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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

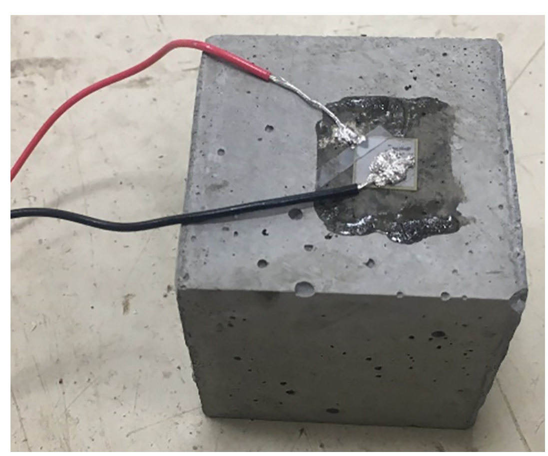

Fig. 1. A PZT patch was bonded to the surface of cement paste.

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