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Smart aggregates for monitoring stress in structural lightweight concrete

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ABSTRACT

Stress monitoring using piezo-electric smart aggregate (SA) provides a useful way to assess damage in concrete structures. Although the feasibility has been verified in normal weight concrete (NWC), efforts are needed for lightweight concrete (LWC) due to the differences in meso-scale factors that is key for SA-based monitoring. In this paper, SA sensors were tested for monitoring stress using four identical LWC cylinders with six SAs embedded in each specimen subjected to typical loading paths and load levels. Based on the test results, the effects of the related meso-scale factors on the feasibility of monitoring were evaluated. After that, the sensors' sensitivity curve and the extent of SA output randomness were quantified. It can be concluded that SAs have potential for monitoring stress in LWC structures during the entire damage process.

1. Introduction

In recent years, there are more and more large-scale civil infrastructures, such as long-span bridges and tall buildings, being constructed. Structural health monitoring (SHM) provides a way to evaluate the structural health condition during its long-term service life, to ensure structural serviceability and sustainability [1,2].

The structural stress status is a critical index of SHM for assessing the structural damage. Based on the evaluations of stress wave propagation in concrete structure, piezo-electric smart aggregate (SA) has been proposed by Song et al. [3]. This SA is composed of a patch of lead zirconate titanate (PZT) shielded by mortar [4] or artificial marble [5,6]. Due to the low strength of that encapsulating material, the SA can only be used for stress monitoring lower than 5 MPa [7]. Based on the demand on seismic stress monitoring in high strength, a new type of SA using the granite as the encapsulation has been developed by Hou et al. [8,9], which can help monitor shear or compressive stress in concrete during earthquakes. By using a specially-designed charge amplifier, SA sensors are capable of monitoring compressive stress up to 45 MPa at frequency down to 0.05 Hz [10].

Since a SA sensor is similar to a coarse aggregate in terms of its size and material properties, its measurement shows the stress state of the coarse aggregate, other than the concrete. The prediction of concrete stress is essentially based on the statistical correlation between concrete stress and the SA stress which is highly influenced by the mechanical properties of concrete in meso-scale that differs for different type of concrete. So far the statistical correlation between SA stress and concrete stress has been established only for normal strength concrete and high-strength concrete [7,11].

Lightweight concretes (LWCs) find applications in civil engineering due to their thermal insulating ability and reducing a structure's dead weight. Based on the range of thermal conductivities, densities, and compressive strengths which can be produced, LWC can be classified as insulating, insulating/structural, or structural LWC [12]. The structural LWC is considered suitable for seismic design because of the weight reduction it offers, which limits base shear. LWC has therefore been used in many bridge structures as well as in building structures in seismically active areas [13–17].

The meso-scale mechanical properties and the failure modes of the LWC are quite different from that of normal weight concrete (NWC). Normally, the Young's modulus and the strength of the coarse aggregates of LWC are about 1/9–1/3 and 1/30–1/10 of those of the NWC [18–20], resulting in a lower Young's modulus and a steeper descending branch in the stress-strain relationship for LWC compared with those of NWC [21,22]. During the damage states, the cracks initiate in the coarse aggregates for LWC while in mortar or the mortar-aggregate interface for NWC [23–25], and the cracks in LWC at peak stress are more sparser and wider than those in NWC [24,25] as shown in Fig. 1. Due to the inadequate development of micro-cracks, the ability for energy dissipation of LWC structures under seismic loading should be worse than that of NWC structures.

So far, the statistical correlation between SA stress and concrete

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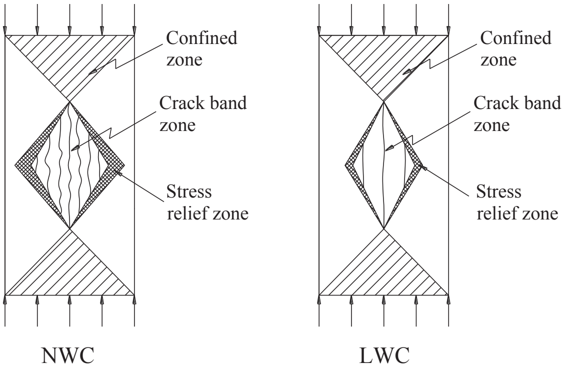

Fig. 1. Comparison of crack modes between NWC and LWC at peak stress.

stress for LWC which is the key for concrete seismic stress monitoring has not been established yet. In this paper, the similar test scenario as described in literature [7,11] was carried out for the typical structural LWC. The influences of meso-scale mechanical properties and the failure modes on the statistical parameters of sensitivity curves for LWC were discussed.

2. Experimental set-up

2.1. Introduction of SA sensor

The SA sensor is composed of a piece of PZT patch sandwiched between a pair of granite hemi-cubes using epoxy as presented in Fig. 2. Each SA inclusion was a cube 25 mm on a side. The soft PZT denoted as P-5H which has the dimension of 15 × 15 × 0.3 mm with a major composition of $Pb(TiZr)O_3$ featuring high sensitivity was adopted. Table 1 shows the properties of the PZT. The detailed design and calibration of the SAs has been reported by Hou et al. [8].

2.2. Materials

The lightweight aggregate used as the coarse aggregate in this experiment was shale ceramisite. The shale ceramisite had a maximum particle size of 25 mm, a 7.12% ultimate water content, and a barrel pressure intensity of 4.5 MPa. The dry loose bulk density of the lightweight aggregate was 788.3 kg/m^3, which is less than the specified upper limit for structural LWC: 880 kg/m^3 [26]. Fig. 3 shows the shale ceramisite.

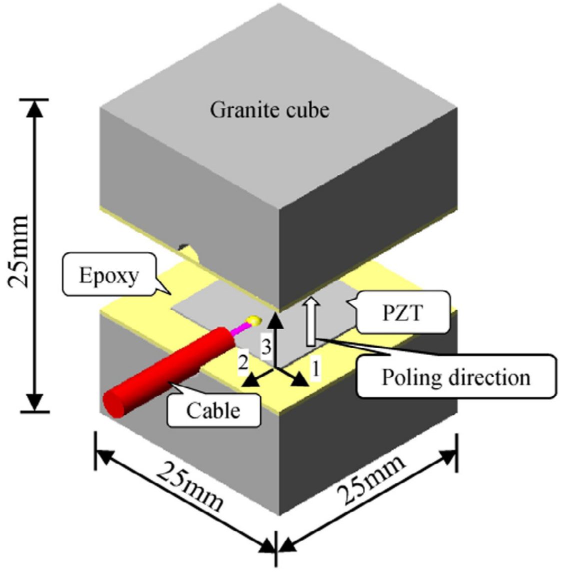

Fig. 2. Structure of the SA sensor.

Table 1
Properties of the PZT.

Parameter	Value
Young's modulus (GPa)	46
Density (kg/m^3)	7450
d_{31}, d_{32} (pC/N)	−186
d_{33} (pC/N)	670
d_{15} (pC/N)	660

Fig. 3. The shale ceramisite aggregate.

Table 2
Grading of the lightweight aggregate.

Range of particle sizes (mm)	2.36–4.75	4.75–9.5	9.5–16	16–19	19–26.5
Percentage (%)	0.1	7.3	77.0	11.5	4.1

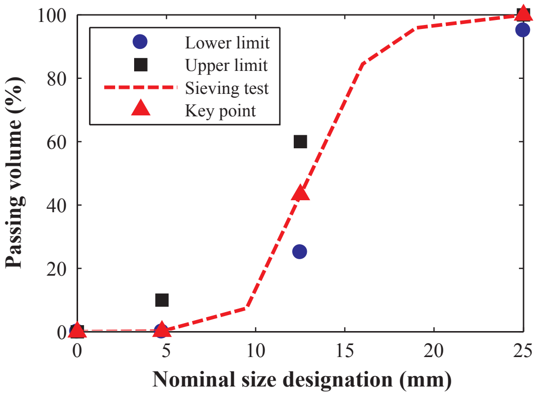

Fig. 4. Measured coarse aggregate grading compared with the ASTM standard.

The lightweight aggregate's grading is shown in Table 2 and compared with the ASTM standard in Fig. 4. The grading of the lightweight aggregate used in the tests was within the range approved in the ASTM standard for LWC.

The compressive strength (standard cylinder of 150 mm diameter and 300 mm height) at the age of 28 days was targeted to be 40 MPa. The cement used was Portland cement P.O 42.5. The fine aggregate was normal weight natural river sand. The lightweight aggregate was first pre-soaked for 24 h to better control the effective water content of concrete. A water-reducing agent—Sulfonated naphthalene formaldehyde condensate (FDN) was used to improve the concrete workability. The mix proportions are shown in Table 3. The equilibrium density of the LWC specimens was 1830 kg/m^3, which is within the range of 1440–1840 kg/m^3 for LWC [27].