Construction and Building Materials 173 (2018) 1–9

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Assessment of self-sensing capability of Carbon Black Engineered Cementitious Composites

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HIGHLIGHTS

- Incorporating CB particles can decrease the bulk resistivity of ECC significantly.
- Incorporating CB particles and AEA can enhance the tensile strain capacity of ECC significantly.
- CB-ECC can be potentially utilized to detect micro cracking at the early inelastic stage.
- A new method of nondestructive testing was proposed in this investigation.

ARTICLE INFO

Article history:
Received 21 January 2018
Received in revised form 26 March 2018
Accepted 4 April 2018

Keywords:
Engineered Cementitious Composites (ECC)
Self-sensing capacity
Gauge Factor (GF)
Carbon Black (CB)
Resistivity

ABSTRACT

The protection and health monitoring of degraded concrete infrastructure required a multifunctional material which possessing good damage tolerance, whilst providing a self-sensing capacity that designed to specifically diagnose cracking. Engineered Cementitious Composites (ECC) presents superb tensile ductility and pseudo strain-hardening property. In this paper, a type of multifunctional ECC incorporating Carbon Black (CB) nano-particles and Air Entraining Agent (AEA) to decrease the bulk resistivity while increasing the tensile strain capacity is studied. The effect of CB particles on the electrical response of ECC, HFA-ECC (high fly ash ECC) and CB-ECC under direct tension was investigated experimentally by four-point probe test. The experimental results showed that the bulk resistivity of all specimens increased with the crack propagation, and the increase ratio in inelastic phase was much higher than that in elastic phase. The Gauge Factor (GF) in the strain-hardening stage was calculated by using the change in bulk resistivity and tensile strain, and the relationship between GF and crack width was also investigated. The combination of CB and AEA obtained the highest sensing ability from elastic stage to first cracking stage, which can determine whether the internal microcracks are generated by the change of the bulk resistivity.

1. Introduction

Piezoresistive property of cement-based materials was already discovered and applied in monitoring traffic in highway and structural health in many years ago. The change in resistivity of concrete itself can be used to sense the strain/stress and damage, which is much more important for engineers and researchers to monitor concrete structure timely and thereby enhance the service life [1]. However, the research of self-sensing concrete is mainly restricted in compressive strain and stress, this is because that brittleness of concrete limits the investigation into self-sensing properties under tension loading.

Engineered Cementitious Composites (ECC), a special type of High Performance Fiber Reinforced Cementitious Composites (HPFRCC), has been researched widely since it was developed by Li and his teams [2] in the 1990s. ECC possesses an extreme tensile ductility, in the range of 3–5% (about 300–500 times that of concrete), and obtains the multiple cracking behavior and keep the crack width constant at 60 μm while the number of cracks increase. Therefore, it is feasible to investigate the self-sensing properties of ECC due to its excellent mechanical performance especially in tension. ECC, as a sensor, has many advantages compared with embedded/attached strain/stress sensors. For example, (1) it could detect a wider strain range, including the whole tension stage; (2) it requires no extra sensors to be installed; (3) it could monitor the integrated structure, not just its specific parts over the whole service life [3].

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https://doi.org/10.1016/j.conbuildmat.2018.04.031
0950-0618/

The mechanism of electric conduction in cement-based materials is that the movement of positive and negative ions was connected to micro-pores and promote the electrical conduction of cementitious materials [4,5]. The bulk resistivity of cementitious materials is effected by many factors, including different cement, ratio of water to binder, hydration degree and porosity. Li et al. [6] demonstrated that the resistivity of wet concrete ranged from 10^3 to 104 O-cm while that of dry concrete could increase to 10^8–109 O-cm, this was because that the resistivity of hydration product was much higher than that of pore solution. The large difference in resistivity makes more difficult to use electrically conductive performance of cementitious material in structural health monitoring.

Some conductive materials, such as steel fiber, graphite, and carbon nanotube, was extra added into cementitious material to enhance its conductive ability and simultaneously reduce dependence on ions inside pore solution. Carbon Black (CB), characterized by desirable electrical conductivity and readily dispersible ability in cement paste, was used to improve electrical conductivity of cementitious materials. Therefore, it is feasible to produce ECC material modified with CB, while simultaneously retaining higher electrical conductivity.

For self-sensing properties of ECC, the relationship of change between resistivity and strain during loading test has been successfully developed by a large number of researchers [7–11]. Han and Ou [10] analyzed a number of parameters to evaluate the sensing properties of Piezoresistive Cement-based Stress/Strain (PCSS), including the range of input/output, linearity, repeatability, hysteresis, Signal to Noise Ratio (SNR) and zero drift. For tensile strain monitoring, Ranade et al. [7] defined Gauge Factor (GF) as the relative change in resistivity per unit strain, and characterized it for the piezoelectric resistivity of the ECC material. Due to the excellent strain-hardening behavior and deformation ability of ECC, the uniaxial tensile test and bending test were both used to evaluate the self-sensing properties of ECC [1,12,13]. Moreover, GF can be used to effectively monitor the progress of strain and resistivity changes at different loading stages with specific values [12,13]. Ranade et al. [7] studied the effect of crack pattern on self-sensing properties of ECC and predicted the relationship between single crack behavior and crack width by using two-point probe method with alternating current (AC). However, adding CB into ECC material can increase the sensing ability but reduce its ductility capacity. Li et al. [8] found that increasing the CB content could reduce the bulk resistivity and tensile strain capacity of ECC mainly since the addition of CB leaded to an uneven distribution of fibers. Therefore, in order to achieve a good self-sensing performance, the nano Carbon Black and Air Entraining Agent (AEA) were used to add into ECC mixture to decrease the bulk resistivity while increasing tensile strain capacity in this study. The systematic research on means of measurement and error was done, and four-point probe method under above 1 kHz frequency AC supply was recommended to minimize the error produced by material polarization and contact impedance [9].

In this study, four-point probe method with high frequency AC was used to evaluate the self-sensing properties of CB-ECC during tensile loading. The mechanical properties of ECC, including first cracking strength, ultimate tensile strength, ultimate tensile strain, crack width, crack number and final fracture location, were investigated.

2. Experimental program

2.1. Materials and mixture proportions

The mix proportions are presented in Table 1, where water, silica sand and CB are the ratio to binder (cement and fly ash), while fly ash is the ratio to cement by weight. Carbon Black-VXC72R from Cabot Corporation was chosen to develop CB-ECC in this paper. When the mixture is stirred, in order to obtain good flow ability of fresh matrix, more water and super plasticizer are added since CB has large specific surface area, 254 m^2/kg [12]. So the water to cement ratio of CB-ECC in Table 1 is 0.31 not 0.27. Air Entraining Agent (AEA), main component is Sodium Lauryl Sulfate, was added into matrix in order to form more air bubbles. Portland Ordinary Cement, Type I, was partially replaced by fly ash (Class I) to develop high-tensile ductility of ECC. The size of silica sand used in this paper ranged from 70 to 140 meshes (109–212 μm). PVA fiber, with a surface oil coating of 1.2% by weight, was produced by Kuraray Company in Japan. The physical and mechanical properties of PVA fiber is listed in Table 2.

2.2. Specimen preparation and experimental tests

Firstly, all solid materials, including cement, fly ash, silica sand, AEA and other solid additives, were mixed according to the proportions shown in Table 1 and stirred for 3 min at low speed to ensure that mixtures were well stirred. Then, slowly adding water and super plasticizer at firstly low-speed stirring for 3 min and then at high-speed stirring for 5 min. When the slurry was in a fluid state, the PVA fibers were slowly added, stirred for 5 min at low speed and then stirred at high speed for 6 min. when CB was added, the stirring time would be prolonged. Finally, when the fibers were dispersed evenly and without agglomeration, and the slurry had good workability, the slurry was poured into the prepared molds, slightly shaken and smoothed in a timely manner. The specimens were demolded after 24 h, and then cured under standard condition at 95 ± 5% RH and temperature of 20 ± 2 °C until tested.

The copper tape, produced by 3J Company in China, was used as the electrode. The surface of specimens should be smooth and clean in order to paste the electrodes. The copper tape was cut into the electrode strip with a width of 4 mm and a suitable length. The silver conductive epoxy, produced by Xinwei New Materials Co. Ltd in China, was smeared in the electrode position around shown in Fig. 2, where will paste the electrode strip. The silver conductive epoxy can enhance the conductivity between electrode and matrix. The pasted specimen was placed at room temperature for 24 h.

The size of specimen and the location of electrode tape are shown in Fig. 1. Section 1 is located between two electrode strips connected to the voltmeter with a distance of 30 mm. Section 2 is located between one electrode connected voltmeter and one electrode connected ammeter with a distance of 17 mm. Section 3 is outside the external electrode strip position. The distance between two electrodes connected to the power source is 64 mm. The width and thickness of Sections 1 and 2 is 30 mm and 13 mm respectively. In addition, the distance between two LVDT (Linear Variable Differential Transformer) is 80 mm.

During the uniaxial tensile test, four-point probe method was used to measure the resistivity of specimen, the polarization and contact impedance could be minimized by the change in electrical potential [9,14,15]. The resistivity measurements were carried out using NI-cDAQ-9174 with NI 9203 and NI 9229 separately connected ammeters and voltmeter. An arbitrary/Waveform Generator was added into the circuit in series to offer a constant frequency alternating electrical potential. The frequency range from 1 Hz to 10 kHz can minimize the effect on capacitance of ECC [14]. A constant AC voltage with amplitude of 5 V and frequency of 1 kHz was applied across the outer two copper tape electrodes, and the current produced across the same electrodes was measured by NI 9203 every 1.6 s. The resistance and bulk resistivity of ECC could be calculated based on ohm's law, shown in formula (1) and (2).

$$R = \frac{V}{I} \tag{1}$$

where V and I are the voltage and current measured by voltmeter and ammeter respectively.

$$\rho = \frac{RS}{L} \tag{2}$$

where ρ and R are the bulk resistivity and resistance; S and L represent area of cross section and the distance between electrodes respectively.

The mechanical property of ECC mixtures under uniaxial tension was investigated in this study. All specimens were tested at the age of 28 days. Four specimens for ECC, HFA-ECC and CB-ECC were prepared for tension test. The geometry of specimen and the tensile setup are shown in Figs. 1 and 2.

3. Results and discussions

3.1. Mechanical behavior

The tensile properties of ECC, HFA-ECC and CB-ECC are shown in Fig. 3. As shown in Fig. 4, all specimens showed pseudo strain-hardening behavior and multiple cracking under tension test. Table 3 summarized the tensile properties obtained from the experimental tests. The value in Table 3 was the average of three