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Strength, energy absorption capability and self-sensing properties of multifunctional carbon nanotube reinforced mortars

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ABSTRACT

The development of multifunctional self-sensing mortars reinforced with multi wall carbon nanotubes (MWCNTs) is herein carried out. The purpose is twofold: to determine the impact of nano-modification on the strength, the stiffness, and the toughening effect that MWCNTs can provide; and to evaluate the multi-functionality and smartness of cement mortars, reinforced with 0.08, 0.1, 0.3 and 0.5 wt% of cement well-dispersed MWCNTs. The experimental determination of the mechanical properties of 3, 7 and 28 d nanomodified mortars was achieved through three point bending, uniaxial compression, and fracture mechanics experiments. The evaluation of the smartness of the nanoreinforced mortars was achieved by measuring the fractional change in the electrical resistance of specimens, induced by external cyclic compressive loading in the elastic region. The excellent reinforcing capability of MWCNTs is demonstrated by a significant improvement in flexural strength (87%), Young's modulus (92%), flexural toughness (83%), first crack strength (64%) and first crack toughness (65%). Results from piezoresistivity experiments confirm that the nanoreinforced mortars exhibit an increased change in resistivity under cyclic compressive loading, which is indicative of the amplified sensitivity of the material in strain sensing.

1. Introduction

Recent and ongoing technological aspects of structural materials have focused on developing multifunctional high-performance and advanced self-sensing cementitious materials that could effectively be used as construction materials and at the same time, act as sensors to monitor the health of the structures. Mortar and concrete materials are generally considered inherently brittle with low flexural strength, stiffness and energy absorption capability. To increase the life of a structure, delaying the micro and macro cracking and increasing fracture resistance is very important. This can be achieved by using fibers at the nano scale: as all cracks are formed at the nano scale level, to suppress the initiation and growth of these cracks, the use of carbon nanotubes (CNTs) can enable notable structural concepts. Multiwall carbon nanotubes (MWCNTs) exhibit superior mechanical, thermal and electrical properties. Their Young's modulus can be up to 1 TPa and their fracture strains are in the order of 6% [1]. MWCNTs, with their supreme stiffness, high strength and aspect ratio are excellent reinforcing candidate materials, offering outstanding improvements in the mechanical properties [2–4]. Reinforcement at the nanoscale, in addition to providing fracture resistance, can also beneficially alter the nanostructure of cement based materials [5]. MWCNTs are also highly conductive materials and when subjected to various deformations they have the ability to record electromechanical changes, expressing a linear and reversible piezoresistive response [6,7]. Specifically, it is already known that the carbon nanoscale fibers' piezoresistive characteristics are reversible for strains up to 3.4%. This unique electromechanical response, in combination with outstanding mechanical properties makes them ideal reinforcement for the development of an innovative smart cementitious nanoreinforced aggregate sensor for Structural Health Monitoring (SHM) [8].

Some experiments have been conducted on the strength and the stiffness of mortar nanocomposites reinforced with MWCNTs. However, the data available in the literature appears scattered. Chaipanich et al. [9] added CNTs in a fly-ash cement mortar to produce CNTs-fly ash composites and measured their compressive strength. CNTs were initially dispersed using ultrasonic energy with some part of the mix water for 10 min and then were added to fly ash cement mixes at amounts of 0.5 and 1.0 wt% of cement.

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The experimental results show that the compressive strength of 28 d mortar mixes was found to increase with increasing CNT content and the highest strength obtained was found when CNTs of 1.0 wt% were used (9.6%). Morsy et al. [10] produced cement mortars reinforced with nano metakaolin (NMK) at an amount of 6.0 wt% and CNTs at amounts of 0.005, 0.02, 0.05 and 0.1 wt%. The addition of CNTs (up to 0.02 wt%) to NMK cement mortar improves the compressive strength of the composites. The improvement was 11% higher than blended mortar containing 6.0 wt% NMK but the addition of CNTs at amount of 0.1 wt% leads to decreases the compressive strength. Hamzaoui et al. [11] used pre-prepared aqueous solutions which contain CNTs at different amounts of 0.01, 0.02, 0.03, 0.04, 0.05 and 0.06 wt% of cement. The authors concluded that the mortar nanocomposites reinforced with CNTs at an amount of 0.01 wt% exhibit a 29% and 21% increase in flexural strength and compressive strength, respectively. Yazdani et al. [12] measured the flexural and compressive strength of mortar nanocomposites containing MWCNTs at an amount of 0.1 wt% of cement. The experimental results showed a 22% increase in flexural strength and no increase in compressive strength of the mortar with the addition of MWCNTs. Recently, Stynoski et al. [13] used dispersed plain carbon nanotubes (pCNTs) and silica-functionalized carbon nanotubes (sCNTs) at an amount of 0.125 wt% in cement mortars and reported an increase in flexural strength of 5–10% and in Young's modulus of 15–20% for both types of CNTs. More recently, Manzur et al. [14] followed a parametric experimental investigation to determine an optimum mix dosage of CNTs for cement mortar. The amount of superplasticizer (0.008 wt%) was mixed with water and sonicated for few minutes. Then the CNTs were added to the aqueous solution and sonicated for 40 min in sequences. An optimum dosage rate of 0.1 wt% CNTs was then determined in order to produce the highest flexural strength in CNT reinforced nanocomposites. For this dosage rate, an increase in 28 d nanocomposites' flexural strength of about 19.5% as compared to control sample has been found.

In the above mentioned studies the effect of MWCNTs on the compressive and flexural strength and stiffness of nanoreinforced mortars was mainly investigated. To the authors' knowledge only one reference [15] exists in the literature on the experimental determination of the energy absorption capability, expressed by the flexural toughness of cementitious materials reinforced with carbon nanofibers (CNFs). Konsta-Gdoutos et al. [15] studied the flexural toughness of various Portland cement pastes containing CNFs as well polyvinyl alcohol microfibers (PVAs). The authors observed that CNFs provided an improvement in flexural toughness of about 40% at 28 d cement paste nanocomposites. An even more impressive increase in the toughness was observed in the 28 d hybrid cement paste specimens with the combination of CNFs and PVAs.

Besides the obvious advantages in improving almost all mechanical properties, the addition of MWCNTs in the cementitious matrix can result in tailoring the electrical properties of the nanocomposites. Limited studies have been carried out on the piezoresistive behavior and sensing ability of cementitious nanocomposites embedded with MWCNTs. Li et al. [16] conducted experiments using treated with acids (SPCNT) and untreated CNTs (PCNT) as reinforcement and concluded that both types reduce the electrical resistance. Piezoresistivity is the effect of change in the electrical resistivity induced by deformation of materials [17]. Luo et al. [18] used cured MWCNT reinforced cement-based composites with 0.1 and 0.5 wt% MWCNTs and measured the electrical resistance under cyclic loading. The results revealed good piezoresistivity and strain sensitivity for both samples, though the trendline of fractional change in resistivity ($\Delta\rho$) presented better stability for amounts of 0.5 wt%. Han et al. [19] examined cement nanocomposites at amounts of 0.05, 0.1 and 1.0 wt% of cement MWCNTs. Experimental results indicated that the piezoresistive sensitivity of the composites first increased and then decreased with the increase of the MWCNT content concluding that the composite reinforced with 0.1 wt% of MWCNTs presents better sensing property. Azhari and Banthia [20] investigated the piezoresistivity response of cement-based composites by using two types of cement-based sensors, one with carbon fibers (CFs) alone and the other carrying a hybrid of both CFs and CNTs. The authors measured the electrical resistance of the composites by using the AC measurement method under cyclic or monotonic compressive loading up to failure. They concluded that the hybrid sensors, containing a combination of CFs and CNTs, provide better quality signal, improved reliability and increased sensitivity over sensors carrying CFs alone. Recently, Kim et al. [21] examined the effect of water to binder ratio on piezoresistivity by fabricating and testing mortar nanocomposites with 0.4, 0.5 and 0.6 water/binder ratios, reinforced with CNTs at amounts of 0.1, 0.3 and 0.5 wt% of cement. The experimental results indicated that the stability of piezoresistivity under cyclic loading and their time-based sensitivity can be improved by decreasing the water/binder ratio of the cement composites. In addition, the variation of piezoresistivity induced by the moisture content can be decreased by low water/binder ratios. More recently, research on the piezoresistive properties and the sensing ability of the nanoreinforced cementitious composites by Konsta-Gdoutos et al. [22] deals with the study of the electrical resistivity and self-sensing properties of cement paste nanocomposites reinforced with well dispersed CNTs and CNFs. The addition of CNTs and CNFs at different loadings was proven to induce a decrease in the electrical resistance, with the cement paste nanocomposites containing 0.1 wt% CNTs yielding better electrical properties. Furthermore, conductivity measurements under cyclic compressive loading provided an insight in the piezoresistive properties of the selected nanocomposites. Results confirm that the nanocomposites, reinforced with 0.1 wt% CNTs and CNFs, exhibited an increased change in resistivity, which is indicative of the amplified sensitivity of the material in strain sensing.

Given the limited and scattered data available in the literature on the effect of MWCNTs in both the mechanical and electrical properties of MWCNT reinforced Portland cement mortars, a thorough experimental approach was followed in this study: (i) to determine the impact of well dispersed MWCNT nanomodification on the strength and stiffness, (ii) to determine in detail the flexural first cracking response, hence the energy absorption capacity; (iii) and to evaluate the multi-functionality and smartness of cement mortars, reinforced with highly dispersed MWCNTs. The experimental determination of the mechanical parameters of the nanomodified cement mortars took place through: three point bending experiments on $4 \times 4 \times 16$ cm unnotched prismatic specimens; uniaxial compression on the half prisms of the flexural test specimens ($4 \times 4 \times 8$ cm); and fracture mechanics tests on notched $2 \times 2 \times 8$ cm specimens. The evaluation of the smartness of nanoreinforced mortars, hence the piezoresistive sensitivity, was achieved by measuring the changes in the electrical resistance of $2 \times 2 \times 8$ cm specimens induced by external cyclic compressive loading in the elastic region. For this experimental procedure OPC mortars with w:c ratio of 0.485 and s:c ratio of 2.75 and well-dispersed MWCNTs at amounts of 0.08, 0.1, 0.3 and 0.5 wt% MWCNTs were fabricated. The efficiency of nano-reinforcing ability of MWCNTs and their strong interfacial adhesion with the mortar matrix resulted in an increase of the nanoreinforced mortars' flexural strength of about 100%. Moreover, the Young's modulus and energy absorption capacity of the MWCNT reinforced mortars is 1.9 and 1.7 times higher than that of the plain mortars. Except for the principal mechanical characteristics, to the authors' knowledge, this work is the first to study the