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Nondestructive Electrochemical Testing Method for Prestressed Concrete Structures

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***Abstract*—**Prestressed concrete is used a lot in infrastructures such as roads or bridges. However, poor grout filling and PC steel corrosion are currently major issues of prestressed concrete structures. One of the problems with nondestructive corrosion detection of PC steel is a plastic pipe which covers PC steel. The insulative property of pipe makes a nondestructive diagnosis difficult; therefore a practical technology to detect these defects is necessary for the maintenance of infrastructures. The goal of the research is a development of an electrochemical technique which enables to detect internal defects from the surface of prestressed concrete nondestructively. Ideally, the measurements should be conducted from the surface of structural members to diagnose non-destructively. In the present experiment, a prestressed concrete member is simplified as a layered specimen to simulate a current path between an input and an output electrode on a member surface. The specimens which are layered by mortar and the prestressed concrete constitution materials (steel, polyethylene, stainless steel, or galvanized steel plates) were provided to the alternating current impedance measurement. The magnitude of an applied electric field was 0.01-volt or 1-volt, and the frequency range was from 10^6 Hz to 10^{-2} Hz. The frequency spectrums of impedance, which relate to charge reactions activated by an electric field, were measured to clarify the effects of the material configurations or the properties. In the civil engineering field, the Nyquist diagram is popular to analyze impedance and it is a good way to grasp electric relaxation using a shape of the plot. However, it is slightly not suitable to figure out an influence of a measurement frequency which is reciprocal of reaction time. Hence, Bode diagram is also applied to describe charge reactions in the present paper. From the experiment results, the alternating current impedance method looks to be applicable to the insulative material measurement and eventually prestressed concrete diagnosis. At the same time, the frequency spectrums of impedance show the difference of the material configuration. This is because the charge mobility reflects the variety of substances and also the measuring frequency of the electric field determines migration length of charges which are under the influence of the electric field. However, it could not distinguish the differences of the material thickness and is inferred the difficulties of prestressed concrete diagnosis to identify the amount of an air void or a layer of corrosion product by the technique.

***Keywords*—**Prestressed concrete, electric charge, impedance, phase shift.

I. INTRODUCTION

CORROSION of PC steel which results from insufficient grout filling has been a major problem in prestressed concrete structures in recent years. Therefore, there is a need to detect insufficient grout filling or PC steel corrosion in its early stage.

There are some electrochemical methods to conduct corrosion diagnosis nondestructively, e.g. the natural electric potential or the polarization resistance measurement. Among them, the alternating current (AC) impedance method is widely used to measure polarization resistance.

The impedance is the concept extension of direct current (DC) resistance to AC and there are various previous studies on impedance of cementitious materials. The AC impedance method is a corrosion diagnosing method to measure the complex impedance of reinforcing bar and the concrete interface, and to model as an electric equivalent circuit. When alternating waves having different frequencies are applied to an object, an impedance in each frequency varies according to current propagation paths which reflect the information of material composition. Also, the reciprocal of the impedance is called admittance, and it consists of conductance component, inductive susceptance component, and capacitive susceptance component. They give information on charge transfer.

Koleva et al. [1]-[3] regard the equivalent circuit of a reinforced concrete to be a physical parameter related to a micro interface between micromaterials such as aggregate, transition zone, pore solution, or cement matrix.

Neithalath's research [4] shows how the surface area of aggregate effects on the frequency distribution of conductivity. And Rhim et al. [5] examined the effect of water content on the frequency distribution of the relative permittivity and the conductivity. Also, Robert [6] investigated the influence of chloride ion on the relative permittivity frequency spectra. Based on these considerations, Fukuyama et al. [7] modeled a prestressed concrete member as a multilayered material with an air layer due to a grout filling defects and have been trying to detect defects of prestressed concrete by analyzing charge behaviors from admittance measurement.

The final objective of this research is to develop a method capable of non-destructive detecting grout filling failure and PC steel corrosion in sheath pipe at the same time using an electrochemical technique.

In this paper, the correlations between various materials assuming prestressed concrete elements and the frequency responses of impedance are examined for understanding the interfacial behavior of materials to clarify an impedance baseline of sound prestressed concrete.

II. OUTLINE OF EXPERIMENT

A. Specimen Preparation

Table I shows the experimental plan, and Table II shows the

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mix design and the basic properties of mortar. Fig. 1 shows the outline of the specimen. The size of the specimens was 120x55x75 mm, and stainless steel plates of 45x75x1 mm were used as the measuring electrode. Steel, polyethylene, stainless steel, or galvanized steel plates were embedded at the center of a specimen assuming PC steel or sheath pipe of prestressed concrete structure.

B. AC Impedance Measurement

In the present research, AC impedance was measured at 20-degree Celsius and 60%RH. AC waves were 0.01 or 1-volt and 65 points frequencies from 10^6 to 10^{-2} Hz.

When an electric field is applied to a dielectric by an outer supply, positions of positive and negative charges constituting atoms and molecules in the dielectric displace relatively, and polarization occurs according to frequencies of the electric field. Due to these frequency responses, a substance mainly behaves as a conductor in the high-frequency range and as a capacitor in the low-frequency range.

The real part of measured complex impedance shows the resistance property related to conductivity, and the imaginary part shows the response of the capacitor formed in the materials interface. Since this capacitor is formed at the interface between different substances, this kind of capacitor is also formed at interfaces between embedded material and mortar in the specimens. Therefore, even when the specimen includes an insulator, electric charges go through the external circuit because of this capacitor, and an apparent electric circuit is formed. A grout filling failure consists of an air layer which is insulative and a grout layer, the interface forms a capacitor. Hence, grout filling failure seems to be detectable by the AC impedance method measuring the capacitors formed between different materials. Similarly, a capacitor between a corrosion product layer and a mortar layer make it possible to detect corrosion.

In the present study, Nyquist diagram and Bode diagram are applied to analyze AC impedance. The Nyquist diagram consists of impedance real part Z' on the horizontal axis and impedance imaginary part Z" on the vertical axis. The Bode diagram shows a relationship between frequencies and absolute values of AC impedance |Z| or phase differences θ which represent the capacitive component. θ is the phase shift of the output signal with respect to the input signal. Generally, when θ approaches -90 ° and it means the capacitive behavior. On the other hand, θ of 0° exhibits a resistive behavior.

TABLE I
EXPERIMENTAL PLAN

Specimen[*1]	Material thickness [mm]				Material age [days]			V
	0.5	1.0	2.0	4.0	7	21	365	
Fe	○	○	○	○	○	○	○	1, 0.01
P	○	○	○	○	○	○	○	
St	○	○	○	○	○	○	○	
Zn	○	○	-	-	○	○	○	

*1: Center of specimen illustrated in Fig. 1, Fe: Specimen with steel plate embedded in the center, P: Specimen with polyethylene plate embedded in the center, St: Specimen with stainless steel plate embedded in the center, Zn: Specimen with galvanized steel plate embedded in the center, V: Potential amplitude [volt].

TABLE II
MORTAR MIX DESIGN

W/C [%]	Unit water content [kg/m^3]	Unit mass [kg/m^3]		Air content [%]	Slump flow [mm]
		C	S		
50	245	490	1469	5.0	210x210

C: Ordinary Portland cement (Density: 3.16g/cm^3), S: Sand from Nishikioka (Density in saturated surface-dry condition: 2.67g/cm^3, Water absorptivity: 1.73%, Fineness modulus: 2.68).

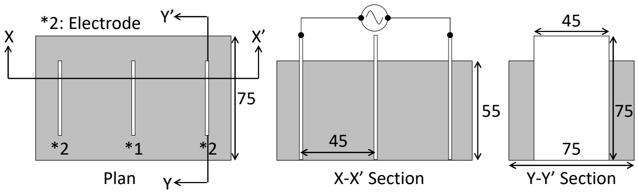


Fig. 1 Configuration of Specimen [mm]

III. RESULTS AND DISCUSSION

A. Effect of Potential Amplitude

Fig. 2 shows the Nyquist and the Bode diagram on the influence of the potential amplitude. The graph of specimen P which contains a 0.5 mm thick polyethylene plate exemplifies the effect of applied potential amplitude. Fig. 2 (a) shows two semicircles are formed in the specimen simulating a combination of mortar and a sheath pipe. The left side is the high-frequency range semicircle and the other is from the low-frequency range. Since one semicircle means a parallel circuit of resistor-capacitor, the specimen can be electrochemically modeled as a circuit in which at least two resistor-capacitor parallel circuits connected in series.

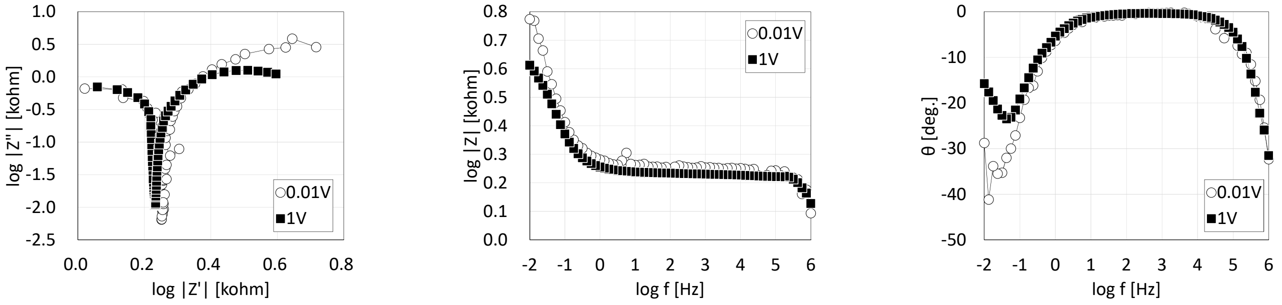
When comparing potential amplitude 0.01 and 1-volt the high-frequency side semicircles show the same tendency, however, in the low-frequency region, there is a difference in the measurement results. From the result of Fig. 2 (b), it seems the influence of the electrode polarization or the interfacial polarization at the mortar /embedded material interface. Also, the fluctuations were observed at 0.01-volt measurement both in the Nyquist diagram and the Bode diagram. This is because concrete is high resistance material and the amplitude 0.01-volt is not enough to cause electric charges internal movement and to form an electric circuit.

Normally, a voltage of around 0.01-volt is often used for corrosion analysis of reinforced concrete, but when measuring the capacitor response of insulative material interfaces as in this study, larger voltage looks to be required.

B. Effect of Material Type

Fig. 3 shows the influence of the type of embedded material. From Fig. 3 (a), the measured systems have at least two electric relaxation mechanism and higher frequency semicircles exhibit the charge transfer resistance between embedded plate and mortar. In Fig. 3 (b), |Z| at about 10^0 to 10^6 Hz becomes larger in the order of P, Fe, St, and Zn. However, the differences are too small to be seen in the low-frequency range about 10^{-2} to 10^0 Hz. The impedance magnitude |Z| of specimen P is the largest because polyethylene is an insulator. Also, the specimen

Zn shows the lowest resistance. It is considered that the differences in resistance are caused by the difference in the internal electric charge mobility and the surface reactivity of the embedded materials. Also, θ changes at approximately from 10^{-1} to 10^{1} Hz. Because the mobility of electric charges in stainless steel is higher, the specimen St shows the response from the higher frequency region compared to the other specimens and forms capacitors. On the contrary, polyethylene is an insulator and electric charges of polyethylene cannot move long distance. Hence, it takes a long time to form polarization, and capacitive behavior appears in the relatively lower frequency range that electric field direction changes in a long time interval.



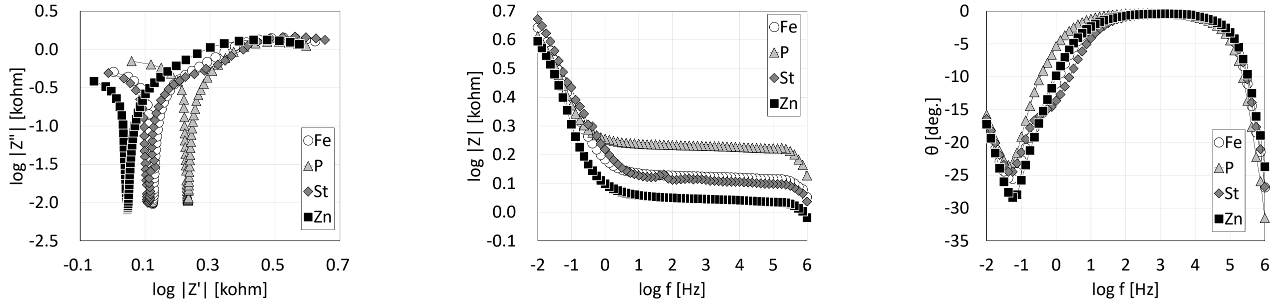
(i) Absolute Impedance |Z|

(ii) Phase Shift θ

(a) Nyquist Diagram

(b) Bode Diagram

Fig. 2 Effect of Potential Amplitude (Specimen P, Material Age 365 days, Plate Thickness 0.5 mm)



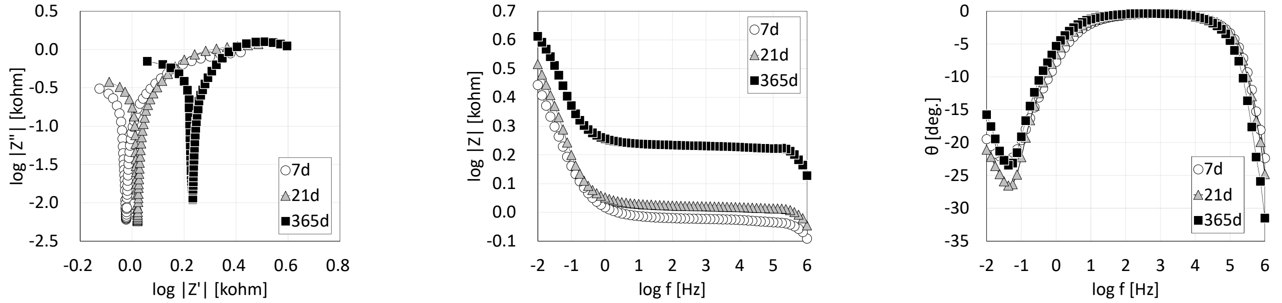
(i) Absolute Impedance |Z|

(ii) Phase Shift θ

(a) Nyquist Diagram

(b) Bode Diagram

Fig. 3 Effect of Material Type (Material Age 365 days, Plate Thickness 0.5 mm)



(i) Absolute Impedance |Z|

(ii) Phase Shift θ

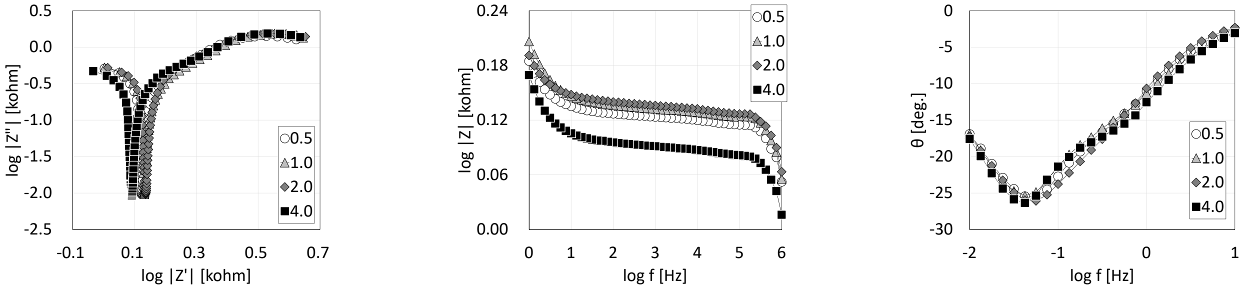
(a) Nyquist Diagram

(b) Bode Diagram

Fig. 4 Effect of Material Age (Specimen P, Plate Thickness 0.5 mm)

C. Effects of Material Age

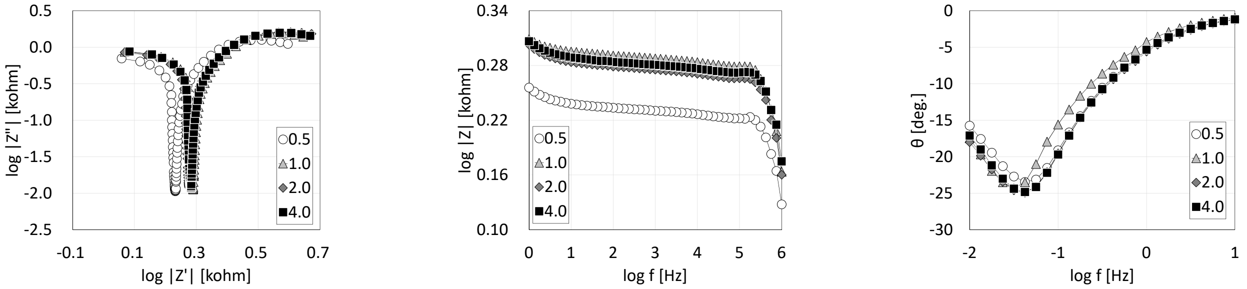
Fig. 4 shows the influence of the material age. Fig. 4 (a) describes electric relaxation behavior and the higher frequency semicircle indicates the response of bulk mortar including cement hydrate, sand, and pore solution. In Fig. 4 (b), there are the differences in the impedance magnitude |Z| in all frequency ranges. The mortar densification with the age and the change of the moisture content per volume affect the types of charges which contribute to conductive behavior. On the other hand, there is hardly any difference in the frequency distributions of phase shift θ. This is because the types of electric charge originated from the mortar which contributes to the resistive and the capacitive component does not change even if the material age changes.



(1) Absolute Impedance |Z| (2) Phase Shift θ

(i) Nyquist Diagram (ii) Bode Diagram

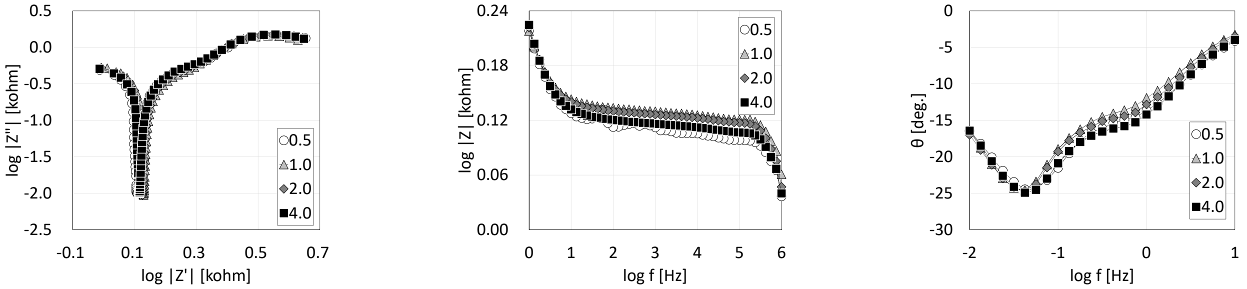
(a) Specimen Fe



(1) Absolute Impedance |Z| (2) Phase Shift θ

(i) Nyquist Diagram (ii) Bode Diagram

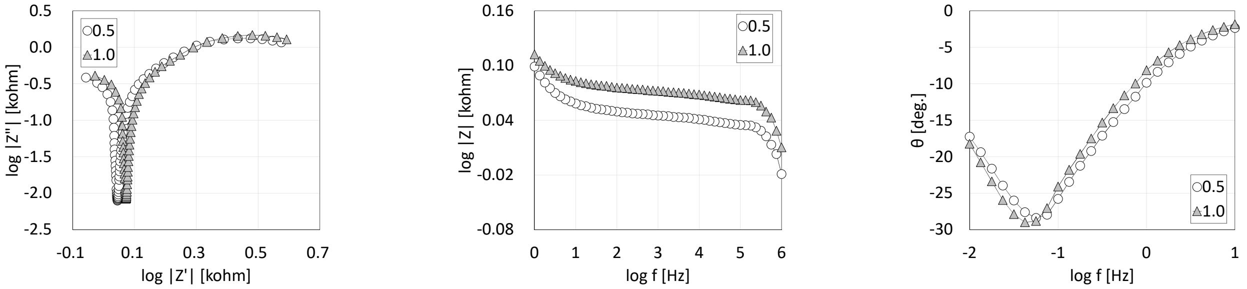
(b) Specimen P



(1) Absolute Impedance |Z| (2) Phase Shift θ

(i) Nyquist Diagram (ii) Bode Diagram

(c) Specimen St



(1) Absolute Impedance |Z| (2) Phase Shift θ

(i) Nyquist Diagram (ii) Bode Diagram

(d) Specimen Zn

Fig. 5 Effect of material thickness (Material Age 365 days)

D. Effect of Embedded Plate Thickness

Fig. 5 shows the influences of the embedded plate thickness. In Bode diagram of θ, each specimen did not show any clear influence of plate thickness. So, the differences of plate thickness seem to have effect only on the resistive component. In the result of the specimen Fe, the specimen with 4.0 mm plate shows a unique behavior. However, it is difficult to identify the others by the thickness order. The specimen P contains the insulative material polyethylene and the specimen with 0.5 mm plate shows the lowest impedance. Results of specimen St and specimen Zn are difficult to interpret only by the idea of conductive charges.

Here, the electrical resistance of the material depends on the internal mobility of charges and the charge transfer resistance at the material interface. Therefore, the influence of the material thickness is not apparent when electric charges which contribute to conductivity exist in the substance sufficiently more than the required amount. Also, a contact area between materials is considered as a determining factor of impedance. However, a porous material like mortar is unavoidable to have variety in the contact area. In other words, in the scope of the present study, although the possibility that the kind of substance contained in the system can be discriminated by complex impedance measurement, it has not been able to grasp the thickness or amount of the material.

IV. CONCLUSION

This research clarified the following items.

1) If appropriate voltage amplitude and frequency are used, it is possible to measure the AC impedance of an object divided by an insulator. And it was better to employ 1-volt signal to grasp the behavior of cementitious material's interfacial capacitor to aim the discrimination of material and the defect detection.
2) The material age has an influence on the absolute value of impedance but has little influence on the phase shift.
3) When a material is thicker than a certain thickness, thickness of the embedded materials hardly affects the resistive and the capacitive characteristics of the system.

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