공학석사 학위논문

Tidal Effect of Hybrid Cathodic Protection System in Reinforced Concrete Structures

하이브리드 음극방식을 적용한 콘크리트 구조물의 수위변화에 따른 방식특성 연구

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Tidal Effect of Hybrid Cathodic Protection System in Reinforced Concrete Structures

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Abstract

철강 재료는 각종 산업분야에 가장 많이 사용되고 있는 금속재료이다. 그러나 이 재료는 여러 환경에서 부식되기 쉬운 결점이 있으며, 콘크리트구조물의 경우도 이러한 문제로 부터 벗어날 수 없다. 콘크리트구조물을 부식시키는 인자는 여러 가지이지만, 해양환경이나 동계 제빙제에 의해 유입되는 염소이온이 가장 대표적이다. 콘크리트에 침입한 염소이온은 철근표면에 형성되었던 부동태 피막을 파괴함으로써 부식을 일으키게 되는데, 이 과정에서 철근표면이 국부적으로 더욱 산성화되어 가면서 공식을 가속화한다.

지난 수십 년간 콘크리트 부식을 방지하기 위한 기술은 다양하게 발달되어 왔다. 그 중 음극방식(Cathodic Protection)은 콘크리트뿐 아니라 토중, 해양 환경에서 그 방식효능이 널리 인정되었으며, 현재도 광범위하게 적용되고 있다. 음극방식은 외부전원법(Impressed Current Cathodic Protection, ICCP)과 희생양극법(Sacrificial Anode Cathodic Protection, SACP)으로 세분된다. 외부전원법은 방식전류를 정류기와 불용성 양극을 통하여 방식체에 인가하는 방법이며, 희생양극법은 방식하고자 하는 금속과 그 보다 더 낮은

전위의 금속을 전기적으로 연결함여 방식하는 방법으로 각각 장단점을 가지고 있다. 특히 희생양극법은 낮은 방식전위 구동력으로 인해 고 비저항 영역에서는 방식이 어려운 단점이 있으며, 비저항의 정도에 따라 그 방식범위가 달라진다.

해양환경 중 콘크리트구조물에서 비말대(Splash Zone)와 간만대(Tidal Zone)는 부식에 가장 큰 영향을 주는 물과 산소가 동시에 풍부하고 가장 부식이 심한 영역이다. 따라서 해양콘크리트구조물의 방식은 주로 이 부분에 집중되는데 희생양극법만으로는 구조물 전체의 적정방식에 한계가 있다.

따라서 본 연구에서는 희생양극법 및 외부전원법이 가지고 있는 한계점을 보완하고 전체 구조물의 균형 있는 방식을 위하여 두 방식법이 조화되는 하이브리드 음극방식 시스템을 연구하게 되었다.

시험편 구조물은 가로 세로 각각 15 cm, 높이 120 cm의 빔형으로 제작하였고, 해상 조건을 구현하기 위하여 대기부, 간만대, 비말대 그리고 해중부 영역을 각각 30 cm 간격으로 구분하였다. 콘크리트 구조물 중 해수에 침지된 간만대와 해중부는 아연 양극에 의한 희생양극법을 적용하였고, 수면부 상부의 공기 중에 노출된 비말대와 대기부는 외부전원법(Ti-MMO 양극)을 통해 방식하였다. 수위는 고수위와 저수위로 구분하였으며, 각 수위 및 수위가 변할 때 부식 및 방식 거동을 조사하였다. 측정 파라미터는 방식전위, 방식전류, 4 시간 복극전위이었다.

연구 결과를 요약하면 다음과 같다.

1) 희생양극법을 적용하였을 때, 조수간만대 상부 7.5 cm 높이까지 방식 효능이 있었다.(100 mV 복극 기준 만족)

2) 고수위에서 외부전원 시스템이 비말대까지 확장되어 설치된 경우 간만대와 비말대가 방식전류의 누설로 인해 전위는 -1,100 mV ~ -2,050 mV/SSCE의 범위였으며, 구조물은 과방식되었다.

3) 해수면이 고수위에서 저수위로 바뀌었을 때, 간만대에서 희생양극 시스템에 의한 방식효과가 2일 이상 지속되었다. 이를 통해 외부전원 없이 희생양극법 단독으로도 간만대 방식이 가능하다는 것을 확인하였다.

이상의 결과에 의해 콘크리트 구조물의 외부전원법과 희생양극법 병용을 통해 해결할 수 있다는 방식응용 설계에 대한 기초 지침을 제시하였다. 그러나 양극의 위치가 부적절한 경우 과방식으로 인한 문제가 발생할 할 수 있으므로 복합 구조물의 경우, 방식특성 및 최적 방식 조건을 찾기 위한 구체적인 연구가 필요할 것으로 판단된다.

Chapter 1

INTRODUCTION

Reinforced concrete is versatile, economical and successful construction material [1-2]. In general concrete has a high alkaline environment. It means that concrete contains microscopic pores which contain high concentration of soluble calcium, sodium and potassium oxides. These components form hydroxides, which are high alkaline(pH 12-13), when water is present. In this environment, steel in concrete forms compact passive layer, which lead to significantly slow rate of corrosion [3].

Reinforced concrete structures, however, can suffer severe corrosion problems when the water in concrete is contaminated by chloride from de-icing salt in winter season and sea water in marine condition [4]. Chloride ions penetrate concrete cover and lead to the onset of pitting corrosion when their concentration near the steel surface reaches a critical threshold. When corrosion starts in immersed areas, the corrosion rate is negligible because of little amount of oxygen that can reach to the steel surface. Critical conditions for corrosion initiation and propagation, however, are found in splash and tidal zones of marine bridges. The main reasons that these areas have high corrosion rate are due to alternating wet-dry cycles and high oxygen availability.

To protect corrosion damage in chloride contaminated environment, cathodic protection(CP) has been used for decades and now it becomes one of the proven technologies to protect the corrosion damage especially in the harbor structures. CP is an electrochemical method of corrosion prevention which can be applied to metal exposed to conductive environment. It has been known as an optimal ways to protect corrosion [5].

There are two kinds of CP system, which are sacrificial anode CP(SACP) and impressed current CP(ICCP). SACP has inherent simplicity and low maintenance requirement. In addition, it can be attractive way to extend service life after corrosion damage occurred [6-8].

The major problem of SACP, however, is 'throwing power'. The throwing power of CP is the distance of current supply by anode. In many studies, SACP revealed that the height of current supply in a concrete column was limited to a few ten centimeters above the water level, depending on the concrete resistivity [9-11].

It is hard to protect an entire structure by only SACP, especially in the case that the structure is larger and complex. Hybrid CP, i.e. the combination of ICCP and SACP, can be a solution to overcome the difficulty.

The purpose of this study, therefore, was to investigate the protection relationship between ICCP and SACP systems in concrete columns, especially in marine splash and tidal zones. In addition, the proper protection conditions have been studies to improve the protection performance in those complex structures. In this study, the SACP was installed in the immersed area and the ICCP was applied to above the water line to overcome the limitations of throwing power of SACP.

Chapter 2

BACKGROUND

2.1 Corrosion basics

Corrosion is the destructive results of chemical reactions between metal or alloy and their environments [12]. It has long been established that the corrosion of metal in aqueous environments proceeds via electrochemical mechanism. The surface of the corroding metal acts as a mixed electrode, upon which coupled anodic and cathodic reactions take place [13].

The corrosion reactions are shown in Figure 2.1. At anode site, metal atoms are dissolved into solution as positively charged ions(anodic oxidation), and the electrons move from anodic site to cathodic one which react with oxygen and water. In the corrosion processes, the following reaction occurs in anode :

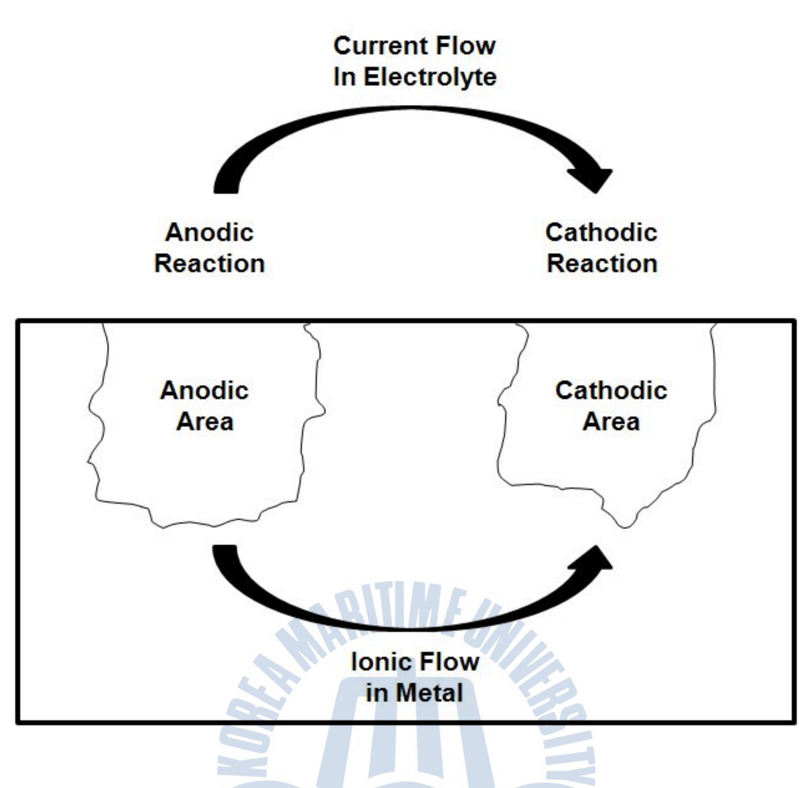

Figure 2.1: Electrochemical model of corrosion in metal

$$M \rightarrow M^{+} + ne^{-} \qquad (2\text{-}1)$$

Typical cathodic reactions are expressed as follows [14] :

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad \text{Oxygen reduction} \qquad (2\text{-}2)$$

$$2H^{+} + 2e^{-} \rightarrow H_2 \qquad \text{Hydrogen evolution} \qquad (2\text{-}3)$$

2.2 Corrosion of steel in concrete

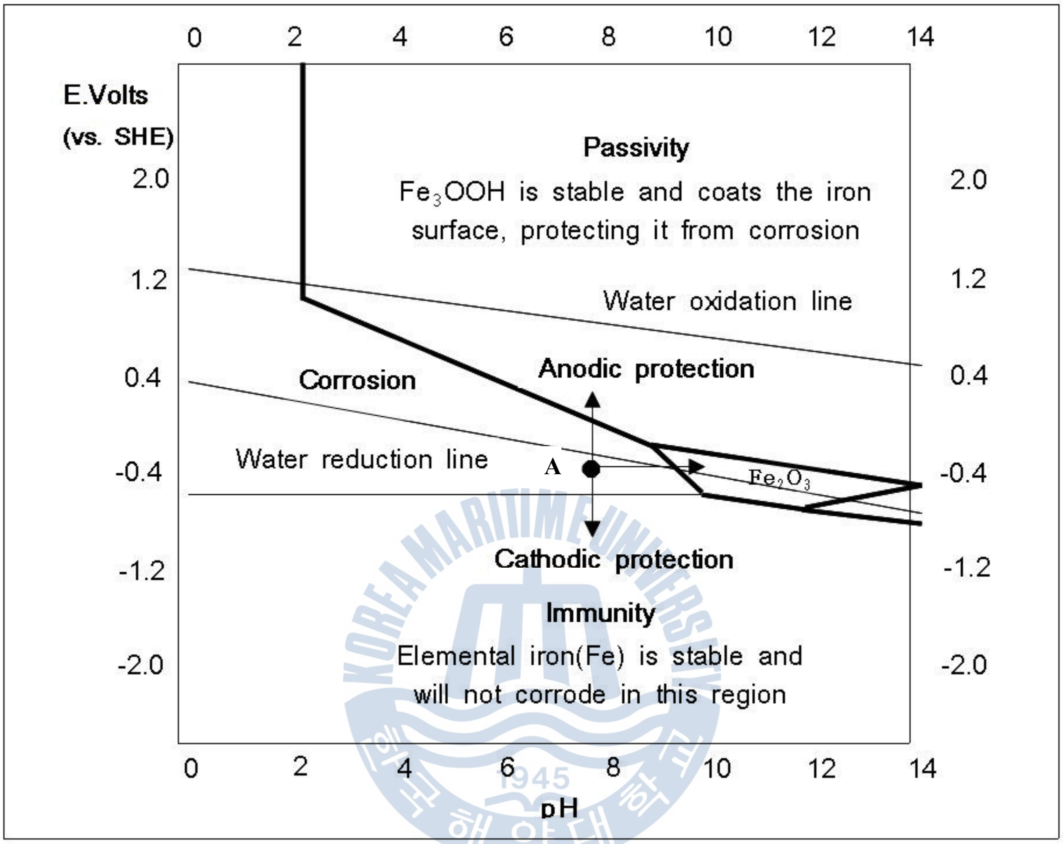

Figure 2.2: E-pH diagram of iron

Concrete has a high alkaline environment. It means that concrete has microscopic pores which contain high concentrations of soluble calcium, sodium and potassium oxides. They form hydroxides, which become high alkaline of pH 12-14 by hydration reactions. In this environment, steel in concrete forms compact passive layer which leads to a significntly slow corrosion rate [3]. It can be confirmed in Potential/pH diagram of iron as shown in Figure 2.2.

When the passive film is destroyed, however, steel in concrete is corroded. The mechanism of corrosion in reinforced concrete is the same as typical corrosion of steel. On the other hand, corrosion of concrete is a massive problem, since in the corrosion process of concrete, the volume of steel is increased at the steel/concrete interface up to 6 ~ 7 times as indicated in Figure 2.3.

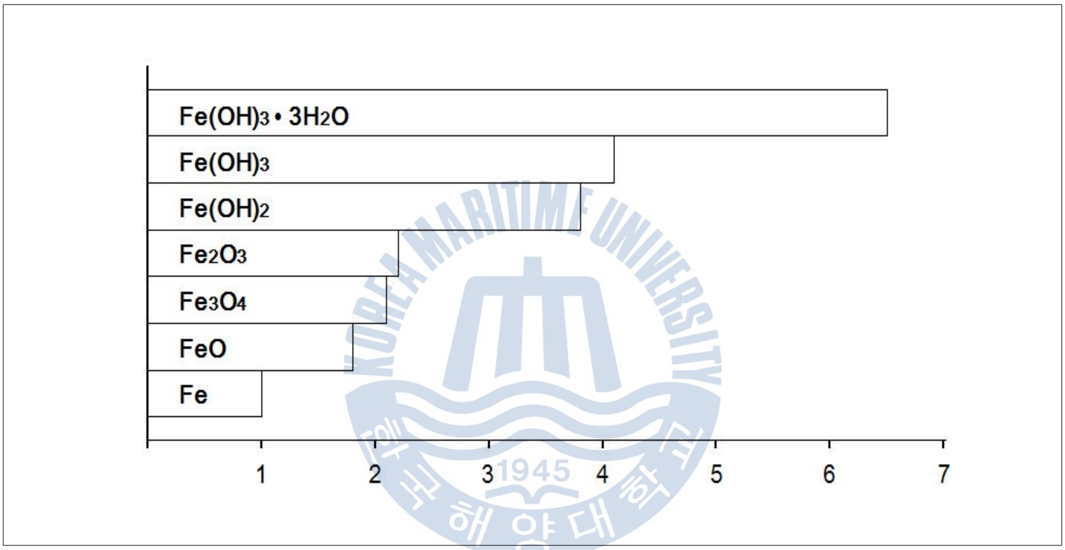

Figure 2.3: Relative volume of iron and its oxides [15]

This leads to the cracking and spalling of concrete structure. The corrosion reactions of steel in concrete are expressed as follows :

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$	Ferrous hydroxide	(2-4)
$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$	Ferric hydroxide	(2-5)
$2Fe(OH)_3 \rightarrow Fe_2O_3 \cdot H_2O + 2H_2O$	Hydrated ferric oxide	(2-6)

2.3 Corrosion of chloride-contaminated concrete

As described earlier, corrosion in reinforced concrete starts with the destruction of the passive layer on steel surface. There are two major conditions that causes the destruction of passive layer. One is carbonation which results in a drop of pH due to the reaction between carbon dioxide and concrete hydrates, producing calcite $CaCO_3$ and water [16-22].

The other is chloride attack. In this study, the electrolyte was seawater. Therefore, it is necessary to discuss more about the condition which contains it. Chloride attack is one of the major threats against the durability of reinforced concrete structure especially in marine and/or de-icing salt environments [4].

Corrosion caused by chloride ion is mainly pitting corrosion. The mechanism of pitting corrosion is somewhat different from that of general corrosion as shown in Figure 2.4. Passive layer is not perfect and pit nucleation is frequently occurred in chloride environment. Pit nucleation leads to the formation of soluble steel ions. These ions react with water to produce steel hydroxide and positive hydrogen ions.

Chloride ions which act as catalyst in corrosion are not consumed in these processes but help a break-down of the passive oxide layer on the steel surface. This is due to the production of hydrochloric acid formed by chloride and hydrogen ions. The local pH reduction promotes further steel dissolution and the acidification-dissolution cycle continues in the process of pit propagation [23].

In the chloride environment, the Potential/pH diagram of iron is significantly different from the original one(Figure 2.2). As shown in Figure 2.5, the area of pitting corrosion is expanded with the amount of chloride [1].

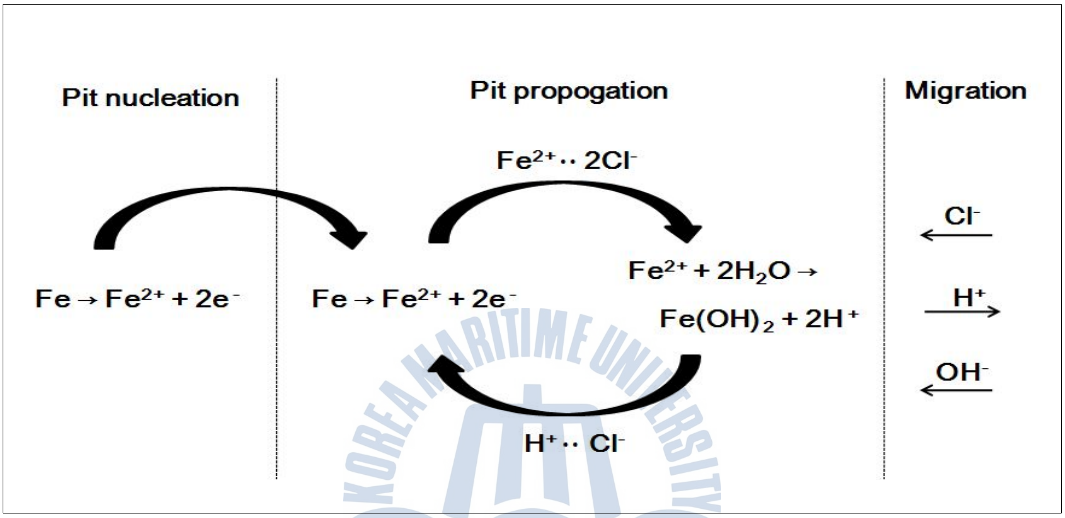

Figure 2.4: An illustration of pit-nucleation and pit-propagation processes leading to corrosion damage

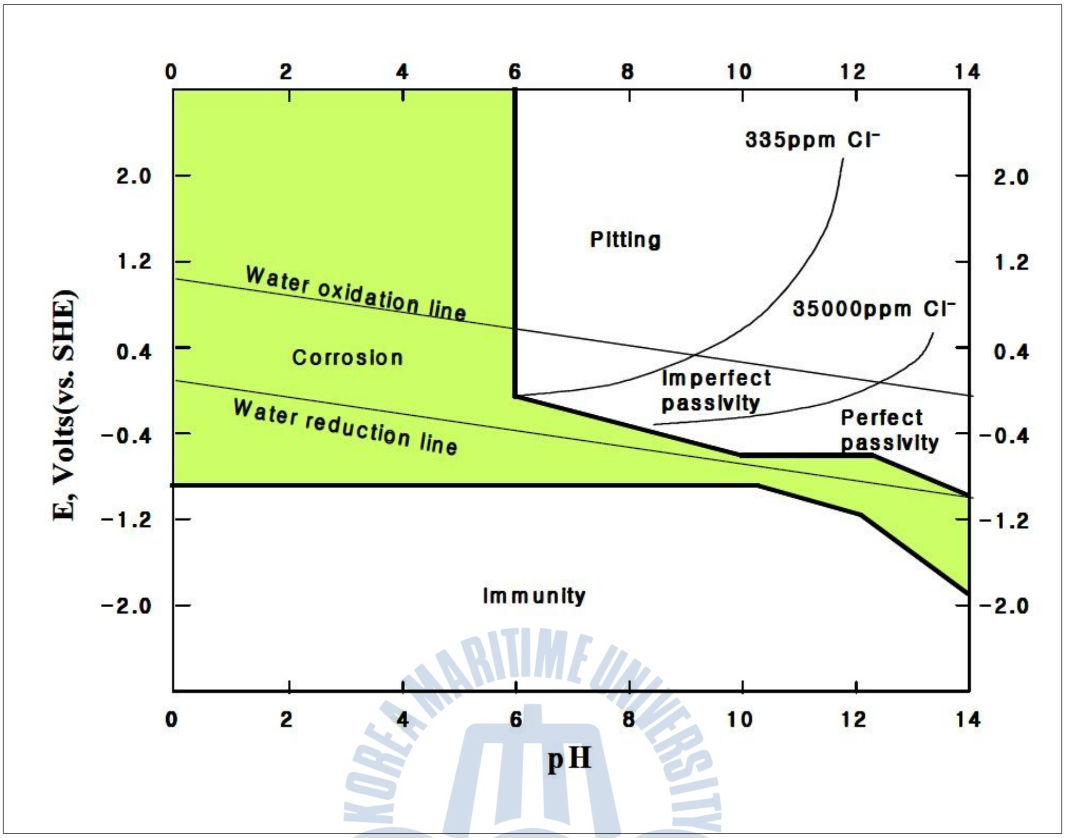

Figure 2.5: E-pH diagram in chloride environment [1]

2.4 Corrosion behavior in marine environment

Seawater cover more than 70% of earth's surface and it is considered as the most aggressive corrosion media to steel. For marine corrosion, seawater is the main corrosion agent, because it is a complex solution of a number of dissolved ionic salts, which reduce the resistivity of electrolyte. The seawater environment can be divided into four zones, i.e. submerged, tidal, splash and atmospheric zone according to the elevation of water level.

Atmospheric zone is the area which is above the highest water level where the structure is no longer continuously wet by spray. In this area, the major factors of corrosion are relative humidity, ambient temperature and chemical pollutants. Splash zone is a part which is wetted by waterdrop formed by wave. Tidal zone is the wet-dry area from low tide to high tide. In the splash and tidal zones, corrosion rate is significantly higher than that of the other zones, due to alternating wet-dry cycle by seawater resulting in severe corrosion. Submerged zone is the area in which is continuously contacted with sea water. In this area, the availability of dissolved oxygen in water is the most important factor to determine the corrosion rate [24].

2.5 Cathodic protection of reinforced concrete

Cathodic protection(CP) is an electrochemical technique to stop or to mitigate corrosion of metal exposed to conductive environments. It has been known as one of the effective methods against corrosion of steel in concrete [5].

The principle of CP is indicated in the iron-water potential/pH diagram shown in Figure 2.2. In this system, the corrosion potential of carbon steel lies in point A. If the corrosion potential go to down to the immunity zone, corrosion of the steel may not be occurred [13].

There are two kinds of CP system, i.e. sacrificial anode cathodic protection(SACP) and impressed current cathodic protection(ICCP). The principle of each CP system is the same, However, there are some differences in their features.

2.5.1 SACP system

SACP is also called as a galvanic protection. It is protective method which is the electric connection of steel with relatively active metals, such as magnesium(Mg), zinc(Zn) and aluminum(Al). As shown in Figure 2.6, it is a simple method which uses only potential difference between reinforced steel and sacrificial anode. The electrons move from sacrificial anode to reinforced steel.

Figure 2.7 show a simplified polarization diagram(E-log i relationship) for the SACP system. Before sacrificial anode is connected with reinforced steel, the reinforced steel is at the point C. In this anodic polarization, current density of reinforced steel is relatively high comparing with the original point B. If sacrificial anode is connected with reinforced steel, anodic polarization of sacrificial anode is increased up to the point D, and a strong protection current flows from the anode. Through this active current movement, the reinforced steel is depolarized to the point B, and protected by the current from sacrificial anode [25].

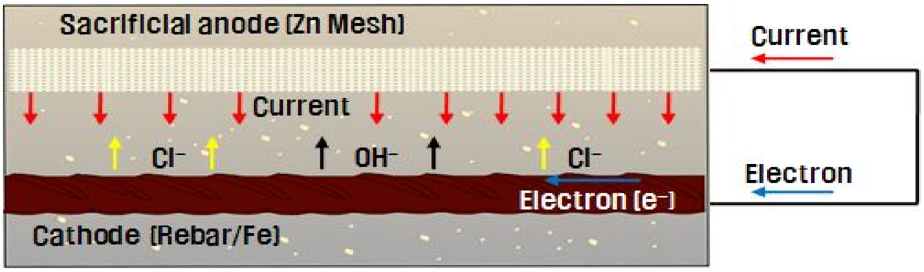

Figure 2.6: Schematic formation of SACP with Zn-mesh

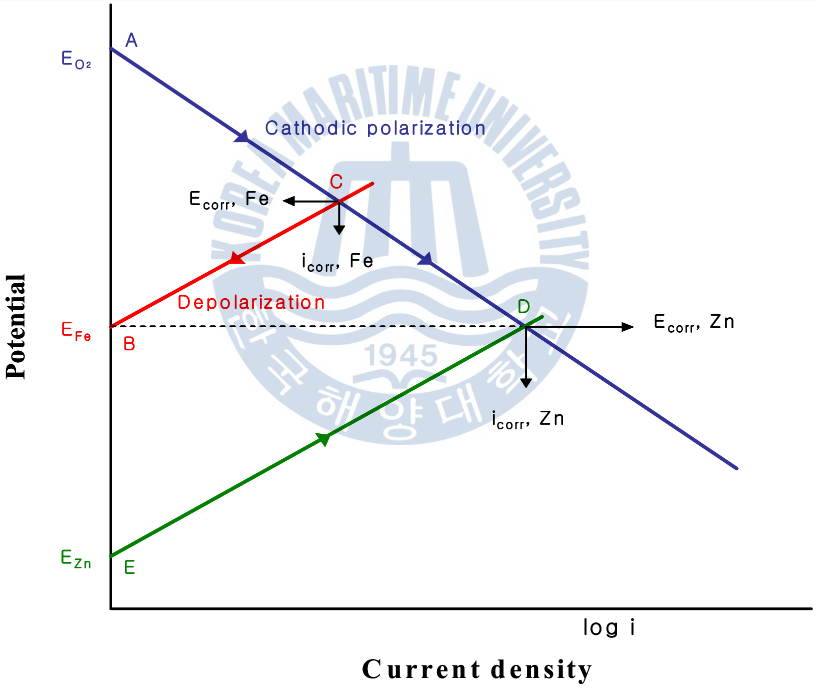

Figure 2.7: Typical polarization curve of SACP

2.5.2 ICCP system

ICCP is a system which provides impressed current by DC rectifier. The major difference between SACP and ICCP is the power supplier, i.e. DC rectifier, which is used in ICCP system. Because of DC rectifier, ICCP is possible to supply more electrons from anode to cathode than SACP system. The anode for ICCP should have high resistance against corrosion, like titanium mixed metal oxide(Ti-MMO).

As shown in Figure 2.8, direct current(DC) is obtained by the conversion of alternating current through rectifier. The positive(+) terminal of DC power supplier is connected to an anode(MMO/Ti-mesh), and the negative(-) terminal to the cathode(Rebar/Fe). This is a flow of electrons from anode to cathode through an conductor [26].

Figure 2.9 show a simplified polarization diagram(E-log i relationship) of ICCP system. When steel in concrete is in free corroding condition, the oxygen reduction in local cathode and the steel dissolution in local anode are occurred. The oxygen reduction is occurred from point A to C with cathodic polarization and the steel dissolution is occurred from point B to C with anodic polarization forming corrosion potential, E_{corr}, and corrosion current density, I_{corr}. With an external power supply, anodic polarization is proceed from point C via point B' to point B with the decrease of corrosion current density, and oxygen reduction in the cathode is increased from point C via point C' to point D. If there is not enough external current, the steel in concrete is only partially protected to the potential of point B'C' with current of $i_{C'} - i_{B'} = \Delta i'$. If there are enough protection current, the steel in concrete is totally protectied in the potential of point BD with current i_C - i_B = $\varDelta i$ [25].

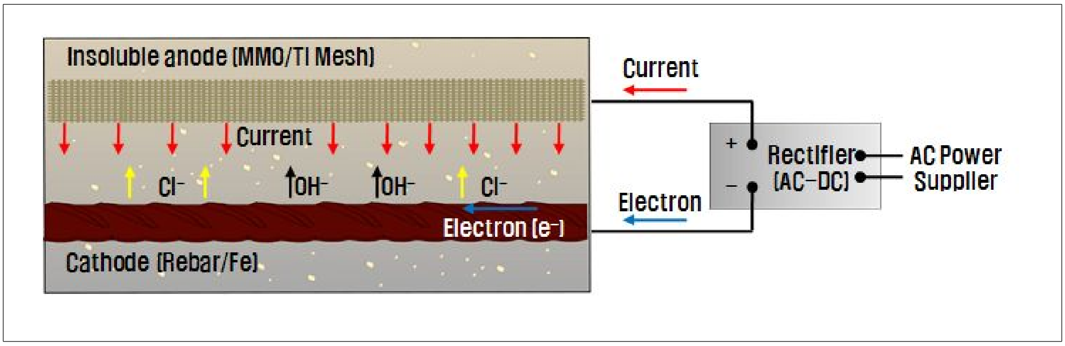

Figure 2.8: Schematic formation of ICCP with MMO/Ti-mesh

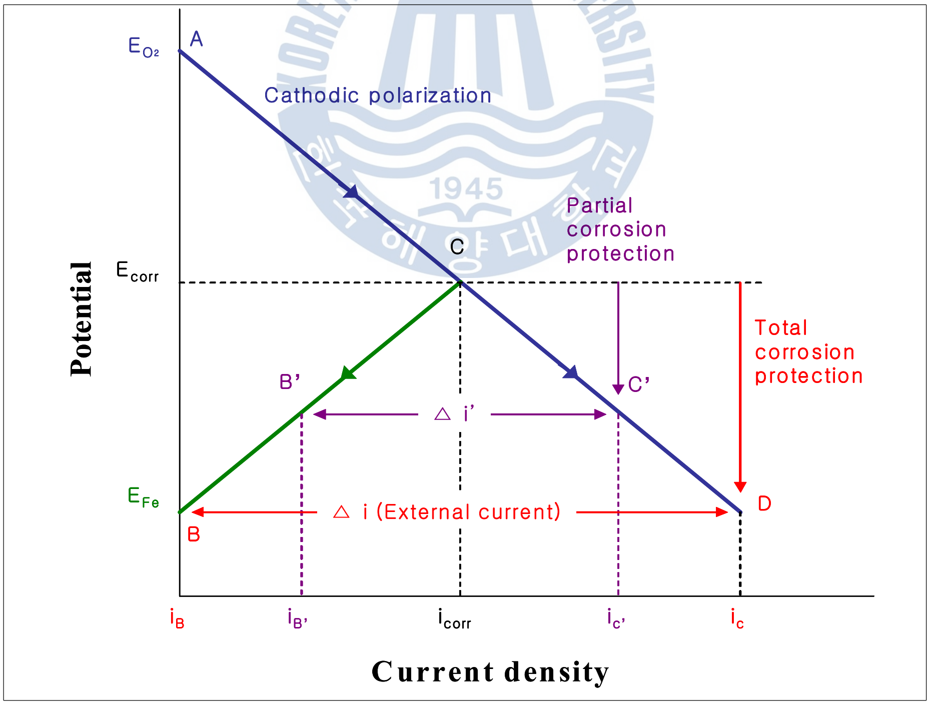

Figure 2.9: Typical polarization curve of ICCP

2.5.3 Hybrid CP system(combination of ICCP with SACP)

In partially submerged concrete structure, the resistivity is widely varied. In the upper dry region of concrete column, the resistivity becomes nearly 1 MΩ. In the fully submerged zone, however, it is as little as a few KΩ [27]. It is nearly impossible for SACP system to protect the high resistivity zone such as atmospheric one of concrete column. SACP, however, can be effectively adopted in submerged zone because of low resistivity. On the other hand, ICCP system can supply higher current density to reinforced steel due to its strong throwing power. It can be applied high resistivity region, like the atmospheric zone in partially submerged column. The advantages and disadvantages of both ICCP and SACP are summarized in Table 2.1 [25].

The hybrid CP system is a combination of SACP and ICCP to obtain the optimum protection of structures. This system maximizes the merits of two systems and minimizes their demerits.

In this study, the hybrid CP was applied to reinforced concrete column to obtain the optimum CP conditions. SACP is applied to the low-resistivity region, such as submerged and tidal zones, and ICCP is applied to the high-resistivity region, such as atmospheric and splash zones.

Table 2.1: Comparison of advantages and disadvantages for SACP and ICCP systems

SACP	ICCP
Advantages	
▪ Almost no required maintenance ▪ Easy to install ▪ Unnecessariness of power supplier ▪ Cost effective ▪ Suitable for low resistivity region	▪ Output control ▪ Long life ▪ Automatic monitoring ▪ Application in both soil and marine environments
Disadvantages	
▪ Periodic replacement of anode due to its limited lifetime ▪ Difficulty to apply in high-resistivity region ▪ Formation of passivity in high alkaline environment	▪ Power supply problem ▪ Partial failure affects the whole system ▪ Interference problem due to stray current ▪ Expertise requirement to install and use ▪ A lot of maintenance cost

Chapter 3

LITERATURE REVIEW

3.1 Availability of SACP in marine concrete column

As described earlier, a sacrificial anode system can be applied on the reinforced concrete structures, and it is attractive way to extend the service life when corrosion is started. In marine environment, the CP using sacrificial anode has been investigated by a number of authors [6-11,28]. The main purpose of these experiments was to determine both the feasibility and the performance of sacrificial anodes in practical field installations to the reinforced concrete structures in marine environment.

Sagues et al. [6] observed that the use of sacrificial anodes with sprayed zine provided sufficient CP current to the location of splash zone of marine reinforced concrete column, where high relative humidities and intermittent wetting of the surface are prevalent. They investigated through the depolarization measurement, with 100 mV depolarization criteria [31] in the splash zone, as listed the results in Table 3.1. From these results, authors asserted that the sprayed zinc sacrificial anode system could be an attractive economic alternative comparing to the conventional spall patching in marine substructure service.

Funahashi et al. [7] studied the aluminum alloy SACP system. This system was installed on selected prestressed concrete piles of a bridge in Florida, US, and monitored for three years. The potential of reinforced steels were satisfied with the 100 mV depolarization criteria by using aluminum alloy anodes during the three year period as shown in Table 3.2.

Bertolini et al. [9] observed that the submerged zone of reinforced concrete column in 3% chloride by weight of cement had sufficient CP performance by sacrificial anode. The result of depolarization tests showed that the submerged zone of reinforced concrete was depolarized close to 550 mV as indicated in Figure 3.1.

Kranc et al. [10] investigated in the effectiveness of CP system in marine piles by combining bulk(submerged zone) and surface(splash zone) anodes. A detailed computer modeling has been used for comparing with the experimental results. This study showed that the submerged and splash zones were protected by both bulk and surface anodes. When reinforced steels were connected with sacrificial anodes, the potential of submerged and splash zones were dropped up to -1,000 mV/SCE(more negative than -850 mV potential criteria [29]) as shown in Figure 3.2 and 3.3.

Table 3.1: 4 hour polarization decay test results by laboratory columns in terms of average potential shift(mV) [6]

Bar Level	Zone	Distance from Water Line(cm)	Exposure Time		
			345 Days	363 Days	650 Days
1	Air	71.12	30	60	27
2		53.34	60	60	45
3		35.56	160	220	127
4	Splash	17.78	260	310	252
5	Tidal(No-Cp)	-	-	-	3

Table 3.2: Depolarization values observed at test location #1 [7]

Test Date	Depolarization(mV)		Test Date	Depolarization(mV)	
	4h	24h		4h	24h
1995.10.25	250	300	1996.06.20	N/A	
1996.01.16	200	N/A	1996.07.16	N/A	
1996.02.15	90	100	1996.09.23	N/A	
1996.03.19	175	200	1997.01.12	N/A	
1996.04.17	82	N/A	1997.06.10	290	310
1996.05.13	N/A		1998.06.26	185	220

* N/A : Connection failed on pile

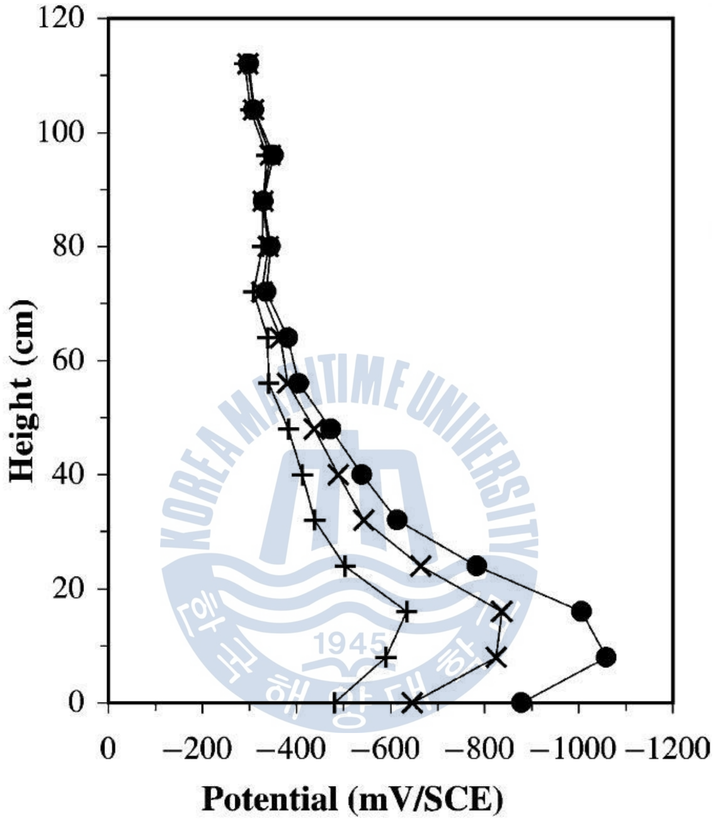

Figure 3.1: Potential distribution of steel in concrete with 3% chloride by weight of cement during a depolarization test carried out after 16 months of application of CP : E_{off}(–●–), $E_{off,4h}$(–×–), $E_{off,24h}$(–+–) [9]

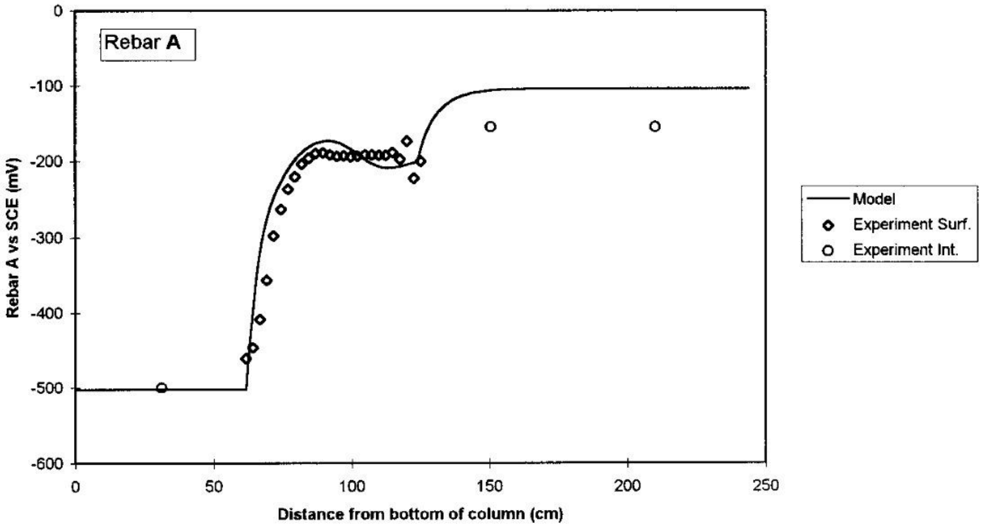

Figure 3.2: Potential at the concrete surface along each rebar (Not connected with sacrificial anode) [10]

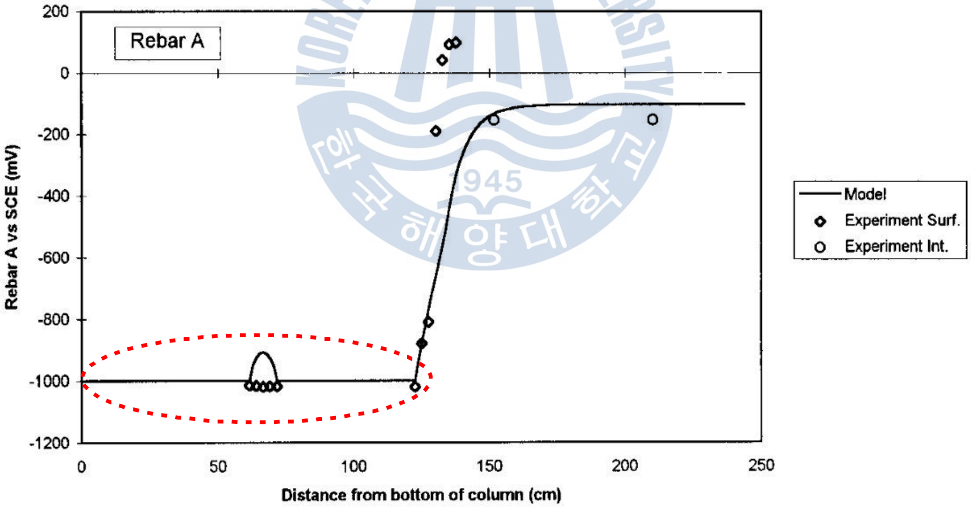

Figure 3.3: Potential at the concrete surface along each rebar (Connected with sacrificial anode) [10]

3.2 Throwing power of CP in sacrificial anode system

The sacrificial anode system is a very attractive way for cathodic protection(CP) since the cost of application is relatively cheap. It has inherent simplicity and low maintenance requirement [6-8]. The major problem of this system, however, is throwing power. In general, the throwing power in CP is defined as a distance of the point reaching CP current from anode. In column, it is the height at which protection can be achieved. In many studies, the CP current by sacrificial anodes was limited to a few tens of centimeters from the water line, depending on the concrete resistivity [8-9, 11, 28].

Bertolini et al. [9] observed that sacrificial anode was less effective to protect the corroded bars above sea water line. From the results of 4 hour depolarization tests for the reinforced concrete contaminated with chloride, it was found that the higher than 100 mV was only observed for the bars up to 40 cm above water line as shown in Figure 3.4.

Presuel-Moreno et al. [11] studied on the effectiveness of CP system in marine piles by sacrificial anodes. Figure 3.5 shows the test results of depolarization potential. Up to 30 cm above the water line, the depolarization potential was more than 100 mV, and in higher elevation than 30cm, it was only 50 mV. It means that areas of 30 cm above the water line is hard to protect by only sacrificial anode.

Hartt [28] conducted other study on the cathodic prevention in partially submerged reinforced concrete column with sacrificial anodes. In Figure 3.6, the depolarization potential of all portions except for 10cm above water line was less than 100 mV.

These results showed that sacrificial anode was hard to protect in high resistivity condition. In this study, therefore, hybrid CP system was adopted to obtain optimum CP potential for not only low resistivity area but also high one of entire structures.

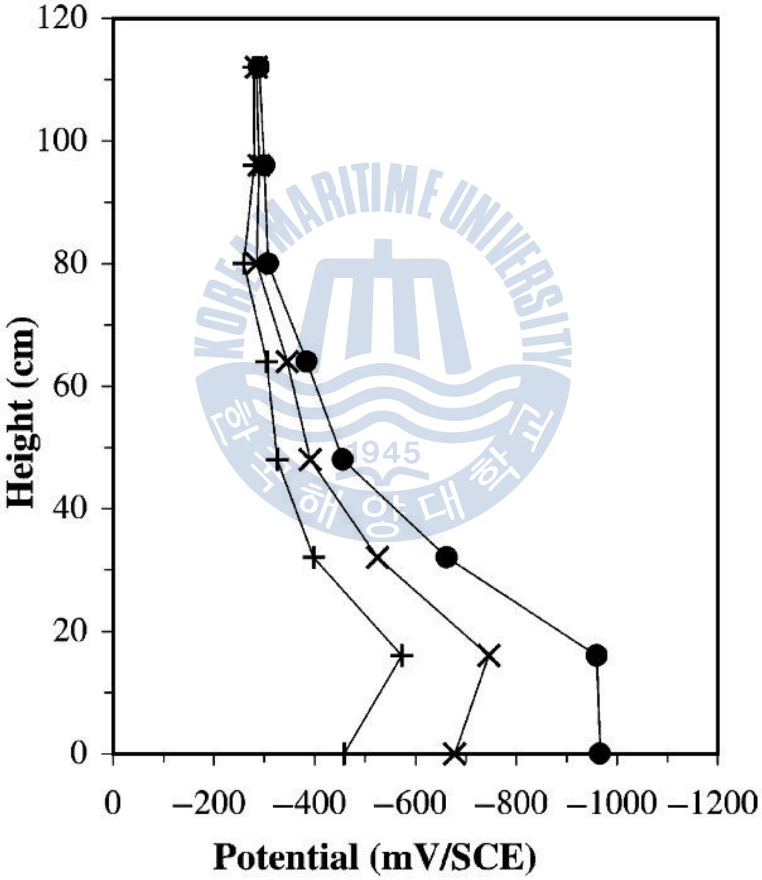

Figure 3.4: Potential distribution of steel in concrete with 3% chloride by weight of cement during a depolarization test carried out after 16 months of CP application [9]

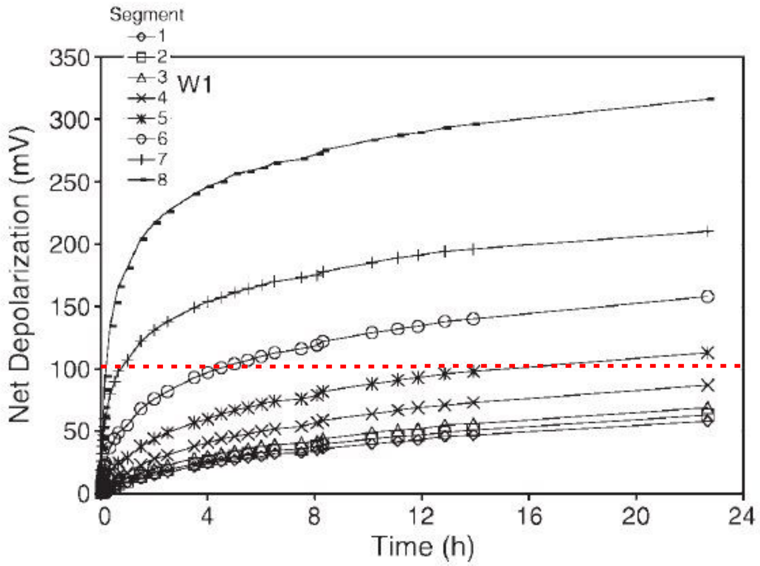

Figure 3.5: Depolarization measured for rebar segment of column [11]

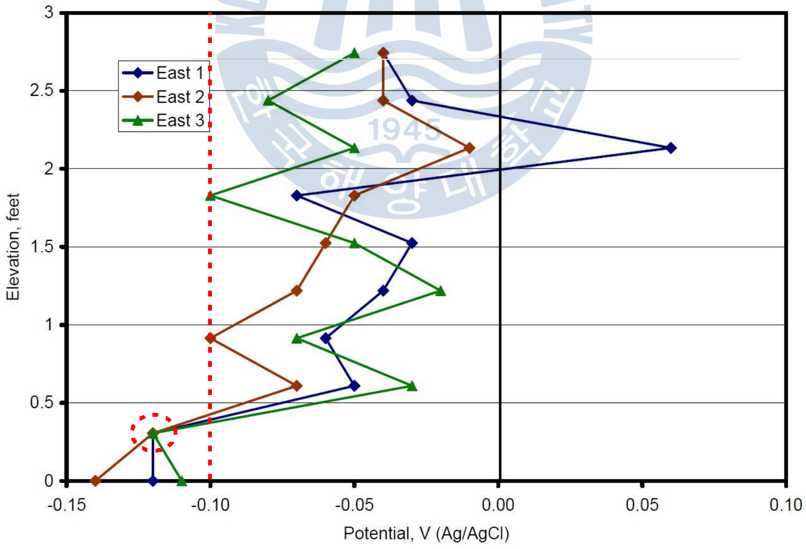

Figure 3.6: Depolarization of column after two hours [28]

Chapter 4

EXPERIMENTAL PROCEDURES

4.1 Specimens

The specimen prior to the installation of CP system is shown in Figure 4.1. It was the reinforced concrete beam type column with a base of 150 mm × 150 mm and height of 1,200 mm. The reinforced steel was a typical carbon steel for concrete structures with 16 mm diameter and 1,300 mm long(ASTM #5), and four rebars were embedded in a rectangular shape in concrete. The top 100 mm of rebar was exposed to atmosphere for an electric connection. Concrete mixed design is given in Table 4.1.

After casting, the specimens were cured in the laboratory at a room temperature(20 ± 2℃) for 30 days. The casting and curing processes are shown in Figures 4.2 and 4.3, respectively.

Initially the specimens were corroded in seawater by weekly aging cycle, i.e. four-day wetting and three-day drying for two years. Wet-dry cycles have been conducted by natural seawater to simulate the tidal and splash zones in marine condition.

Table 4.1: Concrete mixed design of reinforced concrete specimen

Gmax	Slump	Air	W/C	S/a	Unit Quantity(kg)			
					Water	Cement	S	GA
9.5mm	10cm	5%	51%	53.3%	210	411	845	752.4

where,

· Gmax = Maximum size of coarse aggregate

· GA = Coarse aggregate

· S = Fine aggregate

· W/C = Water-cement ratio

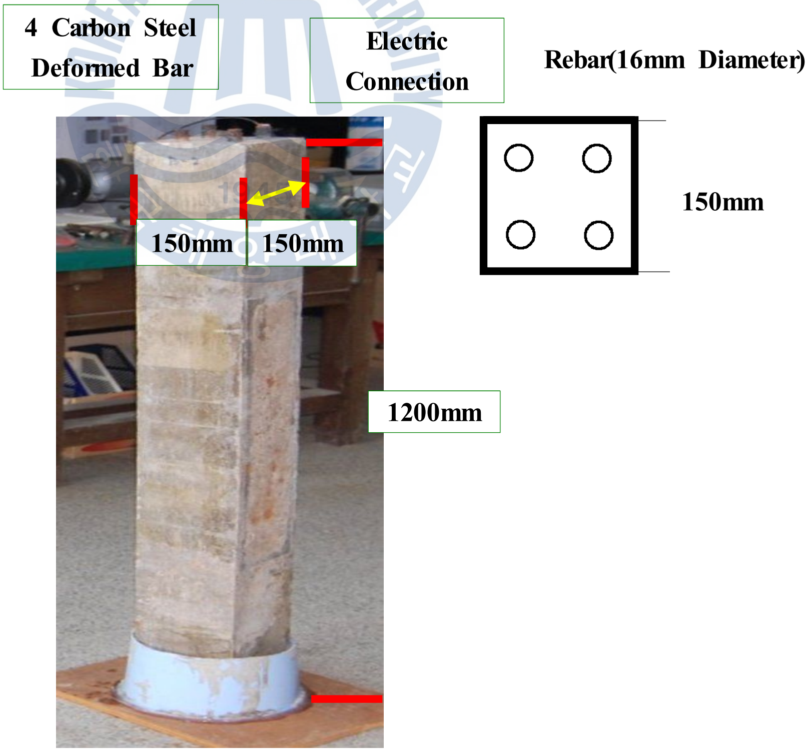

Figure 4.1: Beam-type column specimen with dimension

Figure 4.2: Manufacturing process of specimens

Figure 4.3: Curing of specimens

4.2 Design of CP

The design of CP is shown in Figure 4.4. Each section, which was submerged, tidal, splash and air zones, was divided into 30 cm. The anodes applied in this study were the mixed metal oxide(MMO) titanium mesh for ICCP system, and zinc rod anode for SACP system.

The main difference between Specimens #1 and #2 was the range of ICCP anode installation. The ICCP anode of Specimen #1 was applied in atmospheric zone(top 30 cm), and the ICCP anode of Specimen #2 was in splash zone as well as air one(top 60 cm). The sacrificial anode was only used in the wet condition(submerged and tidal zones).

4.3 Setup of test equipments

After installing the specimens in a tank, natural seawater was supplied. As previously shown in Figure 4.4, zinc bulk anodes were installed in the immersed part of specimens, which can protect in both low and high tide conditions. The rectifier to supply CP current was CR-1212 Power Supply Unit with monitoring not only CP potential & current but also 4 hour depolarization potential. Reference electrode was silver/silver chloride electrode(SSCE). Eight reference electrodes were installed in each specimen with elevation. One reference electrode was installed in submerged and air zones, and three references were in tidal and splash zones at interval of 7.5 cm to monitor CP potential precisely, since relatively severe corrosion damage was expected in these areas. Reference electrode was pre-wetted to decrease any the electrical resistance in the circuit [30]. Target potential for ICCP was -760 mV/SSCE, which is satisfied with the CP criteria for carbon steel according to NACE standard [31].

4.4 Procedures & analysis

Test environment and conditions are given in Table 4.2. First, CP was applied by only zinc-rod anode(SACP) in the low tide(30 cm). After this experiment, hybrid CP(combination of ICCP and SACP) was applied. Second, water level was enhanced up to the high tide(60cm), and CP was applied again by only zinc-rod anode. Hybrid CP was followed thereafter. Third, water level was changed again from high to low tide. These procedures have been repeated twice for reproducibility. There was about one week gab for a potential stability period between each test with different condition.

The test parameters were natural corrosion potential, CP potential, CP current and 4 hour depolarization potential. These parameters have been monitored through the DC power supplier, which were measured and stored every minute by a computer system. Test specimens and monitoring equipments are shown in Figure 4.5.

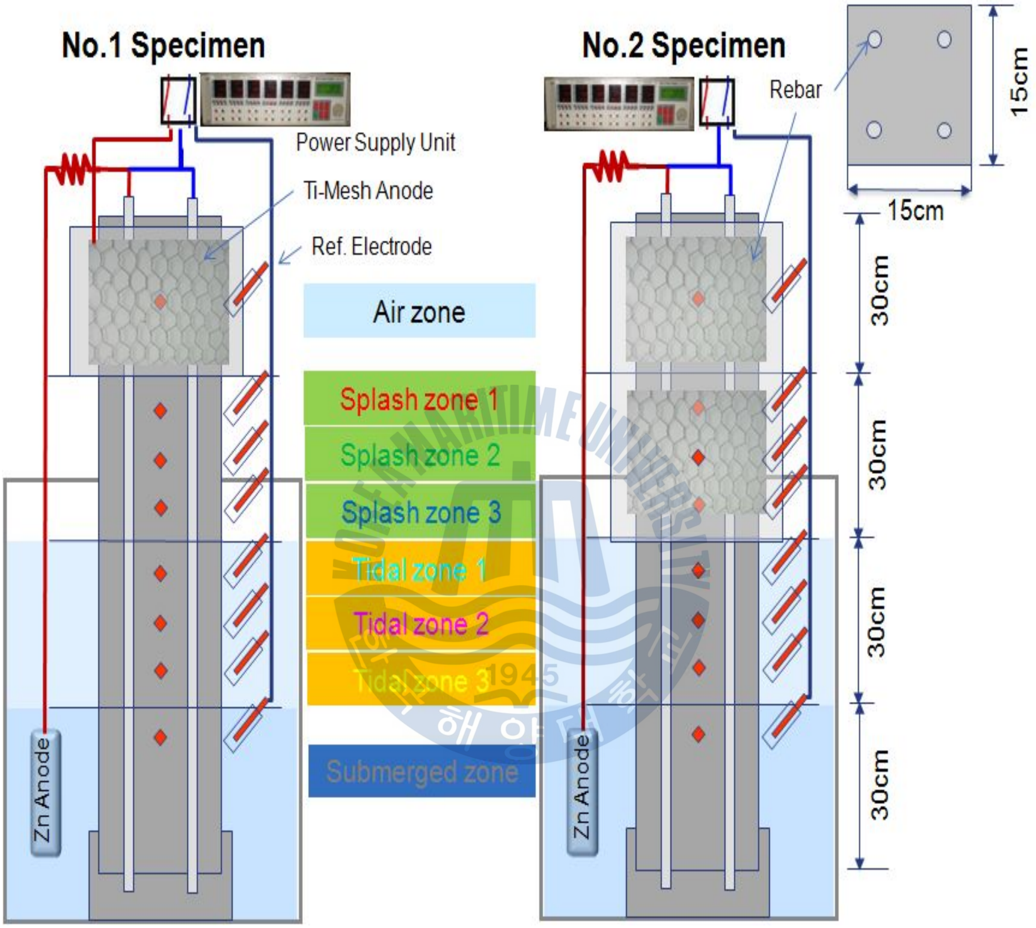

Figure 4.4: Schematic of specimens installed anodes and reference electrodes for cathodic protection

Table 4.2: Experimental environments and conditions

Water Level	Method of Cathodic Protection	
Low tide (30 cm)	SACP	Hybrid CP (SACP+ICCP)
High tide (60 cm)	SACP	Hybrid CP (SACP+ICCP)
From high to low tide (60 → 30 cm)	Hybrid CP (SACP+ICCP)	
From low to high tide (30 → 60 cm)		

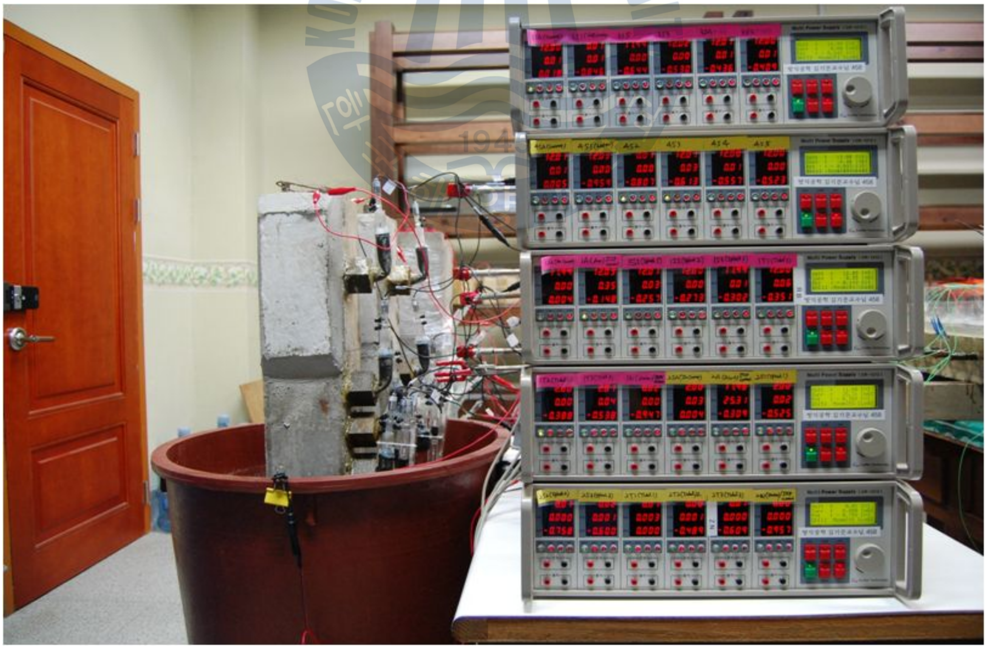

Figure 4.5: Overall view of the experiment

Chapter 5

RESULTS & DISCUSSION

5.1 Experimental results

5.1.1 Test results of SACP at low tide(water level 30 cm)

Figures 5.1 and 5.2(Specimens #1 and #2) show the potential change of reinforced steel at the 8 points of installed reference electrodes after SACP was applied to the low tide zone(water level 30 cm). As indicated in Figure 5.1, when zinc bulk anode was connected to the steel in concrete, the potential above 52.5 cm elevation(tidal zone 3) which was equivalent to 22.5 cm above water level was no change irrespective of CP.

However, the portion below 52.5 cm elevation showed potential change according to elevation after connecting with sacrificial anode. The potential change in the submerged zone was about 650 mV(potential was dropped from -350 mV/SSCE to -995 mV), and those at the elevation of 7.5 cm and 15 cm above the water line were about 200 mV and 50 mV, respectively.

Specimen #2 showed a similar characteristics compared to Specimen #1. As illustrated in Figure 5.2, after connecting to the SACP system, potential change in submerged zone was 594 mV(potential was dropped from -401 mV/SSCE to -995 mV). Moreover, the potential change was occurred up to 67.5 cm elevation. At the 7.5, 15 and 22.5 cm elevations above the water line(tidal zone 1, 2 and 3), potential changes were about 150 mV, 50 mV and 30 mV, respectively. As the same as Specimen #1, the potential at high elevation(above 67.5 cm) was no changed. Specific figures of measured potential change are listed in Table 1 and 2.

Through these results, it was found that the submerged zone was fully protected by SACP system only. The potential of submerged zone was dropped to -995 mV/SSCE, which met -850 mV/CSE(-760 mV/SSCE) potential criteria of NACE [29]. However, CP current was not reached above 30 cm from water line, which was the similar trend recognized through the potential drop results. This means that the SACP system has a limitation to supply CP current in high resistivity area.

Table 5.1: Potential changes at low tide applied to SACP (Specimen #1)

Before connecting anode		After connecting anode		Potential change(mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-350	15.0	-995	645
37.5	-357	37.5	-568	211
45.0	-367	45.0	-414	47
52.5	-365	52.5	-398	33
67.5	-362	67.5	-354	8
75.0	-380	75.0	-381	1
82.5	-385	82.5	-386	1
105.0	-201	105.0	-203	2

* Elevation : Height from the bottom

Table 5.2: Potential changes at low tide applied to SACP (Specimen #2)

Before connecting anode		After connecting anode		Potential change(mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-401	15.0	-995	594
37.5	-330	37.5	-476	146
45.0	-342	45.0	-386	44
52.5	-359	52.5	-384	25
67.5	-383	67.5	-390	7
75.0	-383	75.0	-385	2
82.5	-385	82.5	-395	10
105.0	-191	105.0	-190	-1

* Elevation : Height from the bottom

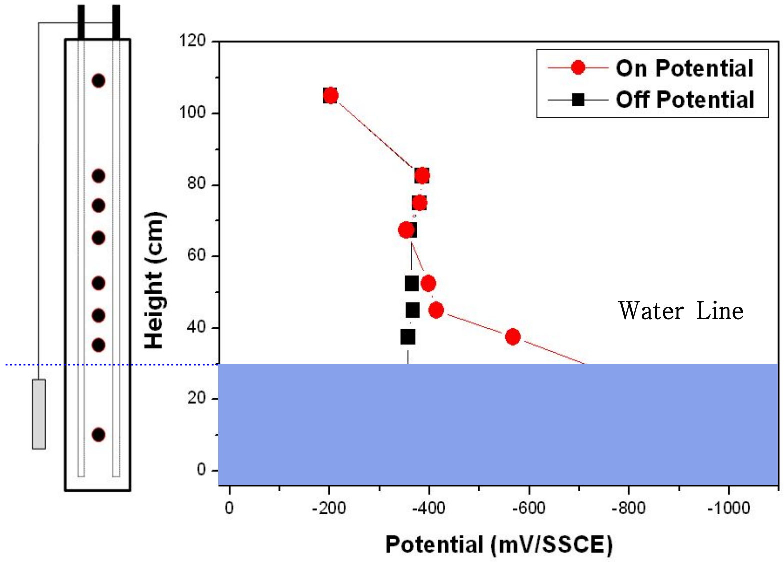

Figure 5.1: Potential changes with elevation between CP on & off states (Low tide, Specimen #1)

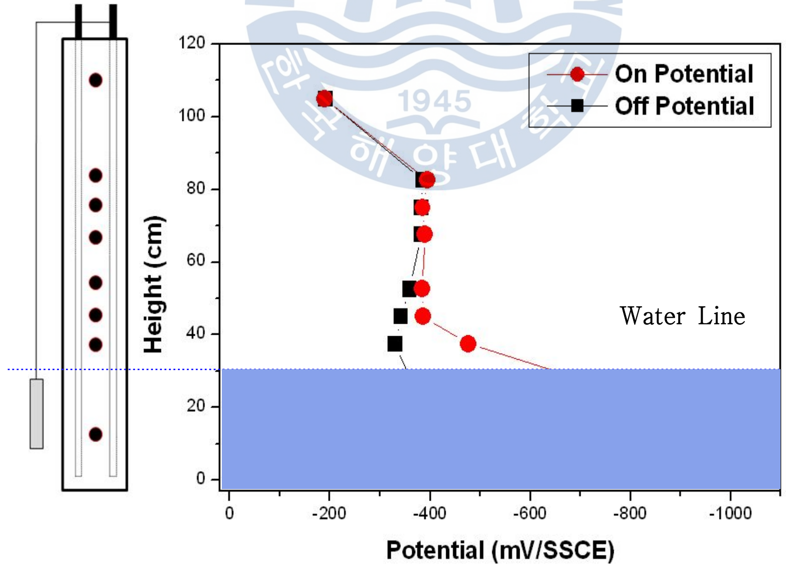

Figure 5.2: Potential changes with elevation between CP on & off states (Low tide, Specimen #2)

Depolarization tests have been regularly carried out by disconnecting the sacrificial anodes from the steel bars for 4 hours. During the depolarization test, potential was recorded and stored through a monitoring system. CP applied to the steel in concrete was considered to be effective, if 4 hour depolarization potential was higher than 100 mV. Especially the -850 mV/CSE (-760 mV/SSCE) criteria which is the criteria for carbon steel is difficult to apply to the steel in concrete, since the potential of steel in concrete is higher than that of without concrete due to the formation of passive layer. In this experiment, 100 mV depolarization criteria was adopted according to the NACE criteria [31]. Figure 5.3 shows typical depolarization curves obtained by monitoring software.

Figures. 5.4 and 5.5 show the comparison of potential along the height of specimen before/after the depolarization tests carried out for 4 hours. The trend of these depolarization measurements was similar to the CP potential change as shown in Figures 5.1 and 5.2. The submerged zone of Specimen #1 and #2 showed the most highest depolarization. Up to 22.5 cm elevation above water line, the depolarization potential was varied, however, the higher position of that showed the same of potential between two specimens. The depolarization of submerged zone were about 520 mV and 450 mV for Specimens #1 and #2, which satisfied with the NACE criteria. Above the water line, however, depolarization potential were little(less than 100 mV), which means that sacrificial anode represented the limitation. The exact figures of depolarized potentials are summarized in Table 5.3 and 5.4(Specimens #1 and #2, respectively).

In Figure 5.6, the height of satisfied 100 mV depolarization potential criteria was only up to 37.5 cm from the bed, which was corresponds to 7.5 cm above the water line.

From these reasons, it was understood that the major problem of sacrificial anode is the current supplying ability, since the current generation of sacrificial anode is relatively low to send it far from anode. When it is applied to the high resistivity region, such as concrete or dry soil, it becomes difficult to protect the structures properly.

Figure 5.3: Depolarization test curves measured by computer software

Table 5.3: 4-h depolarization potentials by SACP at low tide(Specimen #1)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-995	15.0	-478	517
37.5	-568	37.5	-370	198
45.0	-414	45.0	-396	18
52.5	-396	52.5	-392	4
67.5	-356	67.5	-355	1
75.0	-380	75.0	-379	1
82.5	-386	82.5	-386	0
105.0	-203	105.0	-201	2

* Elevation : Height from the bottom

Table 5.4: 4-h depolarization potentials by SACP at low tide(Specimen #2)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-996	15.0	-564	432
37.5	-446	37.5	-341	105
45.0	-384	45.0	-348	36
52.5	-385	52.5	-375	10
67.5	-393	67.5	-389	4
75.0	-373	75.0	-369	4
82.5	-409	82.5	-406	3
105.0	-190	105.0	-186	4

* Elevation : Height from the bottom

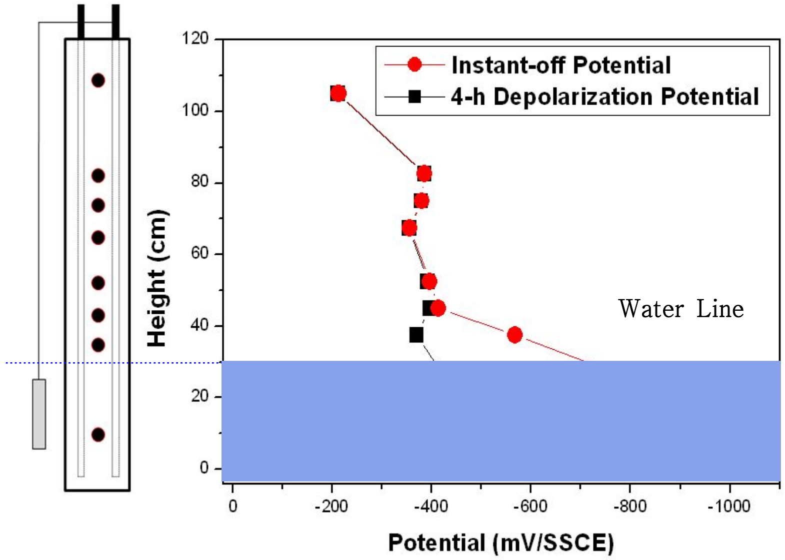

Figure 5.4: 4-h depolarization potential of steel with/without SACP (Low tide, Specimen #1, SACP)

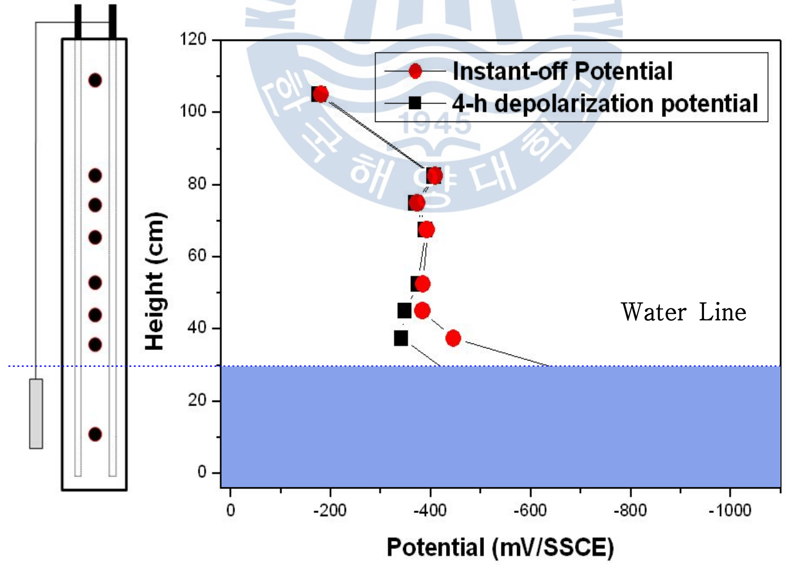

Figure 5.5: 4-h depolarization potential of steel with/without SACP (Low tide, Specimen #2, SACP)

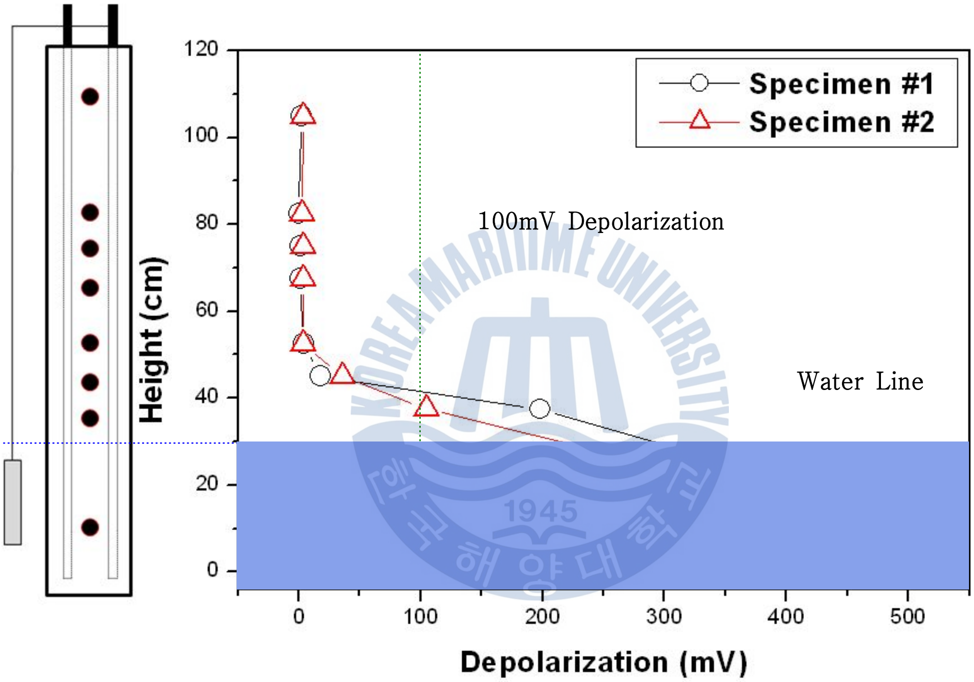

Figure 5.6: 4-h depolarization test results after disconnecting sacrificial anode (Low tide, Specimen #1 and #2, SACP)

5.1.2 Test results of hybrid CP at low tide(water level 30 cm)

Figures 5.7 and 5.8(Specimens #1 and #2) show the potential change of reinforced steel at the 8 points of installed reference electrodes after both SACP and ICCP have applied to the low tide(water level 30cm).

Below the water line, sacrificial anode was applied, and titanium anode, i.e. the anode of ICCP system which was applied above the water line and was different depending on the number of specimens. ICCP was only applied to atmospheric zone in Specimen #1. On the other hands, in Specimen #2, the protection area of ICCP system was extended to splash zone as well as air one. Titanium mesh anode was adopted in this ICCP system as mentioned earlier. The results between Specimens #1 and #2 were somewhat different due to the installation of additional titanium mesh anode.

In Specimen #1, the potential of submerged zone was maintained to -996 mV/SSCE. The CP potentials by sacrificial anode were influenced up to 7.5 cm above water line, which showed -545 mV/SSCE. It was the same trend as the previous results, and the effects of ICCP was observed as well. The area of ICCP system represented the potential to -760 mV/SSCE, which was the area range between 90 cm and 120 cm of height. The area away from ICCP system also showed the slight potential drop. The potential of splash zone 3, which was 7.5 cm away from air zone, was dropped up to -436 mV/SSCE. However, there was no more effect beyond the area, since the ICCP system did not influence to the area due to too high resistivity.

The potential change of Specimen #2 was somewhat different from Specimen #1 because of ICCP anode installation. Since the space between

ICCP anodes was extended, the potential of splash zone was dropped to a negative direction.

The potential of submerged zone(30 cm height) was decreased to -1,000 mV. Moreover, that of areas above 37.5 cm elevation(Tidal zone 1) dropped to -473 mV.

Due to the extension of ICCP anode from 60 cm to 120 cm of height, the potential drop of these areas was confirmed. The potential of air zone, which was the range from 90 cm to 120 cm of height, was dropped to -760 mV, which was the target CP potential of NACE criteria. In addition, between 60 cm and 90 cm of height, the splash zone, also dropped to -700 ~ -850 mV/SSCE. In this area where ICCP anode was not installed, potential was little changed.

These results showed that the role of ICCP anode was significant in CP. In Specimen #2, most parts were protected by both CP systems, however, Specimen #1 had under-protection region due to the lack of ICCP anode. If Specimen #1 is located in natural environment, its splash zone is anticipated to be corroded. Specific figures of potential change are summarized in Table 5.5 and 5.6(Specimens #1 and #2)

Table 5.5: Potential changes at low tide applied to hybrid CP system(Specimen #1)

Before connecting titanium anode		After connecting titanium anode (Hybrid CP)		Potential change(mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-483	15.0	-996	513
37.5	-370	37.5	-545	175
45.0	-396	45.0	-415	19
52.5	-392	52.5	-400	8
67.5	-355	67.5	-365	10
75.0	-379	75.0	-380	1
82.5	-386	82.5	-436	50
105.0	-211	105.0	-760	549

* Elevation : Height from the bottom

Table 5.6: Potential changes at low tide applied to hybrid CP system(Specimen #2)

Before connecting titanium anode		After connecting titanium anode (SACP + ICCP)		Potential change(mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-564	15.0	-998	434
37.5	-341	37.5	-473	132
45.0	-348	45.0	-428	80
52.5	-375	52.5	-470	95
67.5	-389	67.5	-816	427
75.0	-369	75.0	-840	471
82.5	-406	82.5	-728	322
105.0	-177	105.0	-760	583

* Elevation : Height from the bottom

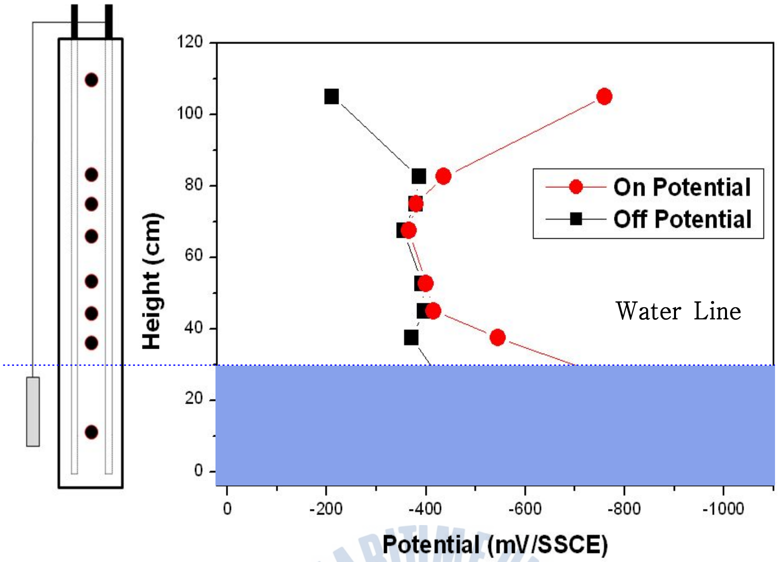

Figure 5.7: Potential changes when hybrid CP system was applied (Low tide, Specimen #1)

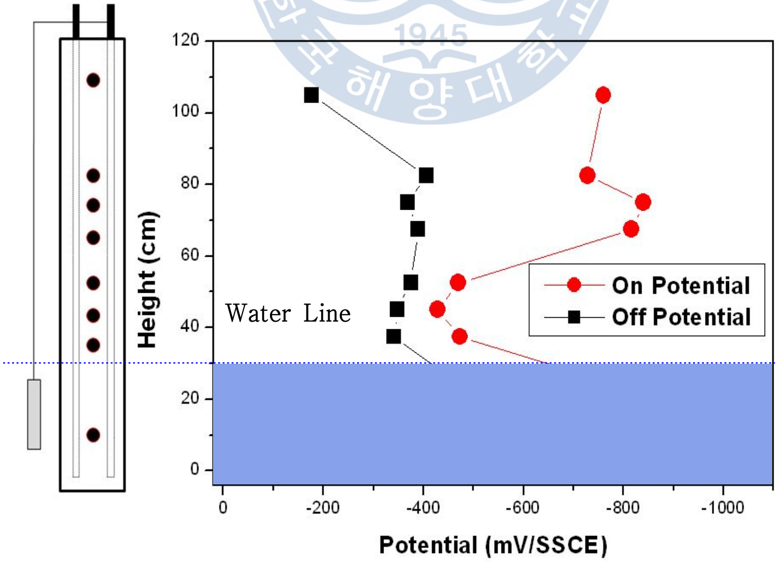

Figure 5.8: Potential changes when hybrid CP system was applied (Low tide, Specimen #2)

Table 5.7 and 5.8(Specimens #1 and #2) are listed specific figures of 4-hour depolarization potential measurements, and Figures 5.9 and 5.10(Specimens #1 and #2) show the distribution of depolarization potentials for 4 hours along the height of specimens.

In Specimen #1, 4-hour depolarization was relatively high in the lower part of specimen(immersed area) where titanium anode was installed. The depolarization potential of submerged zone was 499 mV, and that of 7.5 cm height above the water line was 189 mV which was influenced by sacrificial anode. The air zone was affected by the ICCP system with titanium anode and its depolarization potential was 598 mV.

In Specimen #2, 4-hour depolarization was somewhat different. The trend that immersion zone(submerged zone) was influenced by SACP with zinc anode was similar. The depolarization potential of splash zone, however, was relatively high compared to Specimen #1, due to the ICCP system in splash zone as well as air one.

In Specimen #1, depolarization potential of splash zone was very low. When hybrid CP system was applied to the Specimen #1, the difficulty to protect splash zone was observed as anticipated. On the other hand, splash zone was well portected by ICCP system in Specimen #2. The depolarization potential of its splash zone was in range of 300 ~ 400 mV.

Figure 5.11 shows the variation of depolarization potential with height both Specimens #1 and #2. When hybrid CP was adopted at the low tide, Specimen #1 had a difficulty to protect the splash zone. However, it had no problem in Specimen #2, since the depolarization potential was 300 ~ 400 mV which was well satisfied 100 mV of CP criteria.

Table 5.7: 4-h depolarization at low tide applied to hybrid CP system (Specimen #1)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-996	15.0	-497	499
37.5	-545	37.5	-356	189
45.0	-415	45.0	-398	17
52.5	-400	52.5	-395	5
67.5	-365	67.5	-363	2
75.0	-380	75.0	-353	27
82.5	-436	82.5	-373	63
105.0	-760	105.0	-162	598

* Elevation : Height from the bottom

Table 5.8: 4-h depolarization at low tide applied to hybrid CP system (Specimen #2)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-998	15.0	-569	429
37.5	-473	37.5	-357	116
45.0	-428	45.0	-363	65
52.5	-470	52.5	-396	74
67.5	-816	67.5	-406	410
75.0	-840	75.0	-404	436
82.5	-728	82.5	-410	318
105.0	-760	105.0	-323	437

*Elevation : Height from the bottom

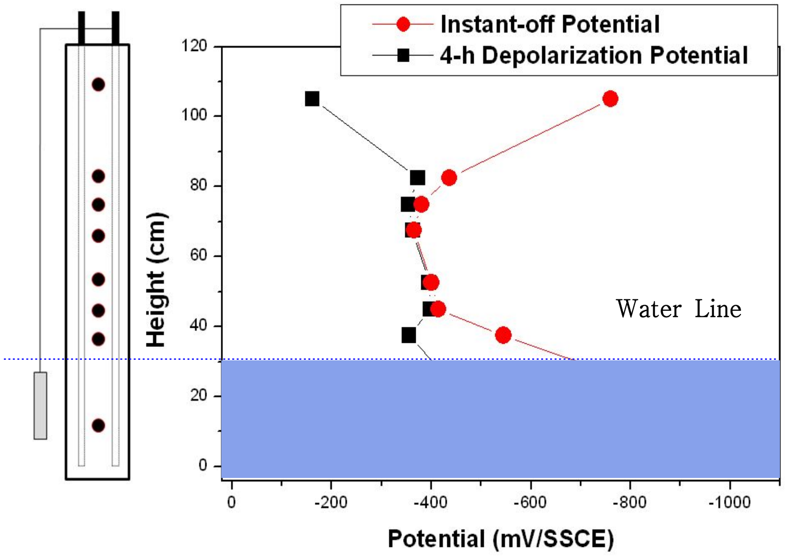

Figure 5.9: 4-h Depolarization test of steel in concrete contaminated with chloride. Only the sacrificial anode was disconnected. (Low tide, Specimen #1, Hybrid CP)

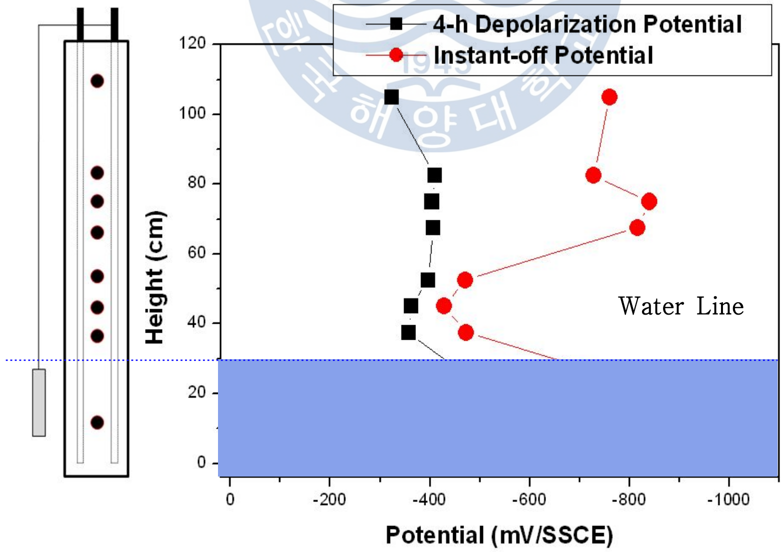

Figure 5.10: 4-h Depolarization test of steel in concrete contaminated with chloride. Only the sacrificial anode was disconnected. (Low tide, Specimen #2, Hybrid CP)

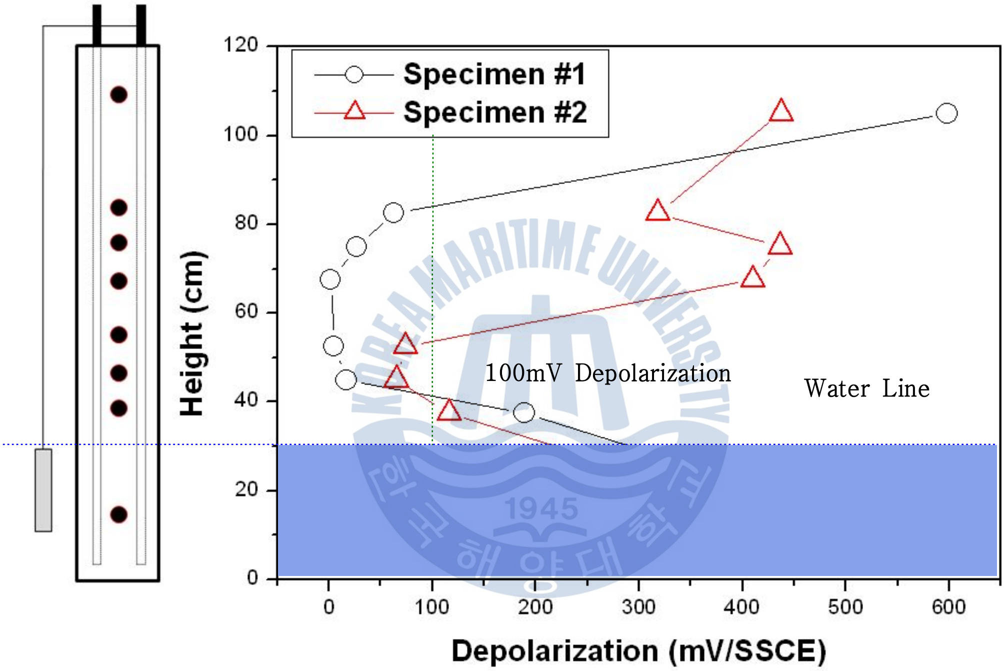

Figure 5.11: 4-h depolarization test result after disconnecting hybrid CP system (Low tide, Specimen #1 and #2)

5.1.3 Test results of SACP at high tide(water level 60 cm)

After experiments at low tide, water level was enhanced to high tide (water level 60 cm). At the high tide, the potentials of tidal zone as well as submerged zone were ranged in 800 ~ 1,000 mV/SSCE. It was hardly seen in the water level 30 cm with SACP, where tidal zone was not protected. In addition, some protection effect has been indicated in these areas, however, there were not enough potential change beyond the water line. These test results are summarized in Table 5.9 and 5.10.

Figures 5.12 and 5.13(Specimens #1 and #2) show the depolarization potential of reinforced concrete when SACP was applied at high tide. Through the 4 hour depolarization tests, protection effect by SACP was analyzed. In Figure 5.12, 4 hour depolarization potential of Specimen #1 was significantly high in immersion portion(submerged and tidal zones). At the 7.5 cm above the water level(splash zone 3), 50 mV depolarization potential took place. At the 7.5 cm above water level, however, depolarization was much less than 100 mV standard.

The trend of Specimen #2 was similar to that of Specimen #1(Figure 5.12). In the case of submerged zone, the protection potential of Specimen #2 was less than that of Specimen #1. 4 hour depolarization results, however, were similar in both cases. More than 100 mV depolarization was observed in the immersed areas of Specimen #2. These results are given in Table 5.11 and 5.12.

Figure 5.14 shows 4 hour depolarization of Specimen #1 at both low and high tide conditions. Regardless of the height of water level, SACP could not protect the high resistivity areas. In this study, the areas of 7.5 cm above the water line were hardly protected by SACP with zinc anodes.

Table 5.9: Potential changes at high tide applied to SACP system (Specimen #1)

Before high tide		After high tide		Potential change(mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-374	15.0	-975	601
37.5	-332	37.5	-930	598
45.0	-384	45.0	-890	506
52.5	-434	52.5	-903	469
67.5	-360	67.5	-592	232
75.0	-351	75.0	-401	50
82.5	-345	82.5	-347	2
105.0	-164	105.0	-175	11

* Elevation : Height from the bottom

Table 5.10: Potential changes at high tide applied to SACP system (Specimen #2)

Before connecting anode		After connecting anode		Potential change(mV)
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-401	15.0	-985	584
37.5	-302	37.5	-893	591
45.0	-336	45.0	-888	552
52.5	-379	52.5	-879	500
67.5	-389	67.5	-637	248
75.0	-370	75.0	-541	171
82.5	-382	82.5	-529	147
105.0	-262	105.0	-212	-50

* Elevation : Height from the bottom

Table 5.11: 4-h depolarization at high tide applied to SACP system (Specimen #1)

Instant-off potential		**4-h depolarized potential**		**Depolarization (mV)**
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-975	15.0	-831	144
37.5	-930	37.5	-799	131
45.0	-890	45.0	-786	104
52.5	-903	52.5	-793	110
67.5	-592	67.5	-549	43
75.0	-401	75.0	-392	9
82.5	-347	82.5	-342	5
105.0	-175	105.0	-172	3

* Elevation : Height from the bottom

Table 5.12: 4-h depolarization at high tide applied to SACP system (Specimen #2)

Instant-off potential		**4-h depolarized potential**		**Depolarization (mV)**
Elevation (cm)	**Potential (mV)**	**Elevation (cm)**	**Potential (mV)**	
15.0	-991	15.0	-838	153
37.5	-906	37.5	-765	141
45.0	-905	45.0	-765	140
52.5	-895	52.5	-768	127
67.5	-642	67.5	-600	42
75.0	-541	75.0	-513	28
82.5	-529	82.5	-508	21
105.0	-212	105.0	-183	29

* Elevation : Height from the bottom

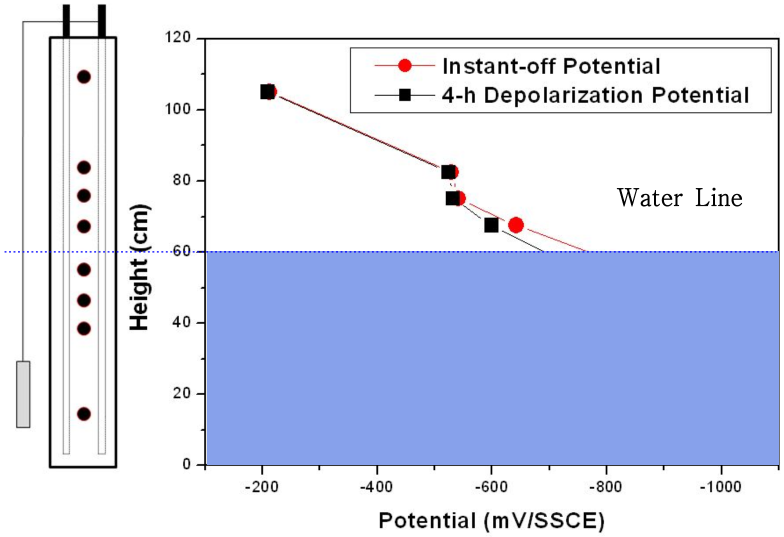

Figure 5.12: 4-h depolarization test of steel in concrete contaminated with chloride. Only the sacrificial anode was disconnected.
(High tide, Specimen #1, SACP)

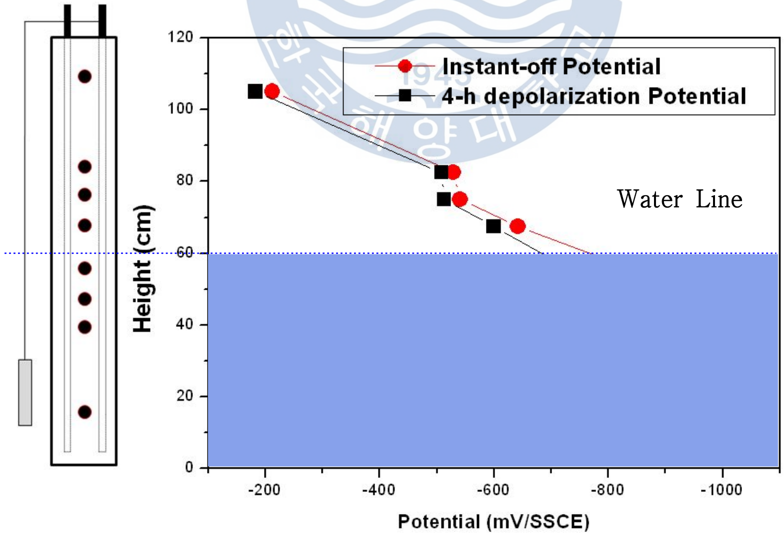

Figure 5.13: 4-h depolarization test of steel in concrete contaminated with chloride. Only the sacrificial anode was disconnected.
(High tide, Specimen #2, SACP)

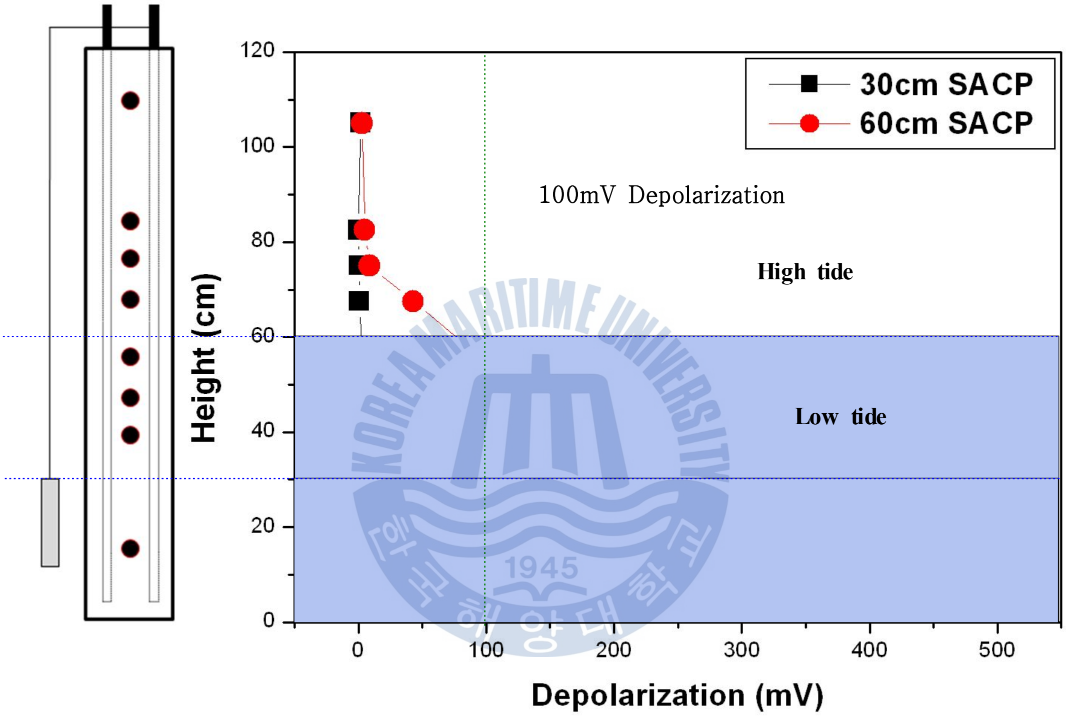

Figure 5.14: Depolarization test of reinforced steel when SACP was applied at both low and high tides

5.1.4 Test results of hybrid CP at high tide(water level 60 cm)

Figures 5.15 and 5.16 show the 4 hour depolarization results for Specimens #1 and #2. CP potentials of tidal zone in both specimens were dropped to -890 ~ -940 mV/SSCE. In Figure 5.14(Specimen #1), 4 hour depolarization of tidal zone was nearly 100 mV(about 90 ~ 120 mV). In addition, with the application of ICCP, the depolarization potential in air zone was dropped to -760 mV/SSCE, which means that ICCP can protect the areas where SACP is difficult to protect. Specific figures of potential change and 4 hour depolarization potential in Specimen #1 are given in Table 5.13 and 5.14.

In Specimen #2, the potentials were dropped excessively up to -1,200 ~ -1,400 mV/SSCE, which was due to the effect of ICCP current on the rebars in immersion area. When the water level reached to the lowest part of splash zone, resulting in low enough resistivity due to seawater, the ICCP current could be readily supplied to this area. Therefore, by supplying ICCP current to tidal and submerged zones, the potential was dropped lower than that of SACP system. Specific figures of potential change and 4 hour depolarization potential for Specimen #2 are listed in Table 5.15 and 5.16.

4 hour depolarization potentials were in the range of 250 ~ 270 mV. This was about 150 mV higher than that of Specimen #1 as indicated in Figure 5.17. Because of the current supply by ICCP, the potential of tidal and submerged zones in Specimen #2 became low enough for CP. In addition, in the case of Specimen #2, the depolarization potential of splash zone was significantly larger than 100 mV standard(in range of 450 ~ 600 mV). This means that

ICCP anode was well functioned in the lowest part of splash zone, since seawater was absorbed into the area where Ti-mesh was installed, and ICCP system supplied protection current easily in this zone.

Table 5.13: Potential changes at high tide applied to hybrid CP system (Specimen #1)

Before applied to hybrid CP		After applied to hybrid CP		Potential change(mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-831	15.0	-987	156
37.5	-799	37.5	-894	95
45.0	-786	45.0	-921	135
52.5	-793	52.5	-926	133
67.5	-549	67.5	-580	31
75.0	-392	75.0	-396	7
82.5	-342	82.5	-398	56
105.0	-172	105.0	-760	588

* Elevation : Height from the bottom

Table 5.14: 4-h depolarization at high tide applied to hybrid CP system (Specimen #1)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-987	15.0	-868	119
37.5	-894	37.5	-786	108
45.0	-921	45.0	-813	108
52.5	-926	52.5	-816	110
67.5	-580	67.5	-543	37
75.0	-396	75.0	-379	17
82.5	-398	82.5	-343	55
105.0	-760	105.0	-147	613

* Elevation : Height from the bottom

Table 5.15: Potential changes at high tide applied to hybrid CP system (Specimen #2)

Before connecting anode		After connecting anode		Potential change(mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-838	15.0	-1,212	374
37.5	-765	37.5	-1,121	356
45.0	-765	45.0	-1,126	361
52.5	-768	52.5	-1123	355
67.5	-600	67.5	-1,400	800
75.0	-513	75.0	-1,330	817
82.5	-508	82.5	-1,195	687
105.0	-183	105.0	-760	577

* Elevation : Height from the bottom

Table 5.16: 4-h depolarization at high tide applied to hybrid CP system (Specimen #2)

Instant-off potential		4-h depolarized potential		Depolarization (mV)
Elevation (cm)	Potential (mV)	Elevation (cm)	Potential (mV)	
15.0	-1,212	15.0	-947	265
37.5	-1,121	37.5	-870	251
45.0	-1,126	45.0	-873	253
52.5	-1,123	52.5	-875	248
67.5	-1,400	67.5	-776	624
75.0	-1,330	75.0	-776	554
82.5	-1,195	82.5	-751	444
105.0	-760	105.0	-364	396

* Elevation : Height from the bottom

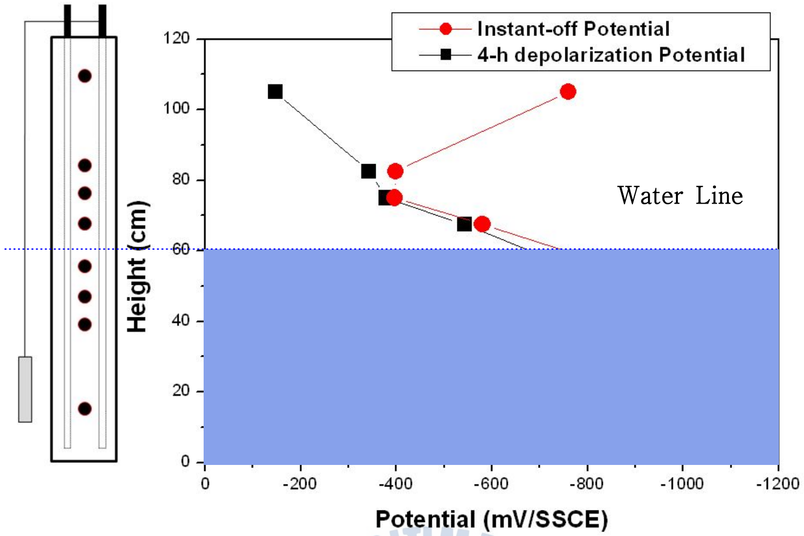

Figure 5.15: 4-h depolarization test of steel in concrete contaminated with chloride. Only the anodes were disconnected.
(High tide, Specimen #1, Hybrid CP)

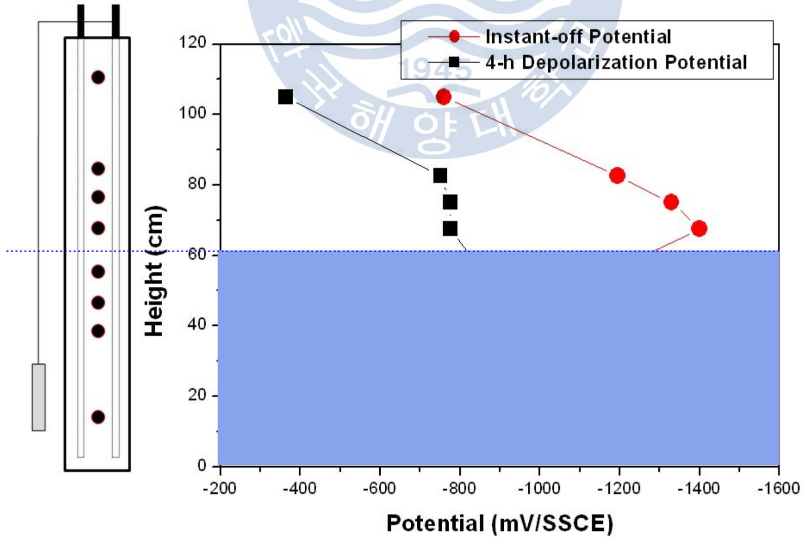

Figure 5.16: 4-h depolarization test of steel in concrete contaminated with chloride. Only the anodes were disconnected.
(High tide, Specimen #2, Hybrid CP)

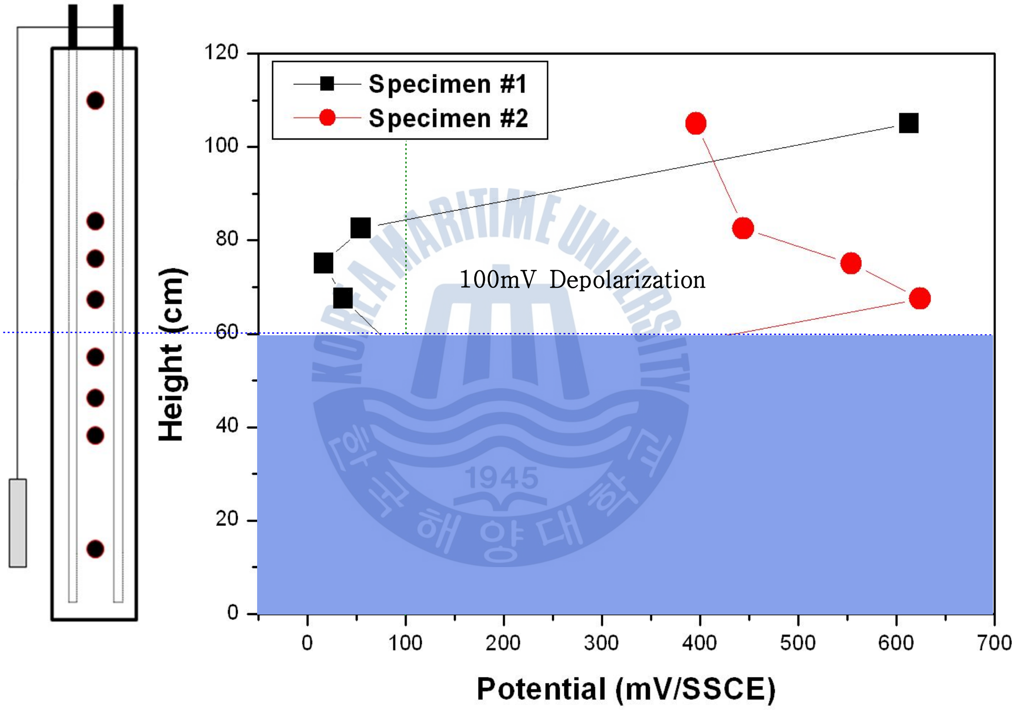

Figure 5.17: 4-h depolarization test results after disconnecting hybrid CP system (High tide, Specimen #1, #2)

5.1.5 Test results of hybrid CP by water level change from high to low tide(water level 60 cm → 30 cm)

Figure 5.18 shows the potential variation of Specimen #1 with water level change from high to low tide. Hybrid CP was applied in this experiment. In the case of high tide, the potentials of tidal and submerged zones were -660 ~ -940 mV/SSCE(tidal zone), -1,000 mV/SSCE(submerged zone), respectively. In addition, potential of air zone was -760 mV/SSCE. When water level went down, the potentials of splash zone 2, 3 and tidal zone were gradually increased, since in low water level, the resistivity of splash and tidal zones became higher. CP protection effect was maintained more than 2 days in SACP system. This means that the SACP can be effectively applied to the tidal zone where the wet and dry of tide is repeated twice a day.

The potential of air zone, on the other hand, was constant around -760 mV/SSCE regardless of water level, since the power of ICCP system was continuously adjusted to maintain the setting potential, -760 mV/SSCE.

Figure 5.19 shows the potential variation of Specimen #2 with water level change from high to low tide. Due to the current leakage, the potentials of tidal and submerged zones were decreased to the range of -1,100 mV ~ -1,250 mV/SSCE regardless of water level. The potential of splash zone, in addition, was excessively dropped up to the range of -1,600 mV ~ 2,050 mV/SSCE. This phenomenon was maintained for more than 2 days, which was similarly observed in the Specimen #1 experiment.

Figure 5.18: Potential variation of Specimen #1 with water level change from high to low tide

Figure 5.19: Potential variation of Specimen #2 with water level change from high to low tide

5.1.6 CP current density variation

Current density(mA/m^2) is a important factor to obtain the proper CP condition. Through a number of laboratory and field experiences, the required current densities for CP was 10-20 mA/m^2, which might extend the service life for the already corroded steel in concrete [32-33]. It is much higher than that for no corrosion steel(2 mA/m^2) [34-37].

In general, many experiments have been taken place with rebar segments to obtain local current density. In the present experiment, however, any rebar segment was not installed in concrete specimen. Therefore, CP current density was measured to grasp current behaviour with water level change. CP current divided by total rebar area was defined as CP current density.

The area of reinforcement bar was simply calculated by following formula :

$$A = \pi DL$$

where,

D : Nominal diameter of deformed bar

L : Length

Calculated total area of steel was 0.24 m^2. Figures 5.20 and 5.21 show the current density change of Specimen #1 and #2. From these results, the current density of ICCP was much higher than that of SACP, when comparing the results at low tide. This is because ICCP can supply much high current to the specimen. Although the SACP system supplied lower current to the reinforced steel than ICCP, the potential of submerged zone was dropped to -1,000 mV/SSCE, and the depolarization potential was more than 100 mV criteria. It means that SACP can be applied to the submerged area efficiently because of its low current density and high depolarization potential.

Furthermore, galvanic current was gradually reduced, since the migration of electrons from sacrificial anode to cathode(protected steel) prevented chloride ion to approach the steel surface, which made the steel repassivation.

In Fugure 5.21, the supplied current of Specimen #2 by ICCP was much higher than that of Specimen #1, and current density of Specimen #1 supplied by SACP was nearly zero. From the potential results, it was assumed that Specimen #2 was over-protected.

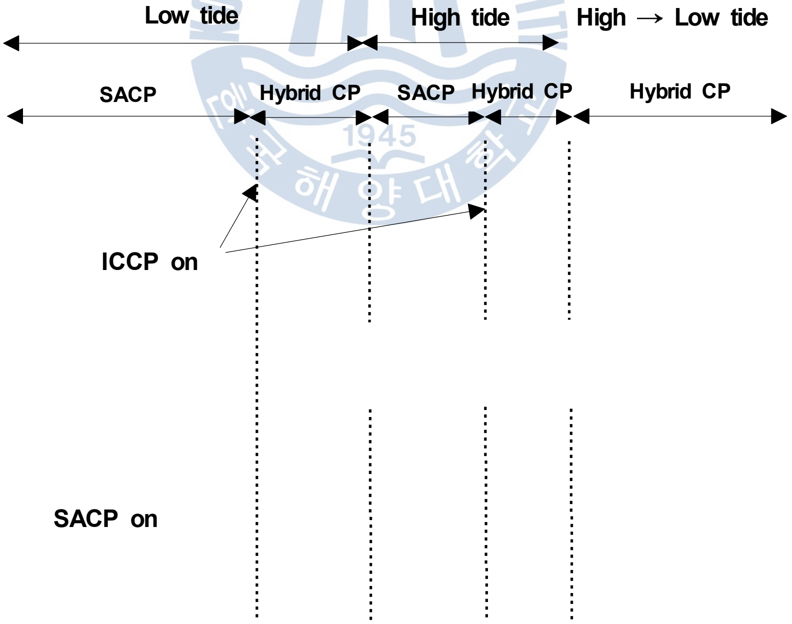

Figure 5.20: Current density variation of Specimen #1

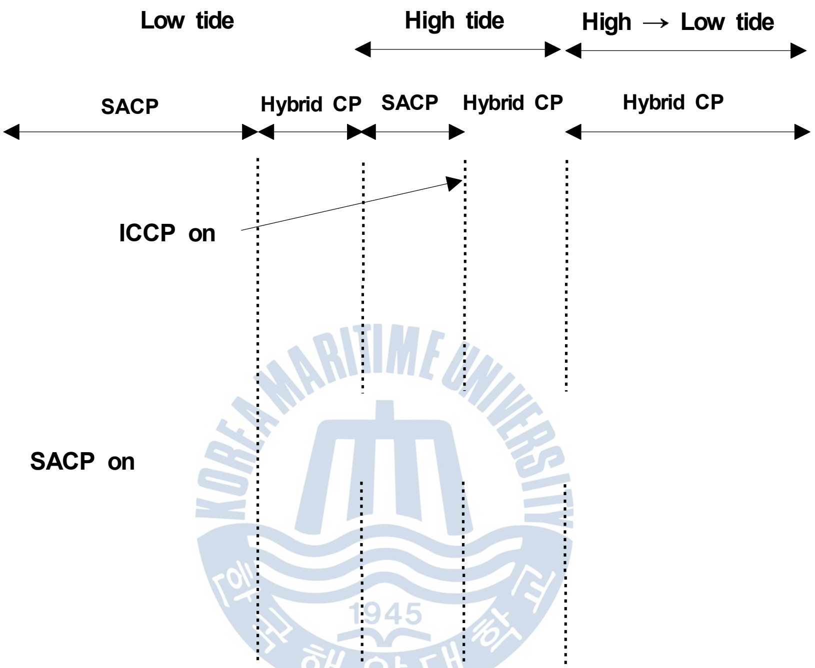

Figure 5.21: Current density variation of Specimen #2

5.2 Discussion

Through a number of studies [6-11,28], SACP has been worked in immersed area efficiently. Throwing power of CP current, however, is the major issue of this SACP system. To obtain the optimum protection design for CP, hybrid system can be an option in high resistivity area, such as splash and atmospheric zones.

When SACP was installed in immersion area, such as submerged and tidal zones, SACP shows the limitation of driving force of CP current observed in many antecedent studies [8-9, 11, 28]. Only 7.5 cm above the water line met 100 mV depolarization criteria in the present study.

When hybrid CP is applied in high resistivity area, it can be protected effectively and possibly meet 100 mV depolarization criteria. In this study Specimen #2 indicated some drawbacks. When water level went up to high tide, the current by Ti-mesh anode was strayed to immersed area, which was indicated potential drop excessively. This stray current may cause loss of current and overprotection of structures. Therefore, ICCP system is installed in the lower part of splash zone, hybrid CP system can not act its role properly.

Furthermore, when SACP is applied to the tidal zone, CP potential was maintained constantly for more than 2 days even after water level goes down to low tide condition. In the case of Yellow Sea in Korea, the variation of tidal zone is 6 ~ 8 m. Therefore, additional studies of CP are necessary in these areas considering the large range of tidal zone.

Chapter 6

CONCLUSION

Application of hybrid CP has been studied in the laboratory by column specimens, and the following results have been obtained:

1) In SACP system, the protection current was influenced up to 7.5 cm above the water level(met 100 mV depolarization criteria).

2) High resistivity areas such as splash and atmospheric zones could not be protected by SACP system only, which was well agreed with the results from literatures.

3) The potential of tidal zone was sustained for more than 2 days when water level went down from high to low tide.
   - It means that the protection in the tidal zone with SACP only is possible in consideration of repeated tidal zone twice a day(about 12 hour cycle).

4) ICCP was applied efficiently in the high resistivity area where SACP was hardly to supply protection current to the splash and atmospheric zones.

5) In case of Specimen #2, when water level dropped from high tide(60 cm) to low tide(30 cm), CP potential of tidal zone was maintained for more than 2 days. However the potentials of submerged and tidal zones were dropped to the range of -1,100 mV ~ -1,250 mV/SSCE, and those of splash zone dropped -1,600 mV ~ -2,050 mV/SSCE.
   - It means that the use of ICCP system in the tidal or splash zones is inadequate, because of possible overprotection, loss of current and stray current problem

As a result of this study, hybrid CP has a better solution to protect the reinforced concrete properly. It is possible to make up for each system's shortcomings as well as to enhance its benefits. In the case of marine bridge hybrid system can be a good choice to protect corrosion. The present study was carried in laboratory only, therefore, more studies are needed to obtain the practical information regarding durability, and economic & environment considerations.

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감사의 글

먼저 2년 동안 항상 곁에서 지켜주신 하나님! 감사합니다. 2년이라는 기간은 저를 한 단계 더 성숙시켜주는 기간이었습니다. 이전에 저는 철부지였고 항상 안일한 생각에 빠져 있었습니다. 하지만 대학원 석사기간은 뜻이 있으면 반드시 길이 있다는 생각을 가지고 항상 긍정적인 생각으로 한걸음씩 나아가게 만들어 주었고, 정말 재미있고 보람찬 기간이었습니다. 2년을 마무리 하면서, 이 자리에 저를 있게 해주신 많은 분들께 감사의 마음을 전합니다.

먼저, 대학원 기간 동안 진심어린 관심과 지도로 저를 가르쳐주시고 올바른 학문의 길로 인도해주신 김기준 교수님께 감사의 마음을 전합니다. 바쁘신 와중에도 부족한 논문을 세심하게 심사해주신 이명훈 교수님, 정진아 교수님 감사합니다. 그리고 많은 가르침을 주신 김종도 교수님, 그리고 항상 저에게 많은 조언을 해주시고 아껴주시고 믿어주신 이상일 교수님께도 감사하다고 말씀드리고 싶습니다.

대학원 생활동안 제 자신에 대해서 일깨워 주신 조규장 상무님, 같이 연구도 하고 땀도 흘렸고 항상 많은 힘이 되어준 하지명 부장님, 많은 조언과 격려를 해주신 창제형, 항상 공부에 관해서 같이 토의를 했던 종혁이형, 많은 공감대를 나누고 나타해지지 않도록 도와준 정한이형, 룸메이트로 항상 많은 부분을 나누고 항상 힘이 되어준 무근이형, 힘들 때마다 도움을 주고 서로 의지할 수 있어 좋았던 재범이형, 같은 실험실이라서 더더욱 의지가 되고 믿음을 준 은진이, 그리고 항상 함께해서 좋았던 후배 경민이와 유송이에게도 감사의 마음을 전합니다.

마지막으로 제가 이 자리에 있을 수 있도록 보살펴 주시고 걱정해 주신 외할머니, 사랑하는 아버지, 어머니, 나의 보물 우리 동생 그리고 힘이 되어준 많은 친구들 모두 사랑하고 고맙습니다.

이 논문을 계기로 제 자신이 한없이 부족한 사람인지 알 수 있었습니다. 하지만 자만하지 않고 더 큰 길로 나아갈 수 있다는 것 또한 알 수 있었습니다. 감사합니다. 하나님 사랑합니다.

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진 충 국