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Mechanical and smart properties of carbon fiber and graphite conductive concrete for internal damage monitoring of structure

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HIGHLIGHTS

- The research provides a pathway to significantly improving the mechanical and smart property of concrete.
- Micro-characterization was used to quantify the effects of carbon fibers and graphite on the microstructure of paste.
- Smart property under flexure of concrete added with carbon materials was investigated.
- Optimum performance of concrete was achieved by an addition of 0.7 wt% CF and 2.5 wt% G.
- Strain dependent resistivity characteristic was well drawn by quadratic polynomial.

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ABSTRACT

The piezoresistivity and smart property under flexure in concrete for water-binder ratio of 0.38 were investigated by adding well-dispersed carbon fibers and graphite to improve its mechanical and smart performance. Thence, the reveal of the smart property under flexure was demonstrated from the experiment by three-point loading as well as the relationship between the strain and variance ratio of resistance was in discussion. The result shows successful in cement mixing by carbon fibers and graphite in 0.7 wt% and 2.5 wt% in mechanical and smart performance which implies that carbon fibers are capable partially replaced by graphite. In addition, the strain dependent resistivity characteristic was able to drawn by quadratic polynomial while the microtopography of the composite material was uncovered by the scanning electron microscopy (SEM).

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1. Introduction

The bearing capacity and service life of concrete structure are constantly degraded by service induced damage under external loading with uncontrollable and irreparable breakings through cracking breach while gradually formed to micro-damage and micro-cracks in early phase. Accordingly, prevention on early deficiencies as discovered promptly and effective measures is an efficiency practical resource for accident preclude where the real-time monitoring of damage in concrete structure might have a significant value in practice [1,2]. Hence, the conductive concrete provides a new pathway for the real-time monitoring of the internal damage in concrete structures instead of the principal defect by conventional monitoring methods such as ultrasonic detection system, radar inspection system and inner sensors system where confine on the durability of concrete and cost material [3].

Conductive concrete as well-known smart materials as the component of concrete containing conductive material with the advantages of lower costing, superior durability and structure reduction loss of mechanical properties in compared with conventional monitoring methods while it is also widely applied to the deicing and snow melting of road and electromagnetic shielding fields [4–6]. Whereas, the well-dispersed conductive component is able to form electric conduction network in the matrix and subsequently possesses the facility to self-sensing of its deformation and damage in concrete [7–9].

It has been found since 1930s, the former Soviet Union initially started working with conductive concrete while added conductive material to prepare conductive concrete used as grounding conductors in power stations [10]. Varadan [11] in 1993 observed the resistivity of carbon fiber reinforced concrete varied linearly with the load in a certain range. The resistivity would recover after unloading if there was no internal damage in concrete caused by the external load. It indicated that carbon fiber could be mixed into concrete as a kind of material to sense the variation of stress and

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Table 1
Physical properties of carbon fibers.

Diameter (um)	Length (mm)	Carbon content (%)	Tensile strength (MPa)	Tensile modulus (GPa)	Density (kg/m^3)	Resistivity (Ω·cm)
8	6	95	3500	210	1740–1790	1.0–1.6

strain [12,13]. Wang et al. [14] in 1999 investigated the electrical conductivity and variance ratio of resistance in carbon fiber reinforced cement based composites under cyclic tension and compression. Wang and Chung [7] in 2006 verified the self-sensing of carbon fiber composite materials in bending. The resistance in specimens showed reversible changes in the early stage of loading, subsequently increased rapidly when the specimen was damaged. Wen and Chung [15] in 2007 found that carbon fibers and graphite partially replaced by carbon black was able to guarantee the function of materials with costs reducing. Chen and Liu [16] in 2008 conducted the uniaxial compression tests and three point bending tests of carbon fiber reinforced concrete while the relationship between the damage in concrete and the variation ratio of resistance was established. Furthermore, Vaidya and Allouche [17] in 2011 discovered the utilization in smart buildings for health monitoring by carbon fiber reinforced geopolymer concrete since the resistance of beam decreased with the strain of concrete. Howser et al. [18] in 2011 conducted smart properties test of concrete with carbon nanofibers (CNF) in 1% while the results shown CNF might restrict effectively the growth of micro cracks whereas improved the compressive strength and toughness of concrete. Chung [19] in 2012 indicated that graphite mixed with carbon black showed successful in heating effect while carbon nanotubes showed poor performance in electrothermal and shielding properties. Rizvi et al. [20] in 2016 conducted the piezoresistivity tests of conductive carbon fiber asphalt mixture and found the frequency response of the composites increased with the temperature.

Generally, the piezoresistivity, thermoelectric effect and temperature sensitivity of conductive concrete [21–23] are in discussion while the smart property under flexure of conductive concrete structure is rarely in mention although the most concrete structure is subject to bending moments such as roads, bridges beam and deck.

This study emphasised on the piezoresistivity and smart property under flexure of carbon fiber and graphite conductive concrete with a water-binder ratio of 0.38. The preliminary empirical formula of relationship between the strain and variance ratio of resistance was investigated as well as the microtopography of the composite material with different amounts of carbon fibers and graphite addition was uncovered by SEM images to systematically analysis the strengthening mechanism of carbon material. All specimens were tested on 28 days with four recycle experiments of the piezoresistivity and moisture content while the outdoor environment factors and resistivity of concrete under long term fatigue load have been ignored.

Table 2
Properties of graphite powder.

Purity (%)	Burning residue (%)	Granularity ≤30um (%)	Sieve residue 0.065 mm (%)
≥99.85	≤0.15	≥95	≤5

2. Experimental procedure

2.1. Material

Portland cement type II (Dalian Nanjing Cement Factory) and fly ash type II (Shanghai Weixi Technology Co. Ltd.) were used as the cementitious material while basalt gravel with a grain diameter ranging from 5 to 15 mm was used as coarse aggregate where the medium-sized sand was used as fine aggregate. Highly-dispersible graphite powder and Type 700-12 k carbon fibers (Nanjing Weida Composite Material Co. Ltd.) were used as electrically conductive components. Carbon fibers exhibit a tensile modulus of 210 GPa and a tensile strength of 3500 MPa. Whereas, polycarboxylic acid superplasticizer (Shanghai Sunrise Polymer Material Co. Ltd.) was used to enhance the fluidity of concrete while defoamer and dispersant (Shanghai Liangxing Auxiliary Co. Ltd.) were participating to eliminate the emergence of bubbles and improve the dispersity of carbon fibers. The properties of carbon fibers and graphite powder are shown in Tables 1 and 2.

2.2. Specimen fabrication

Different fiber content and graphite content were adopted (Table 3) to study the mechanical and smart properties of conductive concrete. Firstly, dispersant (0.4 wt% of cement) was added into the liquid water at 60 °C for well dispersion where the carbon fibers and defoamer (0.4 wt% of cement) were added into the resulting solution after the dispersant was completely dissolved in water accordingly to stir the mixture by glass rod for 2.5 min. The resulted mixture was mixed with cementitious materials, aggregate, graphite, water reducer for 3 min in a planetary mixer. Cement and sand with basalt gravel were mixed in a ratio of 1:2.25:3.36 with cast in $56 \times 56 \times 280$ mm^3 and $100 \times 100 \times 100$ mm^3 oiled molds respectively while specimens were shaped by vibration. Henceforth, two brass-wire electrodes were embedded in specimens to measure the electrical resistivity as shown in Fig. 1. While at least three specimens were fabricated for each group and unmolded after 24 h in standard curing box for 28 d subsequently.

2.3. Measurement

The electrical resistance in conductive concrete was measure by two-pole method. A multi-meter was the appliance to connect

Table 3
Mix design.

NO.	Carbon fibers (wt% of cement)	Graphite (wt% of cement)	Fly ash (wt% of cement)	Water reducer (wt% of cement)	*w/b*
Control	0	0	25	1	0.38
1	1	0	25	1	0.38
2	0.7	2.5	25	1	0.38
3	0.5	5	25	1	0.38
4	0.25	7.5	25	1	0.38

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