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TECHNICAL NOTE

# Real-time Strength Development Monitoring for Concrete Structures using Wired and Wireless Electro-mechanical Impedance Techniques

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## Abstract

The demand for the construction of high-rise buildings and wide-span bridges using High Strength Concrete (HSC) has increased. 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. In this study, a novel method to estimate the strength development of HSC based on Electromechanical Impedance (EMI) measurements using a wireless sensor node is proposed. The EMI of HSC structures with 100MPa strength was tracked to monitor the strength development. In addition, two types of signal processing, resonant frequency shift and cross-correlation coefficient were applied in sequence to examine the trend of the impedance variations more quantitatively. The results confirmed that the proposed technique can be applied successfully to more reliable and economical monitoring of the strength development during the curing process of HSC structures.


Keywords: *concrete curing strength, wireless sensor node, piezoelectric sensor, impedance, high strength concrete*

## 1. Introduction

During the curing process of concrete structures, real-time monitoring for the strength development of the concrete is very promising because it could reduce the construction time and cost by determining the appropriate curing time confirming sufficient strength to progress to the next construction phase. However, it is very difficult to estimate the concrete strength in real-time since it depends on various factors including mixing ratio, temperature, humidity, etc (Mehta and Minterio, 2006; Shariq *et al*., 2010). To tackle this issue, a range of Nondestructive Evaluation (NDE) methods based on the thermal, acoustical, electrical, and mechanical properties of the concrete materials have been developed to monitor the concrete strength development (Lamond *et al*., 2006; Mehta and Monterio, 2006). However, these methods still have some limitations in terms of its filed accessibility, low accuracy, and the cost. As an alternative to overcome those limitations, an electro-mechanical impedance technique using piezoelectric materials could provide a solution for the real-time monitoring of the concrete strength development (Park *et al*., 2000, 2003; Park *et al*., 2009a, 2010, 2011; Park and Park, 2010; Min *et al*., 2010a; Shin *et al.*, 2008; Tawie *et al.*, 2010; Annamdas and Soh, 2010).

In this context, this study presents a series of experimental results using both wired and wireless electro-mechanical impedance Data Acquisition (DAQ) systems to confirm the applicability of the proposed electro-mechanical impedance technique for the real-time monitoring of strength development during the concrete curing process.

## 2. Theoretical Background

### 2.1 Strength Development During Curing Process in Concrete Structures

Figure 1. Typical curing strength development curve of concrete. Concrete is made by mixing cement with sand, aggregate and water. When first mixed the water and cement constitute a paste which surrounds all the aggregates to make a plastic mixture. A chemical reaction called hydration responses between the cement and water, and concrete commonly changes from a plastic to a solid state in a few hours. Thereafter, the concrete continues to develop strength as it cures, and, almost of its strength is developed in the first 28 days (Neville, 1996).

### 2.2 Electro-mechanical Impedance Technique using Piezoelectric Sensors

It is a well-known fact that certain changes in the mechanical

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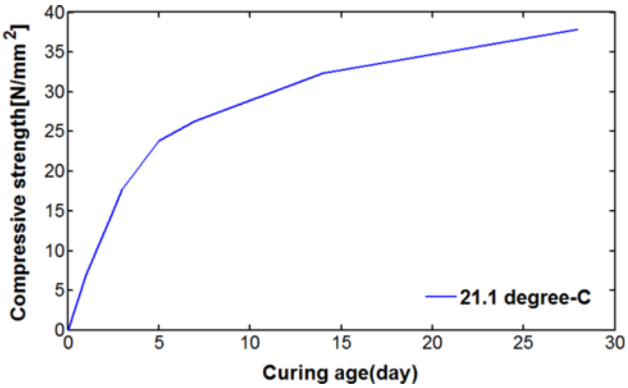



Fig. 1. Shows a Typical Strength-development Curve of Concrete

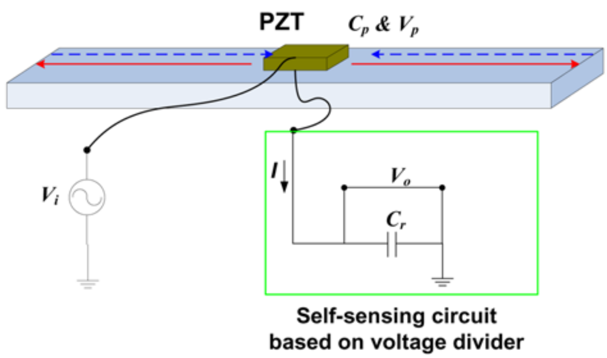
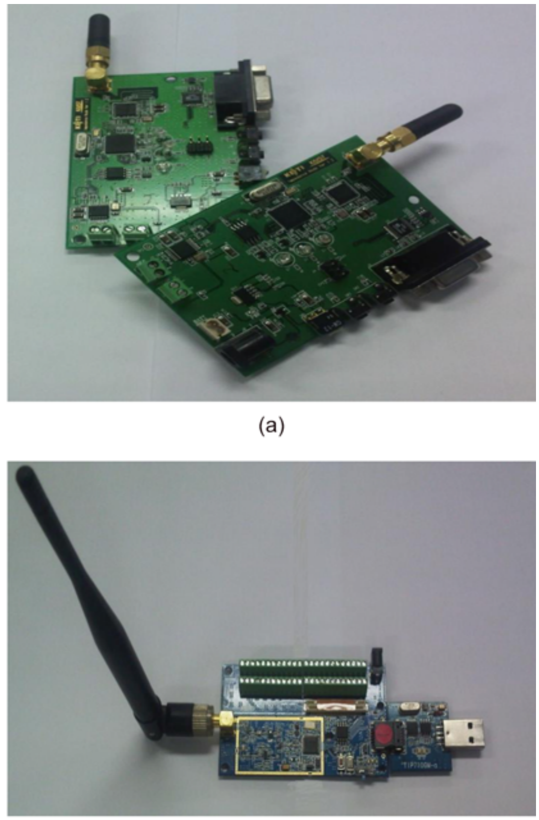



Fig. 2. The Conceptual Diagram of the Self-sensing Circuit



(a)

(b)

Fig. 3. Snapshots of the Wireless Impedance Sensor Node: (a) Wireless Sensor Node, (b) RF Receiver

properties of the host structure lead to corresponding changes in the electro-mechanical impedance characteristics of the piezoelectric sensors attached to the host structure (Giurgiutiu and Rogers, 1997; Liang *et al*., 1996; Annamdas and Soh, 2007). In general, ceramic Type-piezoelectric (PZT) sensors have been the most widely used to apply the electro-mechanical impedance technique to the host structures (Park *et al.*, 2008; Bhalla and Soh, 2004). This study also employs the conventional electro-mechanical impedance technique using the PZT sensors to monitor the strength development in real-time during the curing process of the concrete structures. In particular, on the measurements of the electro-mechanical impedance, a self-sensing circuit board that consists of a single PZT patch, and a voltage divider (capacitor) to acquire the output voltage is utilized (Lee and Sohn, 2006; Lee *et al.*, 2010). The conceptual diagram of the self-sensing circuit is displayed in Fig. 2.

### 2.3 Self-sensing based Wired and Wireless Impedance Measurements

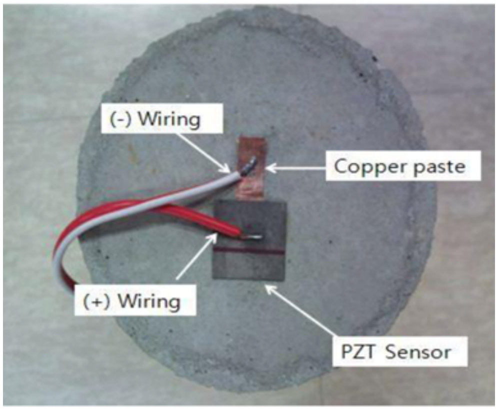
Conventional electro-mechanical impedance methods have used several kinds of wired impedance analyzers, such as HP4194, HP4294A, and Hioki-3320. However, such wired impedance analyzers are bulky and expensive, which is not attractive for in-field applications. Recently, wireless impedance measurement systems-based on wireless impedance sensor nodes have been developed to improve the field applicability of the electro-mechanical impedance technique (Park *et al*., 2009b; Min *et al.*, 2010b). The wireless impedance sensor node reported in the previous research of this article authors (Park and Park, 2010) consists of an impedance measurement chip, a micro-controller unit, and a Radio-Frequency (RF) telemetry module on a small board. The snapshot of the wireless impedance sensor node is displayed in Fig. 3. In this study, a series of experimental studies using both wired and wireless electro-mechanical Impedance Data Acquisition (DAQ) systems were conducted to confirm the field applicability of the electro-mechanical impedance technique-based real-time concrete strength development monitoring.

## 3. Experimental Study

### 3.1 Experimental Setup and Test Procedure

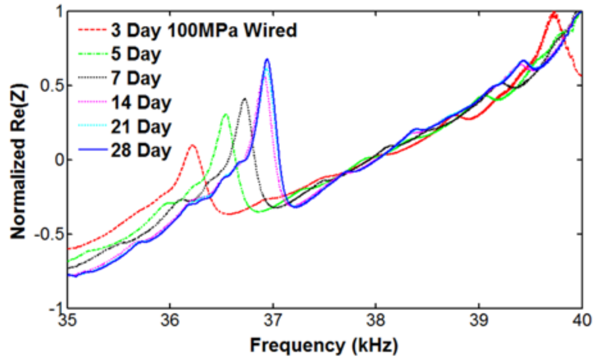
For the proof-of-concept application to measure the electro-mechanical impedance signals during the curing process, three different High Strength Concrete (HSC) cylinder specimens with a designed strength of 100 MPa were prepared by isothermal air curing, as shown in Fig. 4. The PZT sensors with a dimension of 20 mm × 20 mm × 0.508 mm were surface-bonded to the top center of each concrete cylinder on the 3rd day after the casting. Note that a conducting copper paste was utilized to the specimen before the

(a)

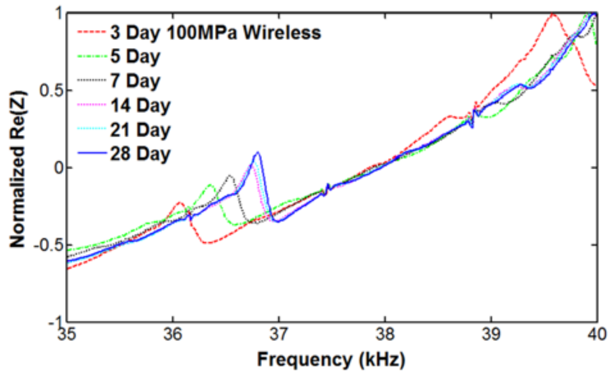



(b)

Fig. 4. Test Specimens: High Strength Concrete Cylinders and PZT Patches: (a) HSC Cylinders with the Design Strength of 100 MPa, (b) Surface-bonded PZT Sensor




(a)




(b)

Fig. 5. Impedance Variations due to Different Curing Ages at HSC Specimen: (a) Wired Impedance Measurement Data, (b) Wireless Impedance Measurement Data

bonding procedure, since the concrete is a non-conducting material.

Then, the electro-mechanical impedance signals were obtained from the test specimens using both wired and wireless impedance DAQ systems, respectively. The wired impedance measuring system consists of a self-sensing circuit board and a NI PXI 1042Q DAQ system including an Arbitrary Waveform Generator (AWG), a Digitizer (DIG), an embedded controller and a LabVIEW software. On the contrary, the wireless impedance measuring system consists of an aforementioned wireless sensor node and a RF receiver for the communication between the laptop and the wireless sensor node.

On the electro-mechanical impedance measurements, a frequency range of 35 kHz ~ 40 kHz was selected to facilitate clear observation of the shift in resonant frequencies in the measured impedance signals. The first test was carried out on the 3$^{rd}$ day after the mixing because before the 3rd day, the PZT sensors could not be attached completely. Subsequent tests were performed at the 5th, the 7th, the 14th, the 21st and the 28th days continuously. In particular, note that Days 3rd, 7th, 14th, and 28th are important days in evaluating the in-place compressive strength in the construction codes of many countries (Neville, 1996). Three cylinders were tested using the wired and wireless systems simultaneously to compare their performance. Furthermore, to improve the signal to noise ratio, the measured signals were acquired 3 times and averaged.

### 3.2 Impedance Variations due to Concrete Strength Development

Fig. 5 shows the measured impedance signals from the both wired and wireless systems at six different curing ages. As displayed in the Fig. 5, the resonant frequencies in the impedance signals shifted gradually to the right according to the increasing curing age due to the strength development of the concrete. This phenomenon was observed as a same fashion from the both wired and wireless impedance measuring systems. This fact confirms that the electro-mechanical impedance technique using PZT sensors can be a powerful tool to monitor the strength development of concrete in real-time.

### 3.3 Establishment of Strength Development Curve throughout Signal Processing Technique

In order to investigate the concrete strength variation according to the curing process more intuitively, it is required to obtain the continuous strength development curve in a visualization aspect by using specific signal processing tools that make the random variations as a regularized index. To this end, this study utilizes two kinds of signal processing methods: One is resonant frequency shift-based signal processing and this other is cross-

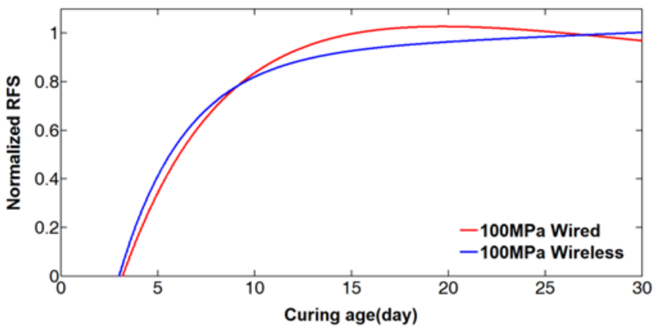


Fig. 6. Resonant Frequency Shift-based Concrete Strength Development Curve

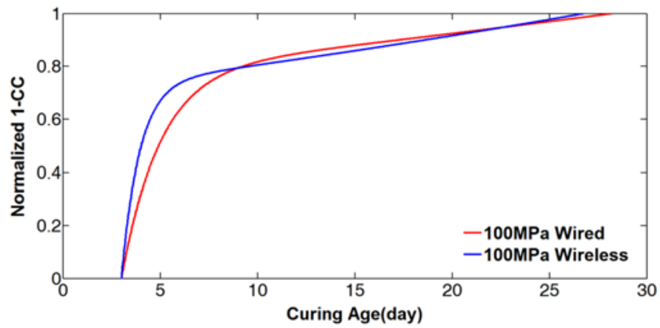


Fig. 7. 1-CC-based Concrete Strength Development Curve

correlation coefficient-based signal processing. Again, note that both signal processing methods were employed to obtain continuous concrete strength development curve that presents the trend of the impedance variations more intuitively.

### 3.3.1 Resonant Frequency Shift-based Concrete Strength Development Curve

To visualize the strength development process during the concrete curing in aspect of continuous monitoring, the related Resonant Frequency Shift (RFS) index displayed in Eq. (1) were calculated at each curing age and its results were plotted, as shown in Fig. 6.

$$RFS = \frac{f_i - f_o}{f_o} \quad (1)$$

Where $f_i$ is the current resonant frequency of the impedance data at each measurement day, and $f_o$ is the resonant frequency of the 3rd day measured impedance data as a baseline. Since the resonant frequency is associated with the strength of a concrete cylinder, the resonant frequency in the impedance signals of the cylinder increased with increasing cylinder strength. The changing patterns between the increasing resonant frequency and the development of the compressive strength were similar. In addition, the RFS of wired and wireless represent a very similar pattern. Therefore, one can say that the RFS index of the electro-mechanical impedance signal can be very effectively used to monitor the strength development of the concrete structures.

### 3.3.2 Cross-correlation Coefficient-based Concrete Strength Development Curve

For the purpose of comparison with RFS index, the cross-correlation coefficient index (1-CC) were also calculated, as seen in following Eq. (2):

$$1 - CC = 1 - \frac{1}{N-1}\frac{\sum_{i=1}^{N}(Re(Z_0) - Re(\overline{Z}_0))(Re(Z_i) - Re(\overline{Z}_i))}{\sigma_{Z_0}\sigma_{Z_i}} \quad (2)$$

where Re($Z_0$) is the real part of impedance function at the baseline (the impedance data of the 3rd day), Re($Z_i$) is the real part of ith day's impedance at each measured day, $N$ is the total number of dataset and $\sigma_{Z_0}\sigma_{Z1}$ are the standard deviations of each dataset, respectively. Fig. 7 shows the 1-CC values calculated from the measured electro-mechanical impedance signal. It is observed that the 1-CC data shows the same pattern with a typical strength development curve. In addition, the wired data and wireless data have a very similar pattern each other. Therefore, one can say that the cross-correlation coefficient index (1-CC) can provide more reliable quantitative information on the strength development during the curing process of the concrete structures.

## 4. Conclusions

This study evaluated the availability of the electro-mechanical impedance-based wireless monitoring technique to estimate the strength development of High Strength Concrete (HSC) structures. Based on the experimental results, the resonant frequencies in the electro-mechanical impedance signals shifted to higher frequencies according to the increasing curing time. The largest change of the Resonant Frequency Shift (RFS) index was observed between days 3 and 5, and the change rate decreased gradually. In addition, the cross correlation coefficient index (1-CC) increased according to the concrete strength development during the curing process. The above phenomena were observed with an exactly same fashion from both wired and wires impedance measuring DAQ systems. Conclusively, in near future, an embedded curing monitoring and structural health monitoring system for high strength concrete structures can be developed and deployed at many locations monitored in real-time at construction sites.

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