ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 18 (2018) 371–384

Available online at www.sciencedirect.com

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journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Electrical and piezoresistive sensing capacities of cement paste with multi-walled carbon nanotubes

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ARTICLE INFO

Article history:
Received 31 May 2017
Accepted 15 September 2017
Available online

Keywords:
Cement-based composites
Multi-walled carbon nanotubes
Electrical resistivity
Gauge factor
Piezoresistive sensor

ABSTRACT

This study examined the feasibility of using multi-walled carbon nanotubes (MWCNTs) in cement paste for piezoresistive sensors. Two types of MWCNTs with different carbon content (>90% and >99%) were incorporated into cement paste at 1% by weight of binder (1 wt%). Plain cement paste and cement composites including 1 wt% graphite nanofiber (GNF) and graphene (G) were also considered for comparisons of the electrical conductivity. The test results indicate that the MWCNTs more effectively improved the conductivity of the cement paste than GNF and G. In addition, composites with MWCNTs with lower flowability had less resistivity than those with higher flowability. The size effect in electrical resistivity was observed in the cement pastes with and without the carbon-based nanomaterials, but it was mitigated by incorporating MWCNTs in the cement paste. The stresses and strains under cyclic compression and monotonic tension were well simulated by the measured fraction change in the resistivity of the composites with 1 wt% MWCNTs. The gauge factor (GF) for the composites with 1 wt% MWCNTs was higher than that of commercially available strain gauges, and it was affected by the loading condition: a higher GF obtained under compression than under tension.

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1. Introduction

For several decades, concrete has been considered as one of the most widely used construction materials worldwide due to its advantages such as excellent strength, durability, and economical benefits. However, the structural integrity of old reinforced concrete structures is able to be reduced because concrete properties change continuously with age, loading condition, and environment. Structural health monitoring (SHM) has thus attracted much attention from researchers [1–3] because it allows to monitor and evaluate the structural

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http://dx.doi.org/10.1016/j.acme.2017.09.007
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integrity of large architectural and civil structures and provides real-time data. Using an SHM system, engineers thus can effectively determine the repair and strengthening needs of existing structures.

In general, conventional SHM systems use embedded or attached strain gauge sensors [4,5]. However, due to several drawbacks of such sensors, i.e., uncertainties in bond properties between the attached sensor and the structural surface and prediction of some zones where structural drawbacks may form (since they are discontinuous sensors), several researchers [2,6] have been developing a new type of self-sensing material called *cement-based sensors* including carbon-based nanomaterials and fibers. These new sensors provide several advantages over conventional sensors, including lower cost, higher durability, larger sensing volume, and not degrading structure's mechanical properties [7]. Cement-based sensors can monitor stress/strain variations in concrete structures by measuring changes in electrical resistivity, which is based on the concept of piezoresistivity. The electrical resistivity of cement-based composites with conductive materials changes with external pressure, causing deformation, and thus, stress/strain changes in structures can be evaluated using variations in resistivity.

Banthia et al. [6] investigated the electrical properties of cement composites with carbon and steel microfibers. In their study [6], composites with carbon fibers exhibited much higher conductivity than those with steel fibers due to their better fiber network and greater inter-fiber continuity. This is attributed to the fact that the carbon fibers were much finer than the steel fibers, which means that the total number of carbon fibers was greater than that of steel fibers at any given fiber volume fractions. In contrast, Wen and Chung [7] reported that composites with steel fibers exhibited higher conductivity than those with carbon fibers because the percolation threshold for the steel fibers was lower (between 0.27 and 0.36 vol%) than that for the carbon fibers (between 0.5 and 1.0 vol%) [8,9]. Based on these results, it is noted that the conductivity of cement-based composites is more strongly influenced by fiber connectivity than fiber type (i.e., carbon fiber or steel fiber). Azhari and Banthia [2] examined the feasibility of using high volume fractions (15 vol%) of carbon fibers and hybrid systems (carbon fibers + nanotubes) in cement paste to measure stress/strain under cyclic compression. The cyclic compressive load and strain were successfully stimulated with the electrical property of the composites, i.e., a fractional change in resistivity (FCR), and the hybrid systems exhibited better signal, reliability, and sensitivity than the paste with single carbon fibers. Le et al. [1] estimated the effectiveness of using 2D graphene nanoplatelets in cement paste for SHM. Their experimental results [1] provided the important information that the percolation threshold is 2.4 vol %, which is equal to 10% by cement mass as a lower bound. Yu and Kwon [10] investigated the self-sensing capacity of carbon nanotube (CNT) based cement composites for traffic flow detection. In their study [10], the acid treatment provided much better piezoresistive response of the composites compared to the surfactant wrapping method, and the addition of 0.1 wt% CNTs was effective to monitor the cyclic compressive behaviors. Various electrical properties of cement-based paste, mortar, and concrete containing CNTs were also examined by D'Alessandro et al. [11]. The percolation threshold value of cement composites was determined to be approximately 1 wt% of CNTs, which was nearly 2 times higher than the percolation thresholds, between 0.3 and 0.6 wt% of CNTs, suggested by Kim et al. [12]. This discrepancy might be caused by the different mixture proportions and fluidities of the cement composites used. Konsta-Gdoutos and Aza [13] even reported that the cyclic compressive stress of cement composites could be simulated by measuring change in resistivity as the amounts of CNT and carbon nanofiber were higher than 0.1 wt%. In addition, Asadi et al. [14–16] have recently reported that the distribution and volume content of CNT are key parameters for improving the mechanical properties of functionally graded CNT reinforced composite elements.

Likewise, many studies have been performed to develop cement-based sensors that include conductive materials. However, to the best of the author's knowledge, only few studies [13,17] have only examined comparative electrical properties and piezoresistive sensing capacities of cement composites with various carbon nanomaterials, such as MWCNT, graphene (G), carbon nanofiber, graphite nanofiber (GNF), carbon black, etc., under compression. In particular, Konsta-Gdoutos and Aza [13] and Yoo et al. [17] consistently insisted that the addition of MWCNTs is more effective in improving electrical properties of cement composites than other nanomaterials, i.e., G and GNF. Furthermore, there is no published study yet evaluating the comparative piezoresistive sensing behaviors of cement composites with MWCNTs under both compression and tension and the effect of MWCNT's purity on the piezoresistive sensing capacity.

Therefore, in this study, we investigated the feasibility of using MWCNTs in cement paste to detect both compressive and tensile behaviors. In addition, the effects of different nanomaterials on the electrical resistivity of the paste were evaluated. Our detailed objectives were to examine (i) the effect of nanomaterial type on electrical resistivity in cement pastes with various ages and sizes, and (ii) the piezoresistive sensing capacities of cement composites containing MWCNTs with two different purities based on the relationship between the FCR and stress/strain under compression and tension.

2. Test program

2.1. *Materials, mix proportions, mixing sequence, and specimen preparation*

In this study, Type 1 Portland cement and silica fume (SF) were used as cementitious materials; their physical properties and chemical composites are summarized in Table 1. A water-to-binder ratio of 0.35 was used. The ratios of SF to cement and nanomaterials to binder were 0.3 and 0.1, respectively. In other words, 1% (by weight of cementitious materials) of nanomaterials was applied for all test specimens. It is well known that fiber dispersion is greatly influenced by the flowability of the cement paste or mortar [18]. Thus, similar flow values, 150 ± 10 mm, were adopted for all test series as per ASTM C1437 [19]. The flowability was controlled using a superplasticizer (SP). The detailed mix proportions are given in Table 2.

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