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INFLUENCE OF TEMPERATURE AND RELATIVE HUMIDITY ON ELECTROCHEMICAL MEASUREMENT VALUES OF STEEL BARS IN CONCRETE

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ABSTRACT:

As our country surrounded on four sides by the ocean, the establishment of maintenance system against chloride attack for port and harbor facilities is a serious challenge in Japan. Port and harbor facilities are inspected and evaluated primarily visually in cooperation with simple non-destructive tests such as hammering tests, but inspection and examination technologies must be improved so that proactive maintenance measures should be taken.
This research was focused on the application of electrochemical monitoring for the proactive maintenance of concrete members due to chloride attack under environmental impacts as a part of efforts to improved technologies for the inspection and examination of steel corrosion in concrete members. In particular, it was a study of the impacts of temperature and moisture content on electrochemical measurement values and on the interrelationships between various electrochemical measurement values, to identify challenges to the establishment of judgment for degree of chloride attack deterioration in reinforced concrete members. Half-cell potential, polarization resistance and specific electro resistance display behaviors that differ according to each environment, and discontinuous measurements using independent indices can result in incorrect judgments of concrete members. Therefore, it is thought possible to perform high precision inspections and evaluation by continuous monitoring considering each environmental impact. In marine environments, the temperature and moisture content inside a single concrete member vary greatly, so further study including measurement locations, quantities and frequencies of electrochemical corrosion monitoring will be performed in the future.

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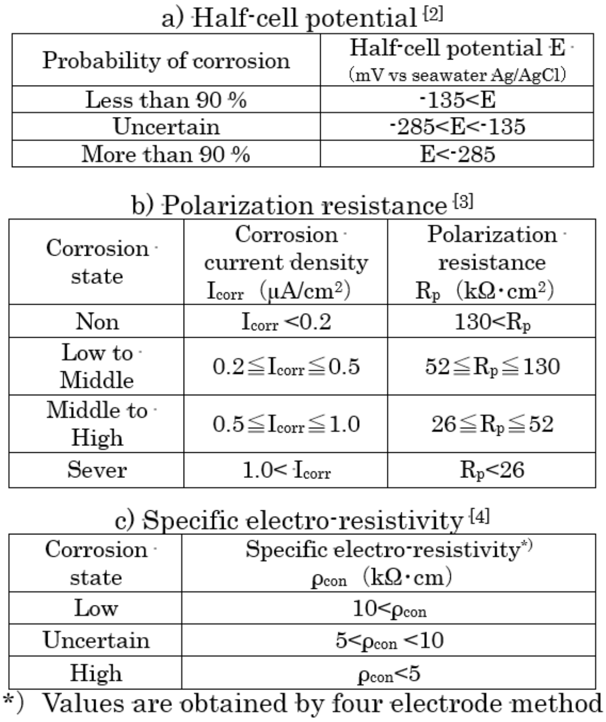
KEYWORDS: steel corrosion, reinforced concrete, electrochemical measurement, environmental impact, monitoring

1. Introduction

As a nation surrounded on four sides by the Ocean, establishing strategic methods of maintaining port and harbor facilities that play major roles as logistics bases is a serious challenge for Japan. Port and harbor facilities are now inspected and evaluated primarily visually in cooperation with simple non-destructive tests such as hammering tests, but inspection and examination technologies must be improved so that preventive maintenance measures can be taken. To deal with chloride attack to reinforced concrete members in ports and harbors in particular, it is vital to establish specific technologies and methods that can be used to judge the incubation and propagation periods [1] when it is impossible to visually clarify the state inside concrete members in order to be able to take proactive maintenance measures. On the other hand, methods of clarifying corrosion of steel inside concrete which are proposed include the measurement of half-cell potential, polarization resistance, and specific electro resistance based on electrochemical methods, and corrosion judgment values are presented such as those shown in Table 1[2], [3], and [4] respectively. However, in fact, there is no clear answer to the question, “will this information about steel corrosion at one location be used to maintain an entire member expanding three-dimensionally. Under actual environments in particular, conditions such as temperature and humidity caused by moment-to-moment variations of weather and by climate change vary, and in some cases, the corrosion judgment standards shown in Table 1 can produce incorrect results. And in marine environments, the state of the temperature and moisture content vary greatly according to locations inside a single member, and in order to quantitatively judge the degree of deterioration by chloride attack in concrete members applying electrochemical methods, it is necessary to establish standards accounting for the temporal impact of environmental change.

Concerning the above, the authors have begun to study the establishment of judgement criteria of steel corrosion in actual concrete members as part of efforts to improve technologies for the inspection and investigation of chloride attack in existing reinforced concrete members in ports and harbors[5]. As part of the study, electrochemical corrosion monitoring to clarify change of electrochemical measurement values, which change constantly from moment to moment as the environment fluctuates has been started, and at the same time, methods of setting measurement locations, number of measurements, measurement frequency, and other settings for actual structures are to be studied. In present study, the impact on the electrochemical measurement values and on the interrelationship between electrochemical measurement values of the fluctuation of chloride and moisture contents of concrete members were examined, to identify challenges to establishing degree of chloride attack deterioration standards for concrete members.

Table 1 Example of judgement of corrosion state of steel bars in concrete based on electrochemical measurements



a) Half-cell potential [2]

Probability of corrosion	Half-cell potential E (mV vs seawater Ag/AgCl)
Less than 90 %	$-135<E$
Uncertain	$-285<E<-135$
More than 90 %	$E<-285$

b) Polarization resistance [3]

Corrosion state	Corrosion current density I_{corr} (μA/cm^2)	Polarization resistance R_p (kΩ·cm^2)
Non	$I_{corr}<0.2$	$130<R_p$
Low to Middle	$0.2\leqq I_{corr}\leqq 0.5$	$52\leqq R_p\leqq 130$
Middle to High	$0.5\leqq I_{corr}\leqq 1.0$	$26\leqq R_p\leqq 52$
Sever	$1.0<I_{corr}$	$R_p<26$

c) Specific electro-resistivity [4]

Corrosion state	Specific electro-resistivity*) ρ_{con} (kΩ·cm)
Low	$10<\rho_{con}$
Uncertain	$5<\rho_{con}<10$
High	$\rho_{con}<5$

*) Values are obtained by four electrode method

2. Experimental Setup

2.1 Outline of the specimens

Table 2 shows the mix proportion of concrete used. The water cement ratio was set at 0.55. The cement used was ordinary Portland cement (density: 3.16 g/cm^3, specific surface area: 3 330 cm^2/g). The fine aggregate was river sand from the Oi River (dry density: 2.60 g/cm^3, water absorbing ratio: 1.86 %, F.M.: 2.66), and the coarse aggregate was from Oume crushed rock (max. size: 20mm, dry density: 2.65 g/cm^3, water absorbing ratio: 0.47 %, F.M.: 6.75). The admixtures were AE water-reducing agent (sulfonic acid type) and an air-entraining agent (alkylether type). To clarify the impact of chloride ion content on the electrochemical measurement values, specimens were made with no chloride ion content and specimens were made by mixing chloride ions with primal mixing water (2.0, 5.0, 10.0kg/m^3 per unit of concrete volume).

The specimens were removed from their molds after wet curing for 7 days then stored in the atmosphere. Then, after aging for 28 days, exposure was started in an environmental control chamber.

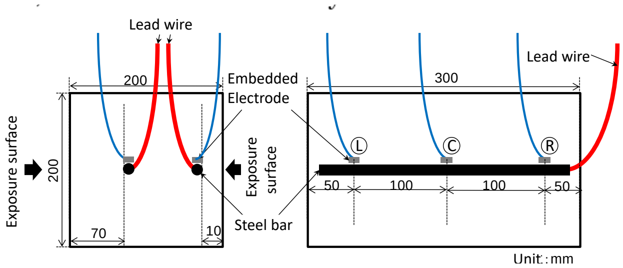


Figure 1 Outline of specimen

Table 2 Mix proportion of concrete

W/C	s/a (%)	Unit quantity (kg/m³)				Unit quantity (g/m³)		Slump (cm)	Air (%)
		Water	Cement	Fine aggregate	Course aggregate	AE water reducing agent	AE agent		
0.55	46.0	162	295	842	1013	737.5	4.43	7.5	4.2

*) Sodium chloride was mixed in water to some specimens so that the chloride ion content were 2.0 kg/m³, 5.0 kg/m³, 10.0 kg/m³ per concrete volume. Hereinafter, labeled as "N-2", "N-5", "N-10", respectively, samples with no chloride ion shall be "N-0".

Figure 1 shows an outline of the reinforced concrete specimens. The specimens were cuboids with dimensions of 200 × 200 × 300 mm and steel bars (SD295A, D13) were installed with covering of 10 mm and 70 mm. Each rebar was equipped with one lead wire and three small embedded type electrodes [6] (called as L, C, and R) to perform later electrochemical monitoring (See Figure 1). The embedded electrodes were cylindrical with external diameter of 13mm and height of 7mm and included a counter electrode and reference electrode made of gold-plated nickel. This study performed electrochemical measurements over time by installing these embedded electrodes at locations about 1mm away from the surface of a steel bar. And the surfaces except the 2 surfaces that were the exposed surfaces (200×300 mm) were covered with epoxy resin.

2.2 Exposure environment

The environments to which port and harbor reinforced concrete members are exposed are categorized to three zones, submerged zone, splash/tidal zone and atmospheric zone; "submerged zones" where they are in constant contact with water, "splash zones" and "tidal zones" where they are exposed to repeated cycles of drying and wetting, and "atmospheric zones", that is a relatively dry environment. It is known that in "splash zones" and "tidal zones", massive quantities of water and oxygen required to enhance corrosion of steel are supplied, and severe corrosion is caused by the failure of passive film of the steel. On the other hand, it is also known that electrochemical values obtained by measurements vary under the impact of the surrounding temperature and water content of the concrete [7]. So, this research exposed specimens with differing chloride ion contents (N-0, N-2, N-5, and N-10) in an environmental control chamber (temperature; 10 to 40°C, relative humidity: (R.H.): 60% and 95%).

2.3 Measurement items and measurement methods

This research performed monitoring over time at intervals of about 1 hour of half-cell potential, polarization resistance, and specific electro resistance. Half-cell potential was obtained by converting the potential measured by the embedded electrodes against seawater Ag/AgCl electrode. The polarization resistance was obtained by applying different frequency of alternative currents between 20 mHz to 10kHz. And the specific electro resistance was obtained by performing a calculation based on the measured value on the high frequency side during the above measurement of polarization resistance. And when the polarization resistance and specific electro resistance were calculated, the measurement area was assumed to be 10 cm2 and the gap between the steel bars and electrodes to be 0.1cm. Along with the above electrochemical measurement values, the temperature and moisture near the specimens and the moisture content on the surface of concrete (based on high frequency capacity type moisture meter) were measured.

3. Influence of temperature and relative humidity on electrochemical measurement values

3.1 Influence of temperature in a dry environment

Figures 2 to 4 show the change over time of half-cell potential, polarization resistance, and specific electro resistance of steel bars inside the specimens. During monitoring, the temperature is gradually increased and decreased between 10°C and 40°C with the relative humidity at 60%. And the length shown in the legend (unit; mm) shows the cover depth. It shows that the half-cell potential value varies according to the temperature, but this trend differs according to chloride ion content and concrete cover depth, so a clear trend was not conformed. On the other hand, it was confirmed that the polarization resistance and specific electro resistance continually rise and fall according to the rise and fall of the temperature in both steel bars.

To confirm the above, Figures 5 to 7 show the influence of the temperature on electrochemical measurement values in the case of relative humidity of 60%. It is confirmed that the half-cell potential to be lower accompanying the increase of the chloride ion content, but it is possible to confirm that it tends to be flat without confirming a clear correlation with temperature. Regarding the polarization resistance and specific electro resistance on the other hand, a negative relationship with temperature is confirmed, with the increase of the temperature accompanied by a fall of both resistance values. Therefore, to judge the degree of chloride attack deterioration of a concrete member using polarization resistance or specific electro resistance, it is necessary to consider the influence of temperature, and it is also necessary to appropriately clarify whether variation of values is caused by change of the state of corrosion or by change of ambient temperature. And the correlation coefficients of the relationships shown in Figures 5 to 7 are described in later (Figures 16 to 18).

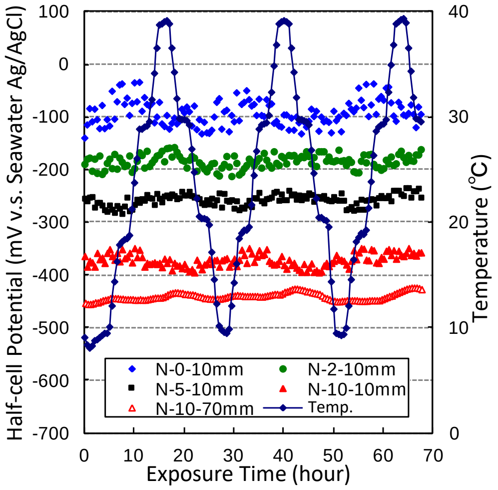


Figure 2 Change of half-cell potential (R.H.60%)

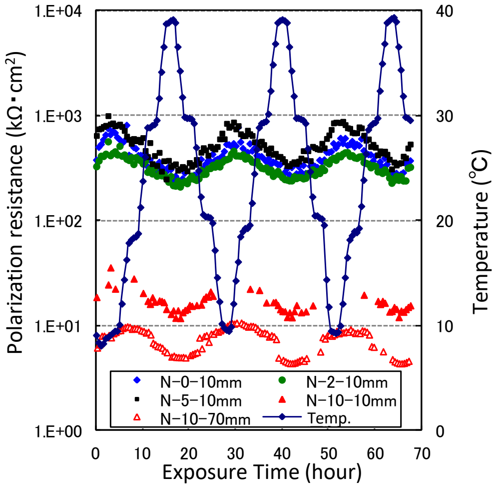


Figure 3 Change of polarization resistance (R.H.60%)

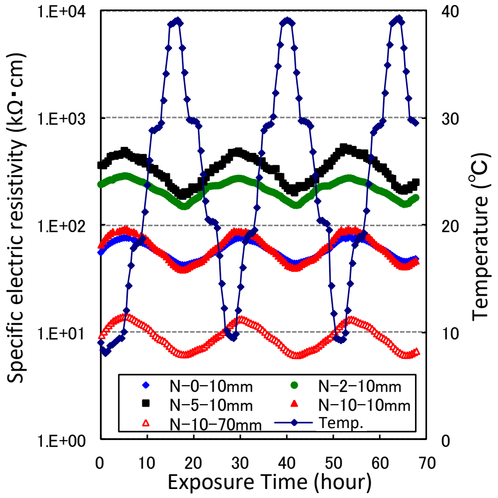


Figure 4 Change of specific electro resistance (R.H.60%)

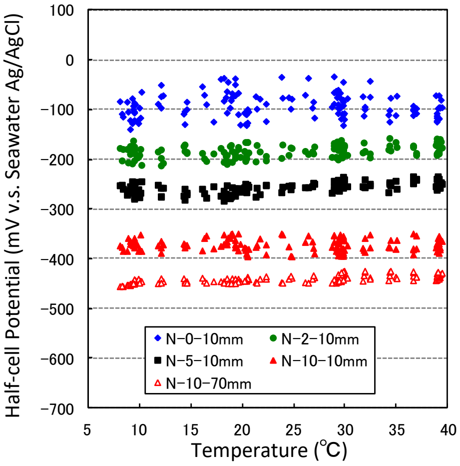


Figure 5 Influence of Temp. on half-cell potential (R.H. 60%)

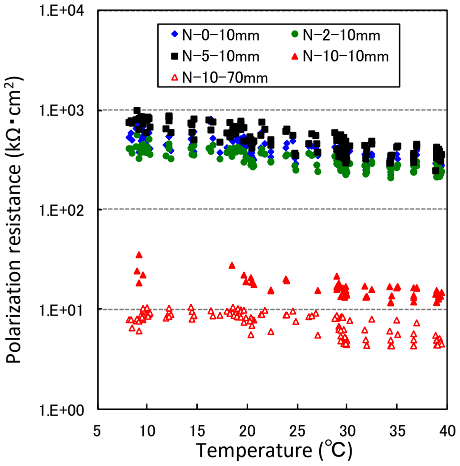


Figure 6 Influence of Temp. on polarization resistance (R.H.60%)

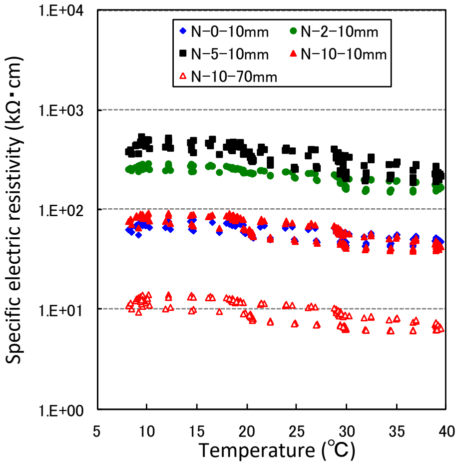


Figure 7 Influence of Temp. on specific electro resistance (R.H.60%)

3.2 Influence of temperature under high humid condition

Figures 8 to 10 show change over time of half-cell potential, polarization resistance and specific electro resistance of steel bars inside the specimens when the temperature is gradually increased and decreased between 10°C and 40°C at relative humidity of 95%. It confirms that the half-cell potential to be lower from -50 mV to -100 mV when the temperature changes from 30°C to 40°C. And it also confirms that the polarization resistance tends to rise and fall as the temperature increases and decreases, but the variation of each measured value is greater than the continuous variation confirmed in the 60 % relative humidity case. This is presumed to be a result of the fact that the moisture content inside the concrete is unequal as a result of condensation etc. and the low frequency current (20 mHz) was difficult to stabilize. The specific electro resistance, on the other hand, tends to continuously vary according to the increase and decrease of the temperature even in a high humidity environment.

As shown in Table 1, the decrease of the half-cell potential reflects the deterioration of the corrosion environment, and the results suggest an increase of the chloride ion content. However the decrease of the half-cell potential confirmed by Figure 8 is also confirmed in specimens containing no chloride ions, and it is judged that it is not a result of change of the corrosion environment accompanying the increase of the chloride ion content. On the other hand, the moisture content of the specimen surfaces during temperature increase obtained by a moisture meter is as shown in Table 3, and it was visually confirmed that the increase of the temperature caused condensation of water on the surface of the specimen. Generally, the half-cell potential is, as shown by Figure 11, determined by anode polarization characteristics that represent the state of the passive membrane and by cathode polarization characteristics that represent the quantity of oxygen supplied. In other words, the decline of the quantity of oxygen around the steel bars, changing the cathode polarization curve from A to B in the figure, reduced the half-cell potential from E_{corr} to E'_{corr}. It is therefore, presumed that the decrease of the half-cell potential confirmed by Figure 8 was caused by condensed water covering the surfaces of the specimens, lowering the quantity of oxygen supplied to the steel bars. In order to reproduce the above phenomenon in an environment with a larger moisture content, a specimen containing no chloride ions (N-0) was exposed in a seawater exposure environment to investigate change of the half-cell potential at this time (Figure 12). Exposure of the specimens was done in a facility that could be used to expose the specimens to seawater of Kurihama Bay in Yokosuka City in Kanagawa Prefecture twice a day (every 4 hours). This confirmed that the half-cell potential of specimens was remarkably decreasing by a seawater spreading, and in particular, in the case of specimens with covering of 10mm, one spraying, and in the case of a specimen with covering of 70mm, three sprayings make the half-cell potential lower by about -250mV. These phenomena occurred in the short period of 40 hours after exposure, so it is assumed to not be the influence of chloride ions in the seawater; but the influence of moisture content as in the laboratory testing. Therefore, in order to judge the degree of steel corrosion in concrete members using half-cell potential, it is necessary to consider the influence of moisture content in cover concrete.

Figures 13 to 15 show the influence on electrochemical measurement values of the temperature in the 95% relative humidity case. These show that the range of fluctuation of half-cell potential is wider at relative humidity of 95% than at 60%, and the range of fluctuation of these values was about 150mV in the case of relative humidity of 95%, and between about 50 to 100mV in the 60% case. Regarding the polarization resistance and specific electro resistance, although the range of fluctuation is large similarly to that of half-cell potential, a negative correlation with temperature was confirmed as in the past, and considering the temperature dependency of both, it is assumed that degree of steel corrosion in concrete member can be judged in a marine environment.

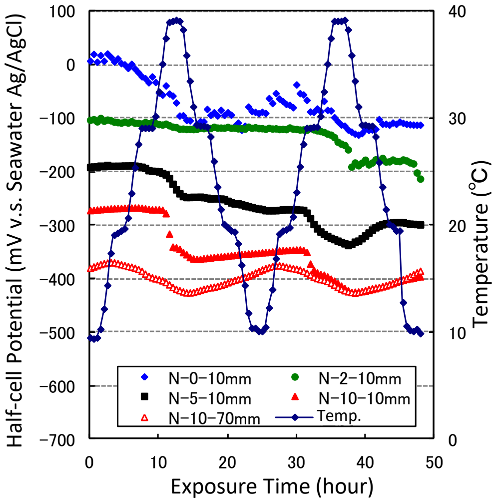


Figure 8 Change of half-cell potential (R.H.95%)

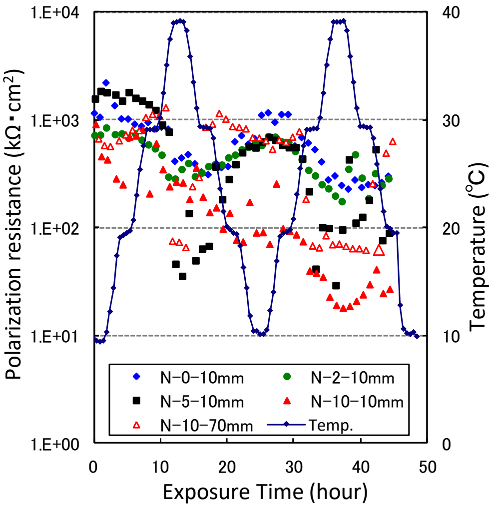


Figure 9 Change of polarization resistance (R.H.95%)

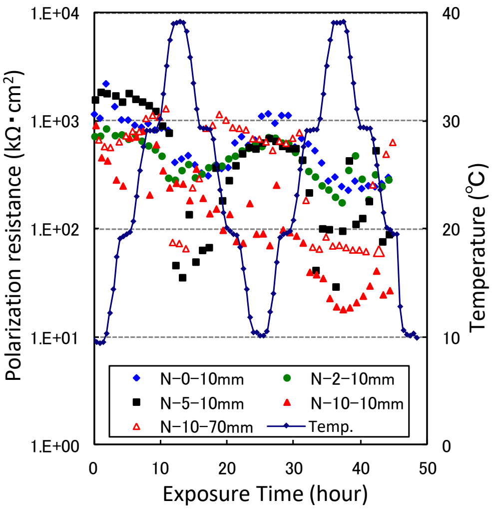


Figure 10 Change of specific electro resistance (R.H.95%)

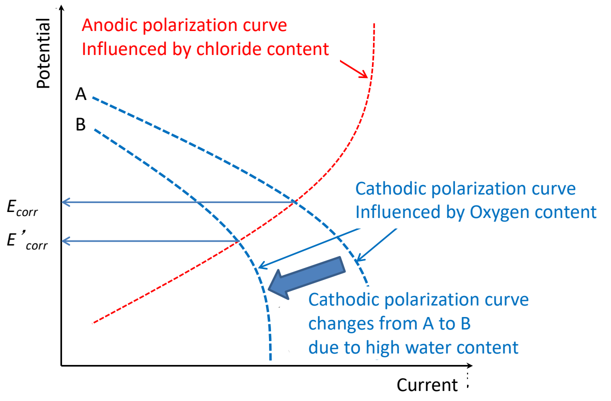


Figure 11 Schematic figure of influence of water on half-cell potential

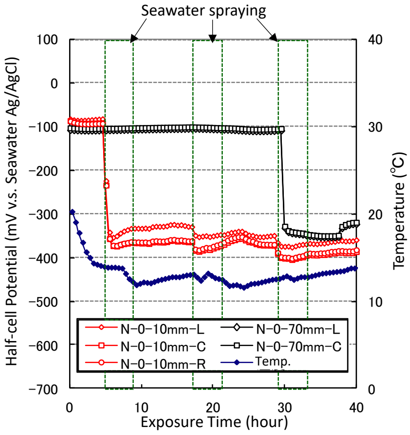


Figure 12 Change of half-cell potential during seawater spraying (L, C, R means position of sensors)

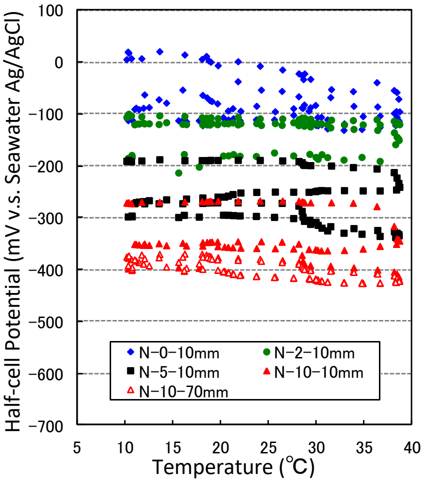


Figure 13 Influence of Temp. on half-cell potential (R.H. 95%)

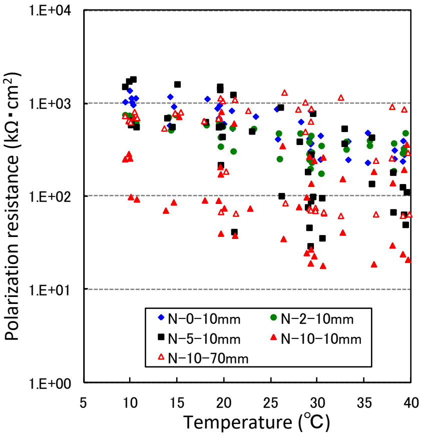


Figure 14 Influence of Temp. on polarization resistance (R.H.95%)

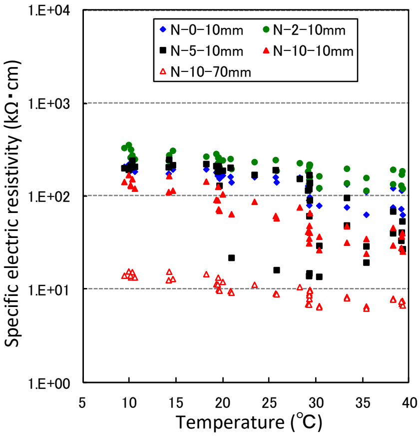


Figure 15 Influence of Temp. on specific electro resistance (R.H.95%)

Table 3 Water content of specimen with temperature elevation (R.H.95%) Unit: %

Label	Concrete cover	10°C	20°C	30°C	40°C
N-0	10 mm	4.2	5.9	6.7	8.1
N-2		3.7	5.2	4.3	8.9
N-5		4.8	6.6	6.7	10.0
N-10		5.1	6.8	7.2	11.2
	70 mm	4.4	7.8	8.3	11.3

3.3 Considering the correlation of electrochemical measurement values with temperature

Figures 16 to 18 show the coefficients of correlation of the relationship of electrochemical measurement values with temperature change shown in Figures 5 to 7 and Figures 13 to 15. They confirm that the temperature dependency of half-cell potential is scattered greatly positively and negatively according to conditions, and that the coefficient of correlation is a low value under all conditions. It is also confirmed that polarization resistance is highly negatively correlated in a case where the relative humidity is relatively low at 60%, but in a high humidity case (relative humidity of 95%), a tendency is seen for the correlation coefficient to fall as the chloride ion content rises. It is confirmed that specific electro resistance, on the other hand, is highly negatively correlated in both cases. Therefore, to evaluate the state of corrosion inside concrete based on actual measured half-cell potential, polarization resistance, and specific electro resistance, it is assumed that temperature has a small influence on half-cell potential and that it is necessary to consider the influence of temperature on polarization resistance and on specific electro resistance. And in order to correctly evaluate what kinds of factors cause fluctuation of electrochemical measurement values, it will be necessary to perform monitoring over time of electrochemical measurement values and temperature and moisture content as was done in this study, and ultimately, necessary to judge the degree of chloride attack deterioration of concrete members considering these factors.

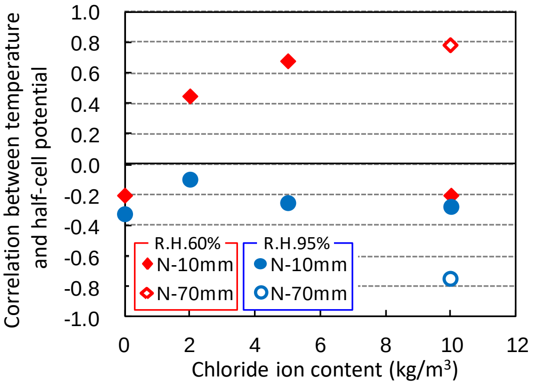


Figure 16 Correlation between temp. and half-cell potential

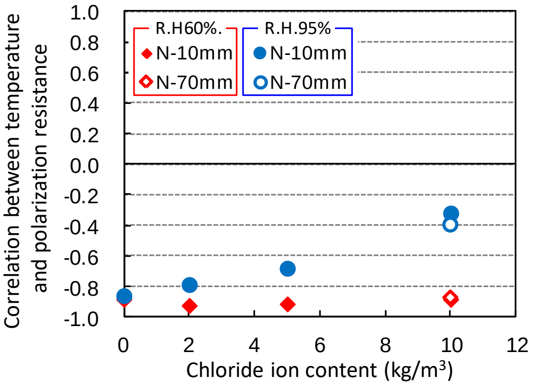


Figure 17 Correlation between temp. and polarization resistance

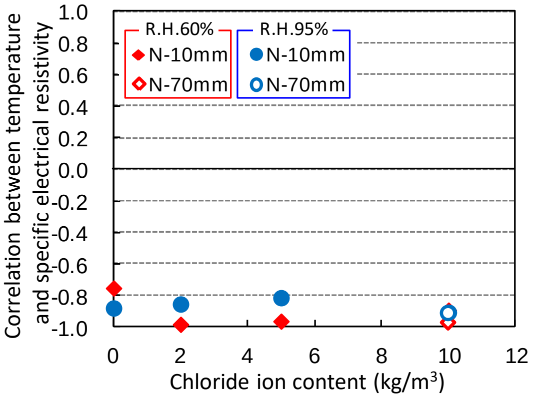


Figure 18 Correlation between temp. and specific electro resistance

4. Discussion

This research was a study of the application of electrochemical monitoring to the judgment of the degree of steel corrosion in concrete members under environmental influences as a part of efforts to improve technologies for the inspection and examination of chloride attack of reinforced concrete members of port and harbor structures. In particular, it was a study of the influences of temperature and relative humidity on electrochemical measurement values and on the interrelationships between various electrochemical measurement values, to identify challenges to the establishment of degree of chloride attack deterioration judgment standards.

Half-cell potential, polarization resistance and specific electro resistance display behaviors that differ according to each environment, and discontinuous measurements using independent indices can result in incorrect judgments of concrete members. Therefore, it is thought possible to perform high precision inspections and diagnoses by continuous monitoring considering each environmental influence. In marine environments, the temperature and moisture content inside a single concrete member vary greatly, so further study including measurement locations, quantities and frequencies of electrochemical corrosion monitoring will be performed in the future.

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