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In-situ crack propagation monitoring in mortar embedded with cement-based piezoelectric ceramic sensors

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HIGHLIGHTS

- Cement-based piezoelectric ceramic sensor is designed for AE signals detection in mortar structure.
- Signal-based AE energy index is introduced to evaluate the fracture energy released during the loading process.
- Sensor-monitoring assessment-integrated system is built to evaluate the health state of mortar structure.

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ABSTRACT

This paper describes a study on using embedded cement-based piezoelectric ceramic sensors to detect crack propagation in mortar specimens under cubic-splitting load by acoustic emission (AE). The main objective is to characterize the fracture process in mortar specimen in the cubic-splitting test. AE sensors (piezoelectric composites as core elements, and a mixture of cement, epoxy resin and hardener as packaging material) can be embedded into concrete and still have broadband frequency response and good matching ability with the cement material. The three-dimensional localization of the AE sources, signal-based AE energy index and variation characteristics of the AE frequency content were used to explain and quantitatively evaluate the fracture processes of the mortar specimens. The results show that the fracture processes in the mortar under the cubic-splitting are evidently brittle fracture and the variation behaviors of the AE frequency content, which exhibited a close relationship with the applied loading processes during the tests. It was also found that the application of cement-based piezoelectric ceramic sensors by means of AE represents a good option to analyze the crack growth in the specimens under increasing load, the location of the cracks and, in addition, it offers the potential for in-situ application.

1. Introduction

As an essential component of tools for structural health monitoring purposes, smart materials currently used in civil engineering structures have attracted much attention over the past decade [1–7]. Concrete is of course the most important construction material in civil engineering. In response to changes in temperature and humidity, it has a large deformation rate over time, which leads to difficulties in adapting smart materials from other engineering fields for use with concrete. Issues that influence compatibility include acoustic impedance matching, deformation coordination caused by temperature and humidity changes, and interface adhesion [8,9]. Accordingly, it is essential to develop novel smart materials that are compatible with concrete for use in developing smart structures for civil engineering applications.

To meet the requirements of civil engineering structures, a novel 0–3 cement-based piezoelectric ceramic composites (using cement as matrix phase and PZT piezoelectric ceramic powder as active phase) has been developed and studied [1,10], and its feasibility for potential applications in civil engineering has been explored [4,11–17]. Cement-based piezoelectric ceramic sensors have the advantages of structural simplicity, low cost, quick response and high reliability [3]. The sensor is highly compatible with concrete and can be embedded in concrete as a coarse aggregate, making it suitable for structural health monitoring in

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concrete [4,18]. Damage in a structure alters its mechanical characteristics and structural damage can be easily monitored based on these changes in mechanical response [19–21], thus providing sufficient failure warning and life-time assessment at early ages.

Acoustic emission (AE), which is the transient elastic waves generated by the rapid release of strain energy in a material [22], is a ubiquitous phenomenon associated with brittle fracture and has provided an abundance of information regarding the failure process [23,24]. Due to its powerful capability in passive health monitoring of concrete structures, the AE technique is considered as one of the most popular NDT method nowadays. In concrete, AE in most cases are generated by the micro or macro crack initiation and propagation. Normally, it is possible to detect AE by piezoelectric sensors and transform them into electrical signals. The electrical signals can be fetched and extracted by a data processing device which recognizes its waveform characters [25]. Often, it is possible to locate the source position of the elastic wave and, based on this information, to trace the crack or damage process of the concrete structure and to evaluate for early failure warning and life-time assessment [26–29]. Besides early failure warning and life-time assessment which are very helpful in practical engineering, the characterization of the detected AE signal has drawn more and more attention since it is the exterior manifestation of the condition of the AE sources (the micro- or macro- crack of concrete). Actually, it helps us indirectly observe micro crack behaviors inside concrete.

In this paper, cement-based piezoelectric ceramic sensors are fabricated and employed as AE sensor to detect the fracture processes of mortar under cubic-splitting loading conditions. The objective is to verify the feasibility of monitoring and evaluating the fracture process on mortar by using a brand new technique involving embedded piezoelectric sensors array and advanced AE monitoring. Furthermore, a sensor-monitoring assessment-integrated system is also built to accomplish the complete health monitoring of the mortar structure. The developed sensors are useful in the application of structural health monitoring technology in actual engineering. The information provided can be utilized to effectively describe the fracture characteristics of concrete structures and elements under various types of loadings.

2. Experimental setup

2.1. Cement-based piezoelectric ceramic composites

The PLN [$0.08Pb(Li_{1/4}Nb_{3/4})O_3 \cdot 0.47PbTiO_3 \cdot 0.45PbZrO_3$] ceramic fine powder and white cement are mixed together to prepare the 0–3 cement-based piezoelectric ceramic composites. The fine ceramic powder is prepared by crunching the commercially available PLN patch in the ball grinder machine for over 6 min. In order to improve the fluidity of the fresh mixture, the superplasticizer W19 (W.R. Grace, Columbia, MD, USA) is used. Using normal mixing (for about 2 min), piezoelectric ceramic powder can be incorporated into the composites with the PLN: cement mass ratio of 4:1 is employed to fabricate the active sensing element. To achieve a uniform mixture, cement and piezoelectric ceramic particles are thoroughly mixed first, then water and superplasticizer (1 wt.% of water) are added into the mixture (water/cement ratio: 0.15). The mixing process is continued until the mixture becomes homogeneous. Then the mixture is compacted to patches (13 mm $*$ 13 mm $*$ 3 mm) with a pressure of 100 MPa. The specimens are put in the curing room at a temperature of 65 °C and relative humidity of 98% for 24 h. In order to accelerate the curing procedure, a high temperature is chosen.

The close adhesion of the electrodes is important because most piezoelectric materials have high permittivity and a large fraction of an applied potential will therefore occur across any low permittivity gap between an electrode and the material surface. Considering the thermal properties of cement material, a special silver paint with very low firing temperature is used to deal with the composite samples as shown in Fig. 1. Additionally, the electrode is formed in the oven after 10 min at 110 °C.

After the major surfaces are painted with the silver paint, the piezoelectric composite is polarized, which is the critical procedure for the fabrication of piezoelectric composites. Polarization is carried out in a silicon oil bath at a temperature of 80 °C, under high D.C. voltage of 4000 V/mm. After polarization the specimens are immersed in cold silicon oil for fast cooling in order to preserve the status of the polarization. The polarized specimens are then wrapped with aluminum foil to eliminate remnant charge generated during the polarization process.

The piezoelectric ceramic particles in the composites are well-dispersed [16]. This conclusion is confirmed by the result of the scanning electron microscopy (SEM) imaging of the composites. From the backscatter SEM image, shown in Fig. 2, the uniform distribution of PZT particles can be observed.

2.2. Cement-based piezoelectric ceramic sensor

The compatibility between the piezoelectric sensor and matrix material is a critical issue in the AE monitoring technique. A superior compatibility in the acoustic and mechanical properties can ensure accurate and reliable monitoring results. To achieve better compatibility between the sensing element and the concrete matrix, previously mentioned issues have to be properly addressed. Li et al. [30] developed a brand-new cement-based piezoelectric composite that has an acoustic impedance value (~10 MRayls) that is quite close to that of the concrete matrix (~8.6 MRayls), which ensures minimum signal distortion and maximum signal energy transmission efficiency. Meanwhile, the coupling issue could be properly solved by embedding the cement-based composite sensor into the cementitious materials. The signal-to-noise ratio (SNR) can be enhanced accordingly. In this experiment, a 0–3 cement-based piezoelectric ceramic composites is used to make a piezoelectric sensor as shown in Fig. 3. The response of the AE sensor in the standard Hsu pencil lead break [31] is shown in Fig. 4. In the time domain, the signal has a very short rise time, and decays very fast. The ring down is very blunt. In the frequency domain, the response has a relatively flat response over the range of 50–500 kHz (40 dB, ±3 dB). Ideally, it is expected that the sensor could have an absolutely flat frequency domain response over the frequency range from 20 kHz to 1 MHz. However, it is observed that the received AE signal mainly covered the frequency range of 50–500 kHz in the cementitious materials specimen testing [32,33]. Therefore, the 0–3 sensors are suitable to be embedded in the mortar specimens and used for AE detection. A total of eight piezoelectric sensors are embedded in the mortar specimen to constitute the detecting array for monitoring AE during the cubic-splitting test.

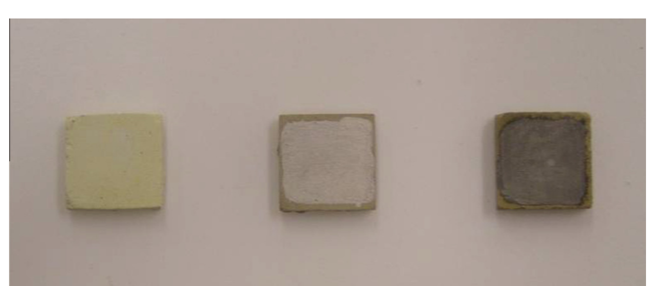

Fig. 1. The composite samples.