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Experimental Study on The Performance of Sacrificial Anode Cathodic Protection Under Low Temperature around -17°C

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Abstract

Temperature influences all the processes involved in corrosion, for instance, anodic and cathodic electrochemical reactions, transport of aggressive species to the steel surface, and ionic flow through concrete. The design of a sacrificial anode cathodic protection system should consider the type and location of anodes to achieve sufficient and durable protection. It is because the current generated from a sacrificial anode is directly related to the environment that it-placed. Anodes in wet or humid climates will typically produce higher levels of current and distribute it to the reinforcement that needs to protect. Thus, this paper reviews performance of sacrificial anode applied in concrete exposed under low temperature around -17°C.

Sacrificial anode installed in the concrete with chloride free or chloride contamination. Reinforcing steel with and without anode connection embedded in the concrete. Freeze chamber with low temperature -17°C and relative humidity (R.H.) 4-5% used as the exposure condition to observe the anode reliability.

The performance of the anodes was assessed using electrochemical test. The results from depolarization test indicate that sacrificial anode is active to polarize the rebar to protection level. Protective current exhibits fulfill the design limit for cathodic protection. On-site corrosion rate measurement also shows that corrosion resistance of reinforcing steel is increased on the rebar with anode protection and grade passivity of rebar becomes in better condition. It means that protective current flow from anode distributes to rebar in the concrete even though under freeze environment condition.

Keywords: sacrificial anode cathodic protection, low temperature, depolarization, current, corrosion resistance.

1. Introduction

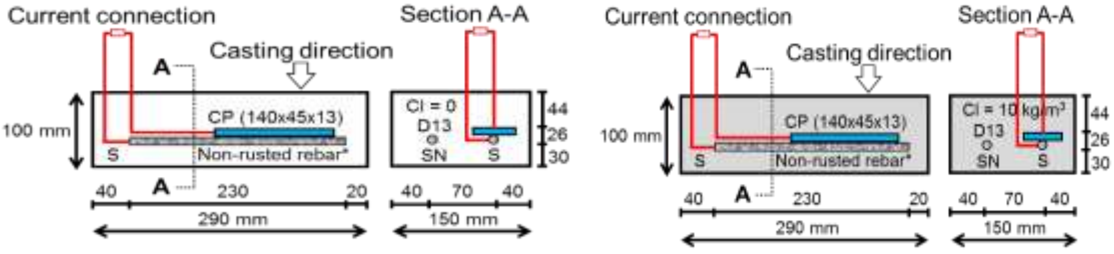
The design of sacrificial anode cathodic protection system should consider the type and location that it is placed to achieve sufficient and long life protection [1]. It is because the current flow generated from sacrificial anode is related to the environment. Anodes in wet or humid condition will produce higher levels of protective current and deliver it to the reinforcement that needs to be protected [2]. All the processes involved in corrosion (i.e., anodic and cathodic electrochemical reactions, transport of aggressive species to the steel surface, accumulation of corrosion products on the steel surface or departure from the interface of steel/concrete, and ionic flow through concrete) are influenced by temperature [3].

Regarding the low-temperature environmental condition, sacrificial anodes which designed for several types of structures in freeze condition, such as RC structure in the northern area, natural gas station, and CO_2 storage, should have sufficient performance to protect the rebar from active corrosion. The effect of sacrificial anode application in the low-temperature condition is not reported in the previous study. Thus, this paper reviews the performance of sacrificial anode exposed under low temperature around -17°C and 4-5% of relative humidity (R.H.).

2. Experimental program

2.1 Specimen Design

The geometry of the specimens employed in the present investigation is illustrated in **Figure 1**. The beams featured total dimensions of 100×150×290 mm and were reinforced with two D13-steel bars. The reinforcement was positioned to obtain a clear concrete cover of 30 mm at the bottom and sides of the beam whereas the distance between bars was kept at 40 mm. Moreover, a galvanic anode F type made of zinc as main material was used as the sacrificial anode. The dimension is 140 mm in length, 45 mm in width and 13 mm in depth, as shown in **Figure 2**.



(a) CP-CL0-F (b) CP-CL10-F

Figure 1: Specimen design (a) CP-CL0-F and (b) CP-CL10-F

Figure 2: Sacrificial zinc anode F type

Ordinary Portland Cement (OPC) was used as a binder, and tap water (temperature 20±2°C) was utilized as mixing water in this study. Washed sea sand is passing 5 mm sieve with a density of 2.58 g/cm^3 and water absorption of 1.72 % which was less than 3.5% as stated in Japan Industrial Standard (JIS), was used as the fine aggregate. Meanwhile, crushed stone with a maximum size of 10 mm was used as the coarse aggregate. All aggregates were prepared under surface-saturated dry condition. The properties of aggregates and admixtures are shown in **Table 1**.

Table 1. Properties of materials

Component	**Physical properties**	
Ordinary Portland Cement	Density, g/cm^3	3.16
Fine Aggregate	Density, g/cm^3 (SSD Condition)	2.58
	Water absoption (%)	1.72
	Fineness modulus	2.77
Coarse aggregate	Density, g/cm^3	2.91
AEWR agent	Polycarboxylate ether-based	
AE agent	Alkylcarboxylic type	

The concrete was designed with water to cement (w/c) ratio of 0.45 and the ratio of fine aggregate to total aggregate volume (s/a) of 0.47. Air-entraining agent and water-reducing admixture were added to the cement mass to obtain the slump and air content in all concrete mixes in the range of 10±2.5 cm and 4.5±1 % respectively.

Chloride ions were deliberately added around 10 kg/m^3 during mixing into concrete to accelerate the corrosion process. Pure sodium chloride (NaCl) was used as the source of chloride ions. The concrete mixture proportions of concrete is ~~are~~ shown in **Table 2**.

Table 2. Mixture proportion of concrete specimens

Material	
Water-cement ratio (w/c), %	45
Sand-aggregate ratio (s/a), %	47
Water, kg/cm^3	190
Cement, kg/cm^3	422
Sand, kg/cm^3	766
Gravel, kg/cm^3	970
Chloride, kg/cm^3	0 or 10
Additive:	
• AE, mL	1900
• AE-WR, kg	1.34

In this study, a 20-year-old deteriorated (rusted) reinforcing steel bar with a diameter of 13 mm was used as shown in **Figure 3**. These steel bars were taken from the specimens exposed in severe chloride environment with high temperature for 20 years. For non-deteriorated (non-rusted) condition, this rusted rebar was immersed in 10% (weight percentage) diammonium hydrogen citrate solution for 24 hours in 40°C accelerated chamber and then the rust was removed by using steel wire brush. At both ends of each element, a 30-cm-long lead wire was screwed on.

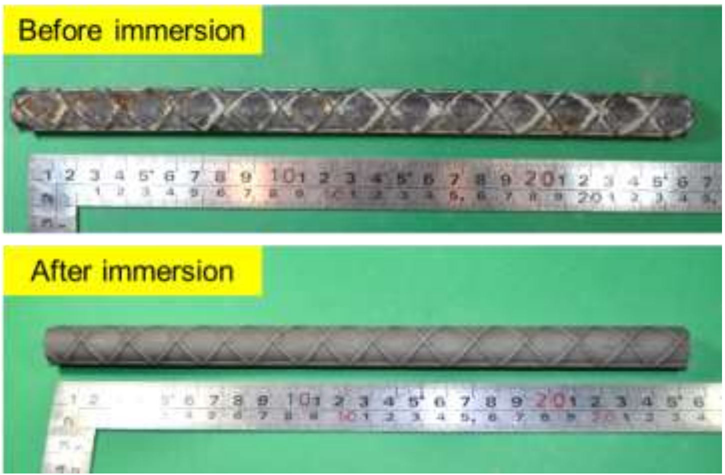


Figure 3. A 20-year-old deteriorated steel bar used in this study

After that, all specimens were stored (in wrapping) at constant room temperature for 28 days. After 28 days of sealed curing, the sacrificial zinc anode was connected to adjacent steel elements (S) to throw protection current. However, these connectors were temporarily disconnected to measure the instant-off potential, the protective current density, and potential decay during switch-off 24h in depolarization test. After curing, the specimens were stored in freeze chamber with -17°C of temperature and 4-5% of relative humidity (R.H.) until the end of the test (900-days).

2.2 Experimental methods

All potential measurements were conducted in constant room temperature around 20±2°C. The step methods are illustrated in **Figure 3**. The current monitoring was conducted undertaken before and after specimens taken out from the freeze, and then specimens were stored in constant room temperature chamber for pre-wetting during 30 minutes and continued by each of testing. After switching off the connection between sacrificial zinc anode and rebar, specimens were stored up to off 24-hours potential measurement at 20±2°C room. The potential measurement was conducted with silver/silver chloride electrode after 1 hour of pre-wetting. Then measured value was converted to the potential of the copper/copper sulfate electrode (CSE) at 25°C.

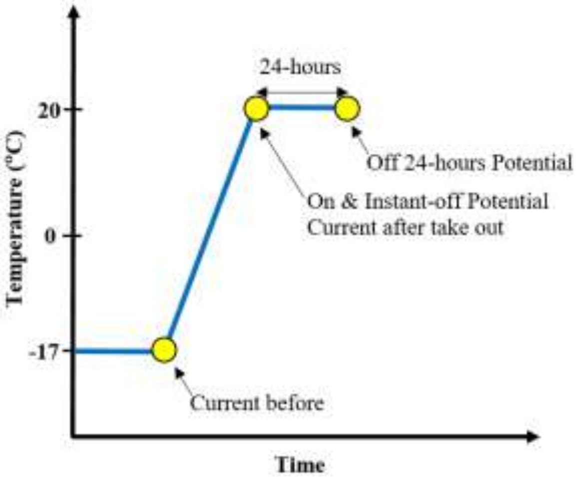


Figure 3: Temperature change during measurement process

2.3 Electrochemical Measurement

Half-cell potentials test of rebar according to ASTM C876-91 (1999) [4] was conducted by silver/silver chloride reference electrode and high impedance multimeter (voltmeter setting) after one hour of pre-wetting. The reference electrode is connected to the negative terminal and the reinforcing bar to the positive terminal of the multimeter [5]. On-potential (E_{on}) of rebar and anode measured under sacrificial anodes protection. Instant-off potential (E_{off}) checked immediately after disconnection and the rest potential (E_{corr}) measured after 24 hours. The potential value is converted to the copper/copper sulfate reference electrode (CSE).

Depolarization test was measured from the potential difference value between 24 hours off potential and instant-off potential. Based on JSCE Concrete Library 107 (2011), the effectiveness of cathodic protection is defined as the depolarization test value is more than 100 mV. Polarization resistance was measured by using AC impedance based apparatus.

3. Results and Discussion

3.1 Protective Current Density and Potential of Anode

The current density generated by the anode to the rebar as a function of exposure time until 900-days is shown in **Figure 4**. On potential and instant-off potential of anodes are illustrated in **Figure 5**. The current density trends were increased gradually from 7-days to 84-days. After this, there was a downtrend from 84-days to 168-days, reaching 0.2 μA/cm^2 and 0.9 μA/cm^2, the current density was decreased to 0.03 μA/cm^2 and 0.12 μA/cm^2 for CP-CL0-F and CP-CL10-F, respectively at the end of the test period (900-days). It means that anodes are very active at the beginning of the exposure, however, due to freezing environment condition, the current flow seems degraded under the design limit of current density on cathodic protection which is between 0.2 - 2 μA/cm^2 as specified in EN 12696 [6]. The current density required to protect steel in atmospherically exposed concrete cathodically is strongly dependent on the corrosion rate on steel bar surface [7].

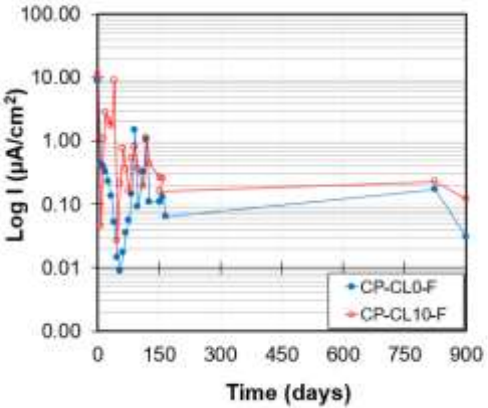


Figure 4: The protective current of sacrificial anodes

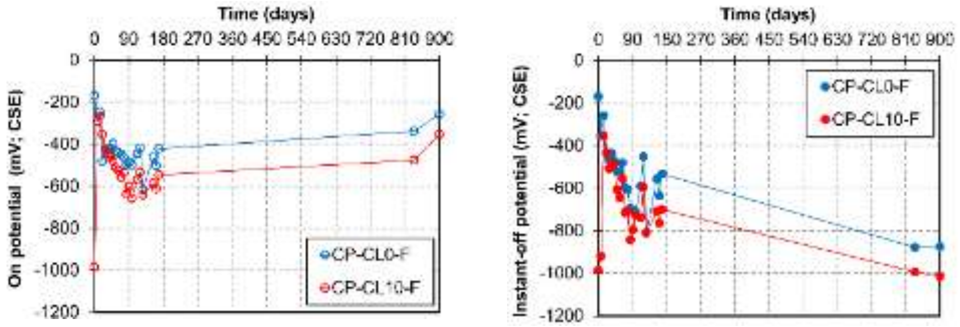


Figure 5: On potential and instant-off potential of sacrificial anodes

3.2 Potential of Rebar

Figure 6 shows on potential and instant-off potential of rebar protected by sacrificial zinc anode, while the half-cell potential of steel bar without the protection of sacrificial zinc anode illustrated in **Figure 7**. From the figure below, it is indicated that during connection, sacrificial anode polarizes the rebar (connected and none-connected with anode). Moreover, corrosion could occur on the rebar in chloride-contaminated concrete (SN-CL10-F) even though under freeze condition.

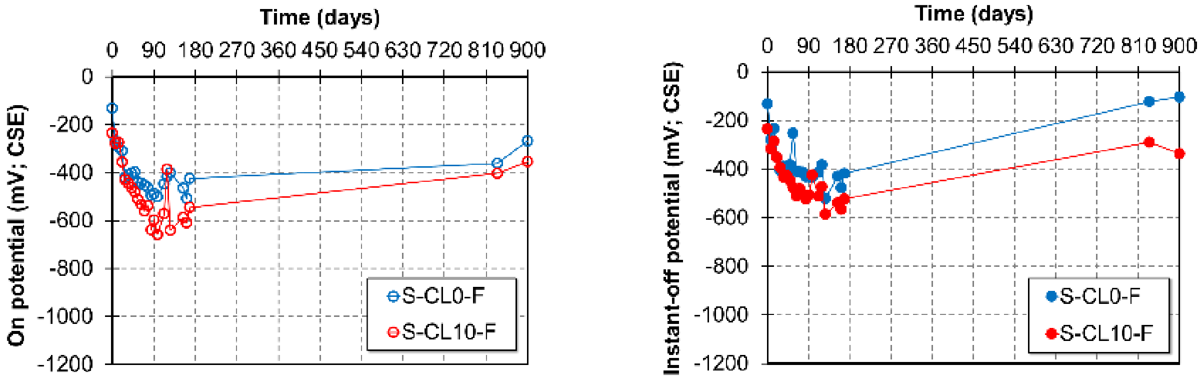


Figure 6: On potential and instant-off potential of a steel bar with sacrificial anode connection

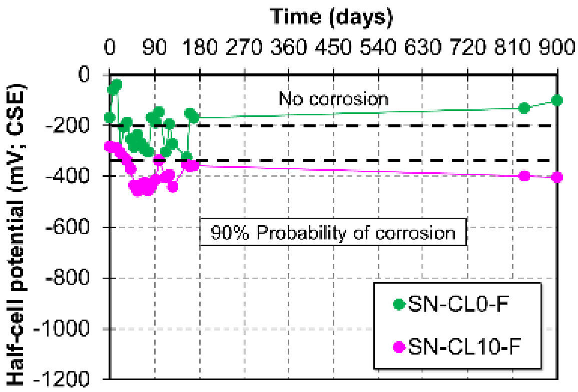


Figure 7: Half-cell potential of steel bar without sacrificial anode connection

Figure 8 illustrates the depolarization development from the specimens. It indicated that sacrificial zinc anode is sufficient to protect the rebar in free-chloride contaminated concrete exposed to the low temperature until 112-days based on 100 mV potential decay criterion.

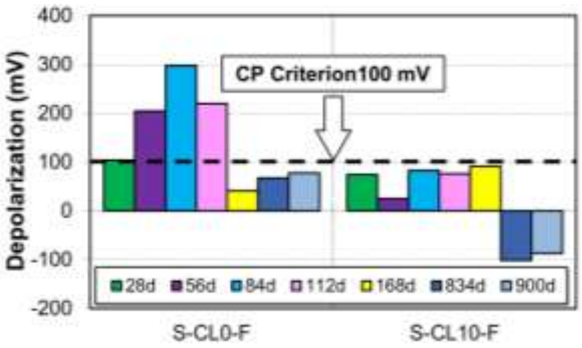
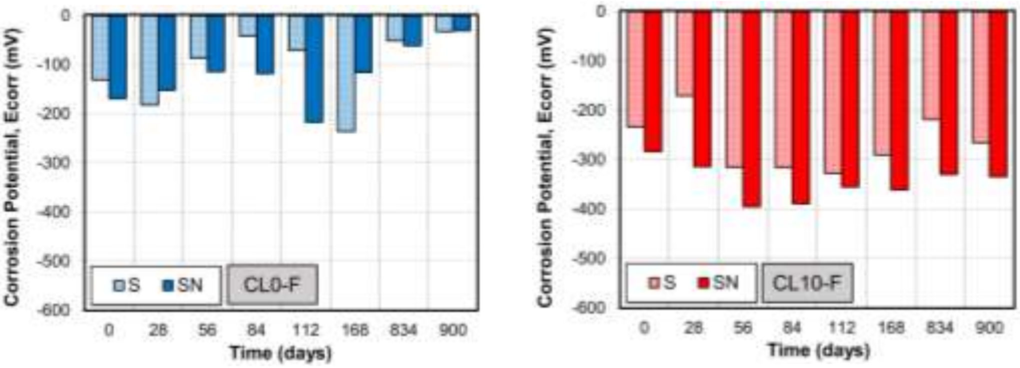


Figure 8: Depolarization test

The corrosion potential (Ecorr) or rest potential of rebar is described in **Figure 9**. Sacrificial zinc anode polarizes not only rebar with anode connection but also rebar without anode connection in free-chloride contaminated concrete. However, the anode could not polarize the rebar in chloride-contaminated concrete. This result coincides with the potential development result of rebar.



(a) (b)

Figure 9: Corrosion potential of steel bar in (a) free-chloride contaminated and (b) chloride contaminated concrete

3.3 Polarization Resistance

The rebar corrosion tendency is strongly dependent upon the corrosion potential and polarization resistance. The relationship between corrosion potential and polarization resistance is illustrated in **Figure 10**. Corrosion resistance of reinforcing steel is significantly decreased on the rebar without cathodic protection connection and embedded in the chloride-contaminated concrete.

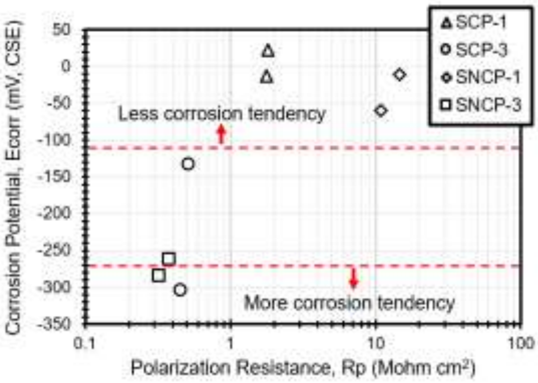


Figure 10: Relationship between corrosion potential and polarization resistance

3.4 Anodic - Cathodic Polarization Curve

The polarization behavior of the sacrificial zinc anode in free-chloride contaminated and chloride-contaminated concrete is shown in **Figure 11**. It is clearly observed that concrete with chloride contaminated has larger current density than free-chloride contaminated concrete. This phenomenon occurred due to chloride contaminated concrete causes the sacrificial zinc anode more active to provide larger current protection.

The anodic and cathodic polarization curve of rebar is depicted in **Figure 12**. It is informed that the chloride content greatly affects the change of passivity grade of rebar and become worse in chloride-contaminated specimen.

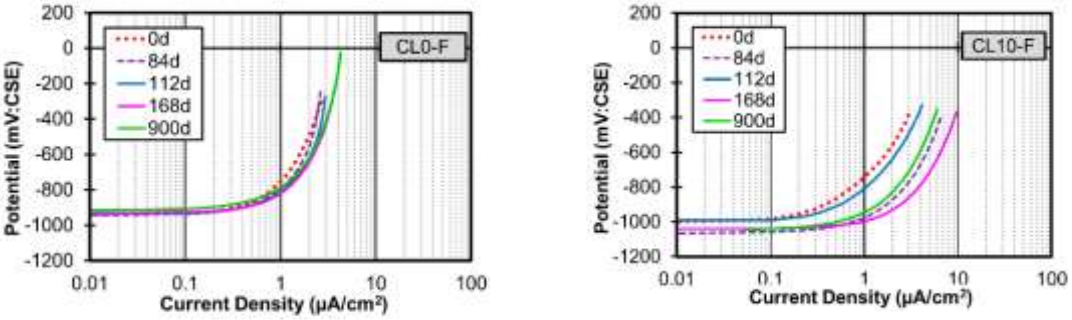


Figure 11: Anodic polarization curve of sacrificial zinc anode

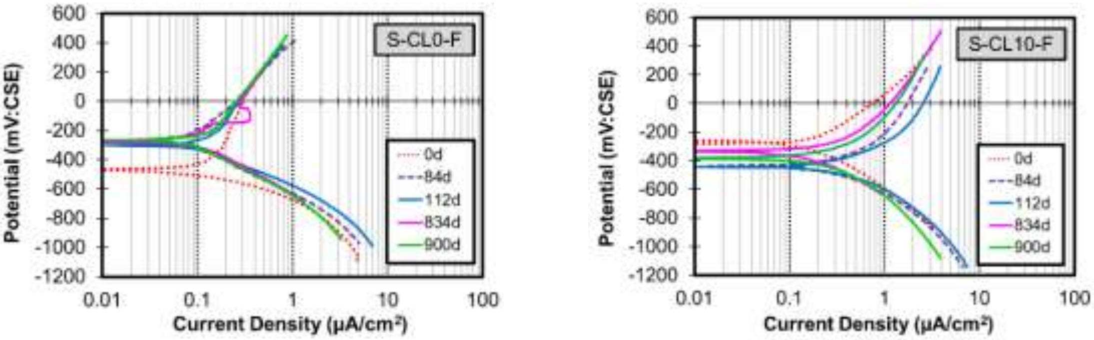


Figure 12: Anodic and cathodic polarization curve of rebar

3.4 Corroded Area

Figure 13 presents actual corrosion conditions of rebar of the specimens after 1003 days. The corroded area was measured except one-centimeter edge from the end of rebar to avoid unexpected corrosion due to the imperfection of coating on the end of rebar. The percentage of corroded area is shown in **Figure 14**.

Figure 13: Appearance of rebar corroded area in CP-Cl0-F and CP-CL10-F

From the visual observation, the corrosion initiation is started from the end and the middle of the rebar span. It may because the imperfection of the coating of the edge span during fabrication. Meanwhile, it was observed that rebar connected to the sacrificial anodes shows a better condition than rebar without sacrificial anodes connection not only in free-contaminated but also in chloride ion contaminated concrete. This indicates that sacrificial anode could prevent the corrosion although the rebar surface is embedded in chloride ions contaminated concrete. The corroded area of rebar with anode connection both in free-chloride and in contaminated are less than 1%, but the larger corroded area is found in the rebar without anode protection.

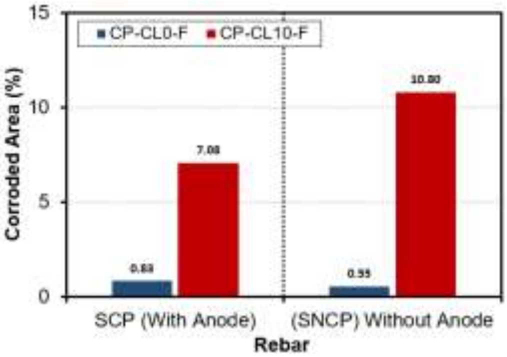


Figure 14: Corroded Area at 1003-days

5. Conclusion

The results indicate that sacrificial zinc anode can work to protect the rebar against corrosion even under very low temperature around -17°C. When the temperature plunges below zero, the anode can polarize the rebar (connected and none-connected with anode) in the free chloride-contaminated concrete to protection level. Corrosion resistance of reinforcing steel is significantly reduced on the rebar without cathodic protection connection and embedded in the chloride-contaminated concrete. Chloride content greatly affects the grade of the passivity of the rebar exposed to low temperature around -17ºC. From the visual observation of steel bar in concrete after more than 1000 days, the effectiveness of sacrificial anode on corrosion prevention was verified.

6. Acknowledgments

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7. References

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