Early-Age Concrete Strength Estimation Technique using Embedded Piezoelectric Self-sensing Impedance

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Abstract

Recently, demands for the construction of Nuclear Power Plants (NPP) using high strength concrete (HSC) has been increased. However, HSC might be susceptible to brittle fracture if the curing process is inadequate. To prevent unexpected collapse during and after the construction of HSC structures, it is essential to confirm the strength development of HSC during the curing process. However, several traditional strength-measuring methods are not effective and practical. In this study, a novel method to estimate the strength development of HSC based on electromechanical impedance (EMI) measurements using an embedded piezoelectric sensor is proposed. The EMI of NPP concrete specimen was tracked to monitor the strength development. In addition, cross-correlation coefficient was applied in sequence to examine the trend of the impedance variations more quantitatively. The results confirmed that the proposed technique can be applied successfully monitoring of the strength development during the curing process of HSC structures.

Keywords : *Concrete Curing, Embedded Piezoelectric Sensor, High Strength Concrete, Nuclear Power Plant, Self-sensing Impedance.*

Introduction

Recently, there has been increasing demand for Nuclear Power Plants(NPP) to satisfy increasing electric demands. Therefore, there is a need for high strength concrete (HSC) with a low W/C ratio and high compressive strength for construction NPP structures. However, the HSC might be susceptible to brittle fracture if the curing process is inadequate. Therefore, to prevent this, it is essential to predict the strength development of HSC during the curing process. In addition, monitoring of the curing strength is important for reducing the construction time and cost because it can determine the appropriate curing time to achieve sufficient strength to progress to the next phase safely. The in situ strength of concrete structures can be determined with high precision by performing strength testing and material analysis on core samples removed from the structure [1]. However, this method can destroy the concrete structure. Therefore, a range of methods based on the thermal, acoustical, electrical, magnetic, optical, radiographic, and mechanical properties of the test materials have been developed to monitor the strength development without damaging the host structure [2-4]. These methods typically measure certain properties of concrete from which the strength and/or elastic constants can be estimated. Among the many techniques, methods using Schmidt hammer or maturity temperature are normally used. However, these methods are hard to apply solely to the construction site because the estimation accuracy of these methods is low.

The recent advent of smart materials, particularly piezoelectric materials, can provide a solution for the real-time monitoring for strength development. Electromechanical impedance techniques that employ piezoelectric materials have emerged as a potential tool for the implementation of a built-in monitoring system for civil infrastructures [5-12]. This technique utilizes high-frequency structural excitation, which is typically > 20 kHz from surface-bonded PZT (lead zirconate titanate) patches, to sensitively monitor the changes in the mechanical impedance of the test structures [13]. In this study, efforts to confirm the applicability of the electromechanical impedance technique using an embedded piezoelectric sensor have focused monitoring on the strength-development during the curing process of HSC.

1   EMBEDDED PIEZOELECTRIC SENSOR

The embedded piezoelectric sensor is developed to measure internal electro-mechanical impedance of concrete. The embedded piezoelectric sensor consists of PZT which is commonly used piezoelectric sensor and semi-spherical type styrene form to protect the PZT. The inside of styrene form is hollow structure to make the one side PZT can be maintain free boundary condition.
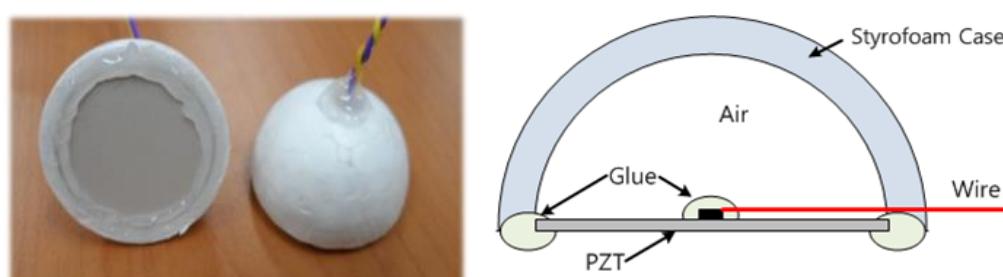

Figure 1 : Embedded piezoelectric sensor

2   SELF-SENSING BASED IMPEDANCE MEASUREMENT METHOD

In this study, impedance measurement systems are based on a self-sensing technique, as shown in Figure 2. A self-sensing circuit as described in Figure 2 is suitable for use in cast-in-site concrete because it is inexpensive and has sufficient accuracy to measure the development of strength, even though the impedance signal is less accurate than other impedance measurement methods. The self-sensing circuit board consists of a single PZT patch, and a voltage divider, such as a resister or capacitor to acquire the output voltage.
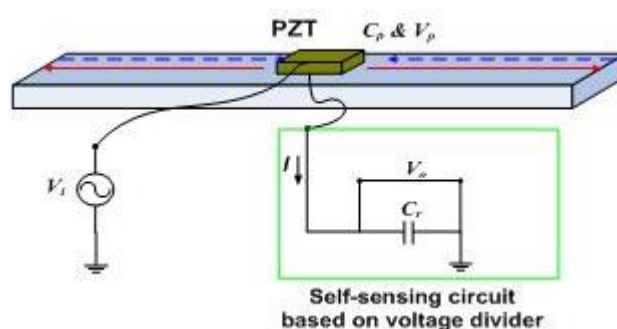

Figure 2 : Schematic diagram of a self-sensing circuit

The impedance is measured in three steps based on the self-sensing circuit as follows: (1) the input voltage (V_i) generated from an arbitrary waveform generator (AWG) is applied to the free surface

of the PZT sensor; (2) the output voltage from the self-sensing circuit (V_o) is measured using a digitizer (DIG); and (3) the admittance, which is the inverse of impedance, is derived from the input voltage, output voltage, and reference capacitance (C_r). The output voltage from the self-sensing circuit consists of the input voltage and mechanical response of the structure (V_r). Although the amplitude of the mechanical responses of the structure is small enough to ignore, the output voltage is dominated by the input voltage and can be approximated as follows [14], [15].

$$V_o(t) = \frac{C_p}{C_p + C_r}(V_i(t) + V_p(t)) \approx \frac{C_p}{C_p + C_r}V_i(t) \tag{1}$$

where C_p is the PZT capacitance and C_r is the reference capacitance of the self-sensing circuit. From (1), the impedance of structure (Z) is derived as follows [14], [15]:

$$Z(\omega) = \frac{V_p(\omega)}{I(\omega)} = [iwC_p]^{-1} \approx \left[i\omega C_r \left(\frac{V_o(\omega)}{V_i(\omega) - V_o(\omega)} \right) \right]^{-1} \tag{2}$$

The impedance was measured by (2) using self-sensing circuit.

3   EXPERIMENTAL STUDY

The mix proportion of NPP concrete is shown in Table 1. The specimen was developed by isothermal air curing. The experimental setup for self-sensing impedance measurement consists of a self-sensing circuit board and a DAQ system (PXI 1042Q, National Instruments Inc.).

The impedance signal was measured each hours after casting and the actual strength was measured at 16, 25, 38, 51, 75, 99 hours after casting by destructive test using cylindrical specimen to compare with impedance signals in early-age of concrete.

Table 1 : Mix Proportion of NPP Concrete

Water	Cement	S/F	Sand	Gravel	AE
155	433	22.8	737	941	0.45

Table 2 : Measured Compressive Strength

Curing Age(Hour)	16	25	38	51	75	99
Compressive Strength (MPa)	10.27	14.06	18.95	22.65	26.02	28.63

Figure 3 : Test specimen

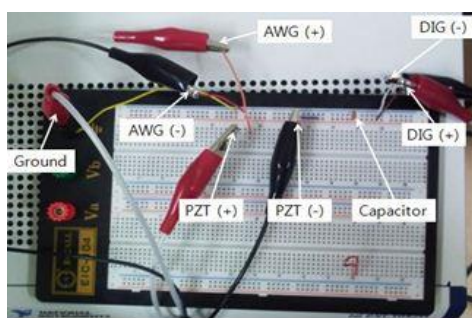
Figure 4 : NI-DAQ system

Figure 5 : Self-sensing circuit

3.1 Impedance Variations Due To Curing Process

The strength of the concrete results from the hydration process of the concrete. During hydration, the mechanical properties of the concrete, such as strength, impedance etc., changed. The impedance technique for monitoring the strength development of concrete employs the change in the mechanical impedance during the hydration process. The resonant frequencies in the impedance signals shifted gradually to the right side with increasing curing age (Figure 6) due to strength development of the concrete. This confirmed that the impedance technique can be used to monitor the strength development of concrete.
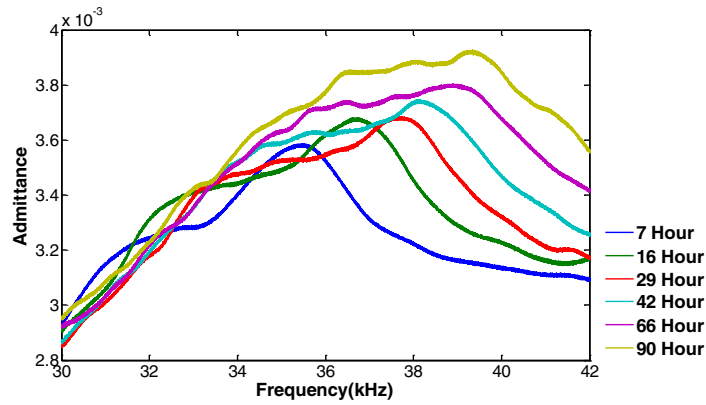
Figure 6 : Impedance variation

3.2 Variation of Cross-Correlation Coefficient

The cross-correlation coefficient index (1-CC) was calculated to provide quantitative information. The 1-CC values were derived using the following equation:

$$1 - CC = 1 - \frac{1}{N-1} \frac{\sum_{i=1}^{N} (\mathrm{Re}(Z_0) - \mathrm{Re}(\overline{Z_0}))(\mathrm{Re}(Z_i) - \mathrm{Re}(\overline{Z_i}))}{\sigma_{Z_0} \sigma_{Z_i}} \quad (3)$$

where $\mathrm{Re}(Z_0)$ is the real part of impedance function at the baseline (the impedance data before embed), $\mathrm{Re}(Z_i)$ is the real part of i-th hour's impedance at each measured data, N is the total number of dataset and   are the standard deviations of each dataset, respectively.
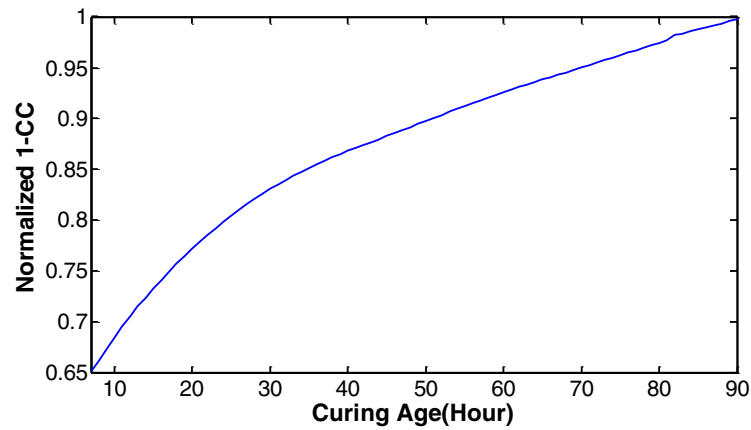

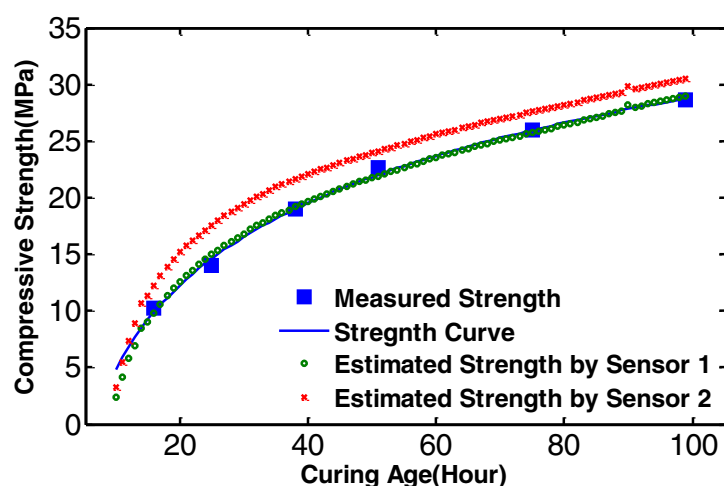Figure 7 : 1-CC-based estimate of strength development

Figure 8 : 1-CC-based concrete strength estimation

The data was normalized to the maximum value of each 1-CC value. The 1-CC data shows the same pattern with a actual strength development curve. The strength estimation equation was derived by mapping the normalized 1-CC and strength of concrete. Figure 8 shows the result of strength estimation. The estimated strengths using two sensors was approximate with actual strength of concrete measured by UTM.

CONCLUSION

This study evaluated the application of embedded piezoelectric sensors for monitoring the strength development of NPP concrete. The applicability of the conventional impedance measuring technique, which is normally used to detect damage, was extended to monitor the curing process of concrete. The impedance signals were obtained at six different curing ages. The compressive strengths of the test concrete cylinders were also evaluated by considering the cross-correlation coefficient. Based on the experimental results, the resonant frequencies in the impedance signals shifted to higher frequencies with increasing curing time, which confirms the applicability of impedance measurements to monitor the strength development of concrete. The strength estimation equation was derived and confirmed by comparing the estimated strength and measured strength.

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