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Electrochemical Characteristics of Zn-mesh Cathodic Protection Systems in Concrete in Natural Seawater at Elevated Temperature

Ki-Joon Kim†, Jin-A Jung, Woo-Cheol Lee[1], and Tae-Seub Jang[2]

Korea Maritime University, No. 1, Dongsam-Dong, Youngdo-Gu, Busan 606-791, Korea
[1]Conclinic Co. Ltd., Seoul, Korea
[2]Busan Metropolitan City, Busan, Korea

The corrosion of steel in concrete is significant in marine environment. Salt damage is one of the most detrimental causes to concrete bridges and port structures. Especially, the splash and tidal zones around water line are comparatively important in terms of safety and life-time point of view. During the last several decades, cathodic protection (cp) has been commonly accepted as an effective technique for corrosion control in concrete structures. Zn-mesh sacrificial anode has been recently developed and started to apply to the bridge column cp in marine condition. The detailed parameters regarding Zn-mesh cp technique, however, have not well understood so far. This study is to investigate how much Zn-mesh cp influences along the concrete column at elevated temperature. About 100 cm column specimens with eight of 10 cm segment rebars have been used to measure the variation of cp potential with the distance from Zn-mesh anode at both 10℃ and 40℃ in natural seawater. The cp potential change and current diminishment along the column specimens have been discussed for the optimum design of cp by Zn-mesh sacrificial anode.

Keywords *: concrete, cathodic protection(cp), zn-mesh sacrificial anode, cp potential, cp current, temperature, natural seawater*

1. Introduction

The corrosion of steel in concrete is well recognized to influence on the durability of concrete structures in marine environment.[1)] The waterline zone, i.e. splash and tidal area, is the weakest part of marine structures including bridges and port facilities, since two major factors of corrosion, oxygen and water, are abundant in seawater, one of the most corrosive media in the nature.

Since the cathodic protection(cp) has introduced in early 19th century, it has become a proven technology for corrosion protection of steel structures not only in underground fields, but also in marine circumstances. The application of cp into concrete has been lately attempted, and a remarkable progress has been achieved during the last two decades.[2)-3)] However, there are still a number of technical things to be understood and improved in this concrete field.

In general the cp technique can be subdivided into two categories, i.e., impressed current cathodic protection[4)-6)] (iccp) and sacrificial anode cathodic protection[7)-9)] (sacp). The sacp is preferred to the concrete structures in sea areas, since the installation and the maintenance of protection system is relatively simple with a low cost. The primary anode for sacp in concrete is zinc, especially in seawater. The mesh type embeddable Zn anode has been recently introduced for applying to concrete bridge piles, especially in waterline zones where the major corrosion problems are occurred in marine environments.

When this sacp system is installed and initiated to operate, the protection current from Zn anode flows through both seawater and concrete. The cp potential/current in concrete is influenced by several environmental factors. The major ones include concrete resistivity and temperature. The former is proportionally related to the permeability of seawater(chloride ions), and the latter the weather due to seasonal change. The cp potential/current with the elevation of concrete pile from underwater to atmosphere conditions, is not well understood, especially for the sacp system by Zn mesh anode. In addition, the cp potential/current variations with temperature are also not well recognized in the present situation.

In this study the cp potential and current have been investigated for the pile protected by embedded Zn mesh anode. Potentials and currents were monitored for the reinforcing long solid bar and several segment ones both

† Corresponding author: corr@hhu.ac.kr

in horizontal and vertical pile specimens. The test parameters were the immersion conditions (full and partial) in seawater and the temperature (10℃ and 40℃). The short-term laboratory experiments have been conducted to simulate bridge piles and port beam structures around waterline.

2. Experimental procedures

2.1 Specimens

In order to simulate concrete pile and beam for bridge and/or port structures, the specimen was designed as shown in Fig. 1. The dimension of specimen was 100 cm×15 cm×7.5 cm with two lines of reinforcing bar(rebar, dia. 10mm) installed in parallel. One is long solid bar and the other 10cm segment ones. The number of segments per specimen was eight and the gab between the segments was 2 cm. For cathodic protection(cp) the commercially available zinc mesh anode, sized 15 cm×15 cm, was embedded at the end of each specimen, and the all rebars were electrically connected for the cathodic protection and for the measurement of potential and current. The water/cement ratio of mortar was 0.7 to increase the permeability of test solution(natural seawater), and the total chloride content in mortar was about 15%, which was composed by mixed seawater (about 3%) with additional 12% of salt both for shortening the test period due to corrosion acceleration and for enhancing the cp effectiveness in severe corrosive media.

The measurement circuit of specimen was shown in Fig. 2. All rebars, long solid bar and segments, were electrically connected to Zn mesh anode for cathodic protection, and 1 ohm resistance was inserted between each rebar and Zn mesh to measure cp current.

The kinds of test environment were listed in Table 1.

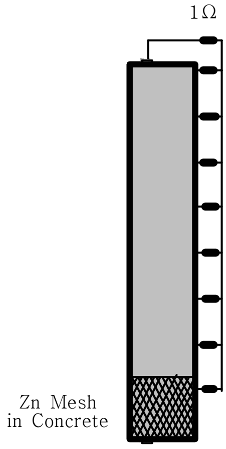

Fig. 1. Schematic of specimen with measurement circuit

Fig. 2. Vertical specimen with measuring terminals

Table 1. Kinds of specimen with test conditions

Spec. ID	Environ-ment	Immersion	Direction	Tempe-rature
P-1	Air	-	Horizontal	40℃
P-2	SW	Full	Horizontal	40℃
P-3	SW	Top Surface	Horizontal	10℃
P-4	SW	Top Surface	Horizontal	40℃
P-5	SW	Bottom 40cm	Vertical	10℃
P-6	SW	Bottom 40cm	Vertical	40℃

Fig. 3. Potential measurement of a specimen

Test environments were natural seawater except one control specimen in atmospheric condition(air). The immersion states were the full or partial in horizontal specimens and the bottom 40 cm in vertical specimens. The temperatures were lab. (around 10℃ in winter season) and 40℃ in constant elevated temperature room. The test solution was natural sea water which was replenished every week in the early stage of test and every 2-4 weeks in the later stage.

2.2 Test methods

The potential monitoring for all specimens have been conducted through the total period of tests, and the current measurement and the 4 hour depolarization tests have been added time to time during the test. The depolarization tests and the current measurements were carried out by Gamry electrochemical measurement system with the function of ZRA(zero resistance ammeter). 1 ohm resistance was utilized to measure the cp current as a shunt. Most of electrochemical test processes were basically followed the ASTM[10] and NACE[11)-12] standards.

3. Results and discussions

Fig. 4 is the potential variation with time for the specimens which were cathodically protected in atmospheric (P-1) and in natural seawater (full immersion) conditions both at 40℃. In atmospheric condition when cp was on, potential dropped only about 100 mV up to the lowest limit around -200 mV/SSCE(Saturated Silver-silver Chloride Electrode), and it was gradually increased up to the initial potential before cp. On the other hand, the potential variation for the P-2 specimen which was fully immersed in natural seawater at the same elevated temperature, 40℃, has been dramatically polarized to the about -950 mV/SSCE in around 200 days. Even there was some fluctuation during the test, the cp potential was nearly maintained the polarized potential up to 1,200 hours(about 50 days). Through these results it was apparent that the cp by Zn-mesh anode in concrete is not adequate due to high concrete resistivity in atmospheric condition, however, the conductive path for cp is excellent in seawater. In both conditions the potential range among the segments from S1-S8 showed independent to the distance between Zn-mesh anode and rebar segment. The similar trend of potential variation was indicated in the test results for the partial immersion specimens, i.e. P-3(horizontal, 10℃) and P-4(horizontal, 40℃), and the temperature effect was negligible as well.(the data were omitted)

Fig. 5 and 6 are the potential variation with time for P-5 specimen tested in seawater at 10℃. In Fig. 5 the cp potential variation for 8 segments were plotted for about 1,500 hours. S1-S3 which is the closest three segments from Zn-mesh anode in immersion part of vertical pile in seawater showed the lowest and the same potential level. The potential trends for the other 6 segments became higher with the height of specimen. The potential variations at the three positions of long bar, i.e. underwater, waterline and atmospheric, were apparently distinguished as shown in Fig. 6. The potential trend for a long bar was nearly the same as for the same level of segments

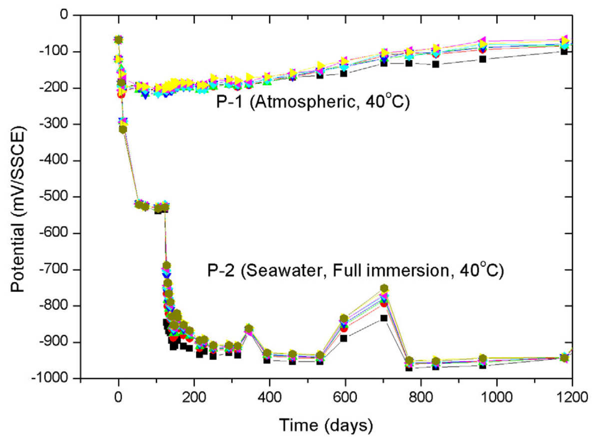

Fig. 4. Potential variation with time of the 8 segments for P-1 & P-2 specimens

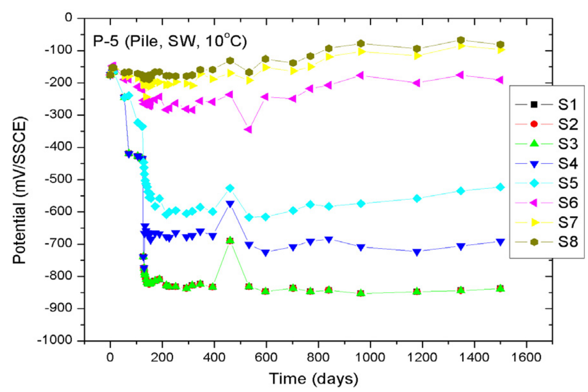

Fig. 5. Potential vs. Time of 8 segments for P-5 specimen

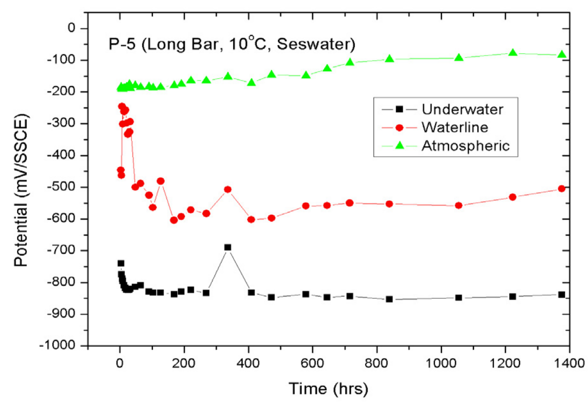

Fig. 6. Potential variations of long bar for P-5 specimen

as indicated in Fig. 5 with the range between around -100 mV/SSCE to near -900 mV.

Fig. 7 is the comparison of average potentials for both segment bars(Fig. 5) and long solid one(Fig. 6). As mentioned before, the potential variation according to the height of pile was devided into three zones, i.e. under-

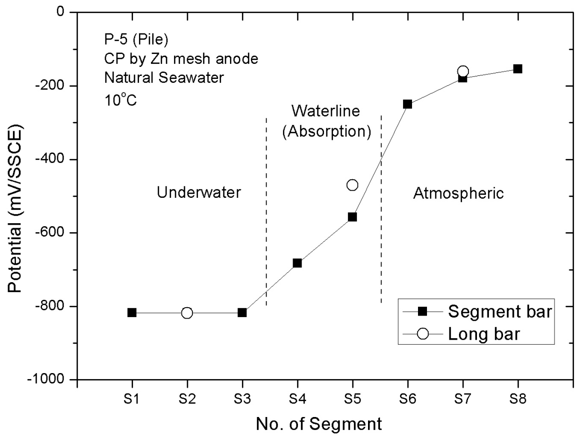

Fig. 7. The potential difference between the segment and the long bars for P-5 specimen

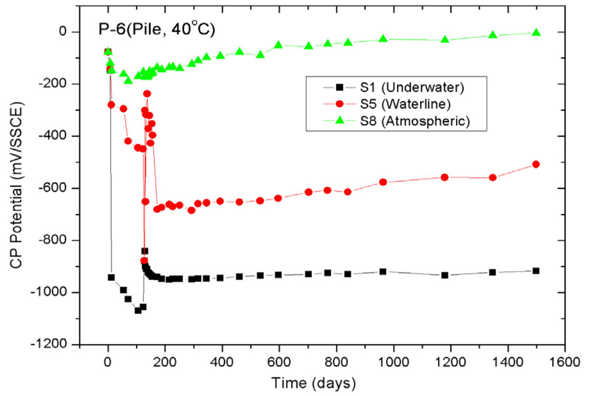

Fig. 8. Potential variations of the long bar for P-6 specimen.

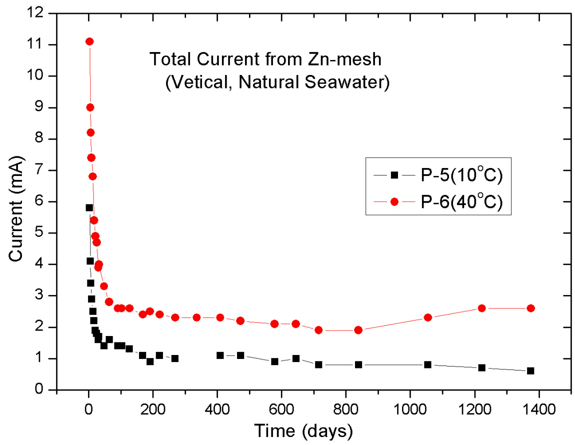

Fig. 9. Total current generated from Zn-mesh anode At two different temperatures

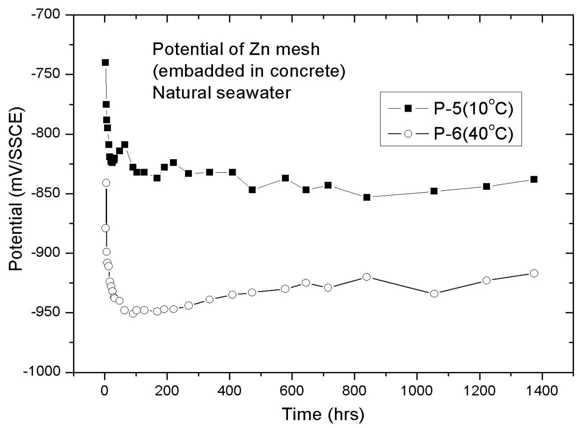

Fig. 10. Potential of Zn-mesh anode at two different temperatures

water(S1-S3), waterline(S4-S5) and atmospheric(S6-S8). The potential in underwater zone was around -800 mV/SSCE, and in waterline zone it was progressively increased up to around -200 mV of potential plateau in atmospheric zone.

Through these results it was recognized that cp potential was significantly influenced by the height of pile due to the permeability of seawater which is directly related to conductivity of concrete. Above the waterline(S4~S8), the capillary action of seawater was gradually reduced with height of specimen resulted in the potential increase which implies the difficulty of cp current supply. In addition the trend of potential variation between segment bars and long solid one were well agreed with the height of pile, therefore, it was known that each position along the long rebar can be representative for the same location of segment one. In other word, the potential measurement by solid bar is accurate enough to evaluate cp state in this study.

Fig. 8 is the potential variation for the long solid bar of P-6 specimen tested in 40℃. Even though there was some unstable variation of potential in the early stage of experiment, the overall potentials at three levels represented the similar trend with P-5 in 10℃.

In order to compare the temperature effect to the effectiveness of cathodic protection, the cp current and potential for Zn-anode have been plotted as presented in Fig. 9 and 10. In Fig. 9 the currents were the total values generated from Zn anode to all cathode, i.e. both segment and long solid bars. After initial unstable period of current decrease, the cp currents at both temperatures were maintained nearly constant at about 1 mA in 10℃ and at about 3 mA in 40℃. As anticipated in general electrochemical reactions, the current at high temperature showed higher than at low one. This is a common phenomena that the higher temperature is, the higher chemical/electrochemical reaction occurs. In this particular case the cp current at 40℃ is about three times higher than that at 10℃. Fig. 10 showed the potentials for the same Zn-mesh anode at two temperatures. The average potentials at two temperatures were about -830 mV at 10℃ and about -950 mV at 40℃.

Table 2. Results of 4 hour depolarization tests for P-5 & P-6 specimens

(mV/SSCE)

Speci. ID		E_{on}	E_{off}	IR drop [E_{off} - E_{on}]	$E_{off,4hrs}$	Decay E [$E_{off,4hrs}$ - E_{off}]
P-5 (10℃)	S1	-862	-853	9	-797	56
	S2	-862	-853	9	-797	56
	S3	-862	-853	9	-797	56
	S4	-692	-687	5	-660	27
	S5	-594	-592	2	-556	36
	S6	-230	-229	1	-220	9
	S7	-145	-145	0	-141	4
	S8	-130	-130	0	-128	2
P-6 (40℃)	S1	-841	-800	41	-577	223
	S2	-841	-800	41	-577	223
	S3	-840	-798	42	-577	221
	S4	-580	-570	10	-432	138
	S5	-389	-387	2	-344	43
	S6	-161	-158	3	-149	9
	S7	-12	-9.2	2.8	-9	0.2
	S8	-5.3	-4.6	0.7	-4	0.6

At the higher temperature the more polarization was observed, which is produced by higher cp current as indicated in Fig. 9.

The amount of real polarization for cp has been measured by the 4-hour depolarization technique using the potentiostat with a function of zero resistance ammeter(ZRA) as mentioned in chapter 2. Table 2 is the test results of 4-hour depolarization potentials for each segment in both P-5 and P-6 specimens, including the potentials when cp on and off conditions to compensate the IR drop in concrete. The decay(depolarization) potentials at two temperatures were ranged 2-56 mV at 10℃ and 0.2-223 mV at 40℃, respectively. Fig. 11 represented these decay potential variations with height of pile (from S1 to S8). In underwater zone (S1-S3) the decay potentials were about 50 mV at 10℃ and 225 mV at 40℃. It was more than 4 factor of potential difference between two temperatures in this zone, however, the difference at 40℃ dropped dramatically in waterline zone(S4-S5), and became nearly the same decay at atmospheric zone. Through these results, it is revealed that the cp polarization is considerably influenced by both temperature and permeability of seawater. Therefore, it is assumed that the cp by Zn sacrificial anode in seawater is much effective during summer season, and the effectiveness becomes dull in cold weather. In general the corrosion rate is tremendously reduced with decreasing temperature. However, more study is needed regarding the interaction between cp polarization and corrosion rate, since the less cp polarization does not always mean high corrosion rate at low temperature.

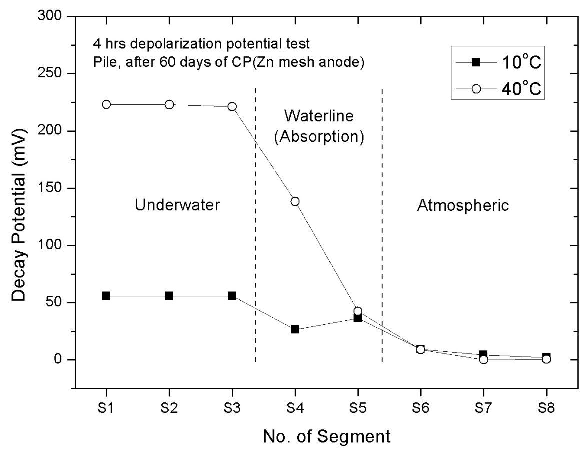

Fig. 11. 4 hours depolarization potential after 60 days of cathodic protection by Zn-mesh anode

4. Conclusions

Through the cathodic protection of concrete(mortar) pile by Zn-mesh sacrificial anode in natural seawater at elevated temperature, the following conclusions have been obtained.

1) In horizontal beam-type specimens, cp potentials have been reached to all-over the length(100cm) of specimen in both full- and partial-immersion states, however, in atmospheric cp potential has not influenced to the reinforcing bar due to the high resistivity of concrete.

2) The cp current at 40℃ is about 3 times higher than that at 10℃ for vertical concrete pile tested in seawater.

3) In underwater condition the 4-hour depolarization potential at 40℃ was more than 4 times higher than that at 10℃, and the difference became narrower with height of pile to the atmospheric.

4) The cp by Zn-mesh in concrete is considerably effective in underwater and high temperature condition, and possibly good or fair in tidal/splash zone, however, it's ineffective in atmospheric one irrelevant to temperature.

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