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Technical Note

Electro-Mechanical Impedance Technique for Assessing the Setting Time of Steel-Fiber-Reinforced Mortar Using Embedded Piezoelectric Sensor

Jun-Cheol Lee [1] and Chang-Joon Lee [2,*]

[1] Department of Architecture, Seowon University, Cheongju 28674, Korea; leejc@seowon.ac.kr
[2] Department of Architectural Engineering, Chungbuk National University, Cheongju 28644, Korea
* Correspondence: cjlee@chungbuk.ac.kr; Tel.: +82-43-261-2429

Abstract: The electro-mechanical impedance (EMI) change in Piezoelectric (PZT) sensors embedded in steel-fiber-reinforced mortar (SFRM) was investigated to assess the material setting time. The EMI was continuously monitored for 12 h by the PZT sensor embedded in SFRM having fiber volume fraction of 0.5%, 1.5%, and 2.0%. The initial and final setting time of the SFRM were estimated using EMI signal change. The penetration resistance test, a conventional test method for the setting time of cement mortar, was also conducted. In the penetration resistance test, it was observed that the initial and the final setting time of SFRM accelerated as the volume fraction of the steel fiber increased. On the other hand, in the EMI sensing technique, the initial and the final setting time of the SFRM were consistent regardless of the fiber volume fraction.

Keywords: electro-mechanical impedance; setting time; steel-reinforced mortar; piezoelectric sensor

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1. Introduction

During the hydration process of cement paste, a phase transition occurs from fluid state to solid state, which is called setting. In general, cement sets within a few hours in contact with water. The cement setting is an important factor in determining for concrete finishing work time, steam curing time, cold joint prevention time, form work release time, etc. [1].

Conventional methods used for the setting time measurement of cementitious materials include the Vicat needle test [2] and penetration resistance test [3]. The Vicat needle test assesses the setting time of cement paste by means of the depth of a needle penetrating into the material. The penetration resistance test assesses the setting time of cement mortar by means of penetration resistance of a needle. These conventional methods are suitable for assessing the setting time of cement paste and mortar. However, it is difficult to obtain a consistent setting time when these methods are applied to fiber-reinforced cementitious materials due to additional resistance caused by the fibers inside the cementitious materials.

Recently, as part of a non-destructive test method for assessing the setting time of cementitious material, a technique using the electro-mechanical impedance (EMI) of Piezoelectric (PZT) sensors has been proposed (Lee et al. [4,5]). In their study, the initial and final setting time of cement paste were assessed using the resonance peak amplitude and frequency of the EMI signal of PZT sensor embedded in the cement paste. The stiffness change due to hydration of the cementitious material in contact with the embedded PZT was found to change the EMI of the PZT sensor, and through this, the degree of hydration of the cement paste could be evaluated.

The basic principle of the EMI sensing technique is as follows: When a PZT sensor coupled (bonded or embedded) with a host structure is driven with a sinusoidal voltage, the coupled region of the structure vibrates due to piezoelectric effect. At the same time, this vibration response causes an electrical response (usually electric current) in the PZT sensor due to the converse piezoelectric effect. Using the input and output signal of the PZT sensors, the EMI can be calculated [6–8].

In many applications of the EMI sensing technique for cementitious materials, a PZT sensor is adhesively bonded on the surface of host structures to couple the PZT sensor and the structure. Several research efforts have been made to monitor the concrete strength development by measuring EMI signals of PZT attached on the surface of concrete. They tried to corelate the EMI signal change and the strength development of concrete [9–12].

Surface bonding is not available for the early hydration stage of cementitious materials since their surface is not hard enough to attach a PZT sensor. For this reason, techniques for measuring EMI by embedding a PZT sensor directly into a cementitious material have been introduced. The EMI sensing techniques using embedded PZT sensor were aimed to monitored concrete strength development at early ages. Gu et al. monitored the early age strength of concrete using a PZT sensor embedded in concrete [13], and Wang and Zhu used EMI sensing technique to predict the change in strength of concrete at an early age by embedding PZT sensor into concrete [14].

Since the electro-mechanical response of the PZT sensor embedded in fiber-reinforced mortar is greatly affected by the cementitious material in direct contact with the PZT sensor, the fibers around the PZT sensor might have little effect on the electro-mechanical response of the PZT sensor. Therefore, the EMI sensing technique using an embedded PZT sensor could be an effective tool for assessing the setting time of fiber-reinforced cementitious materials.

In this study, the EMI signal of PZT sensors embedded in SFRM was continuously monitored to assess the setting time of the material. The setting times assessed by EMI sensing technique were compared with those from penetration resistance test [3], a conventional test method for the setting time of cement mortar.

2. Experimental Procedure

2.1. Materials

KS L 5201 type I (equivalent to ASTM C 150) ordinary Portland cement and standard sand conforming KS L ISO 679 were used for the mortar samples [15,16]. The mixture proportion of the mortar was 50% water-cement ratio, and 1:3 weight ratio of cement-sand. As the fiber ingredient, hooked-end bundle type steel fibers with a length of 30 mm, an aspect ratio of 60, a specific gravity of 7.85 and a tensile strength of 1100 MPa was used. The volume fractions of the incorporated fibers varied as 0% (plain mortar), 0.5%, 1.0% and 2.0%. Table 1 shows the mixture proportion of the mortar samples.

Table 1. Mixture Proportion for fiber-reinforced mortar.

Sample	Water (g)	Cement (g)	Sand (g)	Steel Fiber (g)
Plain	768	1536	4608	-
F-0.5				117
F-1.0				234
F-2.0				468

A bowl mixer was used to prepare the mortar samples. All the dry ingredients (cement, sand, fibers) were added and dry-mixed together for 60 s. Water was added and mixed for 30 s. The mixer was stopped for a minute to scrape down the materials which were stuck on the side and bottom of the bowl mixer. After removal of the attached mortar, additional mixing was performed for 60 s.

2.2. Penetration Resistance Test

The penetration resistance test was conducted in accordance with ASTM C403 [3] in order to validate the EMI sensing technique for assessing setting time of the mortar. The mortar samples were prepared and casted in a cylindrical container with a diameter of 150 mm and a height of 150 mm. A penetrating needle of an appropriate cross-sectional area was penetrated from the surface of the mortar sample, and the resistant load was measured at the same time. The penetration resistance was calculated by dividing the load when the needle penetrates to a depth of 25 mm by the cross-sectional area of the penetrating needle. The initial measurement of the penetration resistance was conducted 1 h after casting mortar samples. Subsequent measurements were made every hour when the penetration resistance was less than 3.5 MPa, and every 30 min after the penetration resistance exceeded 3.5 MPa. Regression analysis was performed with exponential function to obtain the time-penetration resistance curves. Using the regression curves, the time point when the penetration resistance was 3.5 MPa was set as the initial setting time, and the time point when the penetration resistance was 27.6 MPa was set as the final setting time.

2.3. Electro-Mechanical Impedance Measurement

The EMI of PZT sensor embedded in the mortar samples was monitored to assess the setting time of the material. A buzzer type PZT sensor (CBCG2035BAL-2, DAEYOUNG ELECTRIC Co., Ltd., Gyeongsan, Korea, Figure 1) was used to monitor the EMI signal. Acrylic resin was thinly coated on the surface of the PZT sensor to prevent short-circuit state caused by the ions dissolved in the mortar samples [4].

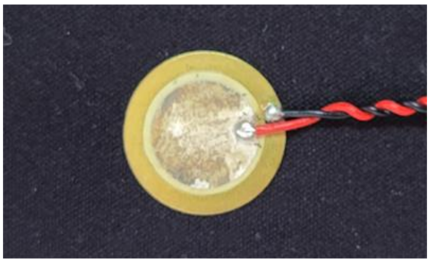

Figure 1. PZT sensor for EMI measurement.

The mortar samples were cast into a cylindrical container with a diameter of 150 mm and a height of 150 mm. The PZT sensor was placed at the center of the container. The initial measurement of the EMI of the PZT sensor was conducted 20 min after placing the PZT sensor and subsequent measurements were conducted every 10 min for 12 h. The EMI of PZT sensor was measured using a LCR meter (3235-50 LCR HiTESTER, Hioki, Japan), and the EMI signals were recorded using a personal computer. For EMI measurements, a frequency range of 20 kHz to 250 kHz was swept in 500 Hz steps. Figure 2 shows the test setup for EMI measurement of a PZT sensor embedded in the mortar sample.

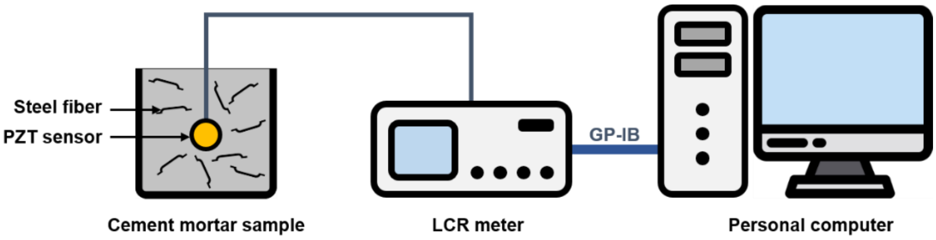

Figure 2. Test setup for EMI measurement of a PZT sensor embedded in fiber-reinforced mortar.

3. Results

3.1. Setting Times from Penetration Resistance Test

Figure 3 shows the penetration resistance of the plain mortar and SFRMs with different fiber volume fractions (0.5%, 1.0%, 2.0%) as a function of time. Table 2 shows the initial and final setting time of the mortar samples evaluated according to ASTM C 403. As shown in Figure 3 and Table 2, the initial and final setting time of the SFRM samples were found to be faster than those of the plain mortar. In addition, the initial and final setting time were accelerated as the fiber volume fraction increased. The initial setting times of mortar samples using 0.5 vol.%, 1.0 vol.%, and 2.0 vol.% steel fibers were 122 min, 158 min, and 199 min faster than that of the plain mortar, respectively. The final setting times of mortars using 0.5 vol.%, 1.0 vol.%, and 2.0 vol.% steel fibers were 133 min, 167 min, and 188 min faster than that of the plain mortar, respectively. The time gaps between the initial and final setting time of the SFRMs were not significantly different compared with that of the plain mortar.

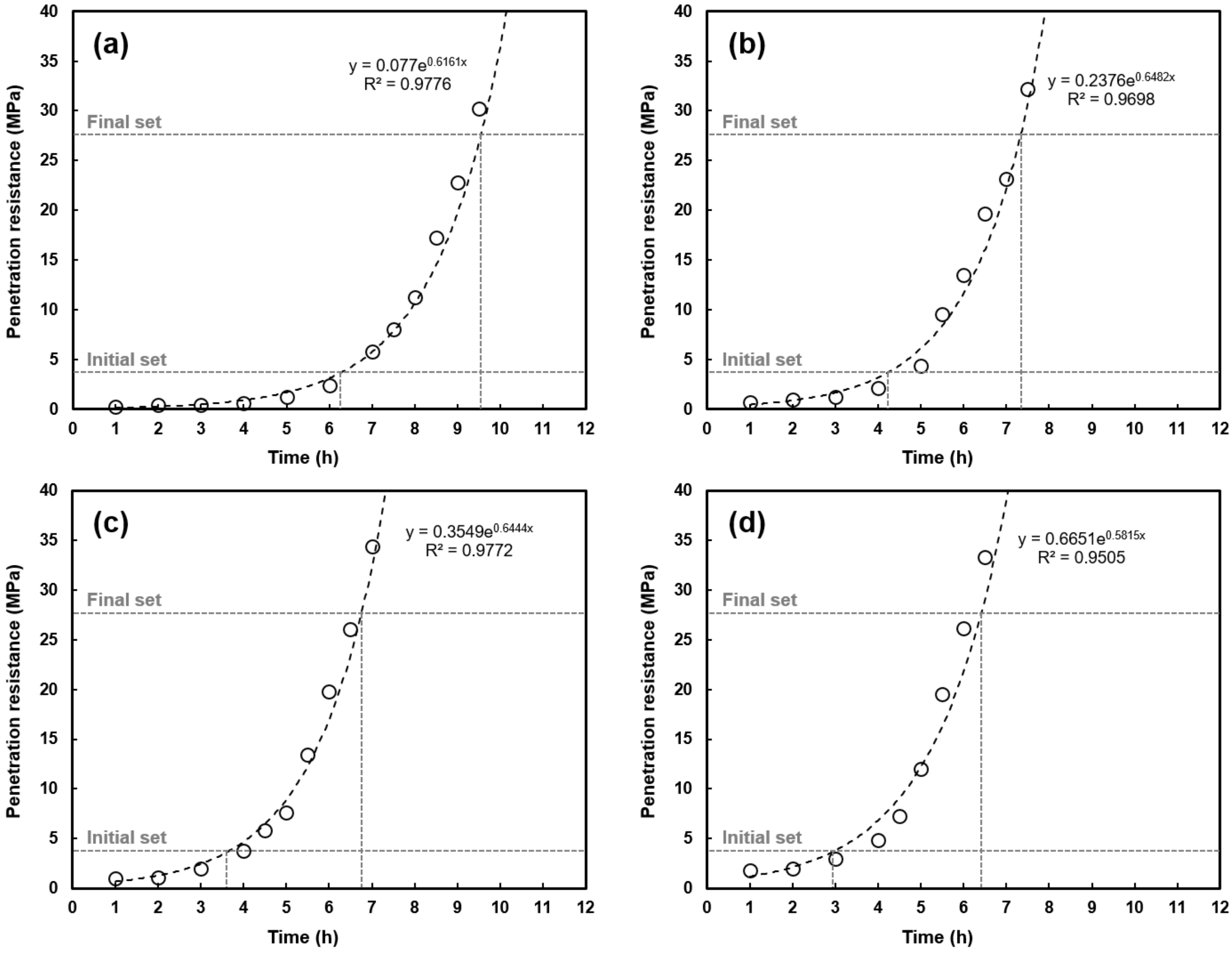

Figure 3. Penetration resistance as a function of the age: (**a**) Plain; (**b**) F-0.5; (**c**) F-1.0; (**d**) F-2.0.

Table 2. Setting times of fiber-reinforced mortar determined by ASTM C 403.

Sample	Initial Setting Time (min)	Final Setting Time (min)	Time Gap between the Initial Set to the Final Set (min)
Plain	371	573	202
F-0.5	249	440	191
F-1.0	213	406	193
F-2.0	172	385	213

3.2. *Electro-Mechanical Impedance*

Figure 4 shows the change of EMI signal of PZT sensor embedded in the mortar samples according to material age. The EMI resonance peak amplitude continued to decrease over time without significant change in the EMI resonance peak frequency until about 6 h after casting. After that, the EMI resonant peak frequency moved to the high frequency region. Afterwards, the EMI resonant peak disappeared at a specific time point.

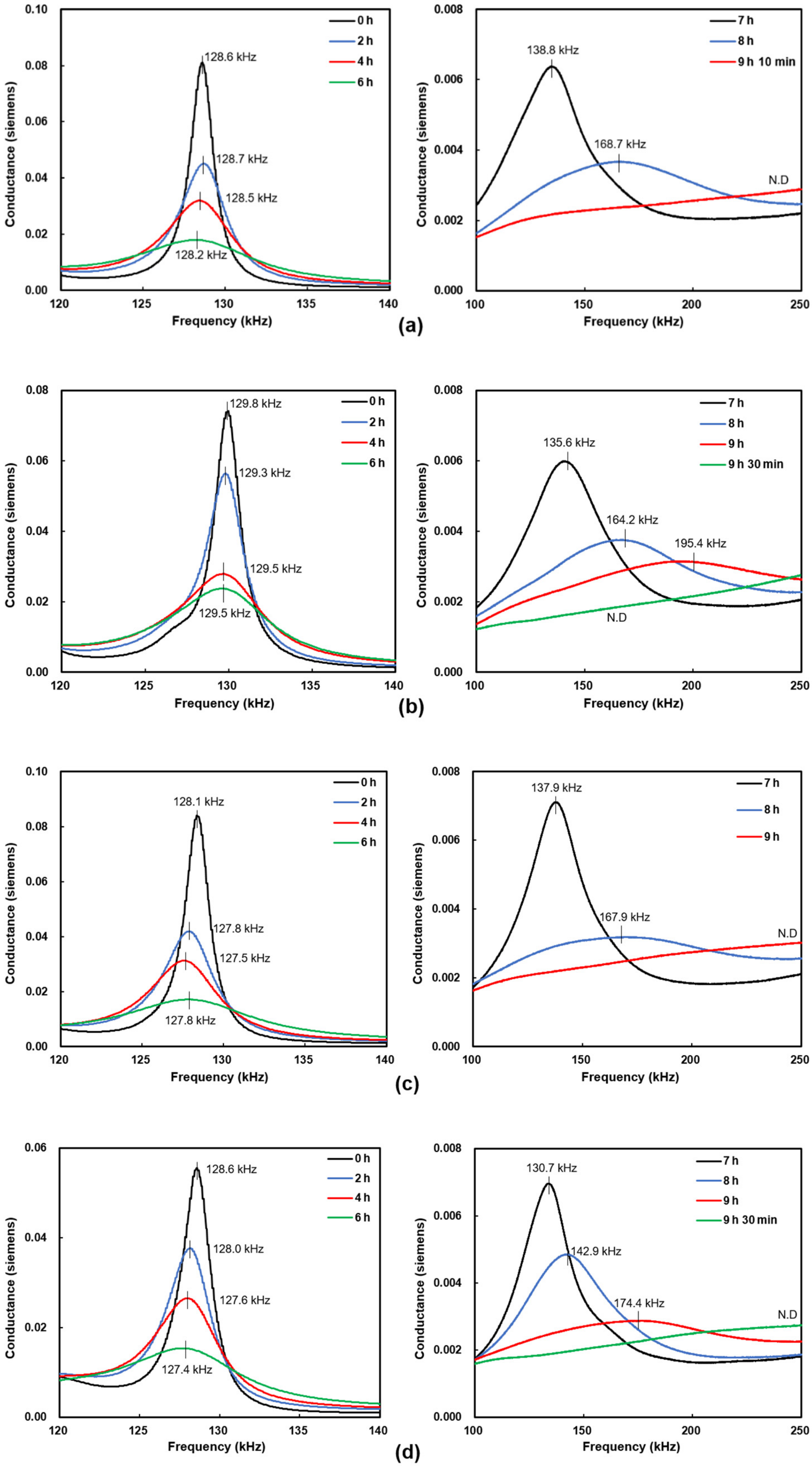

Figure 4. EMI change of PZT sensor according to the material age: (**a**) Plain; (**b**) F-0.5; (**c**) F-1.0; (**d**) F-2.0.

Figure 5 shows the change in EMI resonant peak frequency with time. The EMI resonance peak frequency was not changed significantly at the early stage of hydration of the mortar but started to increase from a specific time point, and then the resonance peak disappeared. In general, when the stiffness of material contacted on PZT sensor increases, the EMI resonant peak frequency moves to a higher frequency range [9–11]. Cement paste exhibits rapid stiffness increase after the initial set during the hydration process. Therefore, the time point at which the EMI resonance peak frequency starts to increase was considered as the initial setting time. A total of 10 min before the resonance peak disappeared was considered to be the final setting time.

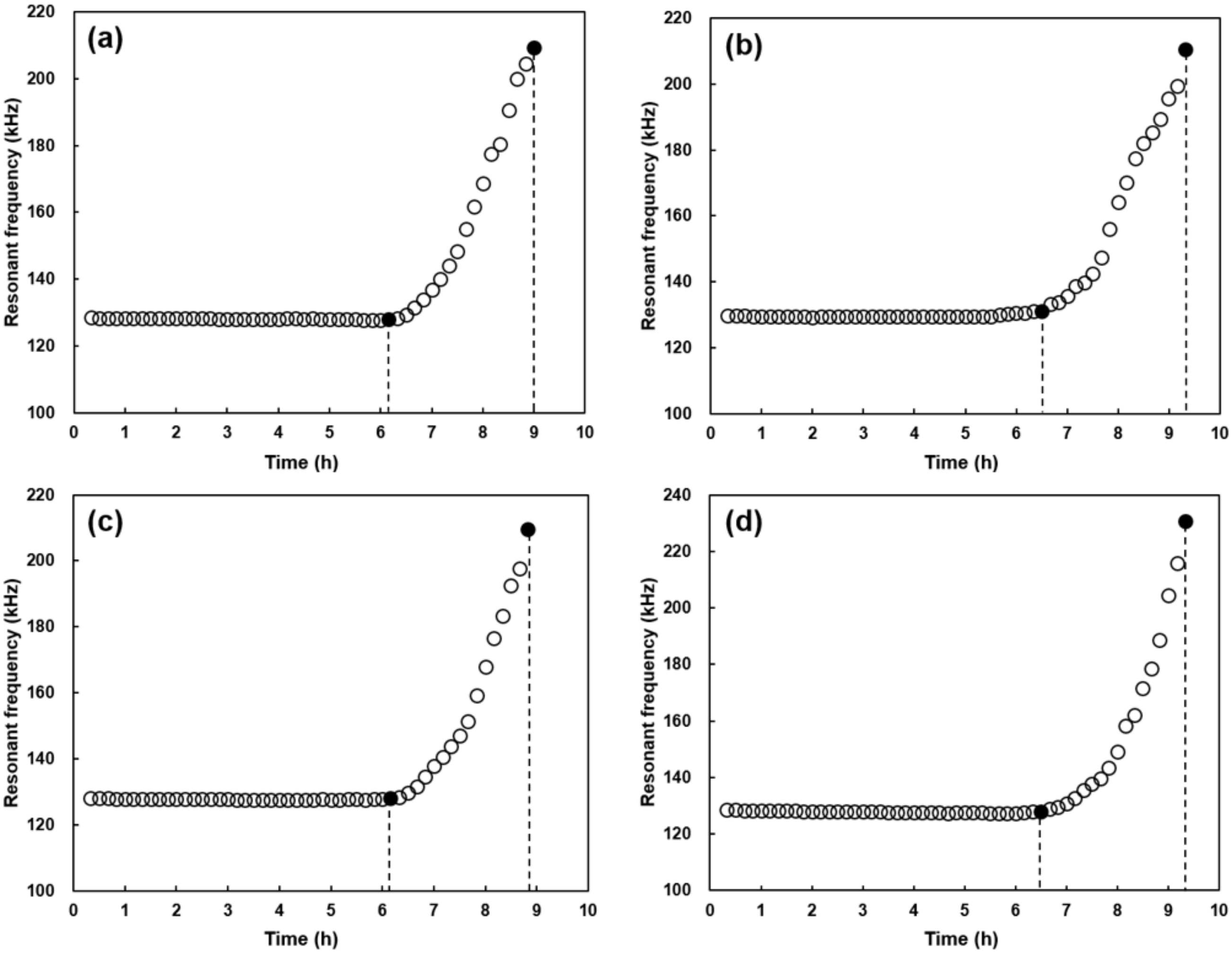

Figure 5. EMI resonance peak frequency as a function of the material age: (**a**) Plain; (**b**) F-0.5; (**c**) F-1.0; (**d**) F-2.0.

Table 3 shows the initial and final setting times of the mortar samples. The initial setting times of the SFRM did not show a significant difference compared to that of the plain mortar (less than 20 min). The final setting times of the mortars with fibers neither show significant difference compared to that of the plain mortar (less than 20 min). The time gaps between the initial setting time and the final setting time of all the mortar samples were almost identical.

Table 3. Setting times of fiber-reinforced mortar determined by EMI sensing technique.

Sample	Initial Setting Time (min)	Final Setting Time (min)	Time Gap between the Initial Set to the Final Set (min)
Plain	370	540	170
F-0.5	390	560	170
F-1.0	370	530	160
F-2.0	390	560	170

4. Discussion

There was no significant difference in the setting times of the plain mortar assessed by the two methods. The initial setting times obtained from the penetration resistance test and the EMI sensing technique were 371 min and 370 min, respectively. The final setting times obtained from the penetration resistance test and the EMI sensing technique were 573 min and 540 min, respectively, showing a time difference of about 30 min. Based on these results, the EMI sensing technique can be said to be an appropriate method to evaluate the setting time of plain mortar.

Since the mixture proportion of the plain mortar and the SFRMs is the same except for the amount of fiber, the setting time of SFRM should have a value similar to that of plain mortar in terms of cement hydration. In the penetration resistance test, both the initial and final setting time of the SFRM samples were accelerated by more than 2 h compared to those of the plain mortar. When a needle penetrates the mortar where the steel fibers are mixed, the steel fibers and the needle in the mortar may come into contact with each other to generate resistance, which increases the penetration resistance. The greater the amount of steel fibers in the mortar, the greater the resistance, so the fibers accelerate the setting time defined in ASTM C 403. Due to the additional resistance caused by the fibers, the setting times of SFRM measured by the penetration resistance test cannot represent the actual stiffness gain of the mortar phase in SFRM. It is noteworthy that the time gaps between the initial to final setting time (Table 2) are very similar regardless of the amount of fibers. This implies that the accelerated setting times measured by the penetration resistance are because the fibers affect the penetration resistance, and the actual stiffness gain of the mortar phase in SFRMs is the same for given material age.

In the EMI sensing technique, both the initial and final setting time of the SFRM samples did not show significant difference compared to those of the plain mortar (less than 20 min difference). In EMI sensing technique, the stiffness gain of the mortar phase in direct contact with the PZT sensor affects the behavior of the EMI signal, but the fibers around the PZT sensor might have little effect on the EMI signal, so the setting times show consistent values regardless of the amount of fibers mixed in the SFRM.

5. Conclusions

In this study, the setting time of SFRM was assessed using the EMI sensing technique. To justify the validity of the EMI sensing technique, a standardized test method, the penetration resistance test, was performed and the results were compared with each other. In the penetration resistance test, it was found that the setting time of the SFRM was accelerated, which is an artifact due to the fibers mixed in SFRMs. However, the setting time of the SFRMs assessed by the EMI sensing technique was consistent regardless of the amount of mixed fibers. In the EMI sensing technique, the setting time assessment is directly affected by the stiffness gain of the mortar phase in direct contact with the PZT sensor; thus, the effect of fibers on the setting time assessment is minimized. This means that the EMI sensing technique is a more effective tool than the penetration resistance test to evaluate the setting time of fiber-reinforced mortar.

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