Cement and Concrete Research 58 (2014) 1–12

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Influence of micro-cracking on the composite resistivity of Engineered Cementitious Composites

Ravi Ranade, Jie Zhang, Jerome P. Lynch, Victor C. Li *

Department of Civil and Environmental Engineering, University of Michigan Ann Arbor, 2350 Hayward St, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 21 March 2013
Accepted 6 January 2014

Keywords:
Electrical properties (C)
Mechanical properties (C)
Micromechanics (C)
High-performance concrete (E)
Composite (E)

ABSTRACT

Engineered Cementitious Composites (ECCs) are structural materials known for their excellent tensile ductility and damage tolerance. Previous experimental studies have shown a strong dependence of electrical resistivity of ECC on applied mechanical tensile strain (piezoresistive behavior), which can be potentially utilized for self-sensing mechanical damage for structural health monitoring. In this paper, the influence of micro-cracks on the composite electrical response of ECC under direct tension is investigated experimentally as well as analytically. For this purpose, the electrical–mechanical properties of two ECCs with different crack patterns are compared at macro (composite) and meso (single-crack) scales. An analytical model linking single-crack electrical response and crack pattern of an ECC to its composite electrical behavior is proposed in this study, and verified for both ECCs with experimental observations. Thus, a fundamental understanding of crack patterns and their effects on piezoresistivity of ECC is developed in this study.

1. Introduction

Advances in structural analysis methods over the past five decades have allowed engineers to account for numerous load combinations and limit states in structural design [1]; yet, structures are often subjected to loads that are not anticipated during design necessitating their constant evaluation during service life for ensuring safety. Such evaluation is often performed using laborious visual inspections by trained engineers at regular intervals [2]; however, the reliability of such subjective evaluation has been often questioned [3,4]. Modern day structural health monitoring (SHM) techniques [5,6] have emerged as potential improvement over visual inspections. However, most of the sensing in SHM is performed through point-based sensors capturing only local damage, and there is a risk of missing critical damage in regions not in proximity to a sensor. A cost-effective distributed sensing alternative that can sense damage everywhere in the structure is needed to mitigate the risk of sudden structural failure, which is the motivation behind the development of self-sensing structural materials.

Structural materials that are self-sensing can potentially provide an effective alternative for comprehensively monitoring structural health due to their omnipresence in a structure. The feasibility of using Engineered Cementitious Composites (ECCs) as self-sensing structural materials has been demonstrated in previous studies (reviewed below). Apart from its excellent mechanical properties as a structural material, ECC possesses a unique combination of damage tolerance and piezoresistivity that make its use as a self-sensing material possible.

ECCs are ultra-ductile fiber reinforced cement-based composites which, unlike typical fiber reinforced concretes (FRCs), have a strain hardening behavior under tension as a direct result of their micromechanics based design [7,8]. The tensile strain capacity (tensile ductility) of an ECC is at least 100 times [9] higher than a structural concrete. At the same time, compressive strength of ECC is similar to that of High Strength Concretes (40–70 MPa). The majority of catastrophic structural failures are tension related, and therefore, particular focus is on the tensile performance of ECC. The high tensile ductility of ECC is achieved by forming multiple micro-cracks (crack width $<100\ \mu m$), which allows the material to gradually undergo controlled damage while sustaining increasing tensile stress [10]. This is in contrast to concrete and FRCs, which rapidly lose their tensile stress capacity after a small amount of damage [11]. The damage tolerance of ECC by suppressing the sudden catastrophic failure mode facilitates the quantification of damage into discrete levels and is a required property of a self-sensing structural material.

ECC, like concrete and other cement-based materials, acts as a piezoresistive material with bulk resistivity of 10^1–10^5 Ω-m, similar to that of a semi-conductor [12,13]. The microstructure of a cured cement-based material contains microscopic pores, partially filled with unbound water and dissolved ions [14]. These ions in pore water are mobilized under an externally applied electric field to create electric current. However, connectivity between the pores is limited in ECC [15], which increases the tortuosity of current flow path. In addition, high contact impedances exist between various phases of the multi-phase microstructure of ECC. Under applied mechanical strain, spatial separation between conductive phases changes causing a change in the bulk resistivity of ECC, which makes the material piezoresistive [16]. The change in resistivity of ECC with strain is more drastic under tension,

---

* Corresponding author.
E-mail address: vcli@umich.edu (V.C. Li).

0008-8846/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconres.2014.01.002

especially during strain hardening, as compared to compression and can be utilized to sense tension related damage.

In the last three decades, researchers worldwide have investigated the piezoresistivity of cement-based materials and its applications in investigating hydration of cement paste, transport properties of concrete, and non-destructive damage detection particularly in concrete containing carbon fibers. In the 1980s, McCarter and co-workers [17–19] pioneered the application of AC impedance spectroscopy to study the microstructure and hydration of cementitious materials. It was realized that concrete's piezoresistivity and its measurement can be correlated to a variety of transport properties of concrete. Since 1990, there has been a widespread application of this technique in a number of studies related to concrete durability and cement hydration in the presence of pozzolanic admixtures. Seminal contributions in these research areas were made by McCarter [20,21], Mason [22–25], Beaudoin [26–28], Bentz and Garboczi [29,30], and their co-workers. The use of piezoresistivity of concrete containing carbon and steel fibers and other conductive fillers to detect linear-elastic strain and onset of cracking has recently gained interest among researchers. Significant advances in this field are credited to Chung [12,14,31–33], Beaudoin [34], Banthia [35,36], Han [37], Azhari [38], and their co-workers. However, none of these studies investigated the influence of inelastic multiple micro-cracking of a strain hardening cementitious composite under direct *tensile* loading on the composite resistivity, which is needed for developing self-sensing, damage tolerant structural materials.

Experimental investigation of the tensile piezoresistivity of ECC was reported by Hou and Lynch [13,16,39]. It was observed that the gauge factor (relative change in resistivity per unit strain) of ECC in the strain hardening region is about 3–4 times higher than that in the elastic (pre-cracking) region due to the formation of multiple micro-cracks which cause significantly larger increase in resistivity than elastic stretching of the composite. Both DC and AC galvanostatic (constant current) methods for measuring resistivity were explored in that study, and it was recommended to use AC current with frequency of at least 1 kHz for future studies to avoid polarization effects. Lin et al. [40] experimentally investigated the use of carbon black in ECC matrix for reducing the bulk resistivity, thereby enhancing the gauge factor to improve the damage sensing performance of ECC. The aforementioned feasibility studies experimentally demonstrated the piezoresistivity of ECC; however, a more insightful approach is needed for understanding the mechanisms at smaller scales behind the composite piezoresistivity of ECC.

The primary objective of this paper is to investigate analytically, as well as experimentally, the influence of inelastic multiple micro-cracking of ECC under tensile loading on its composite resistivity. For achieving this objective, two ECCs with different material compositions and crack patterns are studied, and their electrical–mechanical properties are compared at macro (composite) and meso (single-crack) scales. Detailed crack width distribution observations of the two materials are used to quantify the crack pattern. An analytical scale-linking model, derived using Kirchhoff Voltage Law of electrical circuits [41], is proposed to predict the composite electrical responses of both ECCs based on the observed single-crack electrical response and crack pattern of ECC. While this analytical model applies to all ECCs and other strain hardening cementitious composites, it is verified experimentally for the two ECCs studied in this paper. Details of these tasks are presented in the rest of the paper.

The inelastic multiple micro-cracking, which is at the heart of the damage tolerance of ECC under tension, is recognized as the crucial link between the material's mechanical and electrical properties in this research, as the material deforms beyond its elastic limit. While past studies on utilizing piezoresistivity of concrete and carbon fiber reinforced concrete for damage *detection* (to prevent damage) have focused on the linear-elastic behavior of these strain softening materials, this research focuses on the inelastic behavior of strain hardening ECC and utilizes it for damage *quantification* into discrete levels in terms of gauge factors at various inelastic tensile strain levels. Significant contributions of this research also include the meso-scale insights into the electrical behavior of a single micro-crack and its analytical scale-linking to the composite scale electrical behavior of ECC. The scale-linking framework developed in this research can be applied in the future for studying other properties of ECC influenced by the crack patterns, such as self-healing and transport properties. In addition, a systematic statistical approach for quantifying crack patterns in ECC is developed in this study. Overall, this research is an important step toward utilizing damage tolerant strain hardening cementitious materials, such as ECC, as self-sensing resilient structural materials.

2. Experimental investigation

2.1. Materials and mix proportions

The electrical–mechanical behaviors of two ECCs, named M45-ECC and HFA-ECC, are investigated in this study. The development of M45-ECC was first reported by Wang and Li [42]. HFA-ECC, where HFA stands for High Fly Ash content, contains higher weight of fly ash per unit composite volume as compared to M45-ECC and was first reported in the literature by Yang et al. [43]. The mix proportions of these ECCs are given in Table 1. The REC-15 PVA fiber used in both ECCs has a diameter of 39 μm, length of 12 mm, and specific gravity of 1.3. The nominal strength and elongation at break of this fiber are 1600 MPa and 7%, respectively. As a polymeric material, PVA fibers are non-conducting.

Both ECCs use cement (with water) as primary binder, while fly ash is used as a secondary binder reacting with the by-products of primary hydration. The fly ash to cement weight ratio in HFA-ECC is 2.8 compared to 1.2 in M45-ECC. The water/cementitious material (cement + fly ash) weight ratio (w/cm) in both ECCs is 0.26. Unreacted fly ash particles act as fillers in ECC supplementing the primary aggregate, which is fine silica sand with mean diameter of 110 μm. Unlike concrete, ECC does not contain coarse aggregate for enhancing fiber dispersion and limiting the matrix fracture toughness, which are desirable for achieving tensile ductility. Further details about the constituents and their micromechanics design basis can be found in literature on ECC design [7,42,43].

Table 1
Mix proportions of ECCs.

Constituent/average property	Particle size range in μm (D_{50} in brackets)	Specific gravity	Weight per unit volume, kg/m^3	
			M45-ECC	HFA-ECC
Cement (Type I)	5–50 (15)	3.15	578	324
Fly ash (Class F)	5–50 (20)	2.40	693	906
Silica sand	60–250 (110)	2.60	455	453
Tap water	–	1	330	324
HRWRA	–	1.20	2.7	2.1
REC15 PVA fiber	–	1.30	26	26
Expected density (d_e)			2085	2035
Avg. specimen density (d_{avg})			1831	1701
d_{avg}/d_e (no units)			0.88	0.84