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Identification of Electrical Resistance of Fresh State Concrete for Nondestructive Setting Process Monitoring

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Abstract Concrete undergoes significant phase changes from liquid to solid states as hydration progresses. These phase changes are known as the setting process. A liquid state concrete is electrically conductive because of the presence of water and ions. However, since the conductive elements in the liquid state of concrete are consumed to produce non-conductive hydration products, the electrical conductivity of hydrating concrete decreases during the setting process. Therefore, the electrical properties of hydrating concrete can be used to monitor the setting process of concrete. In this study, a parameter identification method to estimate electrical parameters such as ohmic resistance of concrete is proposed. The effectiveness of the proposed method for monitoring the setting process of concrete is experimentally validated.

Keywords: Nondestructive Setting Process Monitoring, Electrical Impedance Measurement, Electric Resistance of Hydrating Concrete, Genetic Algorithm

1. Introduction

Concrete, which comprised of cement, water, and aggregates, is a representative cement-based material widely used in construction of civil and architectural structures. Like other cement-based materials such as mortar, concrete endures significant phase changes as cement hydration progresses. At the beginning of the hydration process (i.e. just after mixing) concrete behaves like a viscous fluid. However, after a certain amount of time, the transition period (known as "setting process") starts and in this period the phase of concrete gradually changes from fluid to solid due to formation and evolution of hydration products. Finally, at the end of setting process, a subsequent strength gain process begins. Among characteristics of fresh state (i.e. until the end of setting process) concrete, the assessment of the time when the setting process begins is important for scheduling of a concrete placement work since it must be finished before the setting process begins [1].

The penetration resistance (PR) test, which is standardized in many countries including Korea and USA [2], is the most widely used test method to assess the setting time of concrete. In the PR test, the setting time is assessed by periodically measuring penetration resistance values of a test specimen obtained from fresh state concrete. However, though widely used, the PR method has many drawbacks to use it for the setting time assessment of fresh state concrete as it is a destructive test method. For example, in order to prevent the influence of coarse aggregates on the penetration resistance value of fresh state concrete, the test should be done on the sampled mortar extracted from fresh state concrete. However, the extraction of mortar is often difficult owing to viscosity of fresh state concrete [3]. Therefore, the development of a nondestructive testing method, which can directly monitor the setting process of concrete, is necessary.

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Hydrating concrete can be modeled as an electrical circuit as it contains both electrically conductive materials (such as water and ions) and non-conductive hydration products (such as C-S-H) [4]. Therefore, circuit parameters such as ohmic resistance may be used as an index for monitoring of the setting process of concrete since the electrically conductive materials in the fresh state concrete are consumed and simultaneously the non-conductive hydration products are increased during hydration process. Unfortunately, however, no experimental method is currently available to directly measure the parameters of equivalent circuit model of fresh state concrete.

In this study, a parameter identification method based on electrical impedance measurement and genetic algorithm based optimization technique is proposed to estimate the parameters of the equivalent circuit model of fresh state concrete. Then, the effectiveness of the proposed method for nondestructive monitoring of the setting process of the fresh concrete is investigated.

2. Parameter Identification Method

2.1. Electrical Impedance Measurement

Various electrical circuit models of cement-based materials including concrete have been proposed [5]. Among them, 4-parameters model, as shown in Fig. 1, is the most widely used for characterizing hydration process of both the fresh state and the hardened state concretes [6,7].

The electrical components of hydrating concrete consist of the ohmic resistance (R_1) and the capacitive resistance (C_1). R_1 describes the pure resistance behavior of conductive materials (e.g. the water and ions) in the bulk of hydrating concrete, while C_1 determines the dielectric behavior in the interface between the non-conductive (e.g. aggregates and hydration products) and the conductive materials in the bulk [6,7]. On the other hand, since the measurement electrodes and the hydrating concrete are electrically different materials, polarization effect in the interface between the electrodes and the concrete cannot be avoided. Therefore, the polarization effect in the electrode-concrete interface should be included in the model. The parallel circuit consisting of a ohmic (R_2) and a capacitive (C_2) resistances is effective to characterize for this effect [6,7].

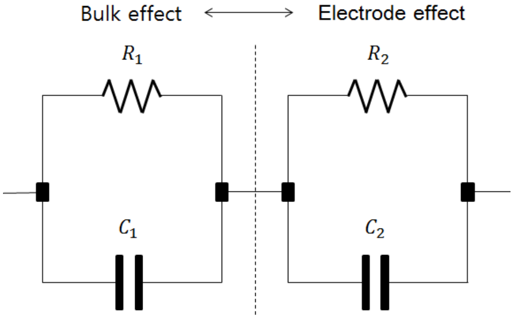

Fig. 1 Conventional equivalent circuit model for concrete

Since the conductive components in concrete are consumed and the non-conductive components are generated during hydration process, all of which affect C_1 and R_1 parameters in the equivalent circuit model. Therefore, if we monitor C_1 and/or R_1, it may be possible to characterize and assess the setting process of hydrating concrete. However, no experimental method is currently available to measure C_1 and/or R_1 directly.

Theoretical impedance of the circuit given in Fig. 1 is given as

$$Z=\underbrace{\left(\frac{R_1}{1+\omega^2R_1^2C_1^2}+\frac{R_2}{1+\omega^2R_2^2C_2^2}\right)}_{Real(Z)} + j\underbrace{\left(\frac{\omega R_1^2C_1}{1+\omega^2R_1^2C_1^2}+\frac{\omega R_2^2C_2}{1+\omega^2R_2^2C_2^2}\right)}_{Imag(Z)} \qquad (1)$$

where Z is the electrical impedance, ω is the frequency of applied alternating current(AC) field, and $j=\sqrt{-1}$ [7]. When ω approaches zero value, Eq. (1) becomes

$$\lim_{\omega\to 0} Z(\omega)=R_1+R_2=R_{dc} \tag{2}$$

where R_{dc} is direct current (DC) resistance which can be measured by a resistance meter. If R_2 maintains constant during measurement, only R_1 contributes to R_{dc}. However, since R_2 is depending on conditions of the electrode-concrete interface, we cannot convince the change of R_{dc} is due only to change of R_1. Therefore, DC measurement method may not be effective for monitoring the setting process of hydrating concrete as R_2 may distort the monitoring results. Due to this reason electrical impedance measurement method, which utilizes alternating current (AC), is used for setting process monitoring of cement-based materials.

2.2. Circuit Parameter Identification

Measured electrical impedance is expressed as

$$Z(\omega)=X(\omega)+jY(\omega) \tag{3}$$

where $X(\omega)$ and $Y(\omega)$ are measured values of the real part (resistance) and the imaginary part (reactance) of Eq. (1) for AC with frequency ω. In Eq. (1), four parameters (R_1, C_1, R_2, and C_2) and one variable (ω) determine the values of $X(\omega)$ and $Y(\omega)$. This means that not only R_1 and C_1 also other parameters affect the measured values of $X(\omega)$ and $Y(\omega)$.

In this study, an optimization technique is employed to obtain R_1 and C_1 from the measured electrical impedance (Z_m) and the theoretical impedance (Z_t) of the equivalent circuit model. The objective function for optimization is proposed as

$$\begin{aligned}&\min\ J(R_1,C_1,R_2,C_2)\\&=\sum_i^n\left(\left[|Z_t(R_1,C_1,R_2,C_2;\omega_i)|-|Z_m(\omega_i)|\right]^2\right)+\lambda\end{aligned} \tag{4}$$

where λ is a penalty term.

Among available optimization techniques, genetic algorithm (GA) is used to estimate the design variables (i.e. the parameters in the theoretical impedance) in this study. GA is a robust heuristic search algorithm that can be possible to find a global solution of an optimization problem [8]. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. The genetic algorithm uses three main rules at each step to create the next generation from the current population, which are (1) selection rule to select the individuals, called parents, that contribute to the population at the next generation; (2) crossover rule to combine two parents to form children for the next generation; and (3) mutation rule to apply random changes to individual parents to form children[9]. For more details about GA method, refer to a textbook by Goldberg [9].

3. Experimental Program

3.1. Test Specimens

The electrical impedance measurement and the penetration resistance test were conducted for validation of the proposed method to monitor the setting process of fresh concrete. Mix proportions of test concrete specimens are listed in Table 1.

Concrete specimens were prepared by manual mixing with Type I Portland cement, tap

Table 1 Mix proportions of concrete specimen (ratio by unit weight of cement)

Cement	Water	Aggregates	
		Fine	Coarse
1	0.4	2.7	2.7

water, fine and coarse aggregates. River sand and crushed gravel were used as the fine and the coarse aggregates respectively. Nominal maximum size of the coarse aggregate is 10 mm. Immediately after mixing, concrete specimen for electrical impedance measurement was cast in a cylindrical mold (diameter: 100 mm and height: 200 mm) and then two low resistance copper electrodes (one for a positive polarization and the other for a negative polarization) were inserted in this specimen. A spacing between the electrodes was set to be 50 mm. For penetration resistance test, mortar sample was extracted from the mixed concrete using a sieve with an opening size of 5 mm, and then this sample was cast in a standard penetration resistance test mold.

3.2. Test Setup and Procedures

Electrical impedance measurement was performed on the concrete specimen. Impedance analyzer (Model: HIOKI HI-Tester) was used to measure the electrical impedances of hydrating concrete specimen. AC frequency range was set from 0.005 - 5 MHz (frequency increment: 5 kHz). Electrical impedance was repeatedly and automatically measured at every 10 minutes. A standard penetration resistance test (ASTM C 403 [10]) was performed on the concrete extracted mortar specimen. Penetration resistance was repeatedly and manually measured at every 30 minutes. Note that the elapsed time before the first impedance measurement and penetration test was 30 minutes after concrete mixing. Both the electrical impedance measurements and the penetration resistance tests were performed at the same place in which temperature and humidity were controlled.

4. Results and Discussions

4.1. Parameter Identification

Measured electrical impedances for some selected times after the initial measurement are shown in Fig. 2. It is clearly observed that the electrical impedance of the test specimen varies with the elapsed time after mixing. Especially, just after initial measurement, electrical impedance moves to downward as the time increases. However, a certain amount of the time after initial measurement, the electrical impedance rapidly increases with the time increases. This characteristic behavior of the electrical impedance of concrete will be explained in the later section.

Measured electrical impedances were used to estimate the parameters of the circuit model. The parameters were identified using GA. Examples (e.g. at 1 hour after mixing) of the measured electrical impedance ($|Z_m|$) and the estimated theoretical impedance ($|Z_t|$) are

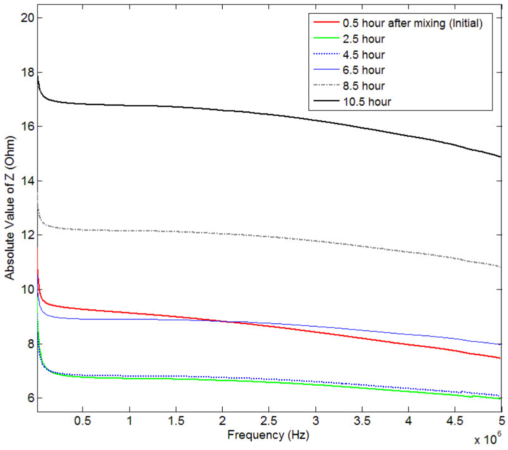

Fig. 2 Measured (absolute valued) electrical impedances of the test concrete specimen

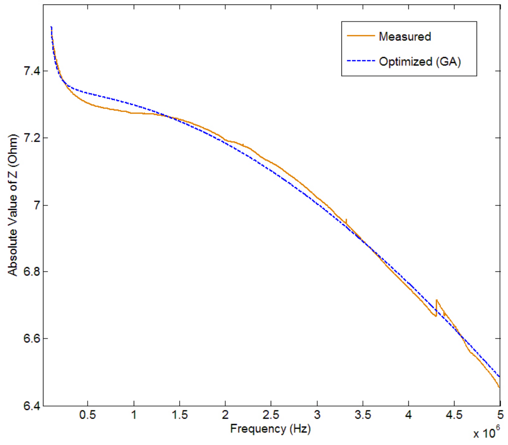

Fig. 3 Example of the measured and the estimated (optimized) electrical impedances of the specimen

Table 2 Parameter values identified

	Concrete Bulk		Electrode-Concrete Interface	
Parameter	R_1 (kΩ)	C_1 (nF)	R_2 (kΩ)	C_2 (nF)
Identified Value	0.0073	9.8835	76.6344	80.0569

shown in Fig. 3. In Fig. 3, the estimated impedance was calculated using Eq. (1) and the identified parameter values listed in Table 2. It is seen that, although some difference is observed, the estimated impedance matches fairly well with the measured impedance. Concrete specimen at this stage (e.g. 1 hour after mixing) is in a liquid state, thus very low electrical resistance is expected at this stage of concrete. In Table 2, it is evidently seen that the identified ohmic resistance of the concrete bulk (0.0073 kΩ) is very low comparing to that of the electrode-concrete interface (76.6344 kΩ). This result suggest that the proposed method is effective to identify the electrical resistance parameters for concrete bulk nevertheless of high resistance difference between the concrete bulk and the electrode-concrete interface.

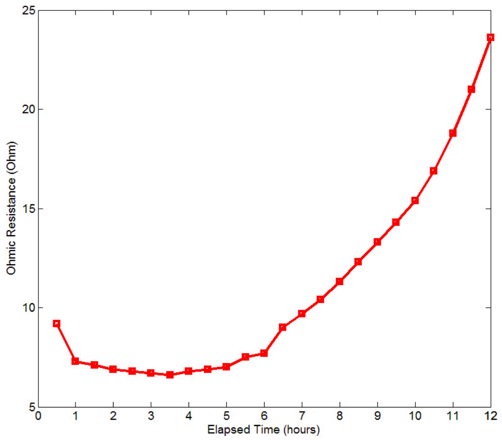

Fig. 4 Identified values of the ohmic resistance parameter for the concrete bulk of the test specimen

4.2. Setting Process Monitoring

The identified values of the ohmic resistance parameter for concrete bulk (R_1) with respect to the elapsed time of hydration process is shown in Fig. 4.

Similar to the electrical impedance responses shown in Fig. 2, the identified ohmic resistance of concrete bulk was initially decreased and then increased. After contacting with water, calcium and hydroxide ions (Ca^{2+} and OH^-) are rapidly released from the surface of cement grains [1]. Since ionic contents in a liquid state concrete bulk are increasing, electrical conductivity of the bulk also increases. This phenomenon explains why the electrical resistance (and hence impedance) of the concrete bulk is decreased initially. However, when the calcium and hydroxide concentrations reach a critical value, the hydration products, CH and C-S-H, start to crystallize from solution and continuously accumulate in the concrete bulk [1]. Hydration products is electrically non-conductive. Therefore, when the hydration products start to crystallize and accumulate in the solution, then the electrical resistance (impedance) of concrete bulk will be increased. This explains the increase of

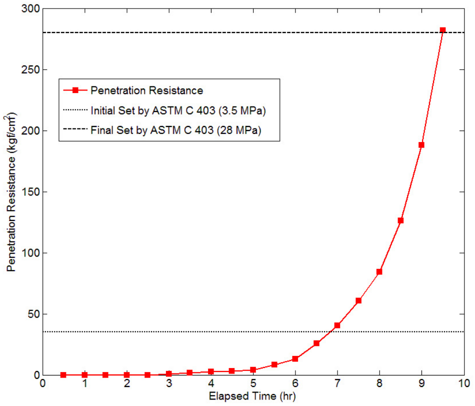

Fig. 5 Penetration resistance values of the test specimen

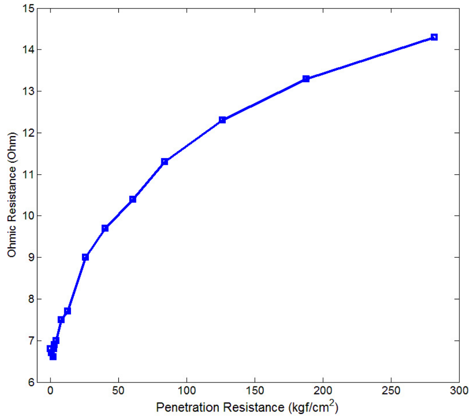

Fig. 6 Relationship between the electrical resistance and the penetration resistance of the test specimen

the electrical resistance of concrete bulk around 4 hours after mixing.

As hydration progresses, the crystallized hydration products grow and connected each other. Before the connection of hydration products appear in the concrete bulk, evolution of mechanical resistance of concrete bulk is not significant. However, when the connection of hydration products appears and further develops in the bulk, the evolution of the mechanical resistance of the bulk is significant [11]. Fig. 5 shows the measured penetration resistance of the test specimen. Initial setting time determined by ASTM C403 criteria (3.5 MPa) was 6 hour 50 min and a final setting time (28 MPa) was 9 hour 30 min after mixing. However, it is observed that a meaningful mechanical resistance is evolved around 4 hours after mixing. Interestingly, the first evolution of mechanical resistance of the test specimen almost coincides with the first increment time of the electrical resistance of the specimen (see Fig. 4).

Fig. 6 shows the relationship (range from 3.5 hours to 9.5 hours after mixing) between the electrical resistance and the penetration resistance of the test specimen. It is seen that the electrical resistance of the test specimen correlates well with the penetration resistance of the specimen. It is well known that the magnitude of penetration resistance value depends on the amount of phase change of cement-based materials due to formation and accumulation of hydration products and which is why the penetration resistance test is performed to setting assessment. Based on this fact and the evidence of the correlation between the penetration resistances and the identified electrical resistance parameters, it can be concluded that the proposed method may be effectively used as nondestructive testing method to monitor the setting process and thus to evaluate the setting time of concrete.

5. Conclusion

In this study, a parameter identification based setting monitoring method for concrete is proposed and validated. The electrical resistance parameter for concrete bulk was successfully identified using GA and the measured electrical impedance response. The identified electrical resistance value of the test concrete specimen correlates well with the penetration resistance of the specimen. Based on the results, it can be concluded that the proposed method may be effectively used for nondestructive monitoring of setting process of concrete.

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