.

In recent years, concrete in the marine environment; The zinc mesh sacrificial anode cathodic protection method is being developed for the protection of the reinforced concrete structure. Until now, however, comprehensive information regarding the cathodic protection technology applied to reinforced concrete pile test specimens utilizing zinc mesh sacrificial anodes remains limited. Particularly, no research has investigated the effective range of sacrificial anode cathodic protection in reinforced concrete structure, specifically regarding the transmission of protection current from zinc mesh sacrificial anode to the reinforced concrete structure. The distribution of protection current varies depending on the porous concrete structure, aggregate, and moisture content of reinforced concrete materials, and the corrosion performance may be reduced due to the high resistivity of the concrete itself. The cathodic protection potential and protection current in concrete are affected by a number of environmental factors, such as resistivity and temperature of the concrete. Concrete resistivity is related to the rate of seawater or salt penetration, and temperature is related to seasonal weather. The distribution of cathodic protection potential and current across the vertical zones of the concrete pile structure, as well as the influence of temperature using zinc anode, are not well understood. In this study, a short-term laboratory experiment simulating a bridge placed in seawater was conducted to confirm the cathodic protection characteristics of a zinc mesh anode according to seawater absorption and temperature conditions in reinforced concrete, and the distribution of potential and current was studied using a long single rebar and several segment reinforcing bars inside the horizontal beam and vertical pile test specimens applied with a zinc mesh sacrificial anode.

2. Experimental Method

2.1 Specimen preparation

In order to simulate concrete piles and beams of bridges or harbor structures, test specimens and measuring terminals were designed as shown in Fig. 1. The test specimen size was 100 cm × 15 cm × 5 cm, with a vertically installed single long rebar measuring 10 mm in diameter. Eight segments of 10 cm in length were positioned at 2 cm intervals along the length of the rebar. For the anode, the zinc mesh sacrificial anode used for commercial purposes was cut into 12 cm × 12 cm sizes and embedded in one end of each test piece. The material composition of zinc mesh are shown in Table 1. Although it is not the actual surface area of the zinc mesh anode and the surface area of the reinforcing bars, the ratio of the area of the specimen and the zinc mesh generally

Fig. 1. View of test specimens and measuring terminals

Table 1. Composition of zinc mesh

Material	Lead	Iron	Cadmium	Copper	Zinc
Composition (wt%)	0.005	0.01	0.005	0.8	balance

applied to the cathodic protection design of concrete structures is 10.4:1. By simply connecting the sacrificial anode installed on the concrete surface to the rebar, the potential difference between the two metals naturally flows the electric current and supplies electrons to the rebar.

All the rebar was electrically connected using external conductors and screws to measure the potential and current of the cathodic protection system. The concrete mixed design of the test specimen is given in Table 2. Water-Cement ratio (W/C) of specimens was 0.5. After casting was conducted, specimens had been cured in the laboratory at a temperature of 20 ± 2 ℃ for 30 days. All the rebar was electrically connected to the anode for the cathodic protection, and a 1 ohm resistor was installed between each rebar and the anode connection terminal to measure the cathodic protection current, and the current value was calculated by converting the voltage difference between the two ends into resistance. The experimental environmental conditions, as detailed in Table 3, involved exposure to natural seawater for all specimens, except for the comparative test specimens kept in an atmospheric state. Horizontal beam specimens were measured in full or partial immersion, and vertical specimens were immersed to a height of 40 cm from the base. Natural seawater was used as a test solution, and seawater was exchanged every week at the beginning of the test, and seawater was exchanged every 2-4 weeks in the later stage. The experimental conditions were 10 ℃ and 40 ℃ in order to confirm the effect of cathodic protection by temperature. We set an environment of 10 ℃, which is the winter indoor temperature of the laboratory where the reinforced concrete test specimens were installed, and a high temperature environment of 40 ℃, which is the temperature that can be heated by the heater of the chamber.

2.2 Experimental measurement

Corrosion potential measurement of rebar is the most common method of electrochemical measurement, and it

Table 2. Concrete mixed design

Gmax	Slump	Air	W/C	S/a	Water	Cement	S	GA
9.5 mm	10 cm	5 %	0.5	53.3 %	210 kg	420 kg	845 kg	752 kg

Gmax : Maximum size of coarse aggregate
W/C : Water-Cement ratio
GA : Weight of coarse aggregate
S : Weight of fine aggregate

Table 3. Types of test specimens by experimental environment conditions

Spec. ID	Environment	Immersion	Type	Temperature
P-1	Air	Dry	Beam	40 ℃
P-2	Seawater	Full	Beam	40 ℃
P-3	Seawater	Top Surface	Beam	10 ℃
P-4	Seawater	Top Surface	Beam	40 ℃
P-5	Seawater	40 cm	Pile	10 ℃
P-6	Seawater	40 cm	Pile	40 ℃

Fig. 2. View of potential measurement of reinforced concrete specimen

measures the corrosion status of rebar inside using reference electrode from the outside of the concrete surface. The potential of the rebar surface is measured using a reference electrode and a high-resistance potentiometer to determine the degree of corrosion by measuring the energy state, i.e., potential, that changes when the rebar is corroded.

Potential monitoring was performed using a Fluke multimeter and a silver/silver chloride reference electrode (SSCE) as shown in Fig. 2, and a 4-hour depolarization test was performed to investigate the potential of the rebar polarized solely by cathodic protection current itself, excluding the voltage drop due to the resistivity of concrete during the experiment.

As a method to check the effect of the cathodic protection, 100 mV depolarization criterion test is performed, and depolarization or decay potential can be determined by potential monitoring over time after cathodic protection is switched off. Good condition of depolarization criterion can be determine if the pure depolarized potential subtract this voltage drop value is more than 100 mV since the value of the rapid increase in potential over a short period of time after disconnection between rebar cathode and zinc mesh anode corresponds to the voltage drop due to the resistivity of concrete.

The NACE 100 mV depolarization criteria are applied as the most widely recognized cathodic protection method in the world. The 100 mV depolarization criteria is a method of cathodic polarization of the subcutaneous material (rebar) potential of 100 mV or more. The cathodic polarization potential here is judged to be sufficient if the pure polarization potential is more than 100 mV, excluding potential change (IR drop) caused by concrete or external environmental resistance. This method is measured by an instant-off test that temporarily shuts off the cathodic protection current supply. In other words, when the power is cut off during the cathodic protection current supply process, the potential rises instantaneously, and the potential jumps rapidly at the beginning of the power cut (within 5 seconds), and then gradually slows down to reach the equilibrium potential. Here, the initial surge in potential is the potential drop value due to the resistance of the concrete itself, and then the potential change that occurs gradually is the depolarization part in which the rebar surface, which was cathodic polarized by the cathodic protection method, is restored to its original natural state of corrosion. The most commonly used criterion based on this method is 100 mV in four hour criterion. Therefore, the potential decay (ΔE) minus the initial potential drop (IR_Ω) is the potential value that was positively polarized by the cathodic protection method (Depolarization), and it is judged to be an appropriate method when it is more than 100 mV by equation (1).

$$\text{Depolarization} = \Delta E - IR_\Omega \qquad (1)$$

For the depolarization potential measurement and current measurement, a Gamry electrochemical measuring device with the function of a zero resistance ammeter (ZRA) was used. At this time, a 1 ohm resistor was used as a shunt for current measurement. The entire electrochemical test was conducted in accordance with ASTM and NACE regulations.

3. Results and Discussion

Fig. 3 shows the potential change of the cathodic protection test specimen under the atmospheric phase (P-1) and full immersion (P-2) in natural seawater at a temperature of 40 ºC. When the cathodic protection was connected, the potential in the atmosphere decreased by more than 100 mV to the vicinity of -200 mV/SSCE, and then gradually recovered. On the other hand, the potentials of the P-2 test specimen were impressively negatively polarized to -950 mV/SSCE in about 200 hours. Although

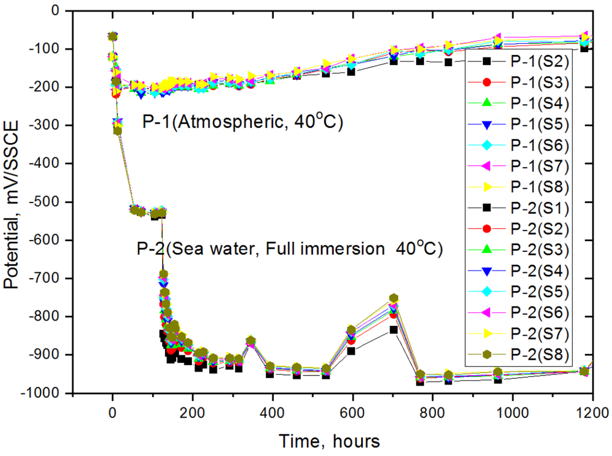

Fig. 3. Potential behavior of 8 segments of P-1 & P-2 specimens

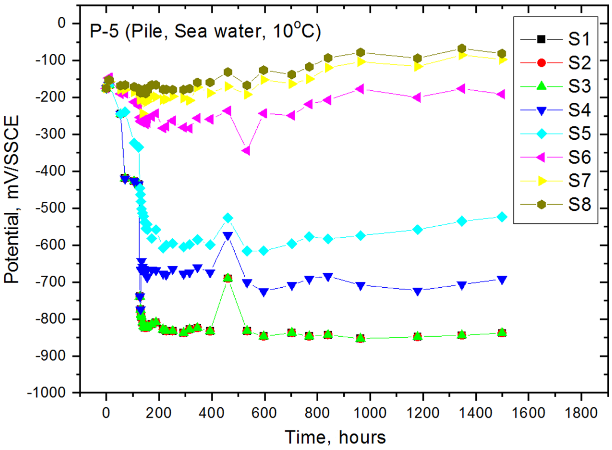

Fig. 4. Potential behavior of 8 segments of the P-5 specimen

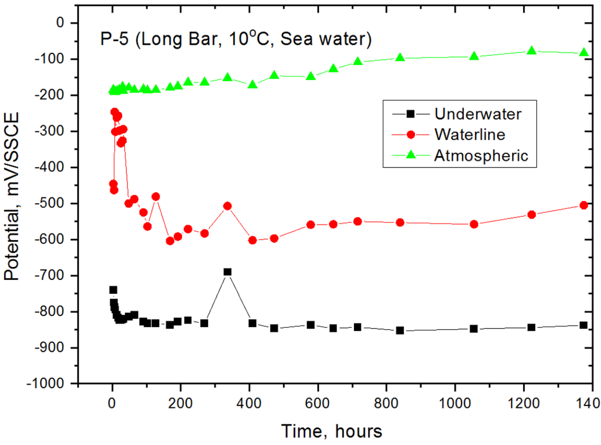

Fig. 5. Potential behavior of internal rebar of the P-5 specimen

there was some fluctuation during the experiment, the cathodic protection potential remained almost constant until 1,200 hours (about 50 days) of the experiment. Through this result, it was clearly shown that the cathodic protection method by the zinc mesh sacrificial anode inside the concrete is not suitable in places with high concrete resistivity such as the atmospheric environment because the flow of cathodic protection current from the anode is not smooth. However, it was found that sufficient cathodic protection current can be supplied in seawater. The conductive connection for the cathodic protection method is secure because of ionic path in seawater condition.

There was little difference in the potential range of the S1-S8 segment under both conditions. From this observation, it is evident that the distance between the zinc mesh anode and the rebar segment remained unaffected. A similar trend was observed in the potential behavior of partially immersed specimens P-3 (horizontal, 10 ºC) and P-4 (horizontal, 40 ºC).

As for the effect of seawater infiltration on the potential for the vertical test specimen, the measurement results of the long rebar of the P-5 test specimen clearly show that the tendency of the cathodic protection potential decreases as the seawater penetration is smoother.

Fig.s 4 and 5 show the time-dependent potential measurements of the P-5 test specimen measured at 10 ºC temperature and natural seawater conditions. The change in cathodic protection potential for 8 segments was measured for about 1,400 hours. The three segments of S1-S3, which are closest to the zinc mesh anode of the immersed site of the vertical pile test specimen immersed in seawater, exhibit the lowest and similar potential values. The potentials of the remaining six segments tend to increase with the height of the test specimen. Fig. 5 compares the potential of locations of long and segment rebar for the same P-5 specimen. Under identical conditions, it was discovered that the measurement outcomes obtained from the long rebar and those from the segmented sections were highly consistent.

The cathodic protection potential at the three positions of the long rebar (the underwater section, the waterline part, and the atmospheric part) was clearly differentiated as shown in Fig. 4. The potential of locations of the long rebar showed almost the same trend in the range between -100 mV/SSCE and -900 mV/SSCE, as shown in the segments shown in Fig. 5.

In addition, the three segments of S1-S3 closest to the zinc anode showed the lowest potential with the best cathodic protection effect, while the subsequent segment potentials increased with the installation height of segment, and they were well matched by the changes in the three regions by height in Fig. 4 (underwater part: S1-S3, waterline part: S4-S5, and atmospheric part: S6-S8). This means that, as confirmed, the cathodic protection potential has a great influence on the conductivity of concrete due to the difference in seawater infiltration depending on the height of the pile on the surface.

Fig. 6 compares the mean potential values of the segments (Fig. 4) with the long rebar (Fig. 5). As mentioned earlier, the potential is classified into three regions (underwater part: S1-S3, waterline part: S4-S5, atmospheric part: S6-S8) according to the height of the pile. The potential in the underwater mid reaches about -800 mV/SSCE and the atmospheric increases rapidly to around -200 mV/SSCE, and stabilizes when it reaches the high potential region in the atmospheric region. These findings indicate that the cathodic protection potential is significantly influenced by the height of the pile, primarily due to variations in seawater infiltration rates, which are directly correlated with the conductivity of the concrete. In the upper part of the surface (S4-S8), the capillary phenomenon of seawater gradually decreases according to the height of the specimen, resulting in an increase in potential. In other words, it indicates that it is difficult to supply cathodic protection current from the zinc mesh anode to the cathode rebar.

In addition, the fact that the trend of potential change measured at the position of each segment in this study is almost identical to the potential change measured on long rebar confirms that the potential change measured by the long rebar is sufficient to evaluate the cathodic protection state.

Fig. 7 shows the cathodic protection potential behavior of a long rebar in a P-6 test specimen tested at 40 °C. Although there was a slight unstable fluctuation in the early stages of the experiment, the overall potential values at the three locations showed a similar trend to P-5 at 10 °C.

To compare the impact of temperature on the efficacy of the cathodic protection method, the cathodic protection current and potential of the zinc mesh anode were compared to Fig.s 8 and 9. The cathodic protection current in Fig. 8 is the sum of the currents flowing from the zinc mesh anode to the entire rebar cathode (both the long rebar and the segment). At the outset of the experiment, following a period of unstable current decline, the cathodic protection current with respect to temperature remained almost constant at 1 mA at 10 °C and 3 mA at 40 °C. As in general electrochemical processes, cathodic protection currents have been found to increase at high temperatures. Fig. 9 shows the cathodic protection potential values for zinc mesh anodes at different temperatures. The mean potential at 10 °C was -830 mV and the mean potential at 40 °C was -950 mV. As shown in Fig. 8, the larger the cathodic protection current provided at high temperature, the more active the polarization is, and the lower the cathodic protection potential.

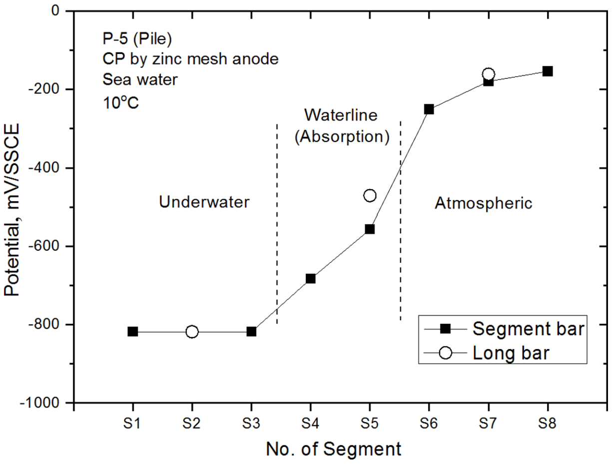

Fig. 6. Potential comparison of P-5 test specimen segment and long Rebar

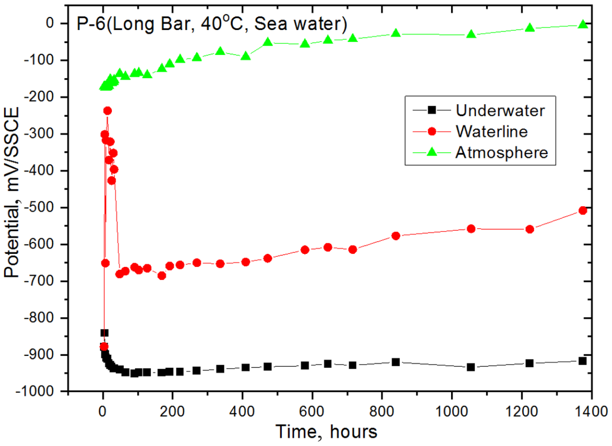

Fig. 7. P-6 Potential behavior of long rebar inside test specimen

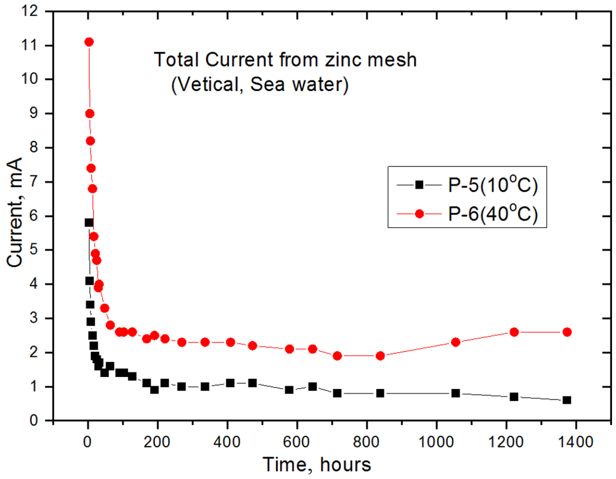

Fig. 8. The variation of total cathodic protection current of the zinc mesh anode with temperature

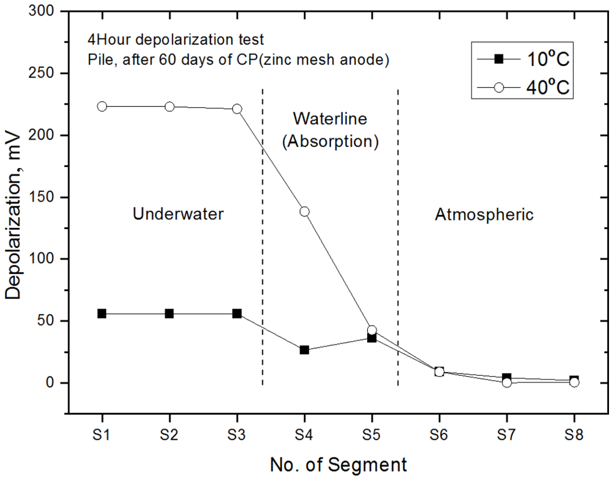

Fig. 10. 4-Hour depolarization potential measured after 60 days of cathodic protection

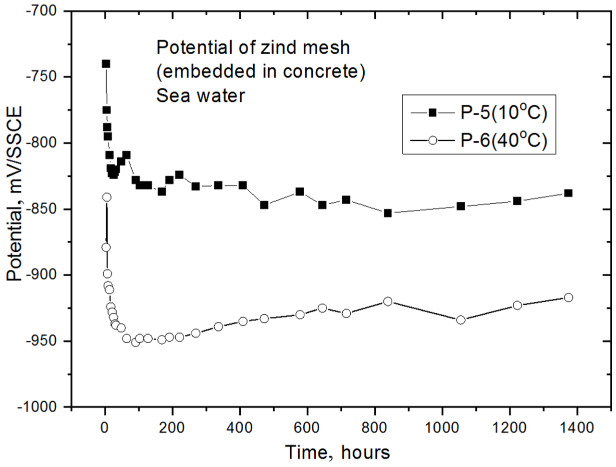

Fig. 9. Potential of zinc mesh anode for the different temperature

The actual polarization amount for the cathodic protection method can be calculated by 4-hour depolarization potential measurement using a potentiostat.

Fig. 10 shows the depolarization potential value for the height of the pile. The depolarization potential values in the submersible part (S1-S3) differ by more than four times, from about 50 mV at 10 °C to 225 mV at 40 °C, and are dramatically reduced in the surface segment (S4-S5), resulting in almost similar double potential values in the atmospheric region.

Through this result, it is shown that the cathodic protection potential of the rebar that is polarized by the cathodic protection current transmitted from the sacrificial anode is significantly affected by the temperature and the penetration rate of seawater, and the value of the transmitted cathodic protection current is low in the atmospheric area, which is an environment with high resistivity, so there is no difference due to temperature. Hence, it can be inferred that the cathodic protection method utilizing zinc mesh sacrificial anodes in seawater exhibits a pronounced effect during summer seasons when temperatures are elevated, while the cathodic protection efficacy diminishes during winter seasons when temperatures are lower. In general, the rate of corrosion decreases rapidly with the drop in temperature. However, since the low polarization caused by the cathodic protection method at low temperatures does not always increase the corrosion rate, sufficient research is needed on the interaction between the cathodic protection method and the corrosion rate. The effectiveness of the sacrificial anode method diminishes in high resistivity area such as dry concrete. However, environments with high resistivity are typically those where moisture absorption is minimal, thereby maintaining the steel surface in a passive state and minimizing corrosion even if the sacrificial anode cathodic protection effectiveness is reduced. However, in areas such as splash or tidal zones where moisture exposure is recurrent, corrosion may occur despite the sacrificial anode cathodic protection, leading to a potential decrease in its effectiveness. Therefore, alternative approaches may be necessary to address the effectiveness of the cathodic protection with zinc mesh anode and the long-term durability of concrete structures in these areas.

4. Conclusion

The following conclusions were obtained through the cathodic protection method of the reinforced concrete specimens using the zinc mesh sacrificial anode.

1. In horizontal beam specimens, the cathodic protection current applied along the entire surface of the specimen. Therefore, it was sufficiently polarized in seawater and meet the cathodic protection standard. However, the specimens exposed to the atmosphere were unable to affect the rebar due to the high resistivity of the concrete.
2. In vertical pile specimens, the maximum reachable range of cathodic protection current was 10 cm from the waterline as observed in the experiment.
3. As a result of the cathodic protection current measurement of the vertical pile specimens, the effect of cathodic protection current increased as the temperature increased. The cathodic protection current at 40 ºC was approximately three times greater than that at 10 ºC.
4. The 4-hour depolarization potential measured at 40 ºC was 4 times higher than that measured at 10 ºC, and the amount of that due to the increase in resistivity as the pile height increased towards the atmosphere.
5. It was confirmed that the cathodic protection method by the zinc mesh sacrificial anode within the concrete had sufficient cathodic protection effect in the underwater part and under high temperature conditions, and was relatively good in the tidal zone and splash zone, however, in the atmosphere, the cathodic protection effect was poor and the effect by temperature was irrelevant.

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