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Strain monitoring for a bending concrete beam by using piezoresistive cement-based sensors

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HIGHLIGHTS

- Three PCSSs were embedded in a bending beam at different stressed positions.
- The PCSSs at compressive and tensile positions can monitor strains along the forcing direction.
- The piezoresistivity of the PCSS in shear span matches its strain feature due to a slight volume change.

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ABSTRACT

Graphite nanoplatelets (GNPs), promising in improving electrical properties of cement-based materials and its smartness, were used to prepare piezoresistive cement-based strain sensors (PCSSs) in this study. Their piezoresistive responses along vertical, horizontal and inclined directions were measured during applying a vertical cyclic compression. After calibrating free PCSSs by analyzing their gauge factors, three PCSSs are embedded in a four-point bending beam at different stress zones, i.e. uniaxial compression, uniaxial tension and combined shear and compression. In addition to investigating piezoresistive responses of PCSSs embedded in the beam, traditional strain gauges and finite element method (FEM) were also used to grasp the strains at relevant positions for comparison. For free PCSSs, It was found that the electrical resistances along vertical, horizontal and diagonal directions drop by amplitudes of 5.5%, 1.8% and 6.7% respectively, as the increasing of vertical compression. The gauge factor along loading direction was calculated to be -160.8, which illustrated a better sensitivity. In the four-point bending beam, the PCSSs in compressive zone and tensile zone can be used to presume the strain variation by considering the gauge factor obtained from the free PCSS. The reaction of the PCSS in shear zone can illustrate its strain features because a slight volume variation happened in this area, which can also be testified to be only 0.012‰with FEM analysis.

1. Introduction

Cement-based materials have been extensively used for various types of structures, including bridges, dams, and skyscrapers. Structural strain and stress monitoring, especially in some critical parts of structures, is becoming increasingly necessary. Traditional sensors, such as electrical resistance strain gauges, piezoresistive ceramics and optical fiber sensors, have been widely applied in structural health monitoring [1–4]. In the last two decades, piezoresistive cement-based strain sensors (PCSSs) have garnered increasing interests in structural health monitoring due to the fact that PCSSs have similar durability with concrete matrix and work harmoniously with it [5,6].

The piezoresistive characteristic, which is also named as pressure sensitive feature, was firstly investigated by incorporating carbon fiber in cement-based concrete [7,8]. Some other functional fillers, such as carbon black [9], carbon nanotube (CNT) [10] and nickel powder [11] were also used to improve the smartness of cement-based composites. The conductive network inside cement-based material was changed under static or dynamic conditions, which affected the electrical properties. As a result, strain, stress, crack and damage can therefore be detected by measuring the electrical signals of cement-based composites. In addition to

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the investigation on free PCSSs (not embedded in concrete structures) under uniaxial external loading, concrete structural members, in which PCSSs were embedded, were designed to determine PCSSs' piezoresistive reactions under complex stress conditions. Sun et al. [12] inserted cement-based strain sensors into concrete-filled steel tubular columns. It was found that the piezoresistive behavior of the embedded sensors show linear feature within elastic phase. Xiao et al. [13] embedded sensors in a bending beam, and found that the sensors for measuring compressive and tensile strain had similar sensitive properties with free sensors, while, the sensor in shear zone was nearly insensitive to shear stress.

Graphite nanoplatelets were found to significantly improve the transport performance and acid resistance [14]. Meng et al.'s [15] work showed that graphite nanoplatelets, at a content of 0.3%, can improve concrete's tensile strength and energy absorption capacity by 56% and 187% respectively. Apart from enhancing the transport and mechanical properties of cement-based composites, Graphite nanoplatelets are promising to incent the smartness of concrete to monitor internal damages in concrete structure [16].

According to recent researches, graphite nanoplatelets show promising utilization in improving the strength, durability and smartness of cementitious materials, which attracts increasing interests of a wide range of researchers. Although valuable achievements in piezoresistance of cement-based composites incorporated graphite nanoplatelets have been reported, the previous studies primarily focus on free PCSSs, whose piezoresistive responses are in accordance with the force direction. The understanding about piezoresistive reactions of smart concrete in-filled with graphite nanoplatelets (GNPs) in directions other than the stress direction is unveiled. Moreover, only a few utilizations of PCSSs in real structural members can be found.

In this study, PCSSs filled with GNPs as conductive additives were investigated to determine piezoresistive responses along vertical, horizontal and diagonal directions during applying a vertical pressure. In addition to this, a four-point bending beam was prepared to embed PCSSs in different representative stress zones. Strain gauges were attached to corresponding positions to capture strains, which were used to compare with the results from PCSSs. A finite element (FE) model was also developed to gain detailed strain field in order to verify the experimental tests. By studying the piezoresistive response of PCSSs under representative stress conditions, suggestions for applying them in practice can be provided.

2. Experimental work

2.1. Materials preparation

In this investigation, standard Type-52.5 cement [17] and sieved dry sand were used for casting the smart mortar specimens. The conductive nanoplatelets, whose main properties are illustrated in Table 1, were sourced from Sixth Element Inc. (Changzhou, China). According to the factory report, the product used in this study is a kind of graphite nanoplatelets. A polycarboxylate superplasticizer was selected as the surfactant to facilitate the dispersion of GNPs into water.

For grasping the micro morphology of GNPs, a Hitachi S-4800 field emission Scanning Electron Microscope (SEM) was employed in this study. After the GNPs were dispersed in water, one drop of this aqueous suspension was placed on an aluminum sheet. Once the water was evaporated, a thin GNPs film was left, and their morphology was captured with the SEM as shown in Fig. 1. The GNPs used in this test are consistent with the factory report and their dimensions are within the parameters in Table 1.

In this experimental study, the mortar used in PCSSs has the mix proportion as shown in Table 2. To fabricate PCSSs, the conductive fillers, GNPs, were added into cementitious mortar. GNPs were added at the amount of 6.4% by mass of cement (1.3% by volume of the mortar composite), which had been demonstrated to possess excellent piezoresistive characteristics [18]. The mix proportion of the beam, in which PCSSs were embedded, is also shown in Table 2. By comparing the mix proportion of PCSSs with the beam mortar, it can be found that extra water and superplasticizer were used to remedy PCSSs mortar's poor workability resulting from high concentration of GNPs possessing super large specific surface area.

A sheet of carbon fiber fabric (from Toray Industries Inc.) was attached onto the bottom of the beam with epoxy to prevent abrupt break when a bending force was applied on it. The carbon fiber fabric with a nominal thickness of 0.167 mm, a tensile strength 4059 MPa and a Young's modulus of 242GPa were utilized in the program as a reinforcement. Epoxy (from Hanma Ltd.) was used as the impregnating and bonding agent, whose Young's modulus was around 1GPa according to factory catalog.

2.2. Piezoresistive properties of the sensors

2.2.1. Specimens casting and curing

The GNPs are nano-particles and have super high surface area, which requires proper treatments to aid the dispersion in water. It was widely reported that physical methods and chemical methods were used to disperse nano particles into water [6]. In this study, a hybrid treatment combining ultra-sonication and surfactant was employed to achieve effective dispersion.

Prior to casting of mortar, GNPs were first ultra-sonicated with the aid of water and Polycarboxylate superplasticizer for half an hour. As the cement and sand were stirred in a mixer, the GNPs dispersion was added into the container of the mixer. After 3 min stirring, the mortar was cast into cube moulds (50 × 50×50 mm) with the assistance of a vibrator.

The workability of the mortar was investigated by a mini-slump test [19], by using a mini-slump cone with dimensions: top diameter 30 mm, bottom diameter 50 mm, and height 65 mm. The measured slumps of the PCSS mortar and beam mortar are reported in Table 2, showing that they have similar workability.

Four copper wire probes, diameter 1 mm, were embedded into cube samples with a depth of 50 mm as shown in Fig. 2. The electrical resistance between any two probes can be detected with a two-probe method [6], which has attracted great interests from researchers due to its simple and convenient operation [20]. Additionally, the preference of two-probe method is due to the reason that the PCSSs embedded in the beam were used to detect the piezoresistive responses between any two electrodes, which can represent horizontal, vertical and inclined directions.

All samples were mixed and cast in accordance with the requirements of ASTM standard [21]. After being demolded, the

Table 1
The properties of GNPs used in the tests.

Factory number	Thickness (nm)	In-plane diameter (μm)	Specific surface area (m^2/g)	Density (g/cm^3)
SE1231 (Sixth Element Inc., Changzhou)	~5	~6.8	191.8	2.2