- Technical Paper -

MONITORING FOR SETTING TIME OF MORTAR USING ELECTRO-MECHANICAL IMPEDANCE OF PIEZOELECTRICITY SENSOR

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ABSTRACT

In this study, the setting characteristics of cementitious materials were evaluated using the change in the electro-mechanical impedance (EMI) signal of piezoelectricity (PZT). The change in the EMI signal based on the age of the PZT sensor embedded in the mortar was compared with the penetration resistance test. Experimental results show that the setting time of the PZT sensor matches with the setting time obtained from the penetration resistance test. As the mortar was hydrated, the EMI resonance peak and the resonance frequency of the PZT sensor changed. It was found that the point at which the resonance frequency moved to a high-frequency band corresponded to a period in which the decrease in the resonance peak was gradual. This change point can be seen as the initial setting time. In addition, the point at which the resonance peak point disappears can be regarded as the final setting point.

Keywords: setting, electro-mechanical impedance, piezoelectricity sensor, mortar

1. INTRODUCTION

Setting refers to the situation where the cement compound that constitutes cement is hydrated with water to become a new compound through chemical bonding, thereby gradually losing fluidity [1,2]. The setting point is the time point for preventing cold joints in the case of concrete construction and is an important factor in determining the timing of steam curing in precast concrete [3]. Therefore, it is very important to measure the setting of mortar when working with cement mortar.

To evaluate the setting of mortar, the penetration resistance test is widely used [4,5]. The penetration resistance test has the following advantages: convenience of use, suitability in laboratory, and low cost of test equipment. However, because the measurement conditions are different in the laboratory and the field, it is difficult to conduct the test in the actual field. To overcome the limitations of the penetration resistance test, a new method for measuring the setting of mortar is being studied [6,7].

However, these problems still remain to be solved, including the need for expensive equipment and the difficulty of field application. Recently, a study focusing on the behavior characterization of cementitious materials using low-cost PZT elements as a method to solve these problems [8], was conducted. In these studies, the material properties were analyzed through the change in the EMI of the PZT material from the behavior of the cementitious material. However, there is little research on the evaluation of the material state at an early age when setting occurs using the EMI method of PZT.

Therefore, in this study, the setting state of mortar was monitored through the analysis of the EMI signal of the PZT sensor with respect to the water cement ratio affecting the setting process and compared with the results of the penetration resistance test, which is a conventional experimental method.

2. EMI SENSING TECHNIQUE

Various techniques for applying PZT elements as a part of the safety evaluation and nondestructive inspection of structures have been recently developed [9]. Because PZT can measure the admittance according to frequency, it is possible to evaluate the integrity of a structure using PZT as an impedance transducer [10,11]. This technique is called the EMI sensing technique [12,13]. EMI technology is theoretically similar to that of dynamics, but its sensitivity is almost the same as that of ultrasound technology. Unlike ultrasonic wave technology, which collects data in the time domain, EMI technology acquires data directly in the frequency domain [14].

In the EMI sensing technique, the PZT sensor acts both as a sensor and as an actuator. EMI technology monitors the change in the mechanical impedance of the copper plate through the electrical impedance of the PZT sensor attached to the copper plate. Using the principle of copper plate vibration, when the current is allowed to flow through the PZT sensor, the mechanical vibration applied to the copper plate can be accepted as an electrical signal through the PZT sensor to analyze EMI signals. Specifically, a sinusoidal voltage is applied to

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the PZT sensor, causing a local area in the PZT-contained copper plate to vibrate. At the same time, this mechanical vibration induces the current of the attached PZT sensor owing to the backward piezoelectric effect. Therefore, the sinusoidal voltage of the PZT sensor and the resulting mechanical vibration can be measured to obtain the electrical impedance (current).

Impedance can be approximated by dividing the input voltage by the current through the sense resistor [15]. The advantage of EMI technology is that it uses low-cost PZT transducers so that the transducer can be permanently attached or embedded in the structure for continuous monitoring. It also has the advantages of simplified data processing and low-cost hardware. EMI technology is used not only to assess the integrity of structures but also to identify material properties. In particular, EMI technology has been used to monitor the strength of concrete at an early age. Soh et al. [16] estimated concrete strength by measuring the EMI signal through a PZT attached to the concrete surface. Shin et al. [17] also continuously monitored concrete strength by measuring the EMI signal from the concrete surface. Considerable research has been conducted to understand the material properties and integrity of structures using EMI technology, featuring the use of PZT transducers attached to the structure.

However, the internal stress distribution that can reflect the load characteristics of the structure is more important in evaluating the structural integrity and material properties. In addition, in the evaluation of material properties, materials such as concrete have disadvantages in that the characteristics of the material at an early age cannot be monitored because the PZT transducer can only be attached after the concrete is cured. Therefore, technologies for measuring EMI signals by embedding PZT transducers directly in materials are being introduced. Gu et al. [18] have embedded a PZT transducer, called Smart Aggregate, directly in concrete to monitor concrete strength at an early age. Wang et al. [19] have embedded PZT in concrete and predicted the change in the strength of the concrete using EMI technology.

Therefore, in this study, the setting state of the mortar was evaluated by analyzing the EMI signal by directly embedding the PZT sensor in the mortar.

3. EXPERIMENTAL PROGRAM

3.1 Experimental Plan

Table 1 shows the experimental design. In this experiment, mortar was used as an experimental specimen to evaluate the setting state of cementitious materials using PZT, and different water cement ratios were used.

The cement used in the experiment is a Type I ordinary Portland cement. The mixing water was distilled water used to remove the factors affecting the hydration of cement. The water cement ratios of the mortar used in this study were 0.3, 0.4, and 0.5. The cement fine aggregate ratio was 1:3.

Table 1 Experimental plan.

W/C	C:S	W	Evaluation Items
0.3 0.4 0.5	1:3	Distilled water	▪ Penetration resistance test ▪ EMI signal of PZT sensor → EMI resonance peak and EMI resonant frequency

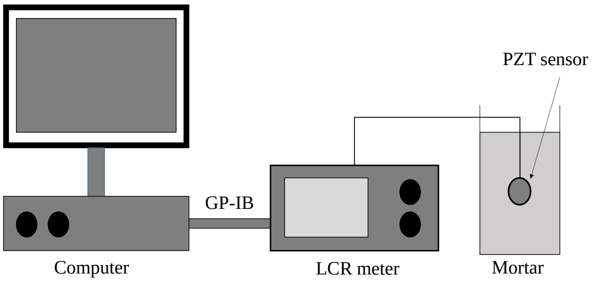


Fig. 1 Schematic diagram of EMI measurement equipment.

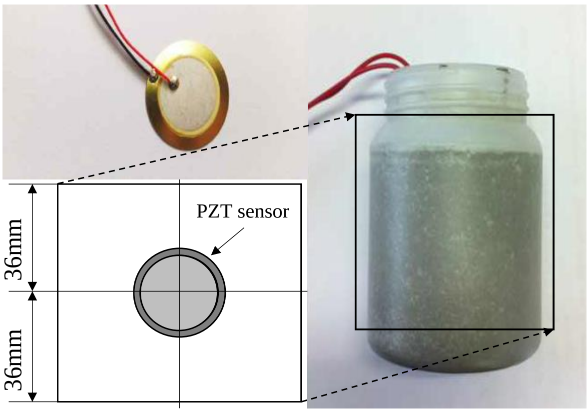


Fig. 2 PZT sensor and landing position.

Table 2 PZT sensor specifications.

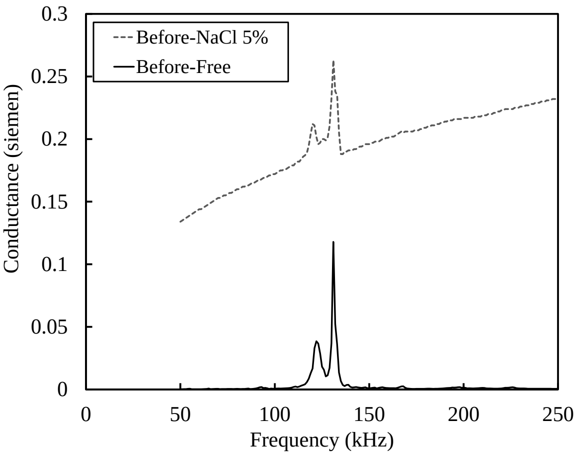
Frequency (kHz)	Resonant resistance (Ω)	Capacity (pF)	Metal
3.5 ± 0.5	350	30,000 ± 30	Brass

Figure 1 shows a schematic diagram of the EMI measurement equipment. The EMI signal of the PZT sensor was measured by embedding the PZT sensor in the mortar and using the LCR meter.

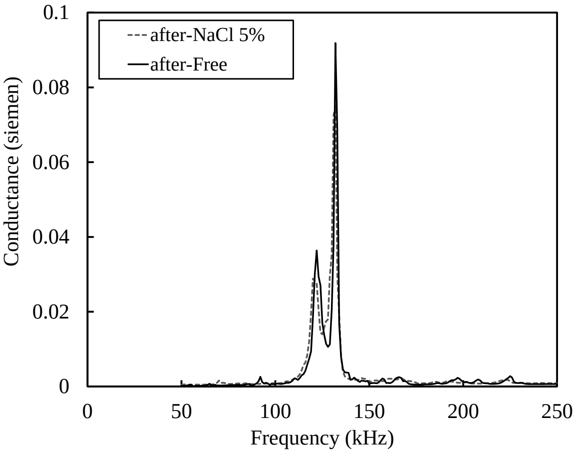
Figure 2 shows the PZT sensor and the embedding position used in the experiment. The PZT sensor used in the experiment is a commercially available Buzzer-element with a piezoelectric plate, 20 mm in diameter and 0.1 mm in thickness, attached to a copper plate with a diameter of 20 mm and a thickness of 0.13 mm.

Table 2 shows the PZT sensor specifications. The frequency, resonant resistance, and capacity of the PZT sensor are 3.5 ± 0.5 kHz, 350 Ω, and 30,000 ± 30 pF, respectively.

Figure 3 compares the impedance signal of the PZT sensor before and after insulation treatment, measured by embedding the sensor in sodium chloride



(a) Before coating



(b) After coating

Fig. 3 EMI signatures of PZT sensor.

(NaCl), with the impedance signal of free vibration. When the non-coated PZT sensor was embedded in sodium chloride, the resonance peak was observed at the same frequency as that for free vibration, but the shape of the overall signal varied. This is because the EMI signal evident when the ion was dissolved in the moisture present in the sodium chloride and the electrical impedance was synthesized to cause a short circuit. In this signal, it is difficult to extract the EMI signal of a pure PZT sensor.

However, when the insulated PZT sensor was embedded in sodium chloride, the EMI signals of free vibration and the sodium chloride exhibited similar characteristics. It is considered that the short circuit was effectively removed through the insulation; therefore, it is essential to insulate PZT. In this experiment, a transparent acrylic insulation coating with high alkali resistance was used to insulate PZT.

3.2 Experimental method

The penetration resistance test and EMI signal of the PZT sensor were analyzed after the mortar was manufactured according to KS L 5109. The penetration resistance test was conducted according to ASTM C 403. Experiments were conducted in the laboratory with a constant temperature and humidity of 20 ± 3 ℃ and 60 ± 3%, respectively. The time-intrusion resistance data measured by the penetration resistance test were the results of a regression analysis with exponential curve, and the time when the penetration resistance was 3.5 MPa was taken as the initial setting time, while the time at which the penetration resistance was 27.6 MPa was considered the final setting time.

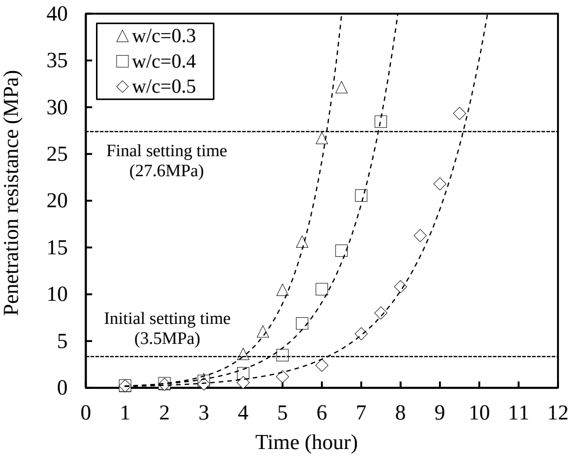


Fig. 4 Results of penetration resistance test according to water cement ratio.

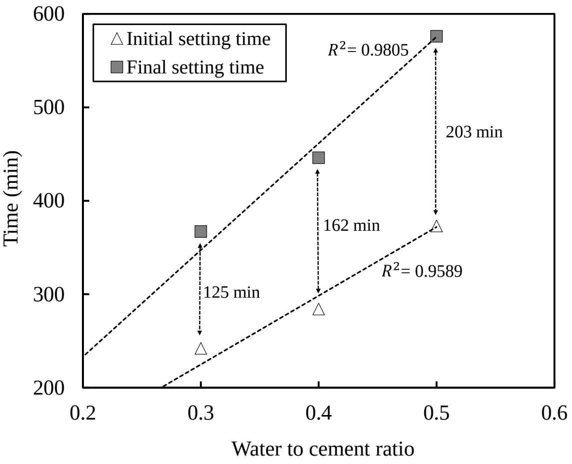


Fig. 5 Setting time of penetration resistance test according to water cement ratio.

To measure the EMI signal of the PZT sensor, the mortar was placed in a plastic container with a diameter of 60 mm and a height of 72 mm, and then a PZT sensor treated with acrylic was buried in the center. At this time, GP-IB was used for data collection. The measurement frequency range was 20–250 kHz, and the measurement frequency interval was 500 Hz, with the measurement performed at 10 min intervals for 12 h.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Setting time by penetration resistance test

Figures 4 and 5 show the results of the penetration resistance test according to ASTM C 403 and the water cement ratio. In general, the lower the water cement ratio was, the faster the initial and final setting

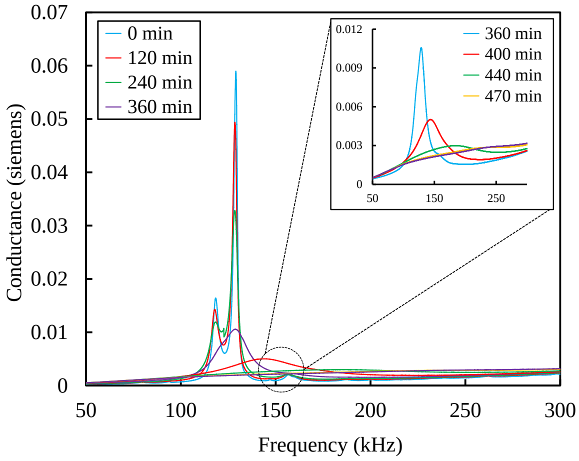


Fig. 6 Example of EMI signatures of PZT sensor embedded in mortar.

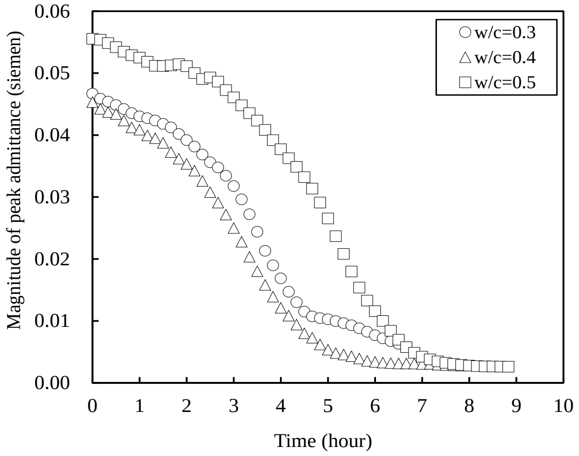


Fig. 7 Magnitude of EMI resonance peak as function of material age.

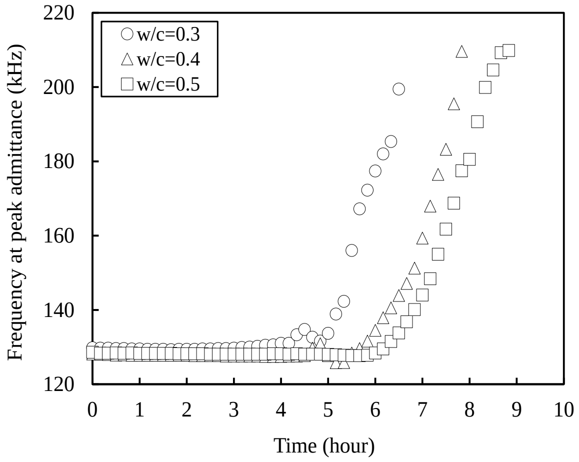


Fig. 8 EMI resonance peak frequency as function of material age.

times were. In addition, the lower the water cement ratio was, the shorter the time interval between the initial and final setting time was, with an interval of 123 minutes for mortar at a water cement ratio of 0.3, 162 minutes for a water cement ratio of 0.4, and 203 minutes for a water cement ratio of 0.5.

4.2 Evolution of EMI of PZT sensor

Figure 6 shows the result of the 0.4 water cement ratio as an example of the EMI signal behavior of the PZT sensor according to the age of the mortar. As a whole, the amplitude of the EMI resonance peak of the PZT sensor shows a continuous decrease with increasing hydration time, and the peak disappears after a certain period of time. By contrast, the resonance peak size decreases with water cement ratio at other levels.

Figure 7 shows the signal of the EMI resonance peak magnitude according to the age of the mortar. With the progression of the hydration of the mortar, the EMI resonance peak magnitude of the PZT sensor shows a steady decrease, and the peak disappears after a certain period of time. The disappearance time of the resonance peak according to the water cement ratio of the mortar was 390 min for a water cement ratio of 0.3, 470 min for a water cement ratio of 0.4, and 530 min for a water cement ratio of 0.5.

Figure 8 shows the EMI resonance frequency signal of the PZT sensor according to the age of the mortar. The resonance frequency does not change largely at the beginning of the hydration reaction but shows a tendency to abruptly move from the specific time point to the high-frequency region, until the resonance peak disappears.

The time of the resonance frequency shift as a function of water cement ratio was 270 min for a water cement ratio of 0.3, 290 min for a water cement ratio of 0.4, and 400 min for a water cement ratio of 0.5.

4.3 Compared with EMI signature of PZT sensor and penetration resistance test

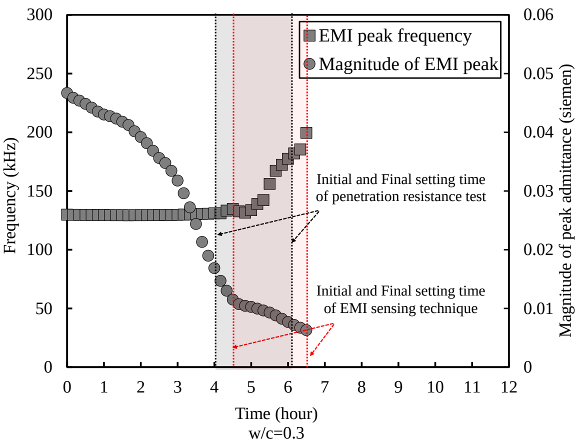
Figure 9 shows the behavior of the EMI signal and penetration resistance test results according to the water cement ratio of the mortar. The disappearance time of the resonance peak behaved similarly to the final setting time of the penetration resistance test with respect to water cement ratio.

The disappearance of the resonance peak is believed to be because the mortar secures the rigidity at the time of termination and completely suppresses the free vibration of the PZT sensor, so that the mortar and the PZT sensor are integrated and behave together.

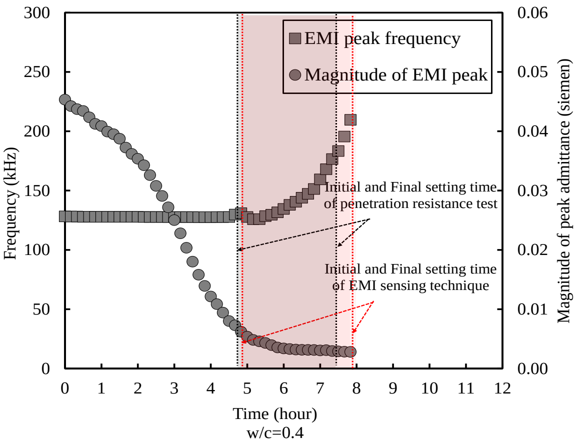
Meanwhile, the time at which the EMI signal shifts to a high-frequency band corresponds to the time at which the decrease in the resonance peak of the EMI signal begins to slow. These behaviors occur when the mortar around the PZT sensor begins to exhibit rigidity and suppresses the free vibration of the PZT sensor.

At the beginning of the hydration time, when the mortar shows its rigidity, only the resonance peak magnitude decreased without a large change in the resonance frequency because of the viscosity change in the mortar. Afterwards, the resonance frequency shifts to a high-frequency band owing to the initial setting of the mortar, and the decrease in the magnitude of the resonance peak slows.

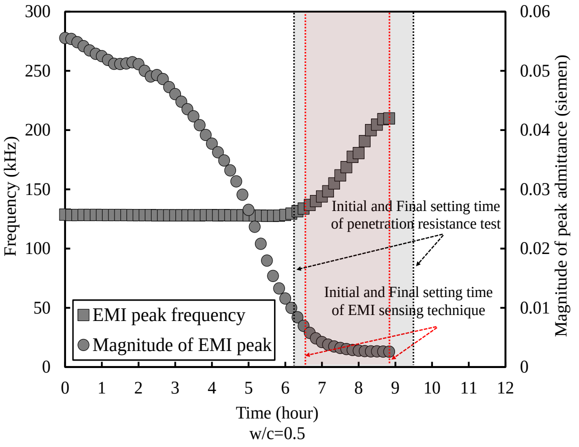
Therefore, the point at which the EMI resonance frequency changes can be defined as the initial setting



(a) W/C = 0.3



(b) W/C = 0.4



(c) W/C = 0.5

Fig. 9 EMI Signal Behavior of Mortar.

time, and the point of time when the resonant peak disappears is the final setting time of the mortar.

Table 3 shows the setting time according to the water cement ratio of the mortar calculated by the penetration resistance test and the PZT sensor. Overall, the time difference in the setting time between the PZT sensing method and the penetration resistance test is less than 30 min. It is considered that the setting time evaluated by the EMI sensing method can be used as a new method for evaluating the setting of the actual mortar.

Table 3 Setting time of mortar according to penetration resistance test and PZT sensor.

W/C	Setting time	Penetration resistance test (Min.)	PZT sensor (Min.)	Time difference (Min.)
0.3	Initial	242	270	28
	Final	367	390	23
0.4	Initial	284	290	6
	Final	446	470	24
0.5	Initial	373	400	27
	Final	576	530	46

5. CONCLUSIONS

In this study, the monitoring results of the setting state of mortar using the EMI signal of the PZT sensor were obtained, and the following conclusions were determined.

(1) As the mortar was hydrated, the amplitude of the EMI resonance peak continuously decreased and then disappeared at a certain point. The EMI resonance frequency did not change very much at the beginning of hydration, but it did shift to a high frequency band after a certain point in time.

(2) The moving point of the EMI resonance frequency was similar to the initial setting time of the penetration resistance test, and the disappearance of the EMI resonance frequency occurred near the final setting time of the penetration resistance test.

(3) Therefore, it is considered that the EMI sensing technique using piezoelectric elements is effective for evaluating the setting characteristics of cementitious materials.

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