Monitoring depth-related electrical resistivity of coverzone mortar by tower type sensor using EIS method

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Tower Type Sensor (TTS) was developed to monitor the depth-related electrical resistivity in chloride-contaminated cement mortar using an electrochemical impedance spectroscopy (EIS) method. This paper also details the arrangements of TTS. Then sensor geometric constant *k* was determined in 0.01 mol/L KCl solution. According to the modified equivalent circuit characteristics of TTS system embedded in the cement mortar, a frequency range from 20,000 Hz to 100 Hz is recommended instead of traditional constant frequency which is found to be less accurate due to neglected interface capacitance.

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1. Introduction

The electrical resistivity of concrete is related to the principal stages in the service life of a structure: the initiation period (chloride penetration) and the propagation period (corrosion rate) [1]. Though resistivity does not show whether steel is actively corroding in concrete, it can elevate the corrosion risk of the reinforcement in cover-zone concrete in time. Recently, the development of structural and material health monitoring systems has been repeatedly suggested as a means to provide life-long quality evaluation and condition assessment for concrete facilities [1, 2].

In recent years, several in-suit sensors and novel test methods have been developed to monitor the cover-zone concrete resistivity [3-6]. It has been shown that the electric resistance method based on a so-called corrosion sensor represents a very suitable technique for the monitoring of the electrochemical state of concrete reinforcement and its corrosion [7]. Further, the sensitivity of electrode contact solutions and contact pressure in assessing electrical resisitivy of concrete was examined by M. D. Newlands *et al*. [8]. The investigated results from that work highlighted the errors may be raised by using different conductive contact solutions and inconsistent contact pressure.

Usually, the electrical resistivity can be measured by four equally spaced point electrodes pressed onto concrete surface (Wenner method). The two outer electrodes induce the current and the two inner electrodes measure the potential drop. In light of the sensor electrode polarisation induced by a direct current, most methods for cover resistance measurements use constant-frequency alternating current (AC) signals [5].

The covercrete resistivity sensor developed by W. J. McCarter *et al*. has been transferred from the laboratory to the field environment and forms part of a long-term field durability study [9]. However, this method has been found to be less accurate, and the results are poorly reproducible if a constant frequency is adopted. Attempts to resolve this dilemma have resulted in the development of electrochemical impedance spectroscopy (EIS) with the varied frequencies.

Consequently, a modulated EIS method with a frequency range of 1,000 Hz to 20,000 Hz was adopted to obtain a more precise electrical resistance value and account for the non-homogeneity of the cement mortar and the interfacial characteristics of the mortar and steel anodes. Subsequently, in order to overcome the limitations due to incomplete and imprecise information related to the mortar properties that can be obtained from the measured resistance, a calibration program has been developed to transform the resistance value to resistivity value directly, which bases its knowledge upon the statistical analysis of the sensor geometric constant.

2. Experimental

2.1 Materials

In this study, Portland cement from Harbin Cement Factory was used for all experiments. River sand with fineness modulus of 2.4 was used as fine aggregate. In the laboratory, fabricated tower type sensors and instruments must be calibrated by placing the electrode tips just in contact with liquids of known conductivity in Table 1.

Table 1. The Potassium Chloride Standard Solutions and its Conductivity at 20 ℃.

Concentration ($mol \cdot L^{-1}$)	Conductivity ($S \cdot cm^{-1}$)
0.01	0.0012737

2.2 Tower type sensor system

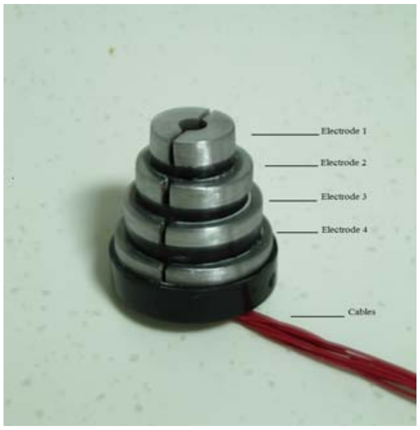

Fig. 1. A typical layout of the TTS system.

A typical layout of Tower type sensor system is shown in Fig. 1. Each of the four steel (Q235) ring electrodes with different diameter spaced 10 mm from each other was fixed on a fabricated nylon tower. The detailed geometrical design of each steel anode is given in Table 2. Cables are led out from the cover-zone concrete after connected to each single electrode E_1~E_4, respectively. This geometrical sensor design ensures that each steel anode has an equal exposure area (A, in mm^2) of about 668 mm^2.

Table 2. The geometrical sizes of the steel anode rings used in this study (mm).

Anode	Inside diameter	Outside diameter	Depth
E_1	8.0	24.0	8.7
E_2	24.0	33.0	7.7
E_3	33.0	40.0	6.7
E_4	40.0	46.0	6.0

To evaluate the electrical resistivity measured by TTS in chloride-contaminated mortar, potassium chloride in 3% mass ratio of cement were added into the cement mortar which was prepared with cement and river sand in the weight ratio of 1/3, and the water/cement ratio was kept at 0.5. TTS system was embedded in the middle of the cement mortar cubic specimen (10 cm× 10 cm× 10 cm). The depth between the bottom of TTS and the upper surface of the cement mortar was 1 cm. Furthermore, specimens were vacuum saturated to partly eliminate the effects of moisture gradient in the cement mortar.

2.3 Electrical resistivity measurement

2.3.1 EIS method

Resistance measurement was measured by EIS method in the frequencies range from 50,000 Hz to 100 Hz using a RST 5200 electrochemical system. Sinusoidal voltage of 10 mV was applied, and direct current potential was set to the corrosion potential (*vs.* counter terminal). One electrode as current input tip was connected to the working electrode terminal, and the adjacent electrode as current output tip was connected to the counter terminal.

2.3.2 Calibration and data analysis

To obtain electrical resistivity of cement mortar, the sensor geometric constant k (in cm) is given as follows:

$$k=R/\rho. \tag{1}$$

where R is resistance (in Ω), and ρ (in Ω·cm) is resistivity. The sensor geometric constant is calculated as:

$$k=A/L. \tag{2}$$

where A is effective contact area (in cm^2) of the cement mortar specimen ends, L is current path (in cm) between two electrodes. For the sensor system with regular shape, A and L are easy to be measured. Unfortunately, the k value of present tower type sensor should be calibrated in above-mentioned solutions of known conductivity (see Table 1) due to its complicated arrangements, especially its unknown current path L.

3. Results and disscussion

Regarding traditional measurements, kinds of constant frequencies were adopted from lack of agreement (for example 128 Hz was adopted in article [1]), and then controversial concrete resistivity value across the kinds of mentioned particular electrode pairs would be obtained after that [1, 5]. Consequently, measurements should be carried out in different frequencies in order to figure the proper imposed frequency out.

Various electric circuits consisting of elements with well defined electrical properties have been used to describe the electrical response of the steel concrete system to a range of possible signals [10, 11]. The response of an electrode in contact with an electrolyte is often represented by a simple circuit made up of the electrolyte resistance R_e in series with aparallel RC branch.

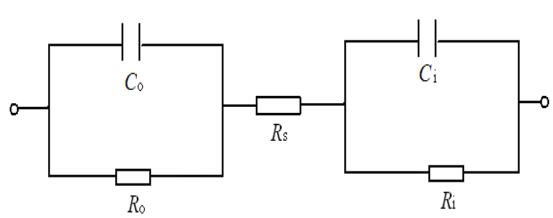

Fig. 2. Equivalent Randles circuit of tower type sensor system in 0.01 mol/L KCl solution.

Fig. 2 depicts the modified equivalent Randles circuit obtained from the present sensor system. Such kind of circuit has been used many times to model the steel-concrete system. Where C_o and C_i are interfacial capacitance (in F) of current output and input electrodes, respectively. R_s represents the cement mortar resistance (in Ω), R_o and R_i are the polarization resistance of input and output electrodes, respectively. According to the equivalent circuit, C_o and C_i are directly short-circuited by means of the interference with the adopted higher frequency current, and then the value of R_s will be obtained.

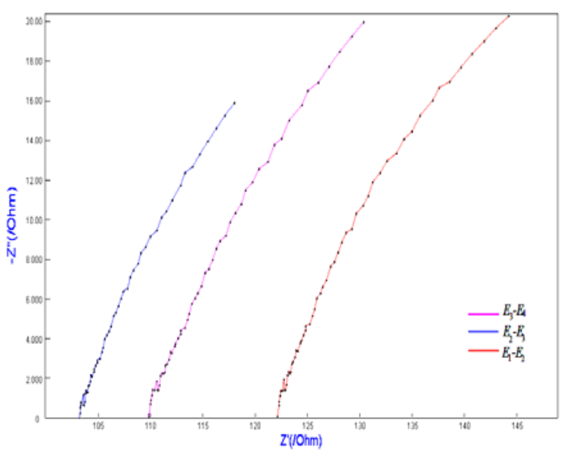

Fig. 3. Impedance behaviors of the tower type sensor in the 0.01 mol/L KCl solution.

As a calibration procedure, Fig. 3 presents the EIS diagram obtained in various frequencies from 50,000 Hz to 100 Hz in 0.01 mol/L potassium chloride solution. With regard to above-mentioned system, the impedance could be given as follows:

$$Z = R_s + \frac{R_i}{1 + jwR_iC_i} + \frac{R_o}{1 + jwR_oC_o} \tag{3}$$

where w (in Hz) is frequency and Z (in Ω) is impedance of present system. According to mentioned equivalent circuit, the values of electrolyte resistance obtained from AC measurements have been attributed to adopted frequncy. The highest frequency impedance plots (w=50,000 Hz) of all measured electrodes agreed with a pure resistance (Z''=0). In such a specific situation, R_o and R_i could be neglected by the bypass effect of C_o and C_i. As the frequency decreases, the appearance of partial capacitance properties was observed in tower type sensor system. That's to say, the measured resistance will be deviated from real resistance on condition that the adopted frequency is not high enough [1].

But unfortunately, the data obtained at higher frequency (more than 20,000 Hz) appears to be less accurate and reproducible due to the limitation of the measurement system and cement mortar imhomogeneous properties. According to the relatively smooth segment in measured curve, the data recorded at frequencies lower than 20,000 Hz are more steady and believable in the present system.

Consequently, the data obtained at frequencies higher than 20,000 Hz should be omitted due to its erratic behavior. And then the fitted resistance value (FR_s) was obtained less than 20,000 Hz which is more proportional to real resistance. The sensor geometric constant is calculated from the fitted resistance and the k values are shown in Table 3.

Table 3. Sensor geometric constant k of built-in electrode pairs of the Tower Type Sensor calibrated in 0.01 mol/L KCl solutions.

Electrode Pairs	FR_s	k (cm)
E_1—E_2	123.60	0.157
E_2—E_3	104.58	0.132
E_3—E_4	110.41	0.141

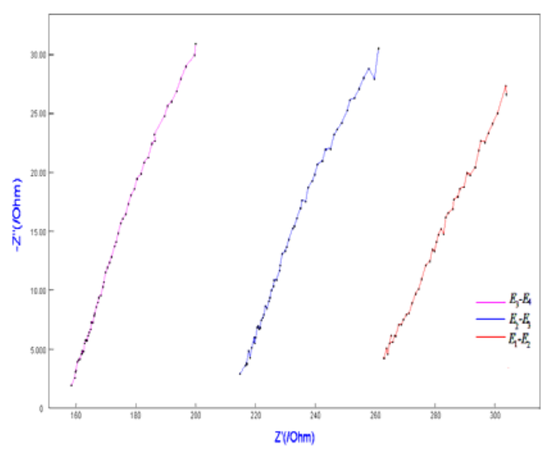

Fig. 4. Impedance behaviors of tower type sensor in chloride-contaminated cement mortar.

Fig. 4 presents the EIS diagram obtained in various frequencies from 20,000 Hz to 100 Hz in saturated cement mortar. According to the literature [12], the charging of a discontinuous and inhomogeneous interface leads to a CPE-like response. A response of this type in the steel electrode-concrete system is therefore to be expected due both to the lack of surface homogeneity of the reinforcements and to the eminently heterogenous nature of concrete [13].

Thus elements C_o and C_i in the circuits in Fig. 2 have been replaced by constant phase elements (CPE). The modified circuit shows in Fig. 5 has been used to qutitatively interpret the response of the electrode steel-concrete system to electrical signals [14]. The sign Q usually denotes such kind CPE. The impedance of Q could be given as follows:

$$Z = \frac{1}{Y_0} \times (jw)^{-n} \tag{4}$$

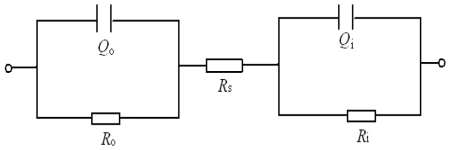

Fig. 5. Equivalent circuit for tower type sensor system in cement mortar.

where n is a factor, Y_0 (in $\Omega^{-1}\cdot cm^{-2}\cdot s^{-n}$) is parameter depicted division physical quantity from capacitance C. In view of similar properties between input electrode and output electrode, the impedance could be simplified according to Fig. 5 and shown as follows [15]:

$$Z = \frac{\frac{1}{R} + Y_0 w^n \cos(\frac{n\pi}{2}) - jY_0 w^n \sin(\frac{n\pi}{2})}{(\frac{1}{R})^2 + (\frac{2}{R})Y_0 w^n \cos(\frac{n\pi}{2}) + (Y_0 w^n)^2} + R_s \tag{5}$$

$$Z' = \frac{\frac{1}{R} + Y_0 w^n \cos(\frac{n\pi}{2})}{(\frac{1}{R})^2 + (\frac{2}{R})Y_0 w^n \cos(\frac{n\pi}{2}) + (Y_0 w^n)^2} + R_s \tag{6}$$

$$Z'' = \frac{Y_0 w^n \sin(\frac{n\pi}{2})}{(\frac{1}{R})^2 + (\frac{2}{R})Y_0 w^n \cos(\frac{n\pi}{2}) + (Y_0 w^n)^2} \tag{7}$$

where R is polarization resistance of the electrodes. If $Y_0 w_n \cos(\frac{n\pi}{2}) >> \frac{1}{R}$, the frequency is so high that the impedance curve of present system in cement mortar will take on a trend of rectilinear regulation (See Fig. 4). Consequently, the relationship between Z' and Z'' could be given as follows:

$$Z'' = aZ' + b. \tag{8}$$

where a represents the slope, and b presents the intercept of the impedance curve in Fig. 4. The value a and value b could be calculated from data shown in Fig. 4, and then the fitted resistance value and resistivity of cement mortar (corresponding to Z''=0) were shown in Table 4. Measured resistance according to traditional method at 128 Hz [1] has also been listed for comparison.

Table 4. Measured resistance values (MR_s), fitted resistance (FR_s) and fitted resistivity values (FR_e) between the built-in electrode pairs for the TTS system embedded in the cement mortar.

Electrode Pairs	a	b	MR_s (Ω)	FR_s (Ω)	FR_e (Ω·cm)
E_1—E_2	0.55	141.4	299.3	255.3	1626.6
E_2—E_3	0.56	131.4	256.2	209.6	1588.4
E_3—E_4	0.71	110.6	195.2	154.7	1097.4

Table 4 shows that the variation between measured value and fitted value in cement mortar resistance are 14.7%, 18.3% and 21.0%, respectively. The variation in the measured resistivity values is due to the influence of interface capacitance between sensor and the mortar, and the degree of influence is the issue. The variation also indicates that the determination of measured resistance can vary with different adopted frequency.

Consequently, the fitted values from the varied frequencies (from 20,000 Hz to 100 Hz) will provide us a more accurate resistance value by minimize the adverse effects of interface capacitance.

4. Conclusions

(1) A novel tower type sensor system was developed which in-suit measured the electrical resistance of cement mortar. By calibration procedure using EIS method, the sensor geometric constant k can be calculated from the fitted resistance value measured in a known resistivity solution.

(2) Such calibration methods are used to implement the lack of geometric information obtained from the measured resistance values, thus it can be applied to the experimental study of the mortar properties more accurately and roundly.

(3) The measured resistance will be deviated from real resistance on condition that the adopted frequency is not high enough to eliminate the adverse influence of interface capacitance. Thus measured resistance values at a constant frequency could be less accurate in the cement mortar.

(4) Due to the EIS behaviors of such TTS system obtained at higher frequencies (more than 20,000 Hz) shows less consistency and accuracy, measured values were fitted according to the values obtained from the frequency range from 20,000 Hz to 100 Hz.

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