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Advanced engineered cementitious composites with combined self-sensing and self-healing functionalities

Hocine Siad [a,*], Mohamed Lachemi [a], Mustafa Sahmaran [b], Habib A. Mesbah [c], Khandakar Anwar Hossain [a]

[a] Department of Civil Engineering, Ryerson University, Toronto, ON, Canada
[b] Department of Civil Engineering, Hacettepe University, Ankara, Turkey
[c] Department of Civil Engineering, IUT of Rennes, Rennes, France

HIGHLIGHTS

- The development of an advanced smart material was studied.
- Mechanical, electrical, self-healing and microstructural investigation were carried.
- The cracking and healing of CF- and CNT-based ECCs were monitored.
- Incorporating CFs or CNTs in ECC mixtures improved mechanical strengths.
- Greater self-sensing and self-healing rates were registered with CNT content.

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ABSTRACT

This study focused on enhancing the self-sensing ability of engineered cementitious composites (ECC) to accurately monitor their cracking behavior and healing performance. The ultimate goal was to develop an advanced smart material that combines self-sensing and self-healing capacities, while preserving the high mechanical and ductility properties of standard ECC. To achieve those features, carbon fibers (CF) and carbon nanotubes (CNT) were added to ECC mixtures in different concentrations. Compressive and flexural strength and mid-span beam deflection capacity testing of sound specimens were performed as part of the mechanical characterization. Recovery rates of flexural properties were assessed on pre-cracked specimens at different healing ages. The combined self-sensing and self-healing capabilities of sound and pre-cracked specimens were evaluated based on electrical resistivity (ER) measurements completed at different moisture states and healing ages. Microstructural analysis was used to investigate outer and inner regions of healed crack lines. Test results showed that mechanical properties, self-healing ability and conductivity of ECC can be improved by incorporating CNFs or CNTs. However, accurate combined self-sensing and self-healing efficiency can only be reached with CNT-based ECCs.

1. Introduction

With so many recent advancements in smart technologies, efforts to develop a new generation of smart materials for the construction industry are on the rise. One potential improvement in this area has been the successful use of high-conductive materials in cementitious composites for multifunctional purposes. Due to their very high conductivity, a variety of carbon-based materials such as carbon fibers (CF) and carbon black (CB) have been tested. Nevertheless, the innovative product that has received the most attention from researchers consists of carbon nanofilament such as carbon nanotubes (CNT) and carbon nanofibers (CNF) used as nano-reinforcement for cement paste [1–3]. In addition to enhancing sensing ability incorporating carbon-based materials into cementitious composites has been shown to improve the mechanical, thermal and durability properties of concrete materials [4–6]. In terms of self-sensing ability, defined as the capability of material to sense its own intrinsic changes without the use of any external devices [7,8], concretes with carbon-based composites have been used for structural vibration sensing [6], shrinkage and fatigue sensing [9], stress and strain sensing [10–12], and damage sensing under dynamic and static loading [13–15]. CFs have been reported to cost less, have greater conductivity and lower strain sensing than carbon nanofilament materials [16]. However, due to the different degrees of carbon material dispersion and diverse damage

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[*] Corresponding author.
E-mail addresses: hcine_siad@yahoo.fr, hsiad@ryerson.ca (H. Siad).

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evaluation methods, there is debate about whether CFs or carbon nanofilament (CNF and CNT) provide greater accuracy in the quantitative estimation of microcracking, especially in the plastic deformation region [16–20].

Engineered cementitious composites (ECCs) are special ultra-ductile fiber-reinforced concretes developed in the past two decades to enhance the fragile behavior of conventional concretes [21]. Using micromechanical models, ECCs have been designed with moderate PVA fiber concentration of around 2% to combine high tensile strengths and ductility and multiple micro-cracking behavior. Formation of multiple microcracks with controlled tight crack widths, one of ECCs most important properties [22], has been achieved through an intrinsic balance within the fiber to matrix interface that limits the initiation of localized microcracks during loading. Although ECCs have generally been described as having narrow crack widths of around 100 μm, Sahmaran et al. (2012, 2013) [23,24] reported that widths of 50 μm and 30 μm can be easily reached, especially for high volume fly ash-based ECCs.

The typical mixture composition of ECC covers controlled volumes and types of cementitious materials, very fine sand, water, superplasticizer, and small, randomly oriented PVA fibers. The ingredient properties and proportions are carefully selected through the use of theoretical design method to reach the appropriate strain-hardening response [21]. Along with their unique mechanical, physical and chemical characteristics, ECCs have high self-healing ability, even under exposure to a number of environmental conditions [23,25]. This interesting property is mainly related to the low water and high binder volumes in ECC compositions, which may result in high quantity of unreacted particles of cement and admixtures that can react after microcracking and in the presence of moisture [26,27]. However, despite these qualities, traditional ECCs made with non-conductive PVA fibers in addition to conventional concrete ingredients (cement, admixture and fine aggregates), act as low piezoresistive material [4,28]. For this reason, some recent studies have concentrated on improving the conductivity of ECCs by incorporating carbon-based materials such as CFs, CB, CNTs and graphene nanoplatelets (GNPs) to achieve higher mechanical and self-sensing ability [4,22,28–31]. Those studies showed that including high electrically-conductive composite in ECC mixtures can result in promising self-sensing material with improved mechanical properties and microcracking behavior. Among the limited studies focused on strain and damage sensing of ECCs, CB was tested under continuous loading with high strain and damage sensing [28]. More recently, Al-Dahawi et al. (2017) [4] studied the electrical resistivity response of conductive materials-based ECCs to repetitive loading and unloading, concluding that the self-sensing of imposed loading/unloading was more effective in the plastic ranges, especially for CF-based ECC. Considering the low sensing to pre-cracking in traditional ECCs without conductive materials, initial pre-cracking – usually estimated on electrical resistivity measurements – can lack precision, which may seriously influence the accuracy of estimated self-healing rates.

To date, there has been no investigation into the combined self-sensing and self-healing efficiency in piezoresistive ECC. Therefore, this study has attempted to develop an advanced ECC composition with combined self-sensing (to pre-cracking and to recovery) and self-healing aptitudes, using different concentrations of CFs or CNTs with conventional ECC compositions. Considering the high technical qualities of non-conductive ECC, the goal is to enhance self-sensing ability without challenging the high mechanical and ductility properties and self-healing ability of traditional ECC. The self-sensing ECC can be used in new generation of structural elements which, through a systematic assessment of their electrical change, can allow an automatic and repeated detection of any irregular deviation in their intrinsic performances. The incorporation of CFs or CNTs is expected to highly improve the conductivity of concrete material and consequently the sensing ability to the opening and closure of microcracks, at their early time of occurrence, thus the damage and self-healing can be timely evaluated without using complicated devices. These unique properties, together with a relative ease of production make ECC attractive to various civil engineering applications, including bridges, tunnels and buildings, as well as in infrastructure repair work. In this study, in addition to mechanical testing, the combined self-sensing/self-healing efficiency was assessed by conducting electrical resistivity (ER) measurements at different moisture states. Using scanning electron microscopy coupled with energy-dispersive X-ray (SEM-EDS), microstructural investigations along the outer and the inner regions of healed crack lines were conducted to determine any presence of CFs or CNTs inside the microcracks, and to inspect any changes in the self-healing products.

2. Experimental program

2.1. Materials

Materials used in the preparation of ECC mixtures included Portland cement (PC) conforming to ASTM C150 Type I cement [32], class-F fly ash (FA), silica sand (SS) with average and maximum aggregate sizes of 150 μm and 400 μm, respectively, and high range water reducing admixture (HRWRA). Physical and chemical properties of PC and FA are shown in Table 1. The fiber used to reinforce the ECC matrix was polyvinyl alcohol (PVA) with a diameter of 39 μm, length of 8 mm, tensile strength of 1600 MPa, and elastic modulus of 40GPa. Micro-sized carbon fibers (CF) and nano-sized carbon nanotubes (CNT), characterized by their high mechanical performance and electrical conductivity, were incorporated into the ECCs. CFs were 7.2 μm and 6 mm in diameter and length, respectively, with an electrical resistivity of 0.00155 O-cm, density of 1.81, carbon content of 95%, tensile strength of 4137 MPa and elastic modulus of 242 GPa. CNTs were between 10 and 30 nm in diameter and 10 and 30 μm in length, with an electrical resistivity of >0.01 ohm-cm, density of 2.1 and carbon content of >90%. SEM micrographs of CF and CNT are shown in Fig. 1.

2.2. Mixture proportions and specimen preparation

PVA fibers occupied 1.5% of the volume of each ECC mixture, while CF and CNT were 1% and 0.5% by volume of the total mixture, and 0.50% and 0.25% by mass of the cementitious materials, respectively. All ECCs were prepared with a constant FA to PC ratio of 1.2 and water to cementitious materials (PC + FA) ratio of 0.27, as summarized in Table 2.

A 25 L planetary-type mixer was used to cast all ECC mixtures. To homogeneously disperse CF and CNT, the mixing methods used for CF and CNT-based ECCs were conforming to procedures recommended by Al-Dahawi et al. [28]. After one day of casting, specimens were left to cure in plastic bags for six days at 95 ± 5% RH and 23 ± 2 °C. Subsequently, they were moved to a laboratory medium for an additional 21 days at a50 ± 5% RH and 23 ± 2 °C. Several 360 × 75 × 50 mm prisms were cast from each mixture to measure flexural strength and corresponding mid-span beam deflections under four-point bending load, and to assess electrical resistivity (ER) change. 50 mm cubic specimens were also cast to measure compressive strength at different curing ages.

Table 1
Chemical and physical characteristics of PC, FA and RGP.

Chemical Composition%	PC	FA
SiO_2	19.5	57
Al_2O_3	5.1	21
Fe_2O_3	2.92	4.2
MgO	2.5	1.8
CaO	61.8	9.8
Na_2O	0.30	2.2
K_2O	1.11	1.5
Loss on Ignition	2.5	1.3
$SiO_2 + Al_2O_3 + Fe_2O_3$	27.52	82.2
Physical Properties		
Specific Gravity	3.1	2.6
Blaine Fineness (m^2/kg)	408	325