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The performance of stress-sensing smart fiber reinforced composites in moist and sodium chloride environments

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ABSTRACT

The addition of carbon nano-fibers (CNF) to fiber reinforced composites (FRC) based on polyvinyl alcohol fibers can improve the flexural strength of composites. Depending on applied stress, moisture content, and exposure to chloride solutions, the developed CNF composites exhibit specific levels of electrical conductivity. Reported research has demonstrated a strong dependency of electrical response of composite to crack formation in moist and NaCl environments. It was demonstrated that the sensitivity to strain and chloride solution can be enhanced by CNF. The developed technology and smart composite material are scalable for application in nondestructive monitoring of concrete structures that require improved integrity under service loads and stability in harsh environments.

1. Introduction

Concrete is the predominant human-made material used in structural applications. Compared with other construction materials, concrete can resist corrosion and fire, combining high compressive strength with relatively simple construction technology. When correctly designed, mixed, compacted, and cured, concrete has a long service life. However, it is prone to shrinkage and micro-cracking, which lead to progressive deterioration of concrete and reinforcement, often observed due to exposure to freeze–thaw cycles and chlorides. Service life is an important parameter to consider in the design, construction and use of concrete structures. Bridges and buildings are expensive to construct, and when an aging structure fails to function properly, maintenance costs can escalate. Therefore, extending serviceability and safety of structures is a top priority and focus for civil and structural engineers.

While chemical admixtures and fibers are often added to concrete to improve mechanical performance and durability, the use of carbon nano-fibers can add additional innovative capabilities for non-destructive monitoring of stresses, moisture conditions, chloride profiles, and crack propagation in self-sensing concrete structures [1–15]. Self-sensing smart concrete, an important component of smart buildings and infrastructure, can detect potential failures before reaching the critical deterioration threshold. In this way, the proposed approach can significantly reduce the financial burdens for property owners [8].

To effectively improve strength and ductility, incorporation of steel and polymer fibers into concrete mixtures is commonly employed [3,12,15]. Carbon fibers have been used to improve the mechanical and electrical properties of fiber reinforced concrete (FRC) [5,6]. The use of carbon fibers is effective to increase the flexural strength, flexural toughness, and reduce drying shrinkage. For example, polyvinyl alcohol (PVA) fibers can improve the tensile strength and Young's modulus of the composite material by 2.5 and 5.8 times, respectively, compared with the reference [12]. These fibers have been used to improve response under flexural loading, and cementitious materials containing a combination of PVA fibers and carbon nanofibers (CNFs) had gains both in strength and ductility compared with plain samples [13].

Engineered Cementitious Composites (ECC) exhibit a better tensile strength and ductility due to strain hardening [12]. This type of FRC is a piezoresistive material that changes its electrical conductivity in proportion to strain [9,15]. The crack and flaw widening (or closing) affects the conductivity of a cementitious material and so can be used for self-sensing. To create a self-sensing material, the use of electrically conductive materials is not

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required condition; however, in order to improve the sensitivity to strain and damage-sensing capabilities, the use of electrically conductive powders is beneficial [14].

The addition of electrically conductive fibers significantly improves the conductivity of a concrete mixture. Steel and carbon fibers are electrically conductive and were commonly used to improve the conductivity of cementitious materials [6,9,15]. The strain-sensing ability is caused by the change in the electrical resistivity of the concrete under dynamic or static loading, which is attributed to the fiber pull-out caused by increased straining of the material [9,15]. In this way, the use of carbon nanotubes (CNTs) and CNFs in smart FRC that can serve as strain sensors is attractive [10,11,17,18]. Carbon nano-fibers, when dispersed uniformly in a concrete matrix, allow for the bridging of microcracks, which makes an otherwise insulating void electrically conductive [16,17]. It is important to uniformly disperse the fibers within the mix, because clumping can cause adverse effects to concrete strength and affect the conductivity gains; it may also lead to inaccurate or false readings [16–18].

2. Importance of work

Important structures such as bridges and power stations require inspections every two years to ensure that their integrity remains intact. Visual inspection of structures is expensive, subjective and often difficult or unsafe to perform. Remote testing for the chloride ingress in structures, crack formation and propagation, as well as stress monitoring are attractive options which can significantly reduce inspection costs and increase safety. In addition to these benefits, continuous monitoring of infrastructure facilitates a more educated approach for future designs. Currently, the standard maintenance practice is to wait until the damage is visually apparent, and then reactively fix the flaws as they occur. Continuous health monitoring during the construction and service life of the structure allows for a more proactive maintenance program that can target the flawed zones. In addition, future infrastructure can be designed to avoid the discovered deficiencies, saving money and resources and increasing public safety.

3. Experimental methods

Portland cement (Type I from Lafarge) was used in this experiment. Tap water was used to prepare the composites at a water-to-cement ratio of 0.3. Standard silica sand (U.S. Silica Company) was used at a sand-to-cement ratio of 0.5 (Table 1). To improve the workability of the mixture while maintaining a low water to cement ratio, a high-range water-reducing admixture (polycarboxilate type, PCE from Handy Chemicals) was used at a dosage of 0.125% by weight of cement [19]. To improve the flexural response and ductility, PVA fibers (RECS 7 × 6 mm from Kuraray) and carbon nanofibers (PR-24-XT-PS from Pyrograf Products) were added to the mix in the amount of 3% and 0.2% by volume, respectively. The selected fiber loading was based on a preliminary experiment optimizing the mixture proportioning of reference and CNF based compositions. The CNF dosage of 0.2% by volume was selected to provide a balance between the performance and processing technology [18,19]. The nano-fiber content must be kept below the percolation threshold to ensure optimal electrical properties and response, high compressive strength, workability, and to reduce material costs [13,16–18]. The properties of the CNF used in the research are listed in Table 2. The CNF used has an average diameter of 100 nm and has a chemical vapor deposited (CVD) layer of carbon on the fiber surface over a graphitic tubular core (catalytic layer) as revealed by Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM), Fig. 1 [20].

Table 1
Mixture proportions of investigated FRC.

Composition	Reference FRC	CNF–FRC
W/C	0.3	0.3
S/C	0.5	0.5
PCE/superplasticizer, %w cement	0.125	0.125
PVA fibers, %vol	3	3
Carbon nanofibers, %vol	0	0.2

Incomplete dispersion of overdose of CNF may have an adverse effect on the composite strength and result in a matrix with inconsistent conductivity. To realize the proposed concept of smart FRC, even distribution of carbon fibers within the cementitious matrix is important. Preliminary tests demonstrated poor dispersion ability of CNF in water using only ultrasonic treatment (Fig. 2). In this work, adequate dispersion of the CNF was achieved using PCE based superplasticizer and ultrasound treatment. The superplasticizer was first mixed for 2 min with water at 2000 rpm using a high-speed mixer (Silverson L5M-A). The CNFs were added to PCE solution and dispersed at 20 kHz using an ultrasound processor (Hielscher UIP1000hd) at 75% of the maximum power (750 W) for 20 min. A sample of dispersed CNF was collected at 5, 10, 15 and 20 min and analyzed using an optical microscope (Olympus BH-2) at 100× magnification. Fig. 3 shows the progress of CNF dispersion process at various times.

Investigated mixes (Table 1) were produced using a standard Hobart mixer and were cast into 160 × 40 × 13 mm molds. These specimens were left to harden in the molds for 24 h at 23 °C and 75% relative humidity. After 24 h, the samples were removed and cured in lime water at 23 °C for 14 days. Prior to testing, these specimens were dried at 90 °C for 24 h.

Different methods for nondestructive crack detection based on conductivity response measurements have been proposed. Common two- and four-probe methods to detect cracking of cementitious materials under tension strain are Electrical Impedance Tomography (EIT) [11] and Electrical Resistance Tomography (ERT) [13]. The four-probe method requires four electrical contacts on a specimen and uses two contacts to apply the electrical current while the other contacts detect the voltage between the points of interest [19]. The two-probe method has only two contacts at the points of interest that pass the current through the matrix which are used to measure the resistance. The four-probe method is more accurate than the two-probe method as the measured resistance does not include the contact resistance [19]. Furthermore, the conductivity investigation can be realized using alternating current (AC) or direct current (DC). The AC impedance investigation is a very reliable technique for nondestructive monitoring of concrete [3]. This technique requires the operation of more complex equipment (i.e., network analyzers). In contrast, monitoring electrical conductivity using DC, even multi-channel, can be easily realized using relatively simple data acquisition equipment [21]. However, the electrical field created during the DC test leads to polarization, resulting in an increase in apparent and measured resistivity with time [4]. It was found that the compressive stress in a concrete specimen greatly reduces the extent of electric polarization in samples [22,23]. Increased compressive stress decreased the length of time over which polarization occurred, and reduced the maximum extent of this effect in both plain samples and samples with electrically conductive fibers [23].

Specimens were prepared for two- and four-probe electrical resistance measurements; however, this report deals only with two-probe DC testing, which was selected due to simple instrumentation and ease of implementation in the field [16,21]. Electrical resistance was directly measured for a particular channel and recorded using a data acquisition unit (HP 34970A from