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An exploratory experimental and 3D numerical investigation on the effect of porosity on wave propagation in cement paste

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ABSTRACT

Piezoelectric transducers have been widely employed in the field of structural health monitoring (SHM). Currently, most piezoelectric transducers based non-destructive monitoring method lays basis on wave-based method. The change of wave after propagating in the target medium can reflect the internal state of the structure, such as damage and porosity. Owing to that concrete is a severely heterogeneous material at micro scale, the relationship between stress wave parameters and microstructure of concrete such as pores and pre-existing cracks in concrete is still unclear, which limits the generalization of monitoring system in different concrete structures. This paper presents an experimental study by setting up a kind of monitoring platform with piezoelectric transducers to investigate the relationship between porosity in cement paste and stress wave parameters. Meanwhile, 3D models of cement paste specimens were built with X-ray computed tomography (CT) scanning method, and the actual pore structure and distribution inside the specimens were obtained. The test and numerical results share similar decreasing trend of amplitude and velocity with an increment of porosity. It indicates that the proposed 3D model building method provides a vivid way to investigate the influence of micro-structure on stress wave transferring in cement based materials. Additionally, it also provides a promising approach to assess the porosity in cementitious materials using smart aggregate (SA)-based non-destructive monitoring method.

1. Introduction

For identifying the premature failure of constructions induced by load effects or severe environment, kinds of structural health monitoring methods have been proposed to do damage identification and location [1–3]. The changes in structural dynamic characteristics such as mode shape, modal frequency, and damping ratio are generally employed to evaluate the occurrence of damage in concrete [4]. However, these methods are mainly valid for substantial damage occurred in structures, and there exists an increasing difficulty to locate the damage accurately when structures are becoming larger and higher. In order to obtain the detail information of damage in dominant structural members, non-destructive monitoring methods are recommended to evaluate crack size and locations [5,6].

With the development of smart materials, new sensors and data acquisition systems are introduced in structural health monitoring field, which expands monitoring objects, and improves monitoring accuracy and efficiency greatly. Song et al. and Hou et al. proposed a new piezoelectric based transducer, named smart aggregate, which can be embedded in concrete to monitor the health states of concrete structures non-destructively [7,8]. It is formed by embedding a water-proof piezoelectric patch with lead wires into a small cement paste or marble block (see Fig. 1). Owing to the direct and inverse piezoelectric effect, the SAs can be employed as sensors and actuators respectively. A common SA-based monitoring scheme is shown in Fig. 2, which has been validated in monitoring early-age concrete strength [9], micro-cracks in concrete piles [10] or shear walls caused by lateral loads [11], interface debonding between steel pipe wall [12], FRP wrapper and inner concrete [13], and water seepage in concrete [14].

As is known all, concrete is a severely heterogeneous material, which is composed of coarse aggregate, mortar, and some inevitable air voids or micro-cracks. With regard to voids, there are three types of pores in cementitious materials depending on their sizes: micro-pores (gel pore, with dimension of 0.5–10 nm), meso-pores (capillary pores, with radius ranging from 5–5000 nm) and macro-pores resulting from inadequate compaction or deliberately entrained air bubbles [15]. Existing methods for measuring concrete porosity includes pressure or mass method, like mercury injection methods. But pressure method can

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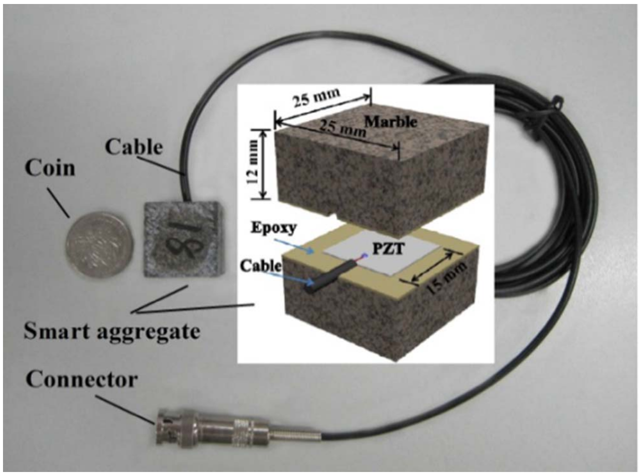

Fig. 1. Fabrication of smart aggregate [14].

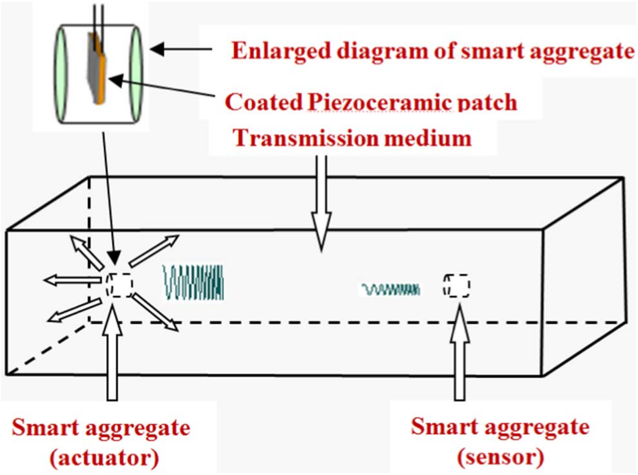

Fig. 2. SA-based monitoring scheme.

only measure open porosity of porous solids, which does not take into account the "close pores" [16]. Moreover, micrographs are also used for statistical determination of pore size distribution [17,18].

As porosity being widely recognized as one of durability indices, it has aroused more and more attention. Recent years have seen wave-based methods which can correlate with concrete porosity. The wave-based non-destructive testing (NDT) methods are significantly dependent on the geometry, size and distribution of preexisting pores of cement based material [19]. The reflection, diffraction, and transmission behaviors can be observed when wave encounters pores or micro-cracks in concrete [20], which may lead to the reduction in energy or velocity of wave. It indicates that the geometry, size and distribution characteristics of preexisting pores in concrete can significantly affect wave transferring in concrete [21]. Experimental investigations have found an obvious decrease of elastic modulus and ultrasonic Rayleigh wave velocity with the increase of porosity in mortar [22]. Application of a micromechanics model to mortar realizes the estimation of porosity by measuring longitudinal and shear wave velocities [23]. But this model is limited by its elasticity and isotropy assumptions. Further, concrete members with different raw materials may have obvious different micro-structures, which brings great difficulty in generalization of monitoring system only validated by test members with specific concrete material [24,25].

Due to the large population and complex and disordered spatial distribution of pores in concrete, it is extremely difficult to correlate the stress wave motion and pore structure characteristics [26,27]. Previous models based on the finite element, boundary element, discrete element and finite difference method give insufficient information of the actual pore structure of the concrete. In the last years, development in computer and electronic engineering enables tomography reconstruction of concrete material [28]. The actual micro-structure of concrete is captured and reconstructed with finite element model.

This paper aims to investigate the influence of porosity on stress wave propagation in porous cement paste. Three groups of cement paste specimens with different porosities were cast. The amplitude and velocity of stress wave propagating in cement paste were measured, and a model of wave propagation was built with 3D reconstruction method, which can take account of the actual conditions of porosity. Finally, the experimental results were compared with the simulation results.

2. Experimental investigation

2.1. Material proportion and test specimen

The properties of the PZT (piezoceramic patch) provided by the supplier are listed in Table 1. In this study, cement paste is selected as the transmission medium of stress wave, considering that it is less complicated than concrete. It is beneficial to study the impact of porosity on wave propagation in cement-based materials without extra complication of aggregates. The size of the cement paste specimen is 40 mm × 40 mm × 160 mm (see Fig. 3). Three groups of specimens (C1, C2 and C3, each group with 3 specimens) were cast, and their mix proportions are shown in Table 2. The air entraining agent was employed to fabricate specimens with different porosities. The porosity and density of the specimens were obtained using MIMICS software, and elastic modulus was measured by test, as shown in Table 3.

2.2. Experimental set-up and method

In this test, a National Instrument (NI, Model:PXI-1042) monitoring system was utilized for amplitude and velocity measurement (see Fig. 4). 5-cycle sinusoidal narrowband excitation signals modulated by Hanning window (see Fig. 5) were generated by the signal emission device (NI). They are with different frequencies (40 kHz, 50 kHz, 60 kHz and 80 kHz) and with maximum voltage amplitude of 1 V. After amplified 100 times by a power amplifier to drive the SA actuator, the voltage signals were transferred to vibration signals, propagating in the cement paste in the form of stress wave, and finally the vibration signals were transformed into voltage signals by the SA sensor and stored in an oscilloscope for data analysis [29].

In this study, the amplitude of the second wave crest was selected as the index (see Fig. 6) and the head wave-echo wave time span method was employed to obtain the stress wave velocity (see Fig. 7). Specifically, the head wave refers to the first arrival signal, while the echo refers to the second received signal, i.e. the reflected signal. This method provides a way to use the time difference between head wave and echo wave to calculate the velocity of the transferring wave (see Eq. (1)).

Table 1
Properties of PZT P-5H.

Size (mm)	Piezoelectric coefficient (pC/N)	Relative dielectric constant	Capacitance (pF)	Density (g/cm^3)	Electromechanical coupling coefficient
8 × 8 × 0.3	450	1600	4500	7.5	0.8