Self-Sensing Cementitious Composites for Smart Structures

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ABSTRACT: Conventional concrete is a dielectric whose properties change based on the constituents of the mixture. Recent advances in the field of nanotechnology have led to the development of advantageous nanoscale fibers, making possible the development of new multifunctional, high performance, advanced sensing cement based nanocomposite materials that could effectively act as sensors to monitor the health of the structures. Depending on their atomic structure, carbon fiber could be semiconductors. When subject to stress/strain, their electrical properties change, expressing a linear and reversible piezoresistive response. In this study the electrical resistivities and self sensing properties of cementitious composites reinforced with well dispersed carbon fibers were investigated. The electrical resistance of carbon fiber cementitious nanocomposites is experimentally determined using the 2-pole method, and compared with resistivity results of cementitious composites without carbon fibers. The piezoresistive properties and the sensing ability of the cement-based composites are also investigated measuring the changes in resistivity under the application of splitting and compressive loading. Results confirm that carbon fiber reinforced cementitious composites exhibit an increased change in resistivity, which is indicative of the amplified sensitivity of the material in strain sensing.

Keywords: cementitious composites, carbon fibers, self-sensing

1 INTRODUCTION

The most commonly used composite material, concrete, has a great importance on civil structures in terms of its mechanical properties such as compressive stress, tensile strength, ductility, toughness etc. Although concrete technology has reached many advantageous mechanical properties, monitoring of structures during service life is still required to be focused on. The infrastructures systems are continuously subjected to damage and deformation so it is inevitable that concrete is deteriorated within its life span. Therefore inspection of damage in economic, trustworthy and sensitive way emerges as very crucial problem in civil infrastructures.

The development of nanotechnology research in carbon based materials provides health monitoring of cement based materials without any adverse effect on mechanical properties. Nano-carbon products possess unique properties for cementitious composites providing multi-functionality including structural self-sensing, electromagnetic shielding and thermal interfacing Chung (2012) Yee and Jenu (2013). By addition of nano-scale carbon products in cement based composites enables self-sensing and piezo-resistivity characteristics that are crucial parameters for monitoring structures.

Besides other health monitoring efforts in civil engineering field, monitoring structures by addition of carbon products instead of using extra sensor is a better solution considering reliability, sensitiveness and maintenance Chung (2000) Han et al. (2014). It is known that carbon based products such as graphite, carbon nanotube, carbon black and carbon fibers have piezo-resistive property in cement based materials. Numerious studies had been undertaken to determine piezo-resistive property of carbon based cementitious composites when subjected to various tests such as compression, tension and flexure Wen and Chung (2006) Chen and Liu (2007) Lin (2011) Konsta-Gdoutos et al. (2013) Han et al. (2014) Park et al (2014) Ranade et al. (2014) Yu (2012).

In this paper, cementitious composites reinforced with carbon fiber in the amount of 1% and 2% by mass of mixture and cured for 7 and 28 days were studied. The primary objective of this study is to investigate effect of carbon fibers in cementitious composites exhibiting strain-sensing ability under compression and splitting tests.

2. EXPERIMENTAL METHODS

In this study, twelve cubical cementitious composites reinforced with carbon fibers (here after known as carbon fiber reinforced cementitious composites or CRF-CC) were experimented. Two different CFR-CC types (in terms of carbon fiber dosage in the amount of 1% and 2% by mass of mixture) were fabricated and tested. Piezo-resistivity and sensing ability of the composites were determined experimentally under splitting and compressive loading tests. Specimens were tested by 2-pole method aiming to observe change in electrical resistance of composites with different curing days (7 and 28) as well as different carbon fiber percentages (1% and 2%) by weight ratio to total content.

2.1. Materials

Carbon fibers used in this study were obtained from DowAksa company and composition of carbon fibers can be seen in Table 1. Length of carbon fiber of 6 mm was selected. The specific gravity of carbon fiber is 1.76 listed in Table 2 as well as other properties of carbon fibers that were used in this research. Ordinary Portland cement and fly ash were preferred as binder and weights of them were shown in Table 3 with other ingredients of composite.

Table 1. Composition/ Information of Carbon Fiber

Ingredient	Composition by weight	Chemical formula	Hazards Identification	TSCA
Carbon fiber	96%	Carbon Fiber	-	Registered

TSCA: Toxic Substances Control Act.

Table 2. Properties of chopped carbon fibers for 6 mm length

Properties	Value	Unit	Test method
Tensile Strength	4200	Mpa	ISO 10618
Tensile Modulus	240	Gpa	ISO 10618
Elongation	1.8	%	ISO 10618
Specific Gravity	1.76	-	ISO 10119

Table 3. Content of Composites by weight (kg/m³)

Cement	Fly ash	w/b ratio	Sand:	Superplasticizer	CF(1%)CF(2%)
1019	1224	0.26	815	8	31-62

CF: Carbon Fiber

2.2. Testing

Cement, fly ash, sand and carbon fibers were added into mixture and subjected mixing for 5 min in mortar mixer, operating at its medium speed. After dry mixing, water was added and all mixture was subjected to wet mixing for 10 minutes. By this method carbon fibers were well dispersed into mixture that is vital for trustworthy of experiments. Also during mixing, superplasticizer was added into mixture to provide better workability and samples were molded to cube specimens with the dimension of (5*5*5) cm. After 1 day twelve samples were demolded and six of them were cured in air at room temperature for 7 days while other six for 28 days.

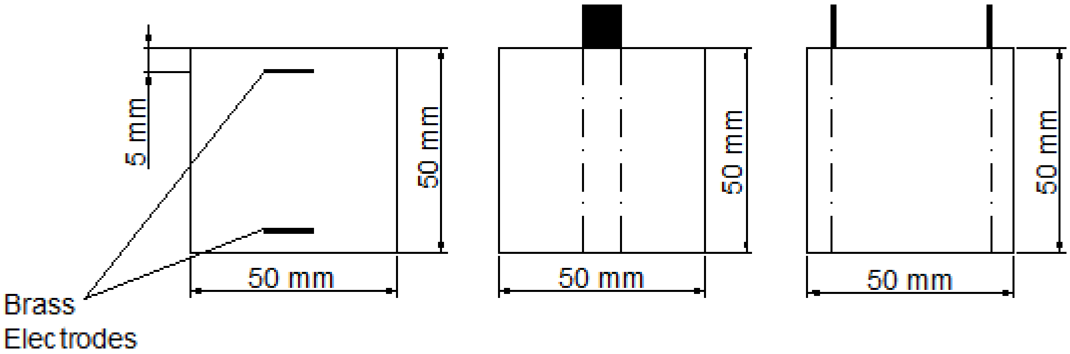
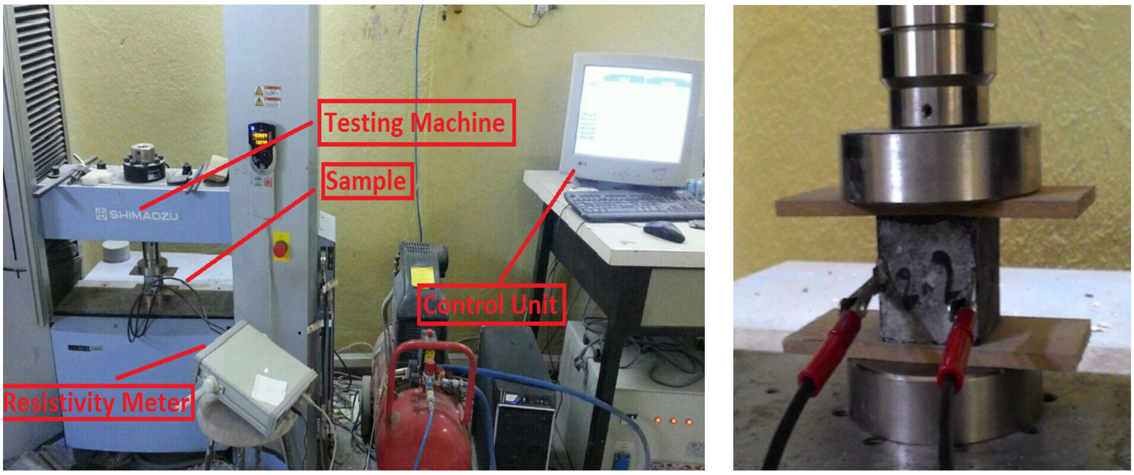


Figure 1. Sketch of fabricated CFRCCs; top view, front view and side view, respectively.

Because of its very high electrical conductivity value, net-shaped brass material was preferred as electrode. In pre-test, samples that have same ingredients and cure methods were tested to decide which brass electrode types yield the most sensitive data for determining the resistivity change. For this purpose, thin brass mesh (1*6) cm and thick brazen mesh (5*6) cm were compared with different distances from edges of the specimens. Aluminum folios that were taped upon the samples by means of conductive gel were also experimented whether it yields more sensitive data or not. In addition, during pre-test stage, compressive loading tests were carried out when two meshes were parallel (where resistivity is expected to increase) and perpendicular (where resistivity is expected to decrease) to load axis in order to observe consistency of both experimental style. Among all pre-test methods, the most sensitive method was determined as two thin meshes (1*6) cm that were put 0.5 cm far from the two edges of specimen, as it is shown in Figure 1. Thick mesh application for CF-RCC was not considered in this paper since it exhibits low sensing ability probably due to experimental restraints under splitting and compression tests. Splitting and compressive loading tests were conducted by using universal testing machine at the 0.3 mm/min deformation speed and resistivity of specimens was obtained by 2 probe concrete resistivity meter. 2-pole AC method was experimented and meshes were put parallel to load axis in both tests. During experiments, both data (resistivity and force-stroke) was collected simultaneously on PC in every 5 second, as illustrated in Figure 2 (a, b).



a) b)

Figure 2 a) Experimental set-up for determining electrical resistivity of carbon fiber reinforced cementitious composites under splitting and compression tests; b) Detailed view of sample.

3. RESULTS AND DISCUSSIONS

3.1. Effect of carbon fiber content on resistivity of CFR-CCs:

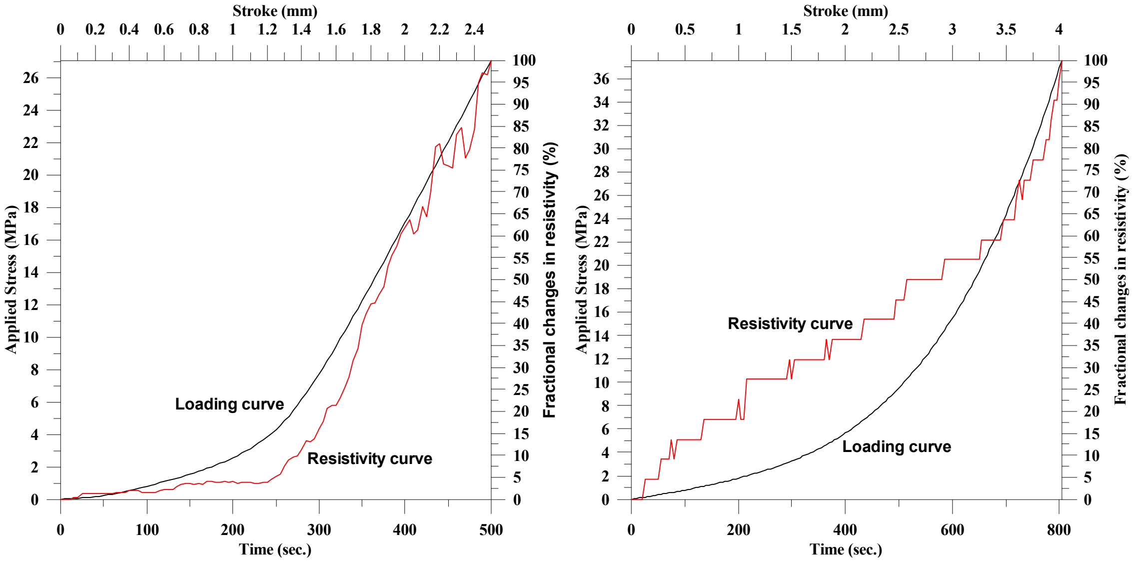
Table 4 demonstrates the effect of carbon materials on the electrical conductivity of composites. As the fiber volume increased from 1% to 2%, conductivity of composites changes resulting in a decrease in the resistivity of all specimens.

Table 4. Initial resistivity values (Ω.m) of cementitious composites with different dosages of carbon fiber

Composites	Resistivity of 7 days (Ω.m)	Resistivity of 28 days (Ω.m)
Plain composite	20.92	90.65
Average of CFR-CC’s (1%)	6.66	27.32
Average of CFR-CC’s (2%)	2.21	2.86

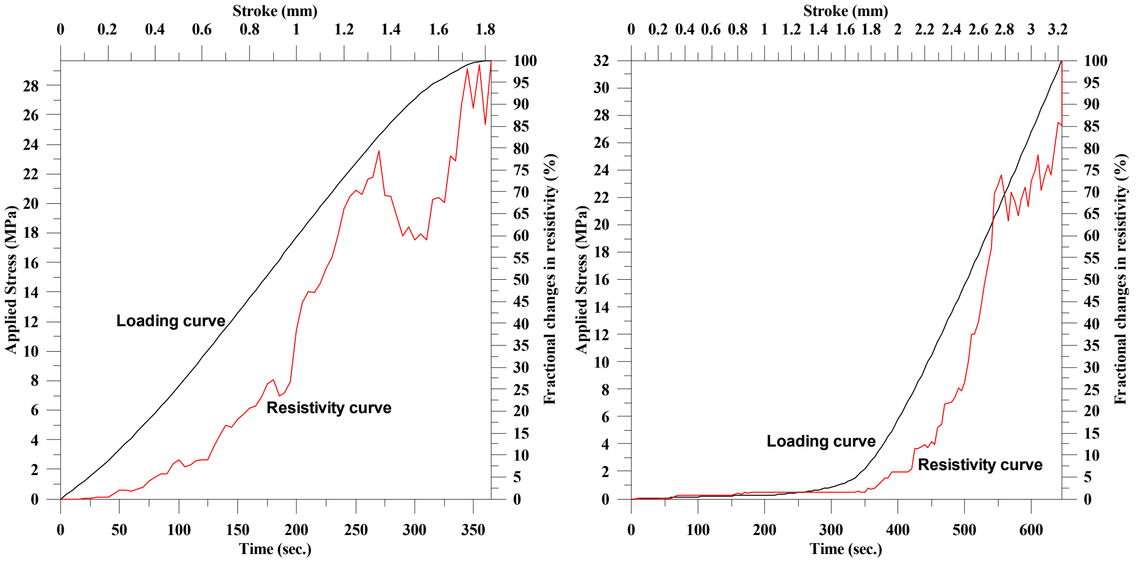
3.2 Piezo-resistivity responses of CFR-CC’s under splitting and uniaxial compression loading:

In the study, experiments were conducted aiming to determine an increased resistivity change of composites owing to separation of carbon fibers from each other under splitting and compression loading. Resistivity responses of all the specimens, when subjected to both tests, are shown in Figures (3, 4, 5, 6). Loading and resistivity curves were also plotted along with the change in the samples’ stroke value and time gap. From the both curves, the change in resistivity of samples exhibited very consistent results with the stress subjecting at specimens. Although all graphs are not presented in the paper, similar observations were obtained for other mixes. Self-sensing behavior of samples (reinforced with 1% and 2% carbon fiber by volume of mixture) was promising under splitting and compression test. All samples were tested in plastic regime and results were adequate to meet self-sensing response.



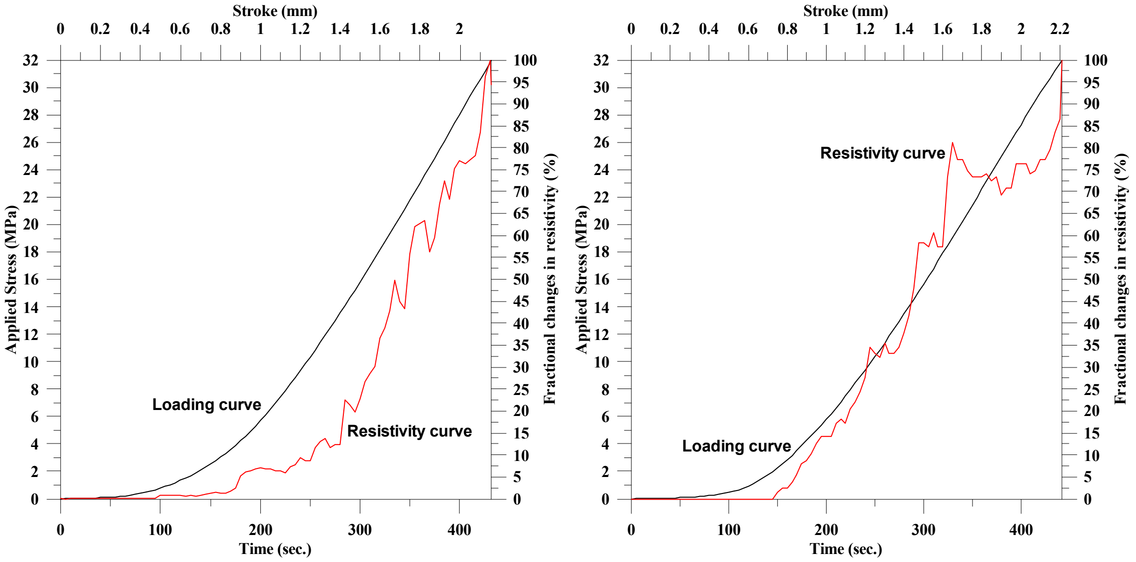
a) b)

Figure 3.a) Self sensing behavior of sample (1% CF) under compression test-7days age, b) Self sensing behavior of sample (1% CF) under splitting test - 7 days age.



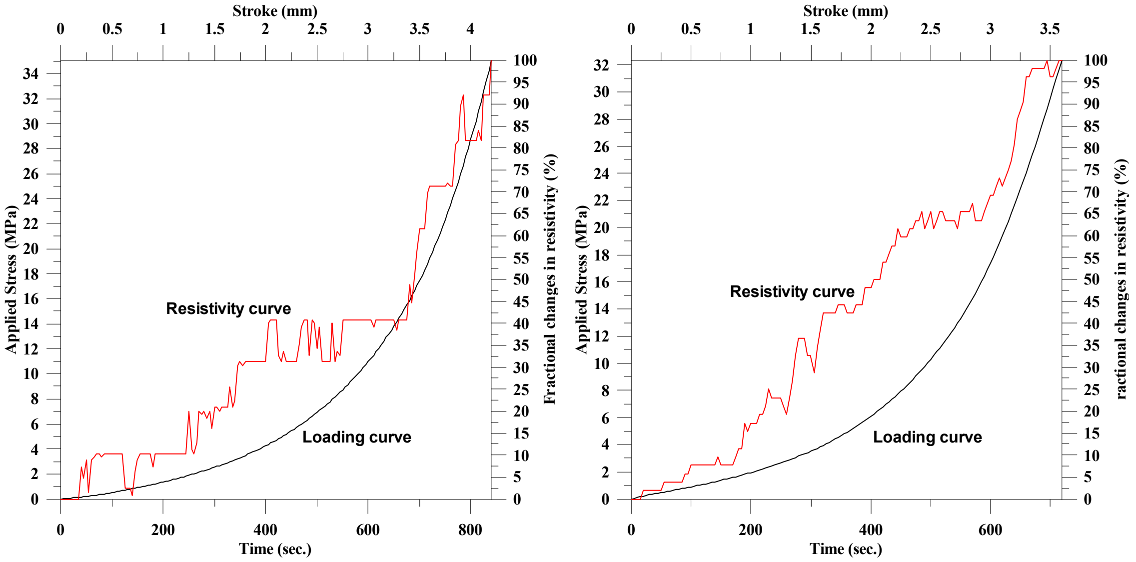
a) b)

Figure 4.a) Self-sensing behavior of sample (2% CF) under compression test-7days age, b) Self-sensing behavior of sample (1% CF) under compression test - 28 days age.



a) b)

Figure 5.a) Self-sensing behavior of sample (1% CF) under compression test-28days age, b) Self-sensing behavior of sample (2% CF) under compression test-28days age.



a) b)

Figure 6.a, b) Self-sensing behavior of samples (1% and 2% CF, respectively) under splitting test-28days age.

Electrodes were put parallel to stress direction during compressive and split tests leading to increase in electrical resistance of composites. As mentioned before, increased carbon fiber dosage triggers dramatic decrease on initial electrical resistance of composites in both 7 and 28 days. It can be proposed that well dispersed carbon fibers within the matrix is important and critical for determining more sensitive results. This could imply that, at least in this study, well dispersed carbon fibers that provide sufficient bonding for mixture was obtained.

4. CONCLUSION

The phenomenon of the damage sensing ability is attributed to fracture of fibers that bridge micro-cracks under various tests. In this study, damage in cementitious composites reinforced with short carbon fibers was monitored by two-probe measurement of the AC electrical resistance. All samples clearly indicate that the greater the stress amplitude, the larger was the damage-induced resistance increase. The results are summarized as below:

- Increased carbon fiber dosage, by amount of 1% to 2%, have led to a decrease in the electrical resistance of carbon fiber/mortar composites.
- The carbon fiber/mortar composites fabricated in the present work exhibited effective sensing ability under split and compressive stress.
- Though all samples were monitored in the plastic regime, results were clearly satisfying for self-sensing response.
- Through the incorporation of a small volume of carbon fibers to conventional mortar, significant changes were obtained in the electrical resistivity of composites responding to compressive and splitting loadings. Results of experiments indicate that cementitious composites gained strain sensing ability by means of carbon fiber usage. Under compressive and splitting tests, an increased change in resistivity point that composites reinforced with carbon fibers can serve as health monitoring in civil engineering applications.

Damage self-sensing by resistance measurement is a promising non-destructive method in carbon fiber reinforced cementitious composites. However, to reach the best effects, carbon fibers need to be better dispersed within matrix to provide good bonding between CF’s and surrounding hydrated cement matrix. Further research on related to topic will increase the understanding of self-sensing principle in civil engineering world thus leading to way for more functional and smart structures for future.

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