Construction and Building Materials 174 (2018) 253–262

Contents lists available at ScienceDirect

Construction and Building Materials

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

Self-sensing properties of Engineered Cementitious Composites

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HIGHLIGHTS

- High self-sensing sensitivity and superb ductility were acquired simultaneously.
- High ductility of CB-ECC achieved by adding AEA.
- Gauge Factor (GF) was calculated to analyze self-sensing behavior quantitatively.
- Crack patterns of CB-ECC, HFA-ECC and ordinary ECC were compared.
- GF shows different trend with tensile strain for different ECC crack pattern.

ARTICLE INFO

Article history:
Received 14 November 2017
Received in revised form 2 April 2018
Accepted 13 April 2018

Keywords:
Carbon Black
Engineered Cementitious Composites
Electric resistivity
Crack pattern
Tensile ductility
Structural health monitoring

ABSTRACT

The piezoresistivity of cement-based material has already been investigated, but mainly restricted to compressive stress sensing due to brittleness of concrete. Conversely, Engineered Cementitious Composites (ECC) presents superb tensile ductility and pseudo strain-hardening property, which offers unique opportunity for exploring sensing of tensile stress/strain. In this paper, Carbon Black (CB) and supplementary cementitious materials (SCM) were incorporated into ECC to decrease the bulk resistivity and simultaneously acquire high tensile ductility. The resistance of ECC, high fly ash (HFA)-ECC and CB-ECC was measured through a two-probe method under uniaxial tension test. All specimens exhibited increase of resistivity once cracks occurred between two electrodes. The fractional Gauge Factor (GF) in strain-hardening segment was calculated and the relationship of GF and tensile strain was experimentally investigated, which could be potentially utilized in the field of structural health monitoring to enhance the safety of concrete infrastructures.

1. Introduction

Electrical resistivity of cement based materials, has been extensively studied and applied in investigating hydration of cement paste and transport properties of concrete. The change in resistivity of concrete in response to external loading, i.e. piezoresistivity can also be used to sense the strain/stress and damage, which is of great significance for engineers to monitor and maintain structures timely and thereby extend the service life. McCarter et al. [1–3] first analyzed the microstructure and hydration of cementitious materials by studying the electrical characteristics in the 1980s. It was realized that the electrical resistivity of concrete is directly related to the rate of hydration of the cement. Chung et al. increased the conductivity of concrete by adding steel fiber and carbon fiber to make the concrete a sensor to detect strain [4]. Recent researches have focused on searching for materials of higher piezoresistive coefficient to achieve sensors with better sensibility, higher accuracy, and wider range mainly by adding conductive additives. Han and Ou et al. found that cementitious composites filled with nano graphite platelets (NGPs) possess sensitive piezoresistive effect and stable repeatability under different loading conditions [5,6]. Nevertheless, the research related to self-sensing concrete is mainly restricted to compressive strain and stress, which may be attributed to the brittleness of concrete that makes it not feasible to study self-sensing properties under flexural and tensile loading.

Engineered Cementitious Composites (ECC) exhibited superb ductility and deformation capability after incorporating a small volume percent of Polyvinyl Alcohol (PVA) fiber. The tensile ductility is obtained by producing multiple micro cracks under loading, and the crack width is controlled by PVA fiber bridging. Hence, it is valuable to investigate the self-sensing properties of ECC due to its excellent mechanical performance especially in tension and

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https://doi.org/10.1016/j.conbuildmat.2018.04.129

flexure. ECC, as a sensor and simultaneously a structural material, has many advantages over embedded and attached strain/stress sensors, for instance, (1) it could detect a wider strain range, including elastic, strain-hardening and tension-softening stage, (2) it does not require installation of external sensors, which could be quite costly and difficult to maintain, (3) it is possible to monitor the entire structure, not just its specific parts over the whole service life [7].

The mechanism in electric conduction of concrete was investigated and it was discovered that the movement of positive and negative ions, like K^+, Na^+, Ca^+ and OH^-, in continuously connected micro-pores contributes to electrical conduction of concrete [8,9]. The bulk resistivity of concrete is influenced by many factors, including type of cement, the ratio of water to binder, degree of hydration, porosity and moisture content. Previous study demonstrated that the resistivity of wet concrete ranged from 10^3 to 10^4 ohm-cm, while dry concrete could increase up to 10^8–10^9 ohm-cm[10], as the resistivity of hydration product is a few orders of magnitude higher than that of the pore solution[9]. Huge variation in resistivity makes it not feasible to utilize electrical properties of cement-based material in structural health monitoring.

Some highly conductive materials, such as steel fiber, graphite, and carbon nanotube, are added into cement-based material to enhance its conductive properties and simultaneously reduce its 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 cement-based composites. CB particles incorporated into the matrix form a spatial network and the resistivity of composites expresses an exponential function of potential barrier width (the distance between two adjacent CB particles) based on tunneling theory [11,12]. Both volume fraction of CB and its dispersion degree determine the potential barrier width, which in turn influences resistivity of the composites. It was found that the CB distributed in the polymer in an aggregate form because of the agglomeration of CB [13–15]. However, there is no research concerning the dispersion and agglomeration of CB in cement paste.

Based on previous research four-probe method with above 1 kHz frequency alternating current (AC) supply was recommended to minimize the error produced by material polarization and contact impedance [16]. Modified two-probe method under direct current was used in this paper due to simplicity and availability of the instruments. Drying induced resistivity was neglected, since relative humidity in lab is nearly stable. The gauge factor [16–18] (fractional change in resistivity normalized by corresponding change in strain) was proposed to evaluate the sensitivity of resistivity to tensile strain and crack patterns. The self-sensing properties of CB-ECC was initially investigated by Li et al. [17], and it was found that increasing CB content reduced the resistivity of composites as expected. However, the tensile strain capacity also decreased due to poor fiber dispersion caused by addition of CB, which has very high surface area. Ranade et al. [18] investigated experimentally and analytically the influence of the microcracking on the composite resistivity using normal ECC and high fly ash ECC. It was found that normal ECC with larger crack width resulted in higher gauge factors, despite of its lesser number of cracks at a given strain when compared with that of HFA-ECC. Nevertheless, they did not include any conductive additive to lower down the bulk resistivity and the crack width ranges of these two mixtures are relatively close. In this paper, the mix design of ECC is manipulated by reducing amount of silica sand, adding more fly ash, incorporation of Carbon Black and other supplementary materials for instance air entraining agent to achieve ECCs with a wide range of bulk resistivity and crack width while still maintaining decent tensile strain capacity. The influence of tensile strain and bulk resistivity on the relative change of resistivity is studied experimentally. Furthermore, the influence of crack width and crack number on gauge factor is also discussed.

2. Experimental investigation

2.1. Material and mix 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 BlackVXC72R from Cabot Corporation was chosen to develop CB-ECC in this paper. More water and superplasticizer were added for admixture with CB in order to acquire good workability as CB has huge nitrogen-specific surface of 254 m^2/kg [19]. Air Entraining Agent (AEA, Megachem Limited) with main component of Sodium Lauryl Sulfate, was added into the mixture to form air bubbles. Type I Portland Ordinary Cement was partially replaced by fly ash (Class F, Jaycee Resources Private Limited) to develop high tensile ductility of ECC. The size of silica sand used in this paper ranged from 160 to 180 mesh (82–93 μm). PVA fiber supplied by Kuraray Company was added, whose length and oil coating by weight are 8 mm and 1.2% respectively.

2.2. Experimental procedures

All dry ingredients including CB and AEA were mixed in a Hobart mixer with 20L capacity for 1 min at low speed, and then water and superplasticizer were added and mixed until homogeneous slurry was formed. Finally, PVA fiber was added into the mixer and then changed to intermediate speed mixing for another 5 min to ensure good dispersion of PVA fiber. CB-ECC required higher w/b, superplasticizer content and more mixing time to make sure there are no fiber bundles. The fresh mixture was cast into oiled moulds, and then covered with plastic sheet. The specimens were demolded after 24 h. These specimens were cured in a sealed plastic container for 6 days and then cured in lab room environment until testing at the age of 28 days.

Copper tape (3M Company), serving as electrodes, was tailored in 4 mm width and 200 mm length, submerged into butanone solution to dissolve the backing adhesive, and then washed by tap water. Dry and clean copper tape was glued with silver conductive epoxy around the surface of dogbone specimens in the position shown in Fig. 1.

All dogbone-shaped specimens prepared for uniaxial tension test were divided into three sections by electrodes and LVDT (Fig. 1). Section I was between the internal boundary of two electrodes and its span was 108 mm, where resistance would be measured. Section II was between outer boundary of electrodes and the LVDTs (linear variable differential transformer), and the length of Section II was 11 mm each. Cross-sectional area in Sections I and II remained unchanged, measuring 36 mm in width and 16 mm in thickness. Section III was outside the gauge length, where cross-sectional area was non-uniform.

The resistance was measured by two-probe method per second using multimeter (GWINSTEK GDM-8261) with its range up to 100Mohm. The bulk resistivity could be calculated based on Ohm's law, shown in Eq. (1).

$$\rho = \frac{RS}{L} \tag{1}$$

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

Table 1
ECC mixture proportion.

Mix	Cement	Fly Ash	Silica Sand	Water	Super Plasticizer (g/L)	AEA (g/L)	Carbon Black	PVA fiber (vol%)
ECC	1.0	1.2	0.36	0.32	3	0.1	0	2
HFA-ECC	1.0	3.0	0.36	0.32	3	0.1	0	2
CB-ECC	1.0	1.2	0.36	0.38	6	0.1	0.01	2