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Transverse strain sensitivity of steel fiber reinforced cement composites tested by compression and split tensile tests

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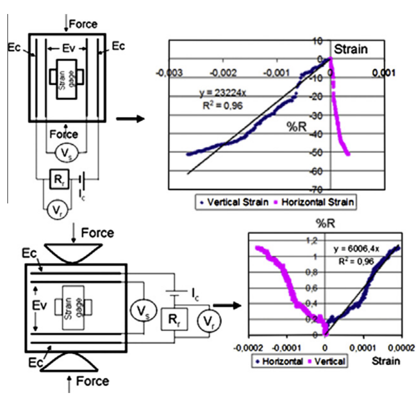
HIGHLIGHTS

- Split tensile, compression tests applied with strain perpendicular to current.
- Resistance of cement composite, strain perpendicular to current was investigated.
- Strong linear relationship between perpendicular strain and %*R* were determined.
- Cross gage factors were higher than gage factors: void deformation mechanisms.
- Results used for decomposing effects of perpendicular strains in cement sensors.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of cement based composites as strain sensors have been studied by different researchers. The effect of "cross talk" for which the strain is perpendicular to electric current in the cement based composite, is an important issue for using the cement based material as a strain sensor. In this study, steel fiber reinforced cement matrix composite was tested with two different compression tests, at which compressive strain and electric current were parallel or perpendicular. The "cross talk compression test" at which electric current and compressive strain was perpendicular has been conducted for the first time in this study. Also, split tensile tests at which tensile strain and electric current were parallel or perpendicular were applied for the first time in this study. The cross gage factors were higher than the gage factors which were explained by mechanisms on variations of electron transfer cross sections. Strong linear relationships between the perpendicular compressive strain–electrical resistance change (%*R*) and perpendicular tensile strain–electrical resistance change (%*R*) were obtained. These strong linear relationships can be used to decompose the effects of "cross talk" in cement based sensor applications.

1. Introduction

Earthquakes, material degradations and other environmental factors decrease the performance of the structures. In USA, 30% of the bridges were found to be structurally not reliable while concrete infrastructures have materials deteriorations [1]. Metal foil strain gages used for structural health monitoring can get point-wise measurement, has low durability, short life time and lower sensitivity than cement based composites [2]. This study contributes to the development of smart cement based materials which can sense strain.

The electrical resistance of cement composite decreases by carbon fiber inclusion and application of load affects electrical resistance [3–5]. There is a relationship between the strain and electrical resistance [6,7]. In this study, the "cross talk" phenome-

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non in which strain and electrical resistance were perpendicular, was investigated.

Two and four electrode methods have been used to monitor the electrical resistance of the cement matrix materials. Current supply and voltage measurements were achieved by two electrodes in two electrode method while they were achieved by different electrode pairs in four electrode method. Sample cross section and distance between electrodes affect the measurements in two electrode method while these were not affected in four electrode method [8,9]. In this study, four electrode method was used in compression and split tensile tests.

In testing cement based composites, perimetral and embedded electrode configurations were applied. In embedded electrode configuration, a conductive plate or mesh was inserted in the material while in perimetral electrode configuration, a conductive wire or paint was attached to the perimeter [1,10–13]. In this study, copper wire mesh was inserted in the material to be used as electrode.

Self sensing cement based materials have been studied in the literature. Damage affects electrical resistance of cement based composites [14]. Nickel particle inclusion in cement matrix composites was applied for vehicle detection sensor applications [15]. Tunneling effect theory and Ohm's law were used to investigate the nonlinear current–voltage behavior of carbon fiber reinforced cement composites [16]. Carbon nanotube reinforced cement based composites were investigated for piezo-electric properties [17]. 0–3 barium titanate-portland cement composite was studied for dielectric, ferroelectric and piezoelectric properties [18]. Compression test and bending test was applied to investigate the strain sensing of carbon fiber reinforced geopolymer concrete [19]. Cement matrix 2–2 piezoelectric composite was investigated for effect of low frequency mechanical. The piezoelectric coefficients and frequency was linearly related while magnitude of the applied load did not affect piezoelectric coefficients [20]. Short conductive fiber-reinforced composites were studied for electrical impedance spectra while numerical simulations were compared with experimental results [21]. DC conductivity and impedance spectroscopy measurements were used to determine the intrinsic conductivities of short conductive fibers in cement matrix composites. Conductivity versus aspect ratio relation can be used to determine the fiber aspect ratio in randomly distributed fiber composites [22]. DC and AC electrical properties were correlated with mechanical properties using direct notched tension test. The effects of crack bridging and fiber volume fraction on electrical properties were reported [23]. The effects of debonding and pullout of single steel fiber from cement matrix on electrical impedance were investigated while cracking was reported to influence the electrical impedance [24]. Microstructural property-impedance spectra relations were reported for fiber aspect ratio, fiber volume fraction, fiber shape and orientation [25].

The fiber dispersion issues of orientation, segregation and clumping in fresh cement matrix composites was related to AC impedance spectra [26]. The electrical conductivities of the transition zone and matrix pastes were found to be different while the difference was at most when hydration was between 0.5 and 0.8 [27]. The position of moisture front in concrete was predicted using the properties of saturated and unsaturated concrete while a finite element model which solved the coupled problem of propagation of moisture and electrical resistance was developed [28]. A model for the overlay current in conductive concrete snow melting system was derived and calibrated with experimental results [29].

In this study, the "cross talk" phenomenon in which the strain and electrical current were perpendicular was investigated for steel fiber reinforced cement based composite. Compression tests for which the strain was parallel and perpendicular to electrical current in the sample were conducted. Also, split tensile tests in which tensile strain was parallel and perpendicular to current were applied. The relationships between the perpendicular strains and electrical resistance change were investigated. The gage factors (measure of strain sensitivity) for compression and split tensile tests were reported for the tests at which strain and electrical current were parallel. The cross gage factors were determined for the tests at which strain and electrical current were perpendicular. It was found that cross gage factors were higher than corresponding test's gage factor. The mechanisms leading to higher cross gage factors with respect to gage factors were presented.

The compression test and split tensile test, for which strain and current were perpendicular, were applied for the first time in this study. The relationships between the perpendicular strain and electrical resistance change can be used for decomposing the effects of "cross talk" in cement based sensor applications. The novel test methods and results presented in this work are contributions to smart materials and structures research.

2. Experimental work

A steel fiber reinforced cement matrix composite was designed. By mass, the ratio of sand/cement was 1; silica fume/cement was 10%; water/cement was 0.4; super plasticizer Sika ViscoCrete High Tech 30/cement was 1%. The densities of each material are presented at Table 1.

The steel fiber was coated with brass for corrosion protection and it had a length of 6 mm, diameter of 290 μm. The volume percent of the fiber in the mix is 1%. Twelve samples of 5 cm cubes were prepared.

Pure copper wire mesh which had a mesh opening of 5 mm and wire diameter of 600 μm was used as electrode. The special 5 cm cube molds used in this study were designed and manufactured for this study. On both sides of each mold, there were 2 mm wide, 46 mm long slots to pass the copper wire mesh electrodes through the mold, as seen in Fig. 1a. The copper wire meshes were placed in the mold, than the mix was cast as in Fig. 1b. After 24 h, the samples were demolded and cured in water for 28 days. In order to reach the steady state moisture content, the samples were kept at laboratory environment for 7 days. James Instruments moisture meter which is a nondestructive moisture meter was used to observe the moisture (Fig. 1c).

2.1. Compression test 1: compressive strain and electric current were parallel

Three samples were tested with compression test at which the compressive strain and electric current passing through the sample were in the same direction. Displacement controlled test was conducted at a rate of 0.5 mm/min. Embedded four electrode method was used at the test. The sample was in series with a reference resistance $R_r = 1000\ \Omega$ and the circuit was fed by 15 V DC as seen in Fig. 2a and b. The electric current was given to the sample by using the two outer electrodes (E_c) while the potential difference across the sample V_s was measured using the two inner electrodes (E_v) as in Fig. 2a and b. The potential difference across the reference resistance ($R_r = 1000\ \Omega$) was measured as V_r. The compressive strain was measured by a strain gage. Simultaneous to the test, the voltages V_s and V_r, the load, the stroke, strain gage data were recorded at a rate of 10 Hz (10 data in a second).

2.2. Compression test 2: compressive strain and electric current were perpendicular

Three 5 cm cube samples were tested with compression test at which the compressive strain and electric current were perpendicular. The tests were conducted at a rate of 0.5 mm/min. The test circuit diagram and sample at test were presented in Fig. 3a and b. A 15 V DC current was supplied by using the outer two electrodes of the sample (E_c) while electrical potential difference across the sample V_s was measured using the inner two electrodes (E_v) as seen in Fig. 3a and b. In series with the

Table 1
The densities of the materials used in the mix.

Material	Density (kg/m^3)
Cement	3150
Sand	1528
Silica fume	650
Water	1000
Superplasticizer	1090
Steel fiber	7850