-Technical Paper-

EVALUATION OF EXHAUSTED CONDITION OF SACRIFICIAL ANODE EMBEDDED IN CONCRETE BY CURRENT ACCELERATION METHOD

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ABSTRACT
This study was carried out to observe the service life of the galvanic sacrificial anode to protect steel bar from corrosion in concrete. Current acceleration method was used by adjusting the current demand 10 times higher than initial current of anode. Results show that by increasing the current demand by 10 times, it makes the service life of anode reduced significantly after 70 days of exposure. It means the higher current delivery function of anode, the service life of anode become shorter. Current acceleration method is effective to investigate the service life of anode in short time.
Keywords: exhausted condition, service life, galvanic, sacrificial anode, current acceleration

1. INTRODUCTION

It is now recognized that cathodic protection (CP) of concrete reinforcing steel is necessary to ensure long term integrity of the structure. The CP system must be designed to provide the required current to every part of the structure for the required design life.

The protection delivered by a sacrificial anode as one of method in CP system is largely determined by current output of the anode system and its distribution to the protected steel [1-3]. This requires determining anode size, weight, number and distribution to supply current for the design life of the structure [4, 5]. Thus, anode life is primarily determined by anode current output, anode charge capacity, anode utilization and anode efficiency. Longer lives may generally be achieved by using more anodes or anodes with high charge capacities that deliver low current densities.

Nowadays, anode service lifetime is one of the challenges that are still to be taken up in CP system. However, to observe anodes during service life will take a long time and long term performance anode data is so limited nowadays. Therefore, this study was carried out in order to observe the galvanic sacrificial anode exhausted condition and service life shortly with current acceleration method through the impressed current system.

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. Washed sea sand passing 5mm sieve with density of 2.58 g/cm^3 and water absorption of 1.72 % was used as fine aggregate. Meanwhile, crushed stone with 20mm 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 galvanic anode made of zinc as main material was used as sacrificial anode. The anode has dimension 140 mm in length, 45 mm in width and 13 mm in depth was used as shown in Photo1.

Table 1 Materials properties

Component	Physical properties	
OPC	Density, g/cm^3	3.16
Fine aggregate	Density, g/cm^3 (SSD Condition)	2.58
	Water absorption (%)	1.72
	Fineness modulus	2.77
Coarse aggregate	Density, g/cm^3	2.91
AEWR agent	Polycarboxylate ether-based	
AE agent	Alkylcarboxylic	

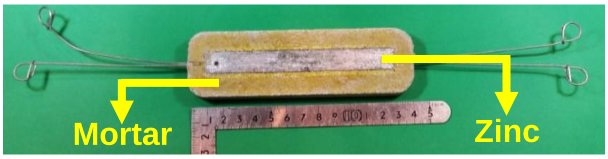

Photo 1 Zinc sacrificial anode

2.2 Mix Proportions

Concrete mix with water to cement (w/c) ratio of 0.45 was used throughout all specimens. Air-entraining

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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. In order to accelerate the corrosion process, chloride ions were deliberately added around 10 kg/m^3 during mixing into concrete. Sodium chloride (NaCl) reagent 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	
Water-cement ratio (w/c), %	45
Sand-aggregate ratio (s/a), %	47
Water, kg/m^3	190
Cement (C), kg/m^3	422
Sand, kg/m^3	766
Gravel, kg/m^3	970
Chloride, kg/m^3	10
Additive per m^3:	
- AE, mL	19
- AE-WR, gr	1.34

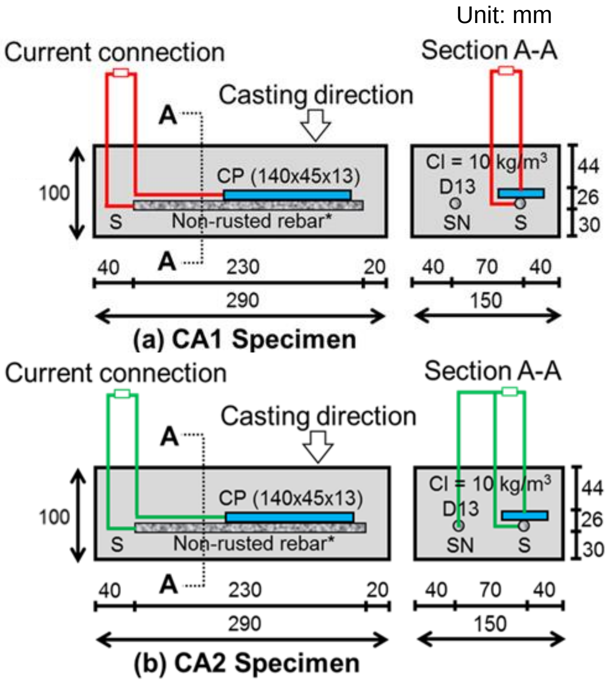
2.3 Specimen Geometry

Prism concrete specimens with 100x150x290 mm in dimension were prepared in this study. Each concrete specimens 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 the cover thickness of 30 mm from the bottom surface of the specimen. The details of the concrete specimen are depicted in Fig. 1.

There were 2 (two) types of current acceleration (CA) method proposed in this study as shown in Table 3; accelerate current from anode to one-steel bar (CA1 specimen) and accelerate current from anode to two-steel bar (CA2 specimen). Originally, the initial current for CA1 and CA2 specimens are 0.07 mA and 0.056 mA, respectively. However, the current was adjusted 10 times higher to 0.7 mA for both specimens. Current flow from galvanic sacrificial anode (SA) to steel bar in CA1 was delivered to one-steel bar only. Meanwhile in CA2, current throwing interrelated with two-steel bar.

Table 3 Detail of current acceleration conditions

Specimen ID	Initial Current (mA)	Accelerate 10 times (mA)	Remark
CA1	0.07	0.7	CP connected to one-steel bar
CA2	0.056	0.7	CP connected to two-steel bar



S : SA be assembled on the steel bar
SN : SA not be assembled on the steel bar
Non-rusted rebar*: rusted rebar after immersed in 10% (weight percentage) diammonium hydrogen citrate solution for 24 hours

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

2.4 Steel Bar

In this study, a 20-year-old deteriorated (rusted) reinforcing steel bar with a diameter of 13 mm was used. Then, 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 to obtain non-deteriorated (non-rusted) condition. These steel bars were taken from the specimens exposed in severe chloride environment with high temperature for 20 years. At the ends of steel bar in repair section, a 30cm length lead wire was screwed. Adjacent steel elements were also connected to the sacrificial anode through wires to measure the flow of the current. 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 potential decay in depolarization test.

2.5 Exposure Condition

After casting of concrete and demolding, all specimens were subject to 28 days of sealed curing with wet towels. Since 28 days of sealed curing, the galvanic sacrificial anode (SA) was connected to the embedded steel bars: S (SA be assembled on the steel bar) for CA1; S and SN (SA not be assembled on the steel bar) for CA2. All specimens were subjected to the air curing with a temperature of 20±2°C and a relative humidity of 60% as exposure site as shown in Photo 2. In addition, Fig. 2 show about scheme of acceleration current in CA1 and CA2 by impressed current cathodic protection system.

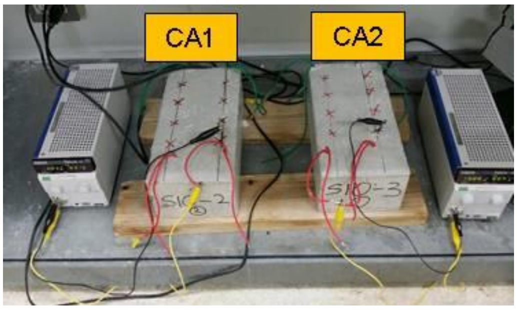


Photo 2 Exposure conditions of CA specimens

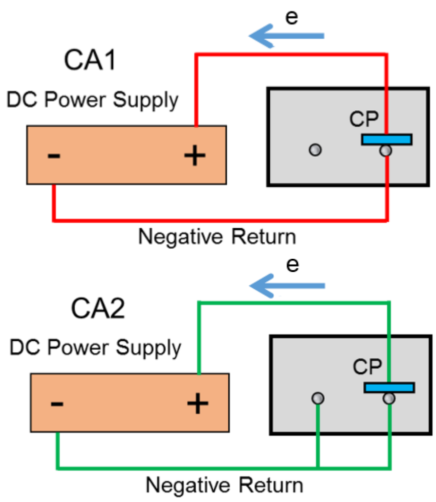


Fig.2 Detail layout of concrete specimen (in mm)

2.6 Monitoring System of Anode Service Life

Electrochemical testing conducted to CA specimens in order to monitoring the polarization behavior of anode and steel bar in concrete. Silver/silver chloride electrodes (Ag/AgCl) is used as reference electrode for potential mapping in this study and convert to Copper/copper sulphate electrode (CSE) with temperature consideration.

The galvanic sacrificial anode (SA) system must be designed to provide the required current to every part of the structure for the targeted design life. Anode service life is primarily determined by anode output, anode charge capacity, anode utilization and anode efficiency. In simple terms anode life is given by the useful mA-hours (charge capacity) of the sacrificial metal divided by the average output in mA.

In practice, only a certain percentage of an anode's mass can be used for current production. As the anodes are used, their surface area getting smaller and the anode resistance increase, because of the non-uniform consumption of anodic mass; thus, anodes can never be fully consumed. Sacrificial anode design requires that the weight of anode material is sufficient to supply current for the design life of the structure. This is calculated by the following formula:

$$y = \frac{w \; x \; U}{Ano.Eff \; x \; I} \tag{1}$$

Where: y = life of an anode (year), *w* = anodic mass (kg), *U* = usage factor or utilization factor (0.9 for zinc), *Ano. Eff* = anode efficiency (kg/A.year), *I* = anodic current demand (A).

At the end of test, visual observation to zinc sacrificial anode was carried out in order to measure service life of anode.

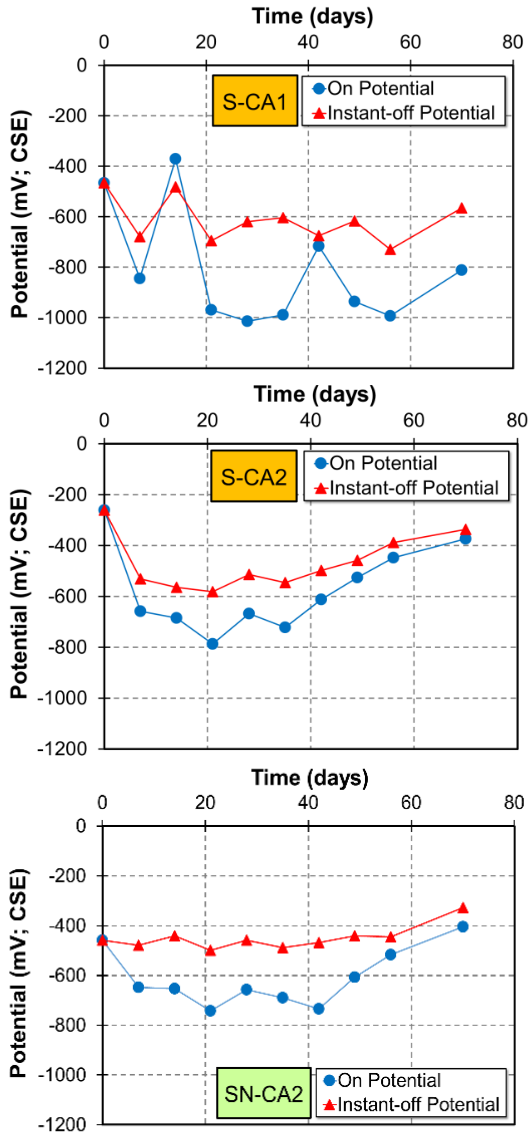


Fig.3 Potential of steel bars connected to anode vs time for both sets of current acceleration method

3. RESULTS AND DISCUSSION

3.1 Steel Bar Polarization

(1) Potential Evolution

Potential of steel bar connected to anode (S-CA1, S-CA2 and SN-CA2) during current acceleration with polarization time is presented in Fig. 3. On potential of steel bar connected to CP (S-CA1) with 10 times current acceleration decreased with fluctuations to more negative during polarization time. In 28-day of exposure time, on potential reached a peak ~-1000 mV. However, potential of steel bar increased to noble value during instant-off condition. During 70-day of exposure time, there were an upward trend to noble value in the on potential and instant-off potential of S-CA1, reaching ~-550 mV and ~-800 mV respectively. It was observed that on potential of S-CA1 ~-200 mV to ~-400 mV more negative than instant-off potential. In general, it was indicates S-CA1 cathodically protected because protective potential of steel bar shown in the range of acceptance performance of cathodic protection -850 mV.

Furthermore, potential of S-CA2 during on and instant-off signified decreased gradually from 0-day until 21-day of polarization time. In 21-day of exposure time, on potential and instant-off potential of S-CA2 reached a peak at ~-780 mV and ~-580 mV respectively. Afterwards, both of potential condition increased gradually to noble value between 28-day and 70-day of exposure time. It was noticed that S-CA2 in the trans-passive region which leading to damage in the passive protective films and resulting mostly in pitting-corrosion as protective potential of steel bar shown increased to positive direction. Meanwhile, on potential of SN-CA2 fell gradually to ~-750 mV after 28 days of polarization period. But, this trends rose gradually to positive direction until at the end of test. There was a plateau in the instant-off potential of SN-CA2 between 0-day and 56-day. Afterwards, instant-off potential rose significantly to noble value at 70-day of exposure time. As same as like S-CA1 and S-CA2, this steel bar also indicates failed polarize by anode at 70-day of polarization period.

Half-cell potential of steel bar without anode connection (SN-CA1) is shown in Fig. 4. There was a downward trend to negative direction between 0-day and 70-day of exposure time. Half-cell potential of steel bar during on and instant-off condition of CP decreased gradually to more than -400 mV vs CSE from 35-day until 70-day of exposure time, which indicates the 90% probability of corrosion according to ASTM C 876-95. The line graphs of half-cell potential indicates that stray current of anode not enough to protect the steel bar from corrosion.

(2) Depolarization

In order to verify the protection conditions in reinforced concrete structures, the "100 mV" decay criterion was carried out in this study by measure the potential decay after switching off the current during 24-h. In addition, 100 mV depolarization criterion was used to demonstrate the effectiveness of CP.

Fig. 5 summarizes the depolarization measurement results for different condition of acceleration method and aging times evaluated. It was observed that active steel bars (S-CA1, S-CA2 and SN-CA2) for both sets of current acceleration method exceed of 100 mV decay criterion during the first month of polarization period. However, after 70 days, only S-CA1 surpasses the 100 mV decay criterion. Meanwhile, passive rebar (SN-CA1) failed to achieve appreciable levels of polarization since in the beginning of polarization period. It is indicates that anode effective to protect the steel bar in the CA1 condition.

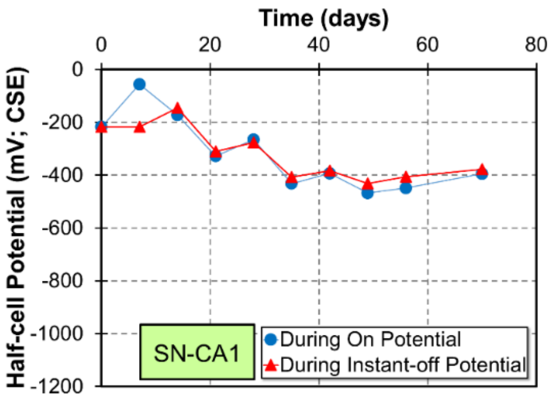


Fig.4 Half-cell potential of steel bar without connected to anode vs time

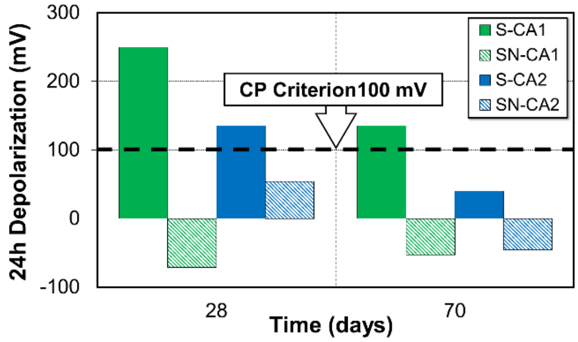


Fig.5 Summary of 24-h depolarization test result of steel bars with time

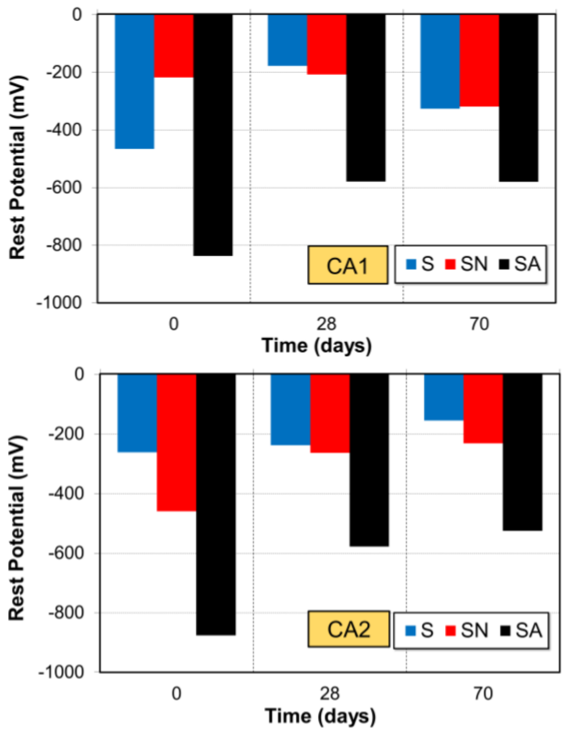


Fig.6 Rest potential of steel bars and anodes after switch-off 24h

(3) Rest Potential

Fig. 6 shows the rest potential values of steel bars (S and SN) and anodes (SA) after switch-off 24h in depolarization test. The half-cell potential of zinc anodes (SA) increased to noble value as shown in Fig. 6. It is due to the low humidity condition which decrease the protective potential of anode.

As can be seen in Fig. 6, the half-cell potential of active steel bars (S and SN in CA2) embedded in chloride-contaminated concrete with current acceleration which connected to this both steel-bar shown less steadily less than -850 mV during polarization period. However, S-CA1 indicates increased to more negative direction from 28-day until 70-day of exposure period which implies protection is going on. And for SN-CA2, the potential denotes probability of corrosion increased to occur. During depolarization process, development of current flow over 24h switch-off were monitored as illustrates in Fig. 7. From Fig. 7, it can be seen that current flow decreased gradually to initial current 0.07 mA after 24h.

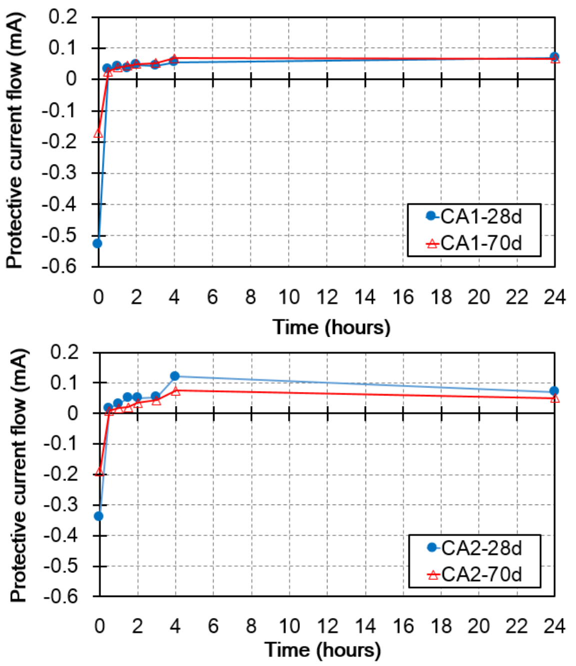


Fig.7 Current flow during 24h of depolarization test

3.2 Anode Polarization

(1) Potential of Anode

The evolution of on potential and instant-off potential of anode with acceleration current connected to one-steel bar (SA-CA1) and two-steel bar SA-CA2) are presented in Fig. 8. The data from Fig. 8 shows that on potential and instant-off potential varies with polarization period. In the beginning of exposure, on potential soared to ~1200 mV for CA1 and ~2000 mV for CA2. Afterwards, on potential reached a peak to ~2300 mV at 42 days for CA1. Meanwhile, on potential of CA2 was at its highest level to ~2500 mV in 28 days.

Furthermore, potential of CA1 and CA2 decreased dramatically to negative direction, reaching less than -600 mV during instant-off condition as the function of polarization period. However, it was indicates that anode difficult to polarize the steel bar because protective potential of anode less than acceptance performance of cathodic protection, -850 mV, over much of test period. From Fig. 8 it was observed that current acceleration stimulate the protective potential tends to noble values during on and instant-off.

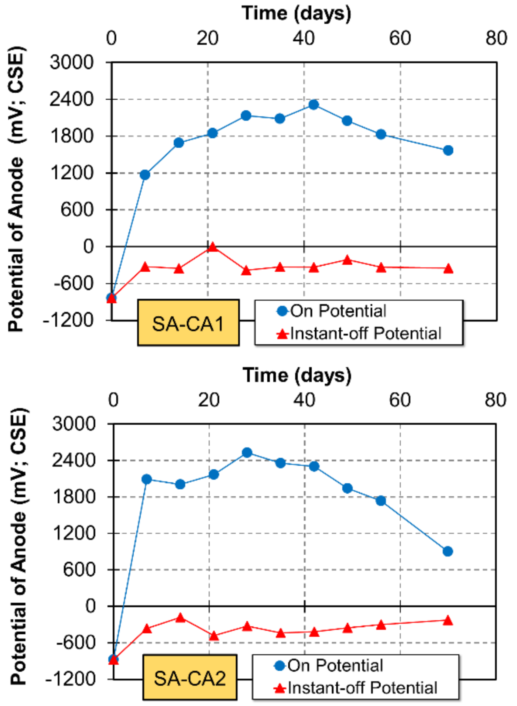


Fig.8 Anode potential evolution with time

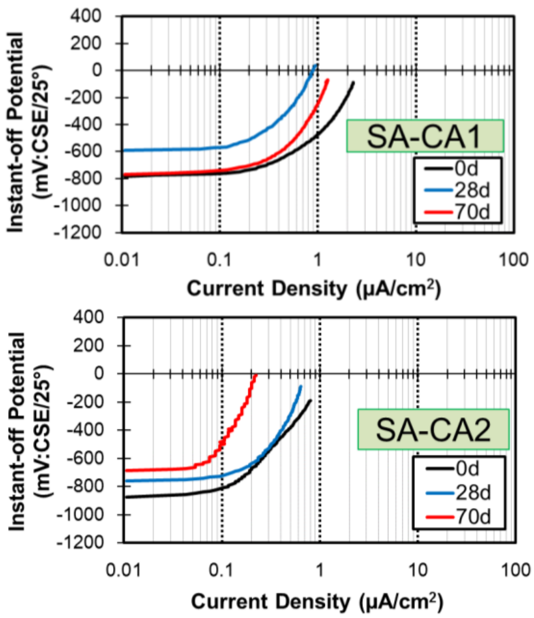


Fig.9 Anodic polarization behavior of anodes

(2) Anodic Polarization Curve of Anode

Fig. 9 describes the anodic polarization curve of sacrificial anode in CA1 and CA2 series measured after anode the switch off by 24 hours. Based on the Tafel`s lope, it was observed that the current density of SA-CA2 gradually decreases time-dependently from 0 day to 70 days of exposure time. Meanwhile, for SA-CA1, current density fell gradually from ~0.15 μA/cm^2 at 0-day to ~0.1 μA/cm^2 at 28-day of test period. However, the current density of SA-CA1 increased markedly to ~0.12 μA/cm^2 at 70-day.

It was observed that there were an increasing anodic polarization with anode age for anode in CA1. Meantime, the curves in Fig. 9 reflect significant performance derating with the function of anode aging for anode in CA2.

3.3 Service Life of Zinc Sacrificial Anode

Sacrificial anode design requires that weight of anode material is sufficient to supply current for design life of the structure. Therefore, at the end of test, visual observation to zinc sacrificial anode was carried out as can be seen in Photo 3. From visual observation, it was found that the weight of zinc decreased from 89 gram to 84.15 gram for anode in CA1 and 83.41 gram for anode in CA2. It means that current acceleration to SA connected to two-steel bar (CA2) accelerate weight loss of zinc higher than connected to one-steel bar.

Photo 3 Visual observation of zinc sacrificial anode

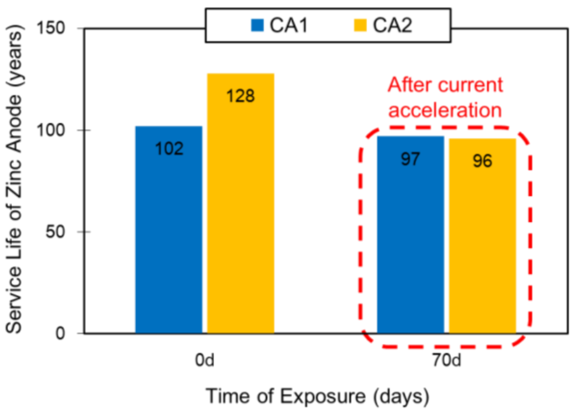


Fig.10 Service life of anode

Based on the weight of anode after exposed during 70 days with current acceleration 10 times higher than initial current, service life of anode is calculated using equation (1).

Fig.10 shows the expecting service life of anode with their own initial output of current, for instance, 0.07 mA for CA1 and 0.056 mA for CA2. With this amount of initial current output and with the initial weight of anode, it is calculated that anode serviceability can reach up to 102 years for CA1 and 128 years for CA2. Afterwards, current of CA1 and CA2 adjusted to 0.7 mA as initial current during acceleration condition.

Meanwhile, during acceleration to throwing power 10 times higher than initial condition, it was observed that service life of anode reduced to 97 years for CA1 and 96 years for CA2. The remaining service life of anode as can be seen in Fig.10. It was observed that by increasing the current demand by 10 times, it makes service life of anode reduced significantly after 70 days of exposure. 70 days here as same as like two years of throwing power of anode without current acceleration. It means that the higher current delivery function of anode, the service life of anode become shorter. In addition, it can be said that current acceleration method successfully to predict the service life of anode in short time observation.

4. CONCLUSIONS

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

1) Service life of zinc sacrificial anode exposed to air curing condition with constant room temperature could predict to reach over 100 years.
2) By increasing the current demand by 10 times, it makes service life of anode reduced significantly after 70 days of exposure. It means that the higher current delivery function of anode, the service life of anode become shorter.
3) Current acceleration method is effective to observe the service life of anode in short time.

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