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Development of cement-based strain sensor for health monitoring of ultra high strength concrete

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HIGHLIGHTS

- A high-strength CBSS is developed with little noise of piezoresistivity.
- The repeatability and sensitivity of the CBSS has greatly improved by oven drying.
- Damage of UHSC can be monitored by the CBSS embedded.
- CBSS can sense strain and stress of the UHSC column up to a stress of 154 MPa.

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ABSTRACT

In this research a cement-based strain sensor (CBSS) with high strength and self-sensing ability is developed, and the use of the high strength CBSS for structural health monitoring of ultra high strength concrete (UHSC) columns is evaluated. Results show that the CBSS with 0.5% brass-coated steel fibers has high compressive strength of >120 MPa. Its piezoresistivity shows little noise, indicating the resistance of the CBSS varies smoothly with the strain. After oven-drying, the repeatability and sensitivity of the piezoresistivity has greatly improved. When the CBSS is embedded in a UHSC column, damage monitoring of the UHSC column can be performed by means of increasing irreversible change in the resistance of the embedded CBSS. The embedded CBSS can sense strain as well as stress of the UHSC column up to a stress of 154 MPa. The piezoresistive behavior of the embedded CBSS undergoes three phases during the monotonic loading, and they are high sensitive, linear phase; medium sensitive, nonlinear phase; low sensitive, linear phase with the increase in load.

1. Introduction

Concrete filled steel tubular (CFST) columns have been widely used for the construction of multi-storey buildings, bridge piers, and other supporting structures [1]. Since CFST columns filled with high strength concrete have higher load carrying capacity than that filled with normal strength concrete, a great deal of studies have been done on CFST columns filled with ultra high strength concrete (UHSC) of which compressive strength is higher than C120/135 [2]. However, it is hard to check the filled UHSC during its service life by means of the visual inspection and the direct core sampling examination since UHSC is enveloped by the steel tube. Conventional ultrasonic transducers have been used to detect each section of CFST columns one by one, which is time-consuming, laborious and especially hard to operate in high CFST structures [3]. Currently, smart sensors such as fiber optic sensors, piezoelectric sensors and magnetostrictive sensors, have been attempted to detect voids and debond between steel tube and core concrete in CFST structures [4–6]. Cement-based strain sensor (CBSS) is also a type of smart sensor, which can sense strain, stress and damage by observing the change in its volume electrical resistivity during loading, which is called piezoresistive effect or piezoresistivity [7]. However, few studies have explored the ability of CBSS to monitor UHSC. In this research a new CBSS is developed and used to perform structural health monitoring (SHM) for UHSC.

In order to obtain CBSS, a conductive substance, usually carbon fibers, is incorporated into a cement paste matrix. The piezoresistivity of carbon fiber reinforced cement composites have been vastly studied [8–12]. Other materials, such as carbon black, carbon

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nanofibers (CNF), carbon nanotubes (CNT), graphite powder or nickel particle, may also be used as the conductive phase [13–15]. In recent years many studies have been focused on CBSS incorporating CNF and CNT, although these materials are more expensive than carbon fiber. Some of the real applications reported include traffic monitoring [16] or wireless and embedded CNT networks for damage detection in concrete structures [17]. Usually, CBSS is used to perform SHM of concrete structures in two methods. Firstly, CBSS used as a sensitive layer or paint was cast or attached on the surface of concrete elements [11,12,18]. Secondly, CBSS is prefabricated in the form of embeddable sensor to be embedded into concrete elements [19]. The latter method is suitable for SHM of CFST columns, and is adopted in this study since concrete is surrounded by steel tube. To our knowledge, compressive strength of currently available CBSS is far below that of UHSC. If they are embedded into UHSC structures, the load carrying capacity of structures will be reduced to varying degrees. In order to improve mechanical properties of CBSS and ensure its strain sensing ability, brass-coated straight steel fiber is employed in this study, which has a nominal diameter of 0.16 mm and a length of 13 mm (The aspect ratio is 81.3). This kind of fiber has been used to manufacture ultra high-performance fiber reinforced concrete. Ductal® concrete is an example, which has been used widely in civil engineering structures [20]. However, little attention has been paid to the piezoresistivity of CBSS containing this kind of steel fiber previously. Chung et al. [21,22] reported that stainless steel fiber of diameter 60 μm or 8 μm could render piezoresistivity to a cement-based material, but the phenomenon was noisy so that the resistivity did not vary smoothly with the strain. Recently, Teomete et al. [23] have tested tensile strain sensitivity of CBSS with brass-coated steel fiber under split tensile tests. The steel fibers had a length of 6 mm, and a diameter of 290 μm (The aspect ratio is 20.7). The CBSS was sensitive to tensile strain even under complex loading conditions of split tensile test. Since the split tensile test is an indirect tensile test which has a complex stress state, direct tension and compression tests remain to be performed. Otherwise, the aspect ratio of fibers will affect conductive properties and piezoresistivity [24].

The objectives of this work are to develop a new CBSS with high strength and self-sensing ability, and to study the possibility of using the high strength CBSS for SHM of UHSC structures. First, basic properties and piezoresistive behavior of the CBSS after air-drying (specimens dried at ambient temperature for several days to stabilize the moisture content) and oven-drying (specimens dried in an oven at 60 °C and relative humidity of 20% for 48 h.) is compared. The aim is to study the effect of moisture content on the piezoresistivity of the CBSS, and to explore if the sensing ability of CBSS can be improved by drying. The CBSS is then embedded in UHSC columns to evaluate its ability to sense stress, stain and damage under different loading procedures. The effect of the stress state on the piezoresistivity of the CBSS is also discussed.

2. Experimental details

2.1. Materials and specimen preparation of the CBSS

ASTM Type I normal Portland cement and natural sand were used. A dark brown solution of polycarboxylate-based superplasticizer[1] which contained 36% solids and had a specific gravity of 1.1 g/cm^3 was used for workability purpose. The straight brass-coated steel fiber[2] with a high tensile strength of 2300 MPa was used to increase compressive strength and conductivity of cement mortar. The diameter of steel fibers was 60 μm, and the length was 13 mm. Undensified silica fume[3] (SiO_2 content 95.54%; loss on ignition 2.2%; moisture content 0.61%; oversize particles retained on 45-μm sieve 0.69%; bulk density 335 kg/m^3) was used in the CBSS to obtain a dense paste matrix.

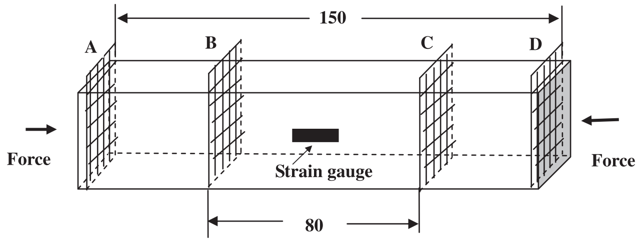

Fig. 1. Arrangement of four electrodes within the CBSS.

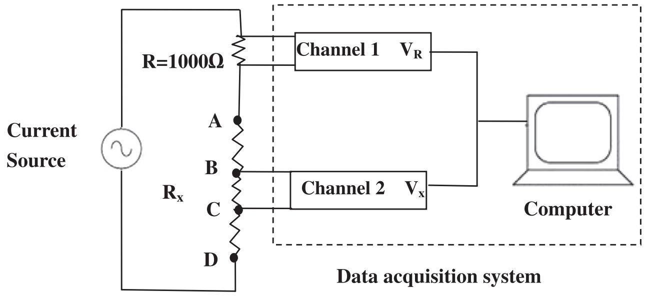

Fig. 2. The circuit diagram for resistivity measurement.

The CBSS had a water/binder ratio of 0.23, a sand/(cement + silica fume) of 1.38 and a superplasticizer/(cement + silica fume) of 1.0%. The mixture contained 8% silica fume by mass of cementitious materials and 0.5% fibers by volume of the mixture. First, cement, silica fume and steel fiber were mixed in a Hobart mixer at Speed 1. Then, about 70% of water was added and mixed for 1.5 min. After that, the remaining 30% of water containing 50% of superplasticizer was added and mixed for 4.5 min. Finally, the remaining superplasticizer was poured into the mixture and mixed for 2 min. Three 50-mm cube specimens were cast for compressive strength test and three 40 mm × 40 mm × 160 mm prism specimens were cast for determining the resistivity and piezoresistivity. All the specimens were moist cured for 28 days.

2.2. Testing methods of the CBSS

2.2.1. Mechanical and electrical properties

Compressive strength was determined using a Denison universal testing machine with the loading rate following ASTM Standard C109 [25]. 4-probe method was used to determine the electrical resistances of the specimen. In 4-probe test, the voltage measurement was made at probes separate from the probes used to apply electrical current, and effect of contact resistance was minimal. The distance between the electrodes did not affect the measurements in 4-probe method [26,27]. Perimetral and embedded electrode configurations have been used in test of cement matrix composites. For the embedded electrode configuration, a metal wire mesh is inserted in the cement composite. In perimetral electrode configuration a conductive tape or wire was stick to the perimeter of the sample using conductive paste [7,14]. The lead wire can be connected with the wire mesh easily, and the joint point is strong. Thus, the embedded electrode configuration is more suitable for the CBSS, which will be embedded into concrete structures for long-term measurement.

In this study galvanized welded wire mesh (with openings of 6 × 6-mm) of 42 mm (width) × 39 mm (height) was embedded in the prism specimens as electrical contact. Copper wire was also soldered on the mesh. Spacing of the mesh is shown in Fig. 1. The spacing of the outer electrical contacts (A and D) was 150 mm apart, and that of B and C was 80 mm. As shown in Fig. 2, a resistor of known resistance (1000 Ω) and the electrical contacts “A” and “D” of the specimen were connected in series. Electrical current[4] in the range from 0.05 μA to 1 mA was supplied to the circuit shown in Fig. 2. The electrodes “B” and “C” were connected to a data acquisition system consisting of Digital Multimeter[5] and scanner card[6] to record the voltage. The voltage across the known resistor (V_R) and the voltage across the specimen (V_x) were recorded using the data acquisition system. According to Ohm’s law, the current flowing through the entire circuit was constant and the following equation holds true:

$$R_x = V_x R / V_R \qquad (1)$$

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[1] ADVA 181, W. R. Grace Pte. Ltd., Singapore.

[2] Dramix@, N. V. Bekaert S.A., Belgium.

[3] Bisley Asia Pte. Ltd., Singapore.

[4] Yokogawa Electric Corporation, Japan.

[5] GDM8261 digital multimeter, Good Will Instrument Co., Ltd, Taiwan.

[6] GDM-SC1 scanner card from Good Will Instrument Co., Ltd, Taiwan.