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Evaluation the compressive strength of the cement paste blended with supplementary cementitious materials using a piezoelectric-based sensor

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HIGHLIGHTS

- PZT sensors is effective to monitor the compressive strength gain of cement.
- RMSD and CC index exhibited qualitative trends of strength gain of cement.
- The RMSD is more efficient than CC index in estimating the compressive strength of cement paste.
- The EMI is a reliable NDT method to enable in-situ monitoring strength gain of cement.

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ABSTRACT

This paper aims to investigate the feasibility of using piezoelectric-based sensors to characterize the compressive strength gain process of cement paste blended with supplementary cementitious materials. The electromechanical impedance technique was used for in-situ monitoring of the strength gain of cement pastes. Two different indices of root mean square deviation (RMSD) and correlation coefficient (CC) have been used to establish a quantitative correlation between the conductance signature obtained by lead zirconate titanate (PZT) sensors and the compressive strength of cement paste. Both indices exhibited a reasonable qualitative trend which was compatible with the trend of strength gain of cement pastes. However, the RMSD was found to be more efficient than CC index in estimating the compressive strength of cement paste over time. The experimental results indicate that EMI can be used as a nondestructive testing (NDT) method to enable in-situ measurement of strength gain process of cement paste with supplementary cementitious materials.

1. Introduction

Developing accurate non-destructive testing methods for determining the in-situ strength of concrete structures has attracted great attention recently. Monitoring real-time strength development of concrete is not only important to determine the in-situ mechanical properties of the structure, but also to ensure the safety of the structure itself during construction. For example, it is important to determine the in-situ strength of concrete for optimal traffic opening time since fast-paced construction schedule exposes concrete pavements and/or structures undergoing substantial loading conditions even at its early ages [1–3]. The current methods for monitoring the strength gain process of concrete are inefficient and expensive, often causing construction delays or cost overruns [4]. Moreover, these methods require a tedious series of laboratory experiments and cannot provide continuous information about early age properties. For instance, maturity testing is the common method to determine the optimal traffic opening time. However, maturity testing requires extensive calibrations of maturity meter for each different mix design and they are very inefficient and costly. As such, these tests including mechanical measurement and chemical analysis are not suitable for monitoring in-situ large-scale concrete structures, and the results are often heavily influenced by the drying process and sample preparation [5,6]. To overcome these challenges, previous literature has

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examined the possibility of using lead zirconate titanate (PZT) based electromechanical impedance technique to characterize the properties of cementitious materials. The EMI technique involves bonding a PZT patch to the surface of the structure which is then electrically excited using an impedance analyzer. The continuous measurement of the electromechanical impedance of the PZT can provide the host structure properties. In fact, any changes in the properties of the host structure are mainly reflected in the measured electrical impedance of the PZT patch. The EMI technique employing PZT patches has been demonstrated successfully for concrete structural health monitoring or damage detection [7–19]. In recent years, the applicability of the EMI technique has been extended to cementitious material property monitoring. The EMI technique has proven as a promising method for strength development monitoring and hydration monitoring of cementitious materials at early-age conditions, typically up to 7 days [20–24]. Moreover, the researchers are interested in developing innovative EMI techniques and establishing evaluation indices to make the monitoring more accurate and effective. For instance, Bahador et al. developed a reusable PZT transducer and an embedded PZT transducer to monitor the initial hydration of concrete [25]. Similarly, Lim et al. monitored the early age hydration of concrete samples by EMI technique with a PZT patch and found that the admittance signature can reveal the stiffness of the concrete increases in the process of hardening [26]. Voutetaki et al. and Chalioris et al. proposed a wireless impedance/admittance monitoring system and explored its ability in damage detection of concrete beam by the combined implementation of embedded smart piezoelectric aggregates and externally epoxy bonded piezoelectric patches [27,28]. In the work conducted by Wang et al., a novel EMI method using an embedded PZT patch was utilized to determine the strength of concrete as well as evaluate the damage development in concrete subjecting to loading. The indexes of root mean square deviation index (RMSD) and cross-correlation coefficient (CC) have been proven to be reliable ones of quantitative assessment of strength gain and structure health [29–31]. These two statistically scalar values have also been employed to effectively evaluate the growth of damage severity of concrete in the publication reported by Chalioris et al. [32].

Up to now, the feasibility of using PZT sensor for evaluating the mechanical properties of concrete structures has been addressed. However, the feasibility of EMI method on an understanding of the strength gains of concrete containing supplementary cementitious materials (SCMs) has not been studied. Unlike conventional strength gain process in a plain concrete, the addition of SCMs changes the hydration rate of cement which results in a different strength gain process from that of a plain concrete. Based on the measurement of electrical conductivity and strength, the change in hydration process and mechanical property was found in the cement paste blended with SCMs including silica fume, slag, fly ash, limestone, crushed clay bricks and polycarboxylate superplasticizer [33–38]. Some relevant matters have also been considered in these publications [39–42].

To this end, this paper aims to systematically investigate the feasibility of using EMI technique for in-situ monitoring of strength gain of cement pastes containing SCMs. To evaluate the efficiency of the PZT sensors in monitoring the strength gain of SCM blended cement, fly ash and silica fume were added to the cement paste which induces a change in strength gain process of cement paste. The outcome of this work can assist in the evaluation of using piezoelectric-based NDT method to determine the strength gain process of cement paste.

2. Experimental program

2.1. Materials and sample preparation

In order to study the hydration behavior of cement paste materials, three different mixes were used including ordinary portland cement (OPC), fly ash class C (FA) and silica fume (SF). The OPC, SF, and FA complied with ASTM C150-17, ASTM C618-15, and ASTM C1240-15, respectively. The OPC, ASTM Type I, was used in this study. Table 1 shows some physical and chemical properties of OPC. A control cement paste sample containing only OPC was made to serve as reference sample (REF). In this study, OPC was replaced by FA and SF at a dosage level of 10% by mass of binder. The water to binder ratio (w/b) was kept constant for all the mixes at 0.30. Table 2 presents the composition of three mixes. The compressive strength of cement paste was determined using the 50 mm cube samples. The specimens were kept stored in a controlled chamber at 20 ± 2 °C. After 24 h; the specimens were demolded and cured in a curing room at 23 ± 2 °C. The compressive strength tests were conducted at 1, 3, 7, 14 and 28 days, according to ASTM C39 [43]. The tests were performed on three specimens and the average values were considered. The EMI signature was recorded for all the samples before conducting the compressive strength test at a certain age. In order to measure EMI signatures, a 10 mm × 10 mm × 0.2 mm PZT patch was attached to the specimen, as shown in Fig. 1. Fig. 2 illustrates the EMI set up, an impedance analyzer (1260 Solartron), and a computer equipped with data acquisition software.

Table 2
Compositions of cement pastes (by weight of cement).

Sample	OPC	FA	SF	W/B
REF	1	–	–	0.3
FA	1	0.1	–	0.3
SF	1	–	0.1	0.3

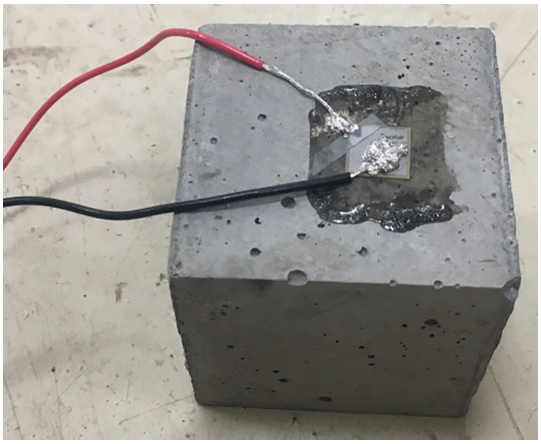
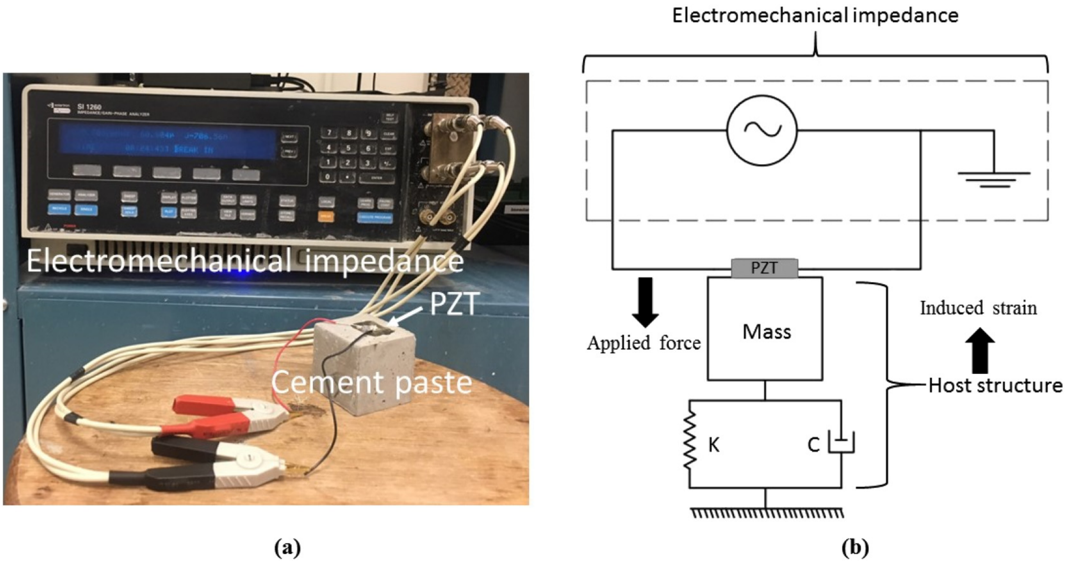


Fig. 1. A PZT patch was bonded to the surface of cement paste.

Table 1
Chemical composition and physical property of OPC.

Material	C_3S	C_2S	C_3A	C_4AF	Na_2O	Blaine fineness	Density
OPC	58 (%)	13 (%)	7 (%)	10 (%)	0.7 (%)	377 (m^2/kg)	3150 kg/m^3



(a)

(b)

Fig. 2. (a) Hydration monitoring tests on cement paste using an impedance analyzer, (b) Mechatronic model illustrating the impedance-based structural hydration monitoring.

2.2. Signal analysis

The PZT patch is subjected to a spatially uniform electrical field due to the finite size of the patch. The patch has half-length equal to l and thickness h. The mechatronic model of EMI technique is shown in Fig. 2 (b). The PZT's admittance (Y) was demonstrated to be the inverse of the impedance [44]. Bhalla et al. [45] proposed the below formula for the electrical admittance of PZT patch model by introducing the concept of "effective mechanical impedance" as follows:

$$Y = G + Bj = 4w\frac{l^2}{h}\left[\varepsilon_{33} - \frac{2d_{31}^2 Y^E}{(1-\upsilon)} + \frac{2d_{31}^2 Y^E}{(1-\upsilon)}\left(\frac{Z_a}{Z_a + Z_s}\right)\frac{\tan kl}{kl}\right] \qquad (1)$$

where Y is the electrical admittance, Y^E is Young's modulus, G is conductance, B is susceptance, j is the imaginary unit, ε_{33} is electrical permittivity, d_{31} is a piezoelectric coefficient, ν is the Poisson's ratio, η is mechanical loss, δ is dielectric loss, κ is the wavenumber, Z_a is the impedance of the PZT patch and Z_s is impedance of the structure. Therefore, any change in properties of the specimens can be reflected in impedance signature of PZT patch which is monitored and analyzed using the above formula.

3. Results and discussion

The frequency band with high mode density is preferred in EMI method as it provides more information about the properties of the specimen [46]. Therefore, selecting an appropriate range of frequency is of great importance. In this study, the frequency range of 2–500 kHz was selected as it has been suggested in previous works [21]. Fig. 3 shows the obtained conductance signature for FA sample at the age of 1, 3, 7, 14 and 28 days. The conductance signature was obtained from the average of five repeated measurements to minimize the noise and error. As can be seen in Fig. 3, there is a strong conductance resonant peak at 400 kHz along with some other obvious dominant peaks in the frequency range of 50–200 kHz. Most of the signature resonant peaks shift upward over time. The clear shift in critical resonant peaks might represent the strength gain process of the cement paste samples over time. Fig. 4 shows the signature conductance for all three mixtures at three days. All the conductance signatures exhibited almost the same trend of resonant peaks. However, a clear deviation can be

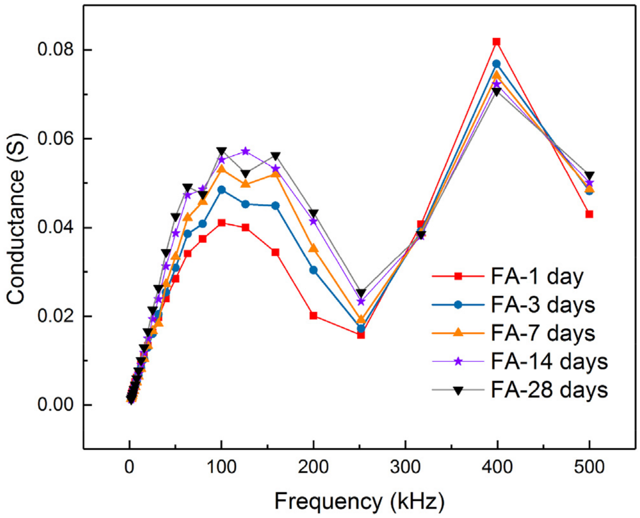


Fig. 3. The conductance signature of FA samples at 1, 3, 7, 14 and 28 days.

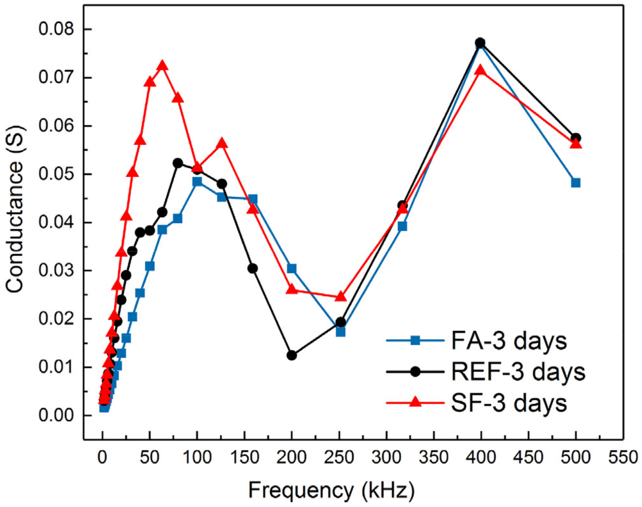


Fig. 4. The conductance signature of REF, FA and SF samples at 3 days.

observed in the frequency range of 20–100 kHz. The SF conductance signature exhibited a higher conductance resonant peak as compared to FA and REF mix. This deviation can be attributed to the higher strength gain of SF mix in the early ages. This might be due to the higher pozzolanic activity of SF at early ages, which leads to the formation of additional C-S-H gel resulting in higher compressive strength [47–49]. Also, FA mix exhibited the lowest resonate conductance peak in a frequency mentioned above range which can be correlated to the lower rate of cement hydration in the presence of FA [50] since the strength gain of cement paste depends on the rate of the cement hydration. The electrical impedance of cement paste is manifested as a result of any change in mechanical properties of cement paste. Hence, any changes in electrical impedance can be detected by EMI technique using PZT patch. This result indicated the sensitivity of using EMI sensing technique for in-situ monitoring of the strength development in cement paste containing different SCMs. The main goal of monitoring the strength gain in concrete is to obtain useful information about the in-situ quality of concrete to provide guidance for construction scheduling, such as the optimal traffic opening time. So far, the EMI conductance signature exhibits only qualitative information on the strength gain of cement paste containing different SCMs over time. However, a quantitative index must be established to use EMI sensing method as a reliable method to estimate the compressive strength and assess the quality of concrete. The admittance signatures measured by PZT are used to monitor certain properties of the host structure. The admittance signature is composed of the conductance and susceptance. Conductance has been successfully used to monitor cement hydration due to its better reflection of the structural change in the host structure [51]. The changes in conductance spectrums consist lateral and vertical shifts in admittance signature which can be easily recorded and quantified [52]. The root means square deviation (RMSD) as one of the statistical techniques was applied in this study to correlate the hydration condition with the changes in the PZT conductance signatures. RMSD is defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(x_i)^2}} \tag{2}$$

where x_i is the baseline signature of PZT and y_i is the corresponding conductance for each monitoring time at different ages. Also, the correlation coefficient (CC) index was employed in this study to determine the relationship between two conductance signatures. In most cases, the results of the CC index are in a good agreement with those of RMSD, in particular, when there is a large difference between the baseline signature and the subsequent signature [53]. The CC index equals the covariance of two measured data divided by their standard deviation:

$$CC = \frac{Cov(x, y)}{\sigma_x \cdot \sigma_y} \tag{3}$$

where σ_x and σ_y are standard deviation of x and y, Cov (x,y) is the covariance of x and y given by

$$Cov = \frac{1}{N}\sum_{i=1}^{N}(x_i - x_m)(y_i - y_m) \tag{4}$$

where x_m and y_m are the mean values of x and y, and N is the number of the samples. In order to monitor the changes in conductance signature over time, a baseline conductance signature was established. The conductance signature of each sample at specific age was further compared to the baseline signature, and the difference was determined using RMSD and CC index. The RMSD plot along with the obtained compressive strength data for all three mixes are shown in Fig. 5. As expected, the compressive strength increases up to day 14, and the rate of strength gain become slower afterward. It can be seen that the RMSD values increase over time regardless of the type of mixes. The obtained RMSD values show a good correlation with the compressive strength gain for all the mixes. However, RMSD index overestimates the compressive strength for all the mixes except for the ones at early ages of SF mix. That might be a drawback of RMSD index which exhibits only absolute values regardless of the deviation direction of conductance signatures. Moreover, the correlation between the compressive strength of cement pastes and CC index of conductance signature was established, as shown in Fig. 6. In general, the CC index exhibited a reasonable qualitative trend which was compatible with the trend of strength gain of cement pastes. However, a big deviation was observed for FA and REF mix at 28 days. The results confirm that the CC index is not an accurate index to predict the compressive strength value. All the obtained compressive strength data

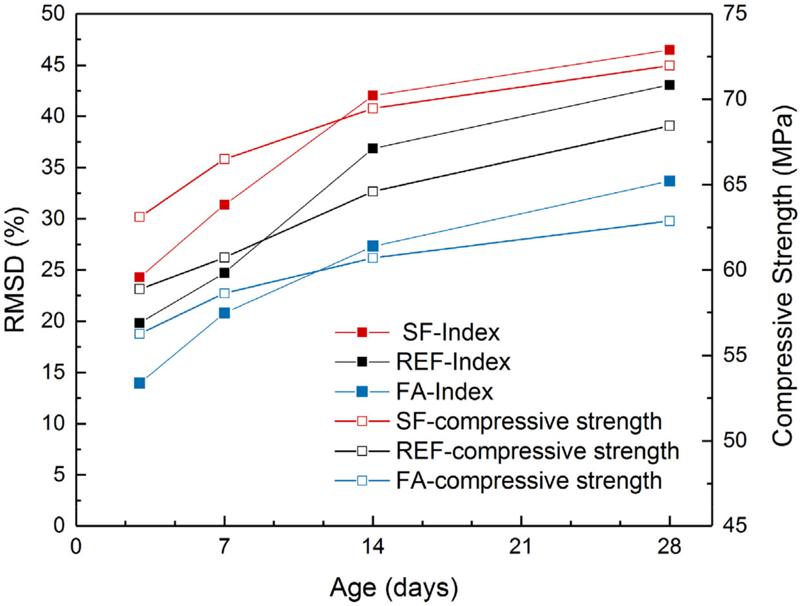


Fig. 5. RMSD index versus the compressive strength of all the samples at 3, 7, 14 and 28 days.

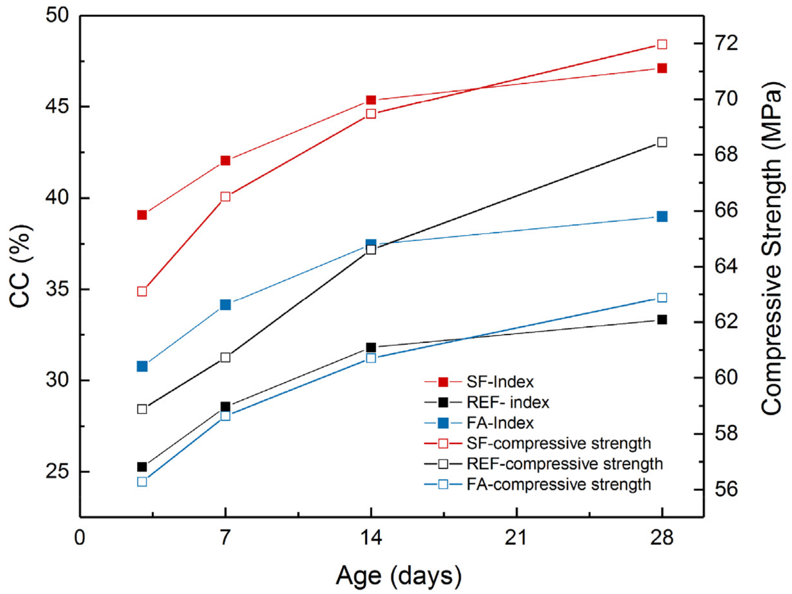


Fig. 6. CC index versus the compressive strength of all the samples at 3, 7, 14 and 28 days.

Table 3
The obtained compressive strength data along with the RMSD and CC index.

Days	SF-Strength (MPa)	RMSD-SF	CC-SF	REF-Strength (MPa)	RMSD-REF	CC-REF	FA-Strength (MPa)	RMSD-FA	CC-FA
3	63.10	24.27	39.08	58.87	19.82	25.25	56.27	13.96	30.76
7	66.49	31.36	42.03	60.72	24.72	28.55	58.63	20.79	34.14
14	69.46	42.01	45.36	64.59	36.86	31.80	60.70	27.30	37.45
28	71.97	46.48	47.12	68.44	43.06	33.30	62.87	33.67	38.98

along with the RMSD and CC index is presented in Table 3. In order to compare the efficiency of each index, all the compressive strength was plotted against each of index value. A linear least square regression fitting curve was calculated for each set of the data. Fig. 7 presents the CC and RMSD index to estimate the compressive strength along with a correlation coefficient. The obtained correlation coefficients for RMSD and CC were $R^2 = 0.90$ and $R^2 = 0.54$, respectively. From the obtained results; one can conclude that the RMSD index reflects the variations of the compressive strength of cement paste more accurate than the CC index of conductance signature.

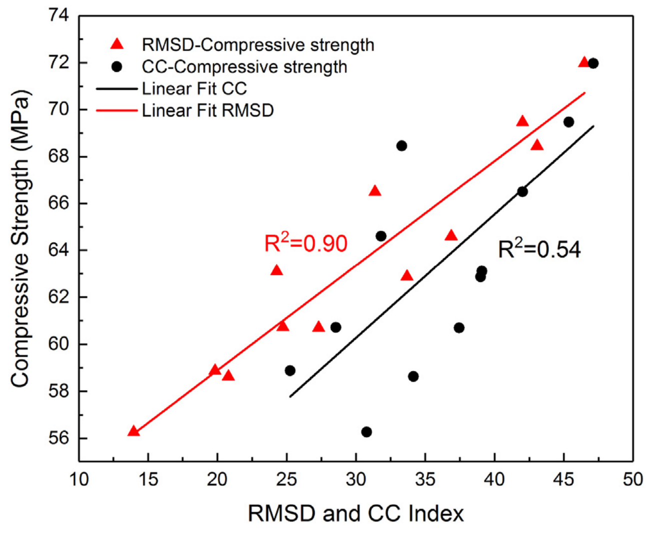


Fig. 7. The correlation between the RMSD and CC index with the compressive strength of all the mixes.

4. Conclusions

This paper studied the feasibility of using the EMI method to characterize the compressive strength gain process of cement paste containing the SCMs. The EMI signatures for three different mixes of cement paste were obtained at 1, 3, 7, 14, and 28 days. The compressive strength of all the cement paste specimens were also determined using conventional ASTM C39 testing method to validate the reliability of using EMI sensing method for strength gain monitoring. The obtained conductance signatures for all three mixes proved the viability of using EMI method to monitor the strength gain in cement paste sample. Two different indices of RMSD and CC have been used to establish a quantitative correlation between the conductance signature and the compressive strength. Both indices exhibited reasonable qualitative trends which were compatible with the trend of strength gain of cement pastes. However, The RMSD was found to be more accurate than CC index in estimating the compressive strength of cement paste over time. The deviation between the experimental data and predicted value by EMI technique increased over the time for all the specimens. The result suggests EMI method can be used as a NDT method for in-situ measurement of strength gain process of cement paste, particularly for the early-age properties. The future work involves evaluating the efficiency of EMI method to estimate the hydration process and strength gain process of mortar past and concrete need to be carried out.

Conflict of interests

The authors declare no conflict of interests.

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