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Structural Health Monitoring Using Piezoresistive Cementitious Composites

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ABSTRACT

The usefulness of fiber reinforced concrete (FRC) in various civil engineering applications is indisputable. Fiber reinforced concrete has so far been successfully used in slabs on grade, shotcrete, architectural panels, precast products, offshore structures, structures in seismic regions, thin and thick repairs, crash barriers, footings and hydraulic structures. Fortunately, carbon fiber reinforced cementitious materials are also piezo-resistive. Piezo-resistivity is a unique material property which allows materials to change its electrical resistance/impedance as a result of changes in the applied stress/strain, temperature and chemical environment. FRCs are therefore smart materials that can act as low-cost sensors. This paper will discuss the piezo-resistive properties of FRC and describe the development of cement-based sensors with carbon fibers and carbon nano-tubes. Emphasis will be on strain detection, but advances have also been made in using their potential as chemical sensors capable of detecting pH changes, carbonation profiles, chloride ingress and corrosion detection.

INTRODUCTION

Structural Health Monitoring

Bridges, buildings, turbines, aircrafts and many other engineering structures are susceptible to deficiencies due to different loading and environmental conditions. These structures, when damaged or deteriorated, no longer meet the required standards and need to be repaired and rehabilitated or even rebuilt. These procedures can be very costly and time consuming if damage is not detected shortly after occurrence.

In order to catch any deficiency in the structure's performance before any serious loss of capacity occurs, a technology has recently emerged known as Structural Health Monitoring (SHM). The purpose of SHM is to accurately monitor the behavior of an engineering structure, constantly assessing its performance and providing continuous data on its current conditions.

SHM is a multidisciplinary technology which involves structural and material design, development of sensors and actuators, signal processing, networking and communication, data mining and analysis, diagnostics and prognostics, management strategies, etc. (Inman et al, 2005).

Research Objective

The sensory system is a very important component of SHM systems. Sensing devices constituting the sensory system are responsible for measuring parameters such as time, load, displacement, strain, acceleration, temperature and moisture.

Because of their low cost, durability and compatibility with concrete structures, recently emerged cement-based sensors would be a very efficient replacement for current conventional sensors in SHM of concrete structures. The ultimate purpose is for these sensors to be near surface mounted or embedded in the host structure as part of a wireless SHM system that is capable of detecting cracks and possibly corrosion (Figure 1). Made of structural material, this type of sensor can be regarded almost as an aggregate because it does not alter the properties or appearance of the host structure.

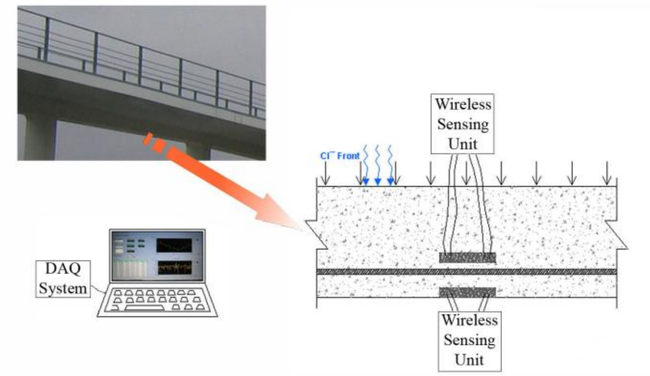


Figure 1. Proposed application of cement-based sensors in SHM of future structures

Cement-based sensors are designed to function based on the principle of piezoresistivity Piezoresistivity is defined as the dependence of electrical resistivity on strain. Materials in which the electrical resistance changes in response to changes in the applied strain are referred to as piezoresistive materials.

In this research, smart cement-based materials are prepared using either carbon fibers alone or in combination with carbon nanotubes.

Nanotechnology and carbon nanotubes

Nanotechnology is the science and technology of developing materials at the atomic and molecular level and generating techniques to measure and use their unique and special electrical, mechanical and chemical properties.

Discovered almost 20 years ago by Iijima [1991], carbon nanotubes (CNT) are one of the most important materials employed in nanotechnology. CNT can be visualized as a modified form of graphite, where a single sheet or several sheets of graphite are seamlessly rolled into a tube structure [Makar et al., 2003]. Single sheets rolled up are referred to as single-walled carbon nanotubes (SWCNT), and multiple sheets rolled up are called multi-walled carbon nanotubes (MWCNT).

Results from a study [Li et al. 2007] indicate that the addition of CNT, treated or untreated, to cement paste leads to a notable decrease in volume electrical resistivity and a distinct enhancement in the pressure-sensitive properties for cement composites.

EXPERIMENTAL PROGRAM

Materials and Specimens

The following materials were used in the preparation of cement-based sensors:

- GU (formerly Type 10) Portland cement with specific gravity of 3.15 (W/C ratio ≈ 0.3 to 0.4).
- Densified silica fume with a specific gravity of 2.27 from Norchem, Inc. used as a densifier as well as a dispersant in the amount of 20% of the cement weight.
- K6371T Carbon Fiber DIALEAD from Mitsubishi Chemical FP America, Inc.; these coal-tar-pitch-based carbon fibers have specifications indicated in Table 1.
- Purified MWCNT, obtained from Cheap Tubes Inc., with specifications listed in Table 2.
- METHOCEL* A15 LV Methylcellulose from Dow Chemical Canada Inc. used to help disperse carbon fibers; in the amount of 0.4% of the cement weight.
- RHODOLINE 1010, which is a water base defoamer obtained from Rhodia Group; in the amount of 0.2% of the cement weight.
- Glenium 3400 NV from Master Builders, which is a polycarboxylate-based Superplasticizer with a specific gravity of 1.1.
- Copper electrodes.

150 mm long samples with 25 mm × 15 mm cross section and 70 mm inner-electrode spacing, as recommended by Banthia et al. [1992], were prepared using different volume fractions (V_f) of carbon fiber (CF) and MWCNT. Specimens were air cured for 24 hours before the moulds were carefully stripped.

Table 1. Properties of carbon fibres

Length (mm)	Diameter (μm)	Specific Gravity	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Volume Resistivity (Ω-m)
6	11	2.12	2620	634	2.3×10^{-6}

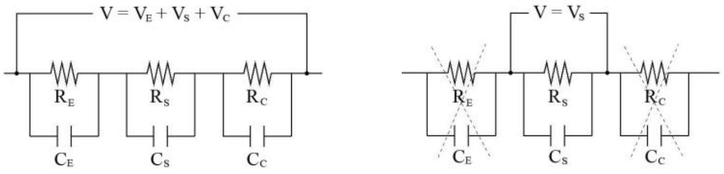
Table 2. Properties of MWCNT

Outer Diameter (nm)	Inside Diameter (nm)	Purity	Length (μm)	Specific Surface Area (m^2/g)	Specific Gravity	Electrical Conductivity (s/cm)
10-20	3-5	> 95 wt%	10-30	233	≈1.5	$> 10^{-2}$

Experimental procedure

Direct current (DC) measurement of electrical resistance has proven to be technically difficult because of the polarization effect, which causes an exponential rise in the measured resistivity [Hou et al., 2005]. Therefore, resistivity measurements in this study are made using alternating current (AC).

There are two commonly used methods for resistance measurements, two-probe and four-probe. While the two-probe technique is much simpler, error sources such as lead inductance, lead resistance and stray capacitance between the two electrodes are incorporated in the measured resistance. In the four-probe method, on the other hand, the effect of lead impedances is reduced because the current and voltage paths are separate. In the two-probe technique, the measured voltage consists of voltages from the electrodes (V_E, which is almost negligible), cement-based sensor (V_S) and contact resistance (V_C). In the four-probe method, however, V_E and V_C are eliminated and the voltage measurement consists of only the sensor voltage, V_S. Figure 2 schematically displays the equivalent circuits for two-probe and four-probe measurement techniques.



(a) **(b)**

Figure 2. Equivalent circuits for (a) two-probe and (b) four-probe techniques

Two-probe resistance measurements increase dramatically as the *L*/*A* (electrode spacing/electrode contact area) ratio increases, whereas the four-probe configuration is unaffected by specimen design. Therefore, the four-probe method was employed for resistivity measurements [Chiarello et al., 2005 and Azhari, 2009].

The electrical resistivity (ρ) of a material with a uniform cross section is measured as its resistance per unit length:

$$\rho = R\frac{A}{\ell} \tag{1}$$

where

ρ = electrical resistivity in ohm meters ($\Omega\cdot$m)
R = electrical resistance of a uniform specimen in ohms (Ω)
A = cross-sectional area of the specimen in square meters (m^2)
ℓ = length of the specimen (or length between the measurement electrodes) in meters (m)

Unless noted, Agilent 4263B LCR meter at 100 kHz AC frequency was used for resistance measurements.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of Current Frequency

The current frequency is a crucial element to be considered. Many factors may have a role in the effect of current frequency: internal factors such as fiber content and specimen geometry and external factors such as moisture and temperature. It has been found that if DC or low frequency AC is used, the cement matrix plays a dominant role in the electrical conductivity, but as the AC frequency is increased the interface impedance decreases and thus the electrical conductivity of the composite is strongly governed by the conductive fibers (Reza at al., 2003). In addition, cement-based composites are capacitive in nature and thus, using higher frequencies reduces the reactance part of impedance.

In order to experimentally investigate the effect of current frequency on the cement-based sensors, a frequency sweep between 1 Hz and 1 MHz was completed - using a Solartron 1260 impedance/gain-phase analyzer - for specimens with different fiber contents.

Purely resistive impedance occurs when the phase angle (θ) is zero. Therefore, phase angles at different current frequencies were compared to find the most efficient frequency. The results, plotted in Figure 3, show that phase angle is for the most part negative, which confirms the fact that these cement-based composites are capacitive rather than inductive. For samples with fiber contents in the 0.5%-7% V_f range, phase angle values fluctuate, lowering at 1 Hz and about 10 kHz. Samples with 15% and 20% V_f of carbon fiber, 3% MWCNT specimens and the hybrid samples (15% CF + 3% MWCNT), exhibit much lower phase angle values especially at frequencies of 100 kHz and below. These samples seem to show inductive characteristics at some frequencies (where θ>0).

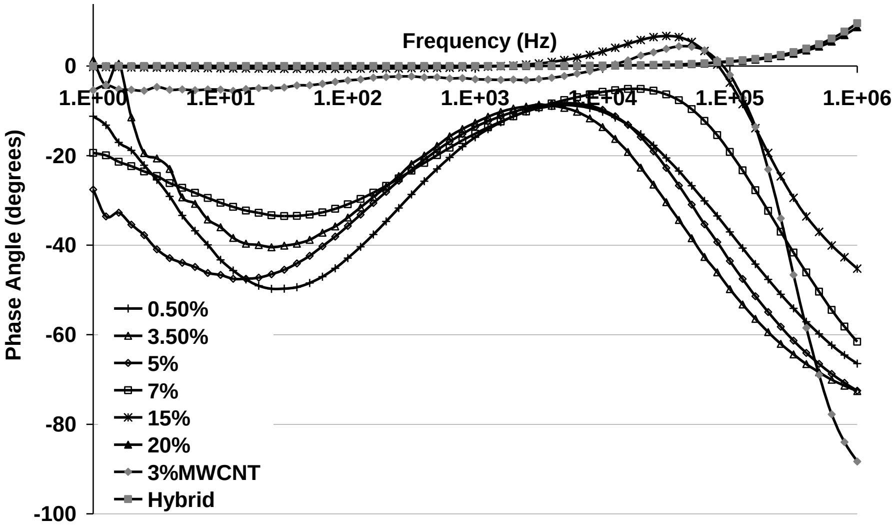


Figure 3. Phase angle at current frequencies between 1Hz and 1MHz

Effect of Fiber Content

The addition of even a small amount of carbon fibers to cement paste significantly reduces the resistivity of the material. Conductivity increases by several orders of magnitude when the volume fraction of carbon fiber reaches a certain critical value, referred to as the percolation threshold [Xie et al.,1996]. Fiber size and shape are important factors in determining the percolation threshold; for example, longer fibers provide higher electrical conductivity at lower fiber volume fractions, whereas the conductivity of specimens containing very short fibers increases very gradually with volume fraction [Chiarello et al., 2005].

Resistivity measurements from samples with various fiber contents, illustrated in Figure 4, indicate that the resistivity values of samples with only 0.5% V_f of carbon fiber dropped considerably (97%) compared with plain samples. The resistivity of the specimens with 0.5% Vf to ~15% V_f remained almost constant, which validates the existence of a percolation threshold. However, the resistivity values could yet be significantly decreased (up to a thousand times smaller than the values at percolation threshold) by adding more fiber to the mix; samples with 20% V_f of fiber exhibited electrical resistivity values as low as 5 Ω·cm, which was expected while these specimens were being prepared, in that there was much less cement paste than fibers and it was very difficult to mix. In order to observe the interaction between fibers and their dispersion, a series of images was obtained using a scanning electron microscope (SEM). SEM images of specimens with three different fiber contents, displayed in Figure 5, show how the increase in fiber content affects the dispersion of the fibers and in turn the electrical properties of the specimens.

The effect of different amounts of MWCNT and SWCNT is also illustrated in Figure 4. It was found that the addition of CNT at 1% or 3% V_f slightly decreases the resistivity of the cement paste. Owing to the extremely high conductivity values reported for CNT, this reduction was expected to be much greater, but the dispersion of CNT was very difficult to achieve even though a sonication process was used. Moreover, even if the dispersion was perfect, the extremely small size of CNT would prevent any contact or network among them in such low volume fractions. This triggered the idea of creating hybrid specimens: 1% MWCNT + 15% CF and 3% MWCNT + 15% CF; these samples yielded a lower electrical resistivity than the 15% CF and 20% CF samples, respectively.

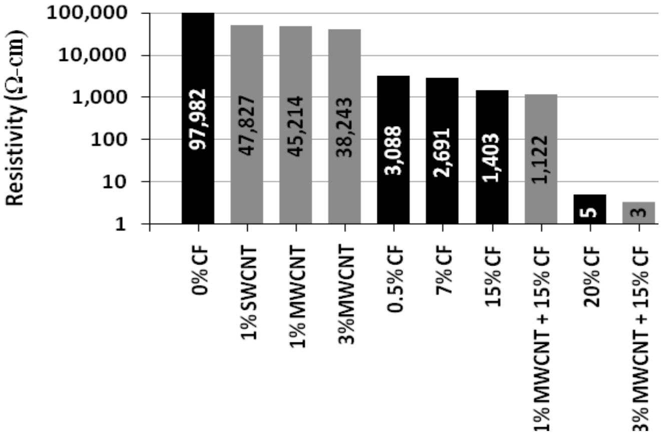
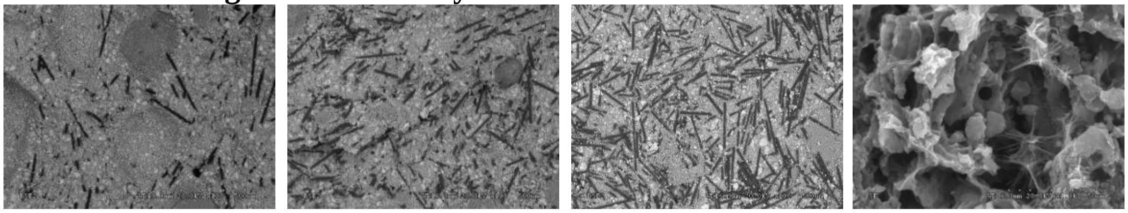


Figure 4. Resistivity at different carbon fiber contents



3.5% CF at x100 magnification

7% CF at x100 magnification

20% CF at x100 magnification

3% MWCNT at x1.0k magnification

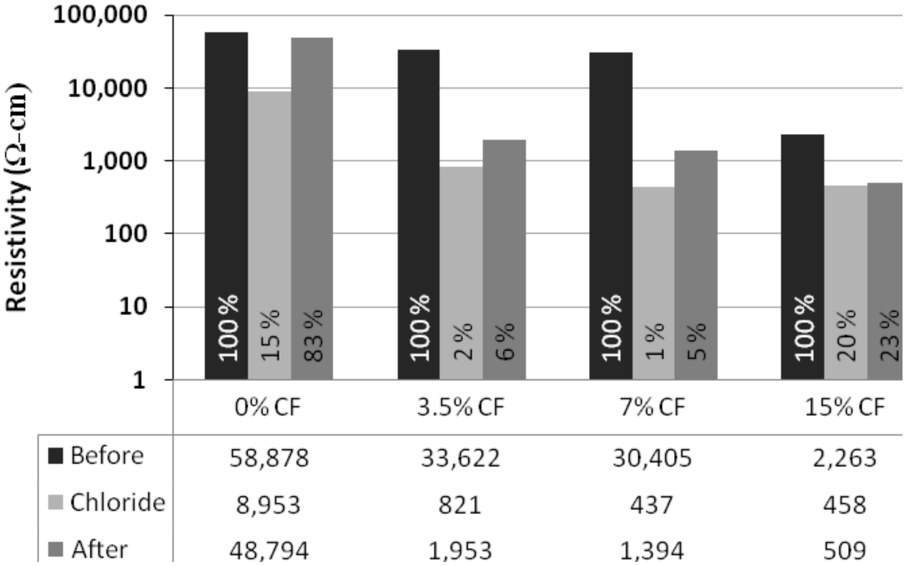
Figure 5. SEM images of various specimens with different carbon fiber content at x100 magnification

Although the “3% MWCNT + 15% CF” hybrid and the 20% CF samples had preferable resistivity values, more suitable for the sensing application, they each had their downfalls; the former was very soft and brittle and the latter was extremely hard to prepare. Therefore samples with 15% CF or 1% MWCNT + 15% CF were selected to be used as sensors.

Effect of Chloride and Moisture

The electrical conductivity of cement-based sensors is through both the conductive fibers and the cementitious matrix. Conductivity of the matrix part of the conduction path is through the pore structure and is referred to as the electrolytic conductivity. The presence of moisture and chloride changes the chemical composition of the pore structure and therefore affects the electrical resistivity of cementitious composites.

To examine the effect of moisture and chloride on cement-based sensors, plain, 3.5% V_f, 7% V_f and 15% V_f samples were kept in chloride solution (100 g of NaCl dissolved in 1 L of water). Resistivity measurements were taken from the specimens at the start of the experiment, after one month of exposure and again after the specimens were completely dried using desiccators. Figure 6 shows the resistivity values of the specimens at these three stages.



	0% CF	3.5% CF	7% CF	15% CF
■ Before	58,878	33,622	30,405	2,263
■ Chloride	8,953	821	437	458
■ After	48,794	1,953	1,394	509

Figure 6. Effect of chloride solution on electrical resistivity of sensors

While one month submersion in chloride solution caused a significant decrease in the electrical resistivities of all the specimens, the plain sample was the only one to recover most of its resistivity. The carbon fiber reinforced samples recovered only a small percentage of their original resistivity after completely drying out. The conduction path in 15% CF samples includes more fiber to fiber contact which makes them less sensitive to the presence of moisture and chloride. It is important to take this effect into consideration if and where the sensors are employed in environments subjected to moisture and chloride. Coating the sensors with moisture resistant material may be a solution to this issue. It was also observed during this experiment that the plain and 3.5% CF specimens experienced some delamination and blemishes, whereas the other two samples remained unaffected, which indicates that carbon fiber reinforced cementitous composites with higher V_f of fiber are more durable when subjected to chloride ingression (see Figure 7).

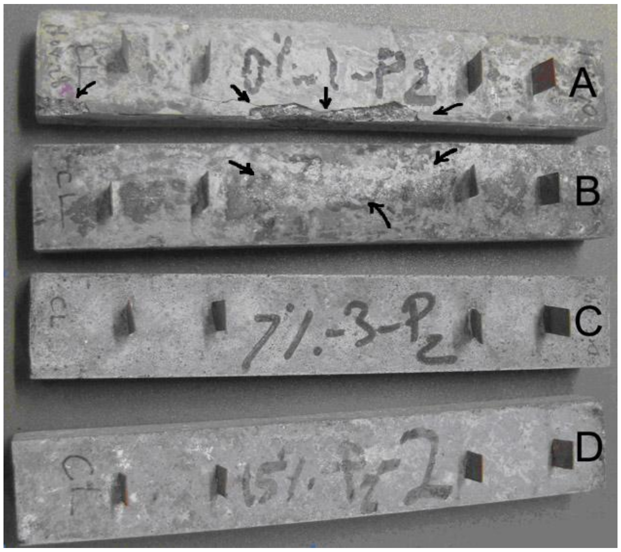


Figure 7. Effect of chloride solution on the appearance of the specimens (A: 0% CF; B: 3.5% CF; C: 7% CF; D: 15% CF)

Piezoresistivity

Changes in the electrical resistivity of cement-based sensors under cyclic compressive loading were monitored to examine their piezoresistive quality.

Cylindrical specimens containing either “15% CF” or “15% CF + 1% MWCNT” were prepared. 10mm strain gauges were attached to the samples to compare the results with measured strain. Specimens were loaded cyclically to 30 kN (approximately 30% of load capacity) while monitoring the Fractional change in resistivity (FCR) and strain.

Figure 8 and Figure 9 display the response of sensors to strain for 15% CF and 15% CF + 1% MWCNT specimens, respectively. Very good correlation between the measured FCR and strain is observed. During each loading cycle, the resistivity values decrease with the increase in compressive load, resulting in negative FCR values, and then increase to the initial value when the unloading branch of the cycle takes place. Closer examination shows that the hybrid sensors (containing both carbon fibers and carbon nanotubes) exhibit better sensitivity and repeatability to strain.

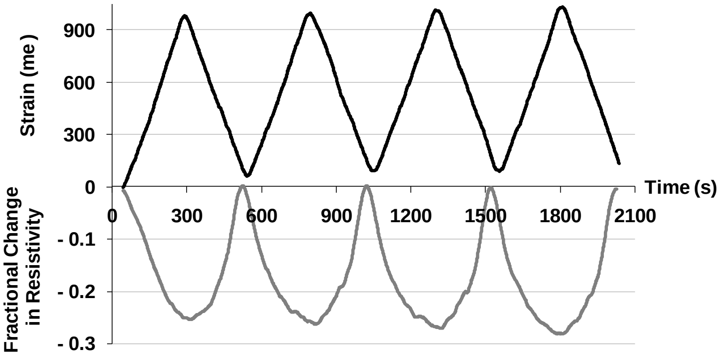


Figure 8. 15% CF sensor under cyclic compressive loading with 30kN amplitude

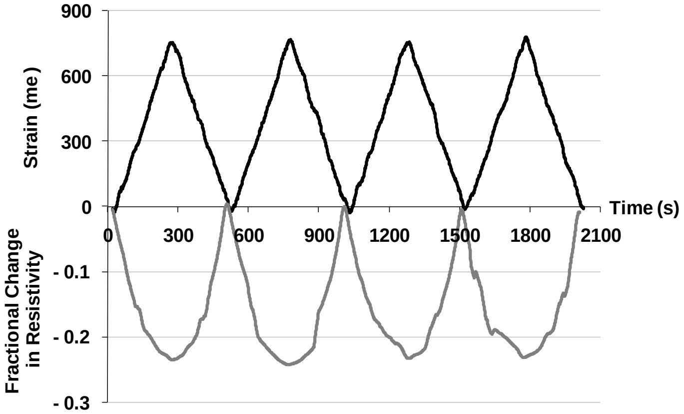


Figure 9. 15% CF +1% MWCNT sensor under cyclic compressive loading with 30kN amplitude

CONCLUSIONS

Cement-based sensors, also described as smart (self-monitoring) structural materials, have recently been developed for use in structural health monitoring (SHM) systems. These sensors are rather inexpensive, durable, very easy to manufacture and install, and best of all they possess mechanical properties similar to concrete, enabling them to perform in the same manner as the host structure. They do not alter the properties or appearance of concrete structures; hence, if integrated into the host structure, they can be regarded almost as an aggregate.

The purpose of this study was to develop piezoresistive cement-based sensors for use in SHM systems by incorporating carbon fibers as well as both single-walled and multi-walled carbon nanotubes in a cement paste matrix.

The effect of fiber content, current frequency and the presence of moisture and chloride on electrical resistivity were investigated. Consequently, the piezoresistive quality of the sensors was confirmed through monitoring their response to cyclic compressive loading. The electrical resistivity of these sensors changed in response to change in strain; decreasing reversibly with the increase in compressive strain.

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