-Technical Paper-

EFFECTIVE LENGTH OF CATHODIC PROTECTION EMBEDDED STEEL WITH SACRIFICIAL ANODE UNDER NON-HOMOGENEOUS CHLORIDE ENVIRONMENT

Rahmita Sari RAFDINAL[*1], Hidenori HAMADA[*2], Yasutaka SAGAWA[*3] and Daisuke YAMAMOTO[*4]

ABSTRACT

This study was carried out to identify the effective length of embedded segmented steel element with sacrificial anode exposed to non-homogeneous chloride environment against macro-cell corrosion. Four concrete specimens which consist of chloride contaminated and non-chloride contaminated concrete were evaluated. Results show that sacrificial anode can protect embedded steel in the boundary of non-homogeneous chloride environment with the effective length is about 120 mm until 200 mm from edge of the boundary.

Keywords: Cathodic protection, embedded steel, sacrificial anode, effective length

1. INTRODUCTION

Macro-cell corrosion with local anode and large cathode mainly occurs in chloride induced corrosion of rebar embedded in concrete and causes very local corrosion damage [1]. One of approaches to study the macro-cell corrosion introduced by Miyazato is segmented steel bar [2].

Moreover, regardless of the method of partial repair concrete, this situation may eventually create an environment characterized by a non-homogeneous distribution of chloride ions [3].

Regarding to the definition of macro-cell corrosion, anodic and cathodic reactions are spacially separated along the reinforcing steel. In the case of segmented-reinfocing steel embedded in concrete, when the corrosion progresses, electronic current travels from element to element through the wire connection. It is supposed that each element only represents either anode or cathode.

Since the length of steel element is different, the possibility of anodic and cathodic reactions occuring in the same element is affected. The longer the length of element is, the possibility becomes larger. As a proceed, it is more difficult to understand or detect the time-dependency property of macro-cell corrosion [2].

Therefore, the objective of this study is to identify the effective length of steel reinforcement element, which is embedded in partial repair of concrete with sacrificial anode, for time-dependent macro-cell corrosion research by electrochemical investigations. All the calculations and discussions are based only on the results of macro-cell corrosion and protective current density, depolarization and anodic polarization curve of sacrificial anode.

2. SPECIMEN PREPARATION AND TESTING

2.1 Materials

Ordinary Portland Cement (OPC) was used in the concrete specimen. Tap water (temperature 20±2°C) was used as mixing water. Sea sand passing 5 mm sieve with 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 fine aggregate. Meanwhile, crushed stone with 20 mm maximum size was used as 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. Moreover, a sacrificial anode with 60 mm in diameter and 30 mm in thickness was used as shown in Photo1.

Table 1 Materials properties

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	

2.2 Mix Proportions

Concrete mix with water to cement (w/c) ratio of 0.45 was used throughout all specimens. Air-entraining agent and water-reducing admixture were used based on 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.

*1 Student, Graduate School of Engineering, Kyushu University, M. Eng., JCI Member
*2 Professor, Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*3 Associate Prof., Dept. of Civil and Structural Engineering, Kyushu University, Dr. Eng., JCI Member
*4 Technical Officer, Dept. of Civil and Structural Engineering, Kyushu University, M. Sci., JCI Member

Photo 1 Sacrificial anode installed on the rebar

There were two types of concrete mix proportions used on each specimen namely existing concrete (with chloride i.e. 4 kg/m^3 and 10 kg/m^3) and repair concrete (non-chloride). In order to accelerate the corrosion process, chloride ions were deliberately added during mixing the existing concrete. Pure sodium chloride (NaCl) was used as the source of chloride ions. The mixture proportions of concrete are shown in Table 2.

Table 2 Mixture proportions of concrete specimen

Material	Existing Concrete		Repair Concrete	
	Series A	Series B	Series A	Series B
Water-cement ratio (w/c), %	45	45	45	45
Sand-aggregate ratio (s/a), %	47	47	47	47
Water, kg/m^3	190	190	190	190
Cement (C), kg/m^3	422	422	422	422
Sand, kg/m^3	766	766	766	766
Gravel, kg/m^3	970	970	970	970
Chloride, kg/m^3	4	10	-	-
Additive:				
- AE, mL	C*0.45%		C*0.45%	
- AE-WR, gr	2.5mL/kg-C		2.5mL/kg-C	

2.3 Specimens

Four concrete specimens with 150x100x795 mm in dimension were prepared in this study to identify the effective length of segmented steel reinforcement element, which is embedded under non-homogeneous chloride environment, namely A1, A2, B1 and B2. Each concrete specimens contained a segmented steel bars with sacrificial anode (SCP), a segmented steel reinforcement without sacrificial anode (SNCP) and a steel bar without segmented and without sacrificial anode (S) positioned in parallel with an in-between distance of 35 mm. Three of bars have a clear cover thickness of 30 mm from the bottom surface of specimen.

It was also ensured that the segmented steel reinforcement showed no sagging in order to maintain a constant cover thickness along the total exposure length. Series A1 and B1 consist of one segmented rebar 75 mm length in repair concrete. Meanwhile, A2 and B2 consist of two segmented 75 mm length in repair concrete which mean 150 mm in total. The length of the element gradually increases from 75 mm to 100 mm. The detail of the concrete specimen are depicted in Fig. 1.

In order to determine the mechanical properties of concrete, 100x200 mm concrete cylinders were fabricated and tested after 28 and 91 days of curing in water. Casting of concrete specimens with non-uniform chloride ion concentrations was carried out in two steps. Firstly, casting of existing concrete with chloride contamined in the molds and demolded after 24 hours. After demolding, all specimens were subject to 14 days of sealed curing with wet towels. Secondly, before placing repair concrete in the molds, sacrificial anode was installed on the steel bar as figures in Photo 1.

Furthermore, followed by casting the repair concrete, demolded after 24 hours and were kept to 28 days of sealed curing again with wet towels. After 28 days of sealed curing, sacrificial anode connected to lead wires on the segmented steel in repair concrete, so current flows to existing concrete was started. Adjacent steel elements were connected through wires to allow the flow of current. However, these connectors were temporarily disconnected for the purpose of measuring macro-cell and protective currents.

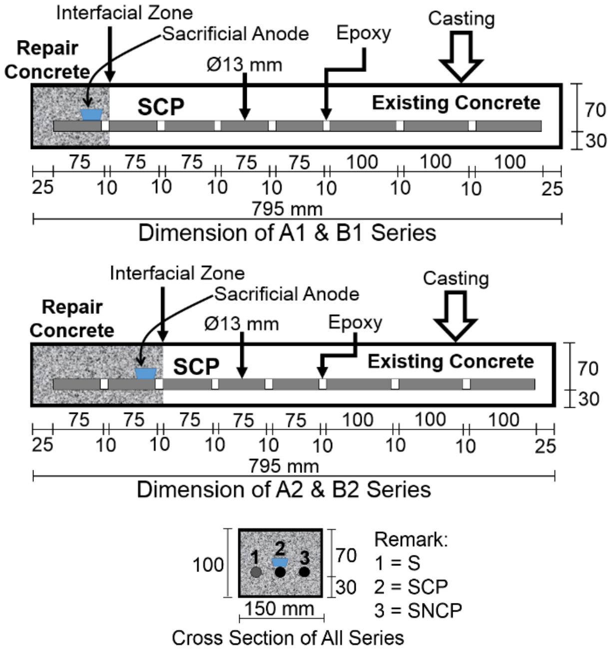

Fig.1 Detail layout of concrete specimen (in mm)

2.4 Segmented Steel Bar

A plain steel bar having a diameter of 13 mm was used as segmented and non-segmented embedded steel. There were two types of segmented steel bars with different length of element as shown in Fig. 1 and Table 3.

From the material aspect, the steel bar was separated by steel elements, however on the view of electrical aspect, it was assumed to be continuous by using lead wire connection. At both ends of each element, a 30 cm length lead wire was screwed.

The elements were bonded by epoxy resin such that no direct electrical connection exist between the elements except through the wires. The thickness of epoxy layer between two adjacent elements was approximately 10 mm.

2.5 Exposure Condition

After existing and repair concrete casting was finished, all specimens were subject to exposure conditions in the form of wet-and-dry cycling. Wet cycle means immersion in 3% NaCl solution through two days followed by five days of dry condition; hence one cycle corresponded to seven days. At the end of dry cycle, measurements were taken weekly. Continuous cyclic exposure condition was maintained throughout.

Table 3 Segmented steel

Specimen	Length of Element (mm)	Number of Element (n)	Position in the Concrete	Chloride Content (kg/m^3)
A1	75	1	Repair	-
	75	4	Existing	4
	100	3	Existing	4
B1	75	1	Repair	-
	75	4	Existing	10
	100	3	Existing	10
A2	75	2	Repair	-
	75	3	Existing	4
	100	3	Existing	4
B2	75	2	Repair	-
	75	3	Existing	10
	100	3	Existing	10

2.6 Exposure Condition

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2.7 Experimental Method

In order to observe performance of segmented steel with sacrificial anode embedded in partial repaired concrete, several electrochemical investigations were conducted. However, this paper focuses on to present about macro-cell corrosion and protection current density, depolarization test and anodic polarization curve testing. Macro-cell corrosion and protective current measurement was carried out periodically once a week at the end of dry cycle by using a data logger. In macro-cell corrosion, a divided steel bar is used to measure the actual macro-cell currents passing through one steel element to the adjacent element as represented in Fig. 2. Depolarization test was regularly carried out by disconnecting the steel bars from sacrificial anodes for 24 hours. In addition, it was continued by anodic-cathodic polarization curve which was conducted in order to determine the conditions of passivity film of steel bars.

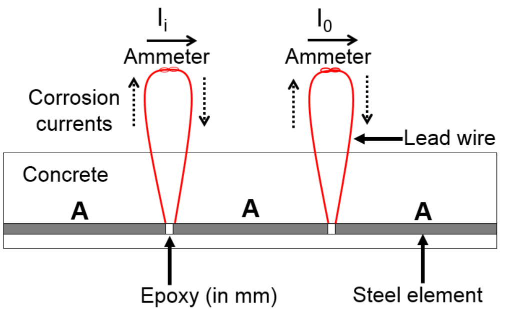

Fig. 2 Method of macro-cell corrosion current measurement

3. RESULTS AND DISCUSSION

Compressive strength of concrete at 28 days were 48.00 and 41.70 MPa for 4 and 10 kg/m^3 of chloride content respectively. Moreover, 50.97 and 48.67 MPa at 91 days for 4 and 10 kg/m^3 of chloride content respectively.

3.1 Macro-cell Corrosion Current Density

(1) One-steel bar element in repair concrete (A1 and B1)

Macro-cell corrosion current density of specimens with non-uniform chloride concentrations were measured periodically by using zero resistance ammeter as shown in Fig. 2. The following equation was used to calculate the macro-cell current density over a steel element [4]:

$$I_{mac} = \frac{I_o - I_i}{A} \quad (1)$$

where I_{mac} = macro-cell current density of a steel element (μA/cm^2); I_o = outflow current in μA from the steel element; I_i = inflow current in μA to the steel element; and A = surface area of the steel element (cm^2). If the value of I_{mac} is positive, the steel element is defined as an anode, and if negative as a cathode.

The macro-cell corrosion current density on SNCP at A1 and B1 with one-steel bar element in repair concrete against the distance from edge of repair concrete are present in Fig. 3(a) and (c). Macro-cell corrosion current density is found in relatively early age, and is disappeared in relative later age. This time dependent behavior is observed for both of specimens. The figures also show that macro-cell corrosion was formed coupling between the steel element located at chloride contaminated existing concrete as an anode and other steel elements as cathode. It was also observed that macro-cell corrosion was formed coupling in the boundary between chloride free concrete as an anode and its surrounding chloride contaminated as cathode, in the early age of exposure period.

(2) Two-steel bar element in repair concrete (A2 and B2)

Fig. 3(b) and (d) illustrate the macro-cell corrosion current density on SNCP at A2 and B2 with two-steel bar element in repair concrete against the distance from edge of repair concrete. In the case of A2, even at 182 days of exposure, macro-cell corrosion was formed coupling in the boundary, and also in the exsiting concrete. In B2 specimen, at early age of exposure, macro-cell current occured. In general, both of A2 and B2 specimens show the same tendency with A1 and B1, wherein the macro-cell corrosion current density tends to change over the exposure time at the interfacial zone of non-homogenous chloride environment.

3.2 Macro-cell Protective Current Density

(1) One- steel bar element in repair concrete (A1 and B1)

The periodic macro-cell protective current density on SCP with one-steel bar element in repair concrete against the distance from edge of repair concrete is shown in Fig. 4(a) and (c). The protective current density is also changed with time of exposure both in A1 and B1. Generally, protective current density decreases along the distance increases. At the 200 mm from the boundary, the protective current become almost zero. It was also observed that macro-cell corrosion was formed coupling with the steel elements both in the existing concrete, at the location over 200mm from the boundary.

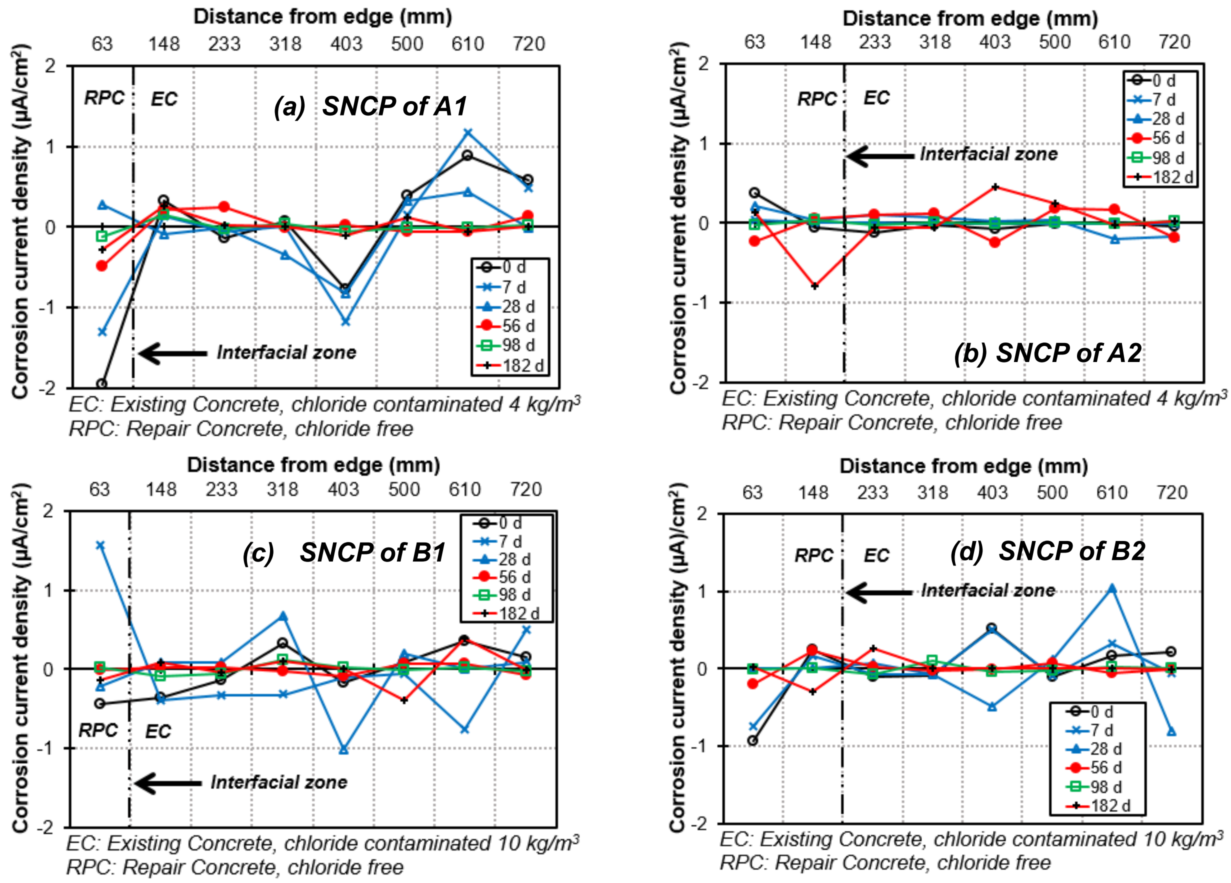

Fig. 3 Macro-cell corrosion current density on SNCP of A and B series with non-uniform chloride contents

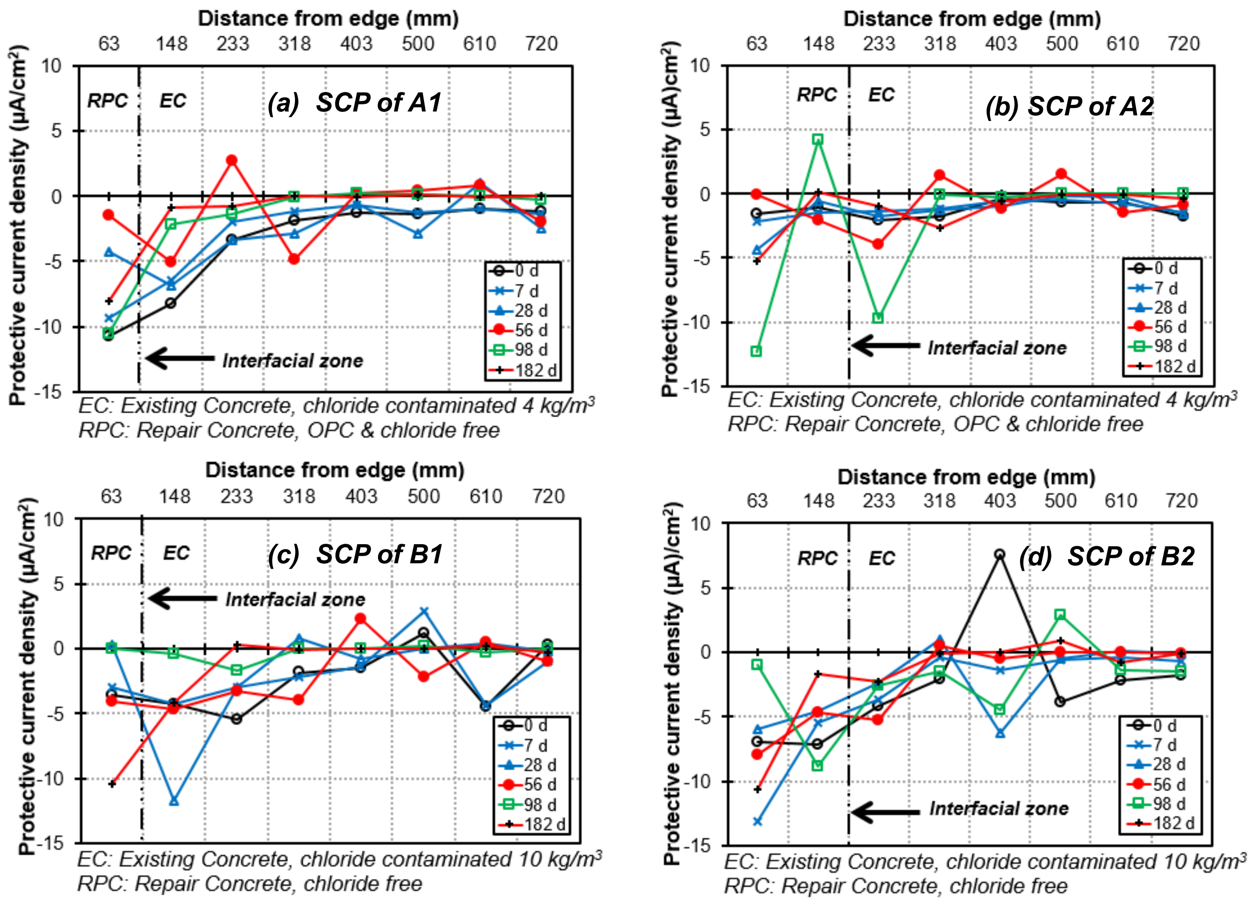

Fig. 4 Macro-cell protective current density on SCP of A and B series with non-uniform chloride contents

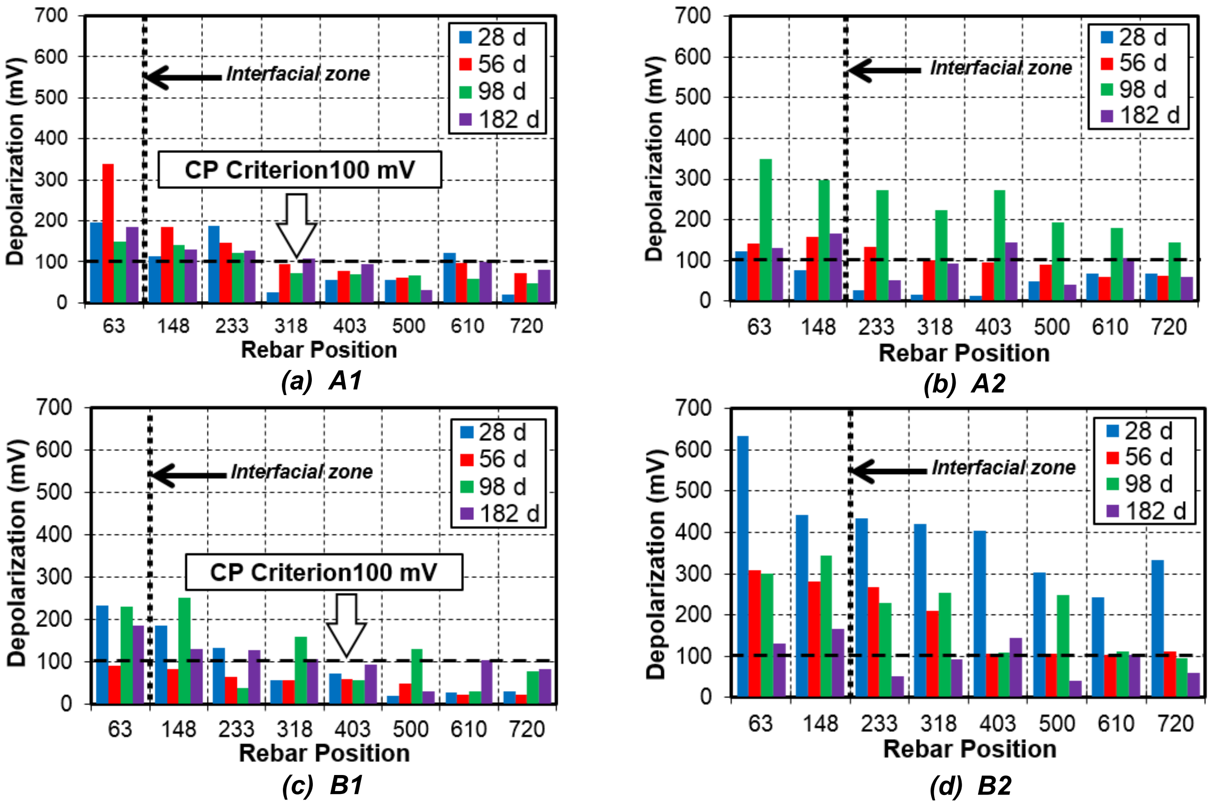

Fig. 5 Depolarization test on SCP of A and B series with non-uniform chloride contents

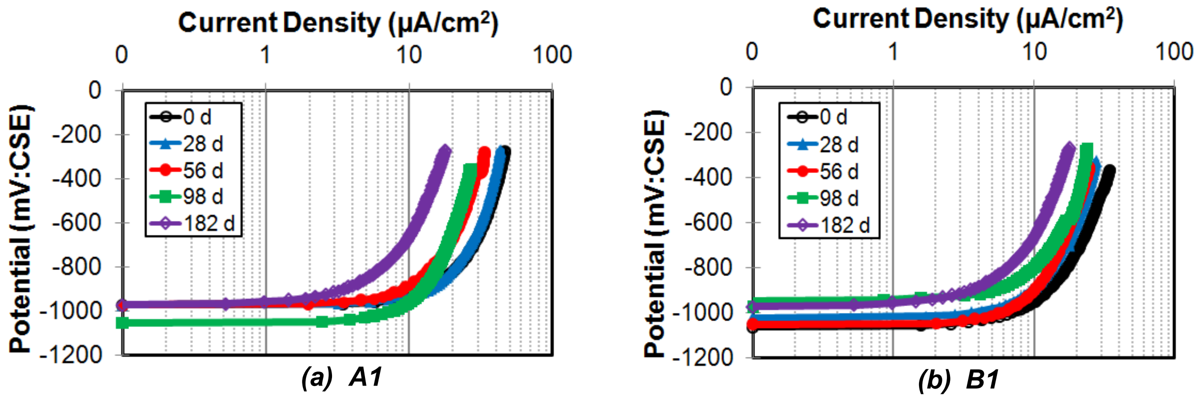

Fig. 6 Anodic polarization curve of sacrificial anode of A1 and B1

(2) Two-steel bar element in repair concrete (A2 and B2)

Fig. 4(b) and (d) illustrate the protective current density on SCP with two-steel bar element in repair concrete for A2 and B2 specimens. It also tends to be stable in flow with respect to time of exposure. And, the protective current decreases as the distance increases. In this case A2 and B2, at the distance about 120 mm, the protective current becomes almost zero. As same as A1 and B1, macro-cell corrosion is also formed coupling with the steel elements in the existing concrete.

3.3 Depolarization Test

Depolarization tests were regularly carried out by disconnecting the steel bars from the sacrificial anode for 24 hours. Instant off potentials was measured immediately after disconnection of the sacrificial anodes (E_{off}) and the potential values was 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}). Fig. 5(a) and (c) depict the depolarization test of A1 and B1 on SCP against the distance from edge of repair concrete. Meanwhile, Fig. 5(b) and (d) illustrate the depolarization test on SCP at A2 and B2 specimens.

From these figures, it was observed that the depolarization decreases as the exposure time increases, and also as the distance increases. From these figures, the distance about 200mm to 300mm from the edge is the boundary of achievement of the 100 mV decay criterion. Roughly, this distance coincides with the distance of the protective current flow is reached.

3.4 Anodic Polarization Curve of Sacrificial Anode

Fig. 6(a) and (b) describe about the anodic polarization curve of sacrificial anode measured at the 24 hours after the switch off. The current density is in the range of 10 to 100 μA/cm². At the age of 182 days, the current density significantly decreased. This means the activity of sacrificial anode is gradually decreased, however, it is still enough to polarize the steel bar to protective levels.

4. CONCLUSION

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

1) From the distribution of protective current density, the utilization of commercially available sacrificial anode is effective to protect the corroding steel approximately 200 mm from the boundary between repair and existing concrete for the one-steel bar element in repair concrete. Meanwhile, the length is about 120 mm for the two-steel bar element in repair concrete.
2) Based on the depolarization test results, in general, it was observed that cathodic protection embedded steel with sacrificial anode is considered to be effective for the steel bar located at the same distance as mentioned in the conclusion (1), judged by the 100 mV decay criterion.

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