-Technical Paper-

EFFECTIVENESS OF STEEL SURFACE CONDITIONS ON CATHODIC PROTECTION BY SACRIFICIAL ANODE IN CONCRETE

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ABSTRACT

The purpose of this study was carried out to observe the effectiveness of initial condition (rusted or non-rusted) of embedded steel in partially-repaired concrete on sacrificial anode cathodic protection systems. Three concrete specimens consisting of "chloride-contaminated existing concrete" and "chloride-free repair sections" were prepared. Environmental change during exposure time was also included as an experimental parameter. Results show that placing non-rusted steel bars in repair concrete sections is the desirable as initial condition when CP (Cathodic Protection) is applied and exposed to both dry and humid conditions.

Keywords: Sacrificial anode in concrete, cathodic protection, rusted steel, potential, depolarization

1. INTRODUCTION

Cathodic protection (CP) is rapidly being accepted as a repair option for steel-reinforced concrete structures deteriorated by steel corrosion caused by chlorides [1]. This technique requires the permanent application of a small direct current to protect the steel [2]. The objective of cathodic protection is usually to polarize the reinforcement to an instant-off potential more negative than -850 mV (CSE) [-770 mV (SCE)]. This potential should decay (become less negative) by at least 100 mV from the instant-off potential within 24 hours after the system is disconnected (so called depolarization). With CP, chloride ions slowly migrate away from the reinforcing steel toward the anode. Furthermore, the production of hydroxide ions at the steel surface causes the concrete to revert back to an alkaline state. These factors quickly arrest the corrosion process when current is applied, and allow the passivating film to reform on the surface of reinforcing steel.

On a practical level, reinstating corrosion protection in concrete using sacrificial anode cathodic protection does not require perfect repairs; only physical damages need to be repaired, without the need to remove a lot of chloride-contaminated concrete and perfect cleaning of steel [3]. Regarding a thorough cleaning of steel before applying sacrificial anodes, the effect of rust removal before CP application has not been clearly reported.

Therefore, the objective of this study is to observe how effective, the difference in initial conditions (rusted or non-rusted) of embedded steel is, in partially-repaired concrete on cathodic protection in concrete.

The results will be discussed with regards to corrosion monitoring by (1) the instant-off potential and half-cell potential of steel bars, (2) the instant-off potential of the sacrificial anode, (3) the protective current of the sacrificial anode, (4) the depolarization test and (5) the anodic polarization behavior of sacrificial anode.

2. SPECIMEN PREPARATION AND TESTING

2.1 Materials

Ordinary Portland Cement (OPC), was used and tap water (temperature 20±2°C) was used as mixing water. Washed sea sand passing a 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 JIS standard, 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 ratio of fine aggregate to total aggregate volume (s/a) was 0.47. 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	

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Moreover, a galvanic anode made of zinc as main material was used as sacrificial anode. The dimension is 140 mm in length, 45 mm in depth and 13 mm in width, as shown in Photo1.

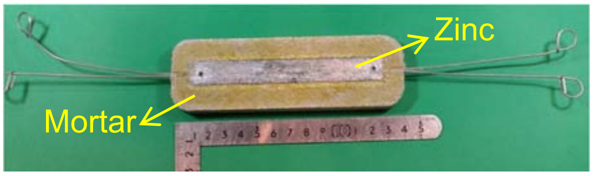


Photo 1 Sacrificial anode installed on the rebar

2.2 Mix Proportions

A concrete mix with a water to cement (w/c) ratio of 0.45 was used for all specimens. 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±2.5cm and 4.5±1% respectively.

There were two types of concrete mix proportions used for each specimen; namely existing concrete (chloride-contaminated) and repair concrete (chloride-free). In order to accelerate the corrosion process, chloride ions were deliberately added around 10 kg/m^3 during mixing into the existing concrete. Pure sodium chloride (NaCl) was used as the source of chloride ions. The concrete mixture proportions of concrete are shown in Table 2.

Table 2 Mixture proportions of concrete specimens

Material	Existing Concrete	Repair Concrete
Water-cement ratio (w/c), %	45	45
Sand-aggregate ratio (s/a), %	47	47
Water, kg/m^3	190	190
Cement (C), kg/m^3	422	422
Sand, kg/m^3	766	766
Gravel, kg/m^3	970	970
Chloride, kg/m^3	10	0
Additive:		
- AE, mL	19	19
- AE-WR, kg	1.34	1.34

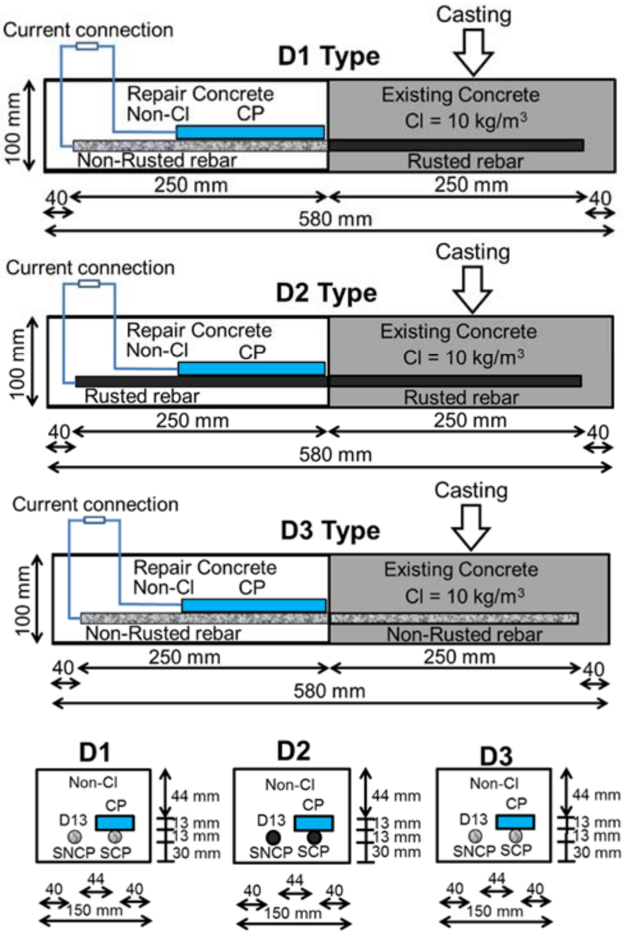
2.3 Specimens

Three concrete specimens with the dimensions of 580 mm in length, 150 mm in width and 100 mm in depth were prepared for this study. Each concrete specimen contained two steel bars with a diameter of 13 mm, same surface conditions and positioned parallel to each other with an intermediary distance of 40 mm and a clear cover thickness of around 30 mm from the bottom surface of the specimen.

The details of the concrete specimen are depicted in Fig. 1. The initial conditions of the three concrete specimens are detailed in Table 3. In addition, a sacrificial anode was applied to the repair concrete section.

Table 3 Specimen specification

Specimen Series	Length of Element (mm)	Initial Condition of Rebar	Position in the Concrete	Chloride Content (kg/m^3)	Cathodic Protection Position
D1	250	Non-Rusted	Repair	-	Yes
	250	Rusted	Existing	10	-
D2	250	Rusted	Repair	-	Yes
	250	Rusted	Existing	10	-
D3	250	Non-Rusted	Repair	-	Yes
	250	Non-Rusted	Existing	10	-



Remark:
CP: Sacrificial Anode Cathodic Protection
SCP: Steel bar **with** Sacrificial Anode Cathodic Protection
SNCP: Steel bar **without** Sacrificial Anode Cathodic Protection

Fig.1 Detailed layout of concrete specimens

The concrete casting process was carried out in two steps. First, the existing concrete was casted and demolded after 24 hours. After demolding, all specimens were subject to 14 days of sealed curing with wet towels. This was followed by installation of the anode on the steel bar, and repair concrete was casted. They were then demolded after 24 hours and kept for 28 days under sealed curing with wet towels.

After 28 days of sealed curing, the sacrificial anode was connected to the embedded steel in the repair concrete. Adjacent steel elements were also connected to the sacrificial anode through wires to measure the flow of the current. At the ends of steel bar in repair section, a 30cm length lead wire was screwed. The connection of wire and steel bar was covered by epoxy resin in order to avoid the corrosion at the connection. Thickness of epoxy layer was approximately 10 mm.

However, these connectors were temporarily disconnected for the purpose of measuring the instant-off potential, the protective current and depolarization. Silver/silver chloride electrode (Ag/AgCl) is used as reference electrode for potential mapping in this study.

2.4 Steel Bar

In this study, a 20-year-old deteriorated (rusted) reinforcing steel bar with a diameter of 13 mm was used as shown in Photo 2. 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 and then the rust was removed by using steel wire brush. At both ends of each element, a 30 cm lead wire was screwed.

Photo 2 20 year-old rusted steel bar

2.5 Exposure Condition

After the casting of both existing and repair concrete was finished, all specimens were subjected to exposure conditions, in the air curing with a temperature of 20±2°C and a relative humidity of 60%. This environment was kept for 105 days of exposure time. After that, the specimens were moved to the wet-dry cycle condition. The wet cycle involved immersion in a 3% NaCl solution for two days followed by five days in dry conditions; hence one cycle corresponded to seven days. Measurements were taken weekly at the end of wet cycle.

3. RESULTS AND DISCUSSION

3.1 The instant-off potential and half-cell potential of steel bars

The instant-off potential is measured between 0.1 and 1second after switching off the protection current in order to remove ohmic drop from the measured potential. There are two positions of potential measurement: 50 mm from the interfacial boundary to repair concrete and 50 mm from the interfacial boundary to existing concrete.

Fig.2 shows the instant-off potential of steel bars with CP in repair and existing concrete. During exposure to dry conditions in a 20°C chamber, the potential was around -300mV to -400mV, which was rather more positive than expected. In addition, the potential of steel bars planted in existing concrete (chloride-contaminated) was slightly more negative than in the repair concrete (chloride-free). The steel bar "SCP-D1" shows the most negative results among the three conditions.

After the exposure conditions changed to wet-dry cycles, the potential of reinforcing steel shifted to the negative direction, due to the change in moisture and oxygen content in the concrete.

As water increases in capillary pores, oxygen diffusion into concrete is reduced [5]. With increasing blockage of oxygen diffusion to the reinforcing steel, the passive film existing on the steel surface becomes unstable and is sometimes eliminated [4]. As a result, the corrosion potentials of non-rusted steel bars (SCP-D1) in repair concrete and rusted steel bars existing concrete was supposed to be more negative than in the specimens SCP-D2 and SCP-D3.

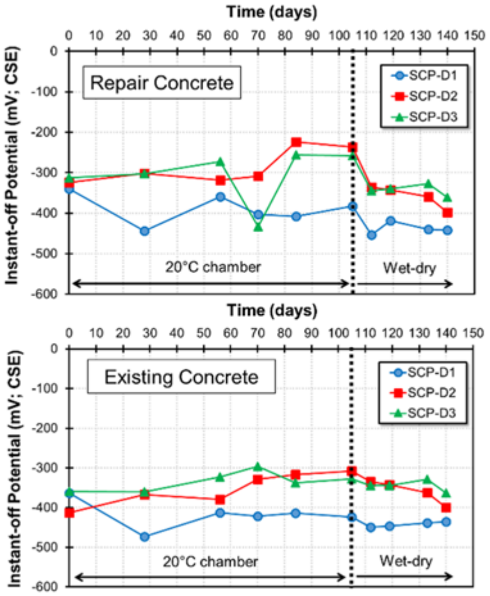


Fig.2 Instant-off potential of rebar with CP (SCP)

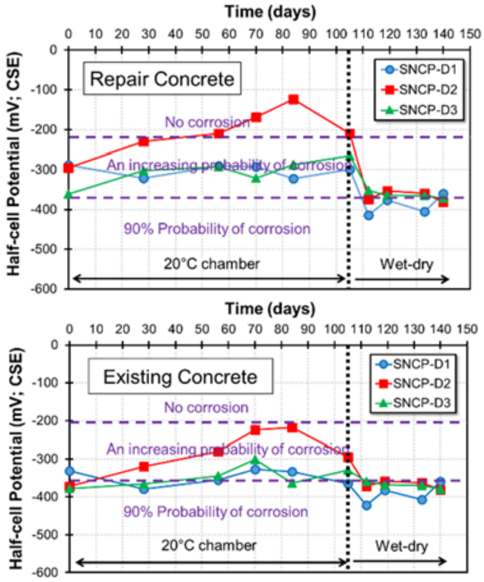


Fig.3 Half-cell potential of rebar without CP (SNCP)

The half-cell potential of steel bars without CP (SNCP) in repair concrete (chloride-free) and in existing concrete (chloride-contaminated) versus time of exposure are presented in Fig. 3. The same trend was found in time-dependent change with instant-off potential of SCP. The potential of D2 was more positive than D1 and D3 during exposure in the 20°C chamber. However, when the environment changed to wet-dry cycles, the potential shifted negatively, to lower than -350 mV for all steel bars. Based on ASTM C876-91:1999, it can be said that there is "a 90% probability of corrosion occurring". The presence of water and oxygen on the steel surface under wet-dry conditions accelerates the onset of corrosion on the D1, D3 and D2.

From the test results of instant-off and half-cell potential of reinforcing bars, it can be said that if the concrete is in relatively dry condition, the half-cell potential is more positive than under moist conditions. Moreover, the rusted rebar D2 shows more positive half-cell potential than D1 and D3. Although the reason for this is not clear, however, oxygen supply in repaired concrete is a factor of this phenomenon.

3.2 Instant-off potential of sacrificial anodes

Fig. 4 shows the instant-off potential of the sacrificial anodes against the time. During exposure at air curing from day 0 until day 105, the potential of anodes in D1, D2 and D3 specimens increased steadily to more positive levels. However, when the environment changed to wet-dry conditions, it shifted to about -500 mV in D3 specimen and around -700 mV in D1 and D2 specimens.

From this it can be said that the potential value of the sacrificial anode was also affected by the moisture level of the concrete, which was similar to with the instant-off potential of steel bars.

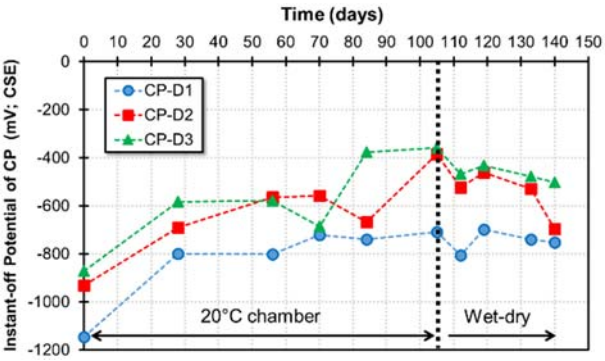


Fig.4 Instant-off potential of sacrificial anode

3.3 Protective currents generated by sacrificial anodes

The protective current generated by sacrificial anodes versus time is illustrated in Fig. 5. It is shows that the current output of CP in D1, D2 and D3 specimens gradually decreased during air curing. However, CP became active again after the environment changed to wet-dry conditions, due to the high moisture content of the concrete.

During 140 days in air curing and wet-dry conditions, the level of protective current was within the design limit of cathodic protection between 0.2 - 2 μA/cm^2 as specified in EN 12696 [7].

From the instant-off potential of anodes shown in Fig. 4 and protective current generated by anodes shown in Fig. 5, it can be obtained that in D1 and D2 specimens, protection potential from anode tends to be more negative and current distribution tends to be larger than 2 μA/cm^2. Meanwhile, in D3 specimen, even the potential and current distribution is smaller than D1 and D2, however, it is still enough to polarize the steel bar to protection level (as described in depolarization test result).

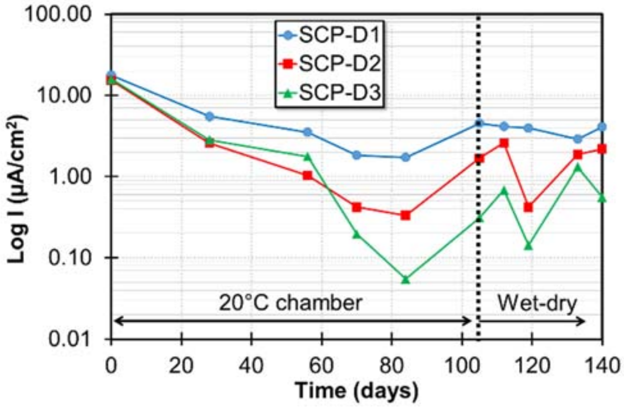


Fig.5 Protective current of sacrificial anode

3.4 Depolarization tests

Depolarization tests were regularly carried out by disconnecting the steel bar from the sacrificial anode for 24 hours. The instant-off potentials was measured immediately after disconnection of the sacrificial anodes (E_{off}) and the potential values were measured after 24 hours (E_{off} 24h).

The commonly used criterion for sufficient protection is 100 mV (the difference of E_{off} 24h and E_{off}). The 100 mV polarization shift was introduced in the early 1980s for evaluating the effectiveness of CP of reinforced concrete. These are the principal criteria currently used in energize cathodic protection systems for reinforced concrete structures [4].

Fig. 6 and Fig. 7 illustrate the depolarization value of the steel bars (SCP and SNCP) in repair and existing concrete sections during exposure to two different environments. It was clearly seen that steel bar with CP (SCP) in D1 type (non-rusted in repair concrete; rusted in existing concrete) achieved "100 mV decay" criterion all the time, which means that a protective condition is achieved on this rebar. On the other hand, steel bars without CP (SNCP) in D1 type just could only achieve the "100 mV decay" criterion in the wet-dry condition. This is an interesting phenomenon in which the steel bar, SNCP, is also polarized by the sacrificial anode. In addition, it is also due to the IR drop effect of the rebar.

For SCP in D3 type (non-rusted in repair concrete; non-rusted in existing concrete), the potential shift in depolarization increased time-dependently. Even in the wet-dry cycles, the steel bars fulfill the "100 mV decay" criterion.

Another interesting observation is confirmed in D2 type (rusted in repair concrete; rusted in existing concrete). In this D2 type, the sacrificial anode used in this study is not enough to fulfill the "100 mV decay" criterion after its switch off from CP after 24 hours.

This implies that the sacrificial anode is much more effective for SCP with a non-rusted surface in repair concrete even if it is rusted in existing concrete. It may be due to that non-rust condition gives the protective current flow larger than the rust condition.

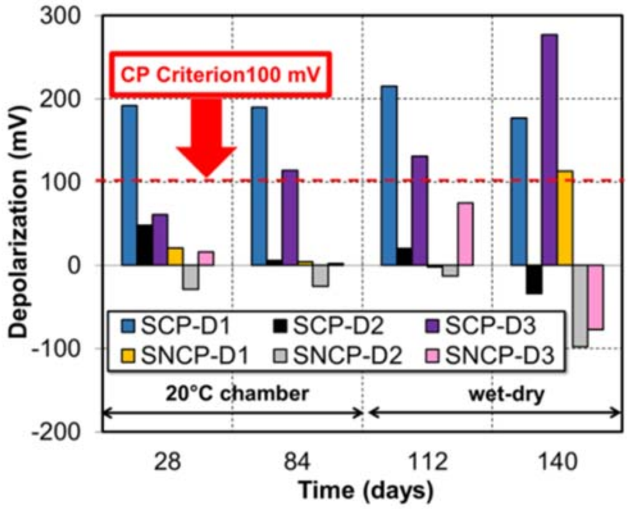


Fig.6 Depolarization values of steel bars in repair concrete (chloride-free)

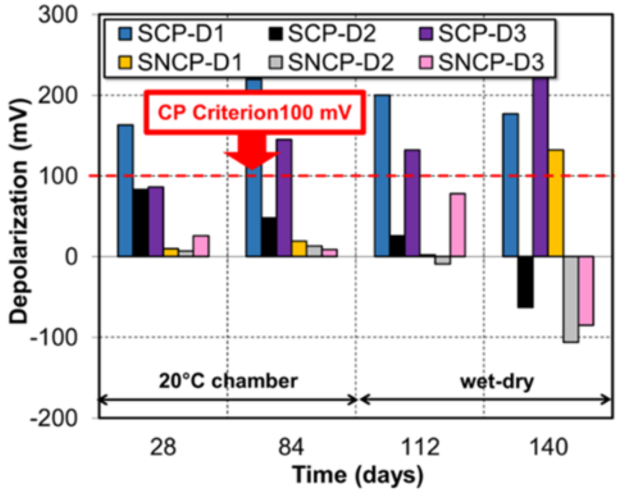


Fig.7 Depolarization values of steel bars in existing concrete (chloride-contaminated)

3.5 Anodic polarization curve of sacrificial anode

Fig. 8 describes the anodic polarization curve of sacrificial anode in D1, D2 and D3 series measured at the 24 hours after the switch off. It was observed that the current density gradually decreases time-dependently mainly for anodes in D1 and D3 specimens from 0 day to 84 days of exposure time. However, it was slightly increased to 10 μA/cm^2 for anode in D1 and around 2 μA/cm^2 for anode in D3 after 140 days. This means that although the activity of the sacrificial anode is gradually decreased, however, it is still enough to polarize the steel bar to protective levels.

Furthermore, in the wet-dry condition, the activity of the sacrificial anode is slightly recovered in D1 and D3. This observation is in good agreement with the protective current condition of CP in Fig. 5.

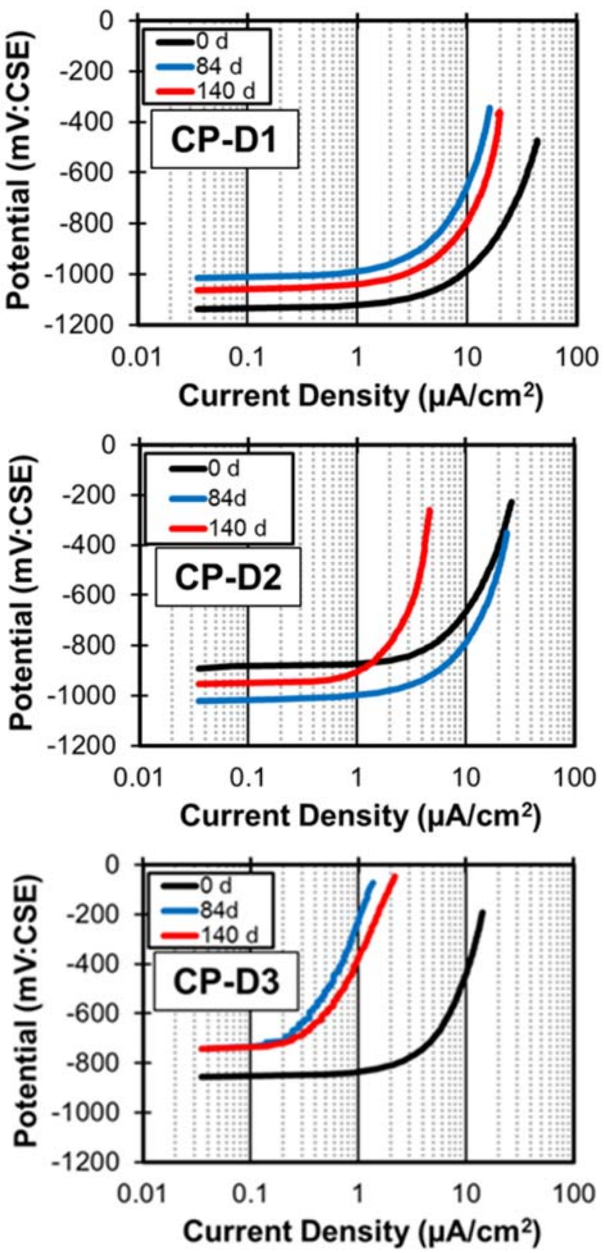


Fig.8 Anodic polarization behaviors of the anode

4. CONCLUSION

From this research, several conclusions can be drawn as follows,

1. The protective current of the sacrificial anode (CP) became more active in the humid conditions than in dry conditions, due to the high moisture content inside the concrete.
2. Based on the "100 mV decay" criterion, protective conditions were achieved on the steel bars of D1 type (non-rusted in repair concrete; rusted in existing concrete) and D3 type (non-rusted in repair concrete; non-rusted in existing concrete). Furthermore, steel bars without CP (SNCP) in D1 type just could only achieve the "100 mV decay" criterion only in the wet-dry condition. It may be due to IR drop effects that occur in the rebar.

3. Embedded rebar with surface rust (D2) showed insufficient protection at all time. This indicates clearly that rust on surface decrease the effectiveness of cathodic protection even in chloride free concrete. Because the rust on the steel bar decrease the current flow from anode to the steel bar.
4. Overall, it can be concluded that non-rusted rebar condition in repair concrete (chloride-free) is the most desirable initial condition when CP is applied on it to protect corroded steel bar in existing concrete (chloride-contaminated).

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