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Communication

Uniaxial compression in carbon fiber-reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions

Sihai Wen, D.D.L. Chung*

Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA

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Abstract

Uniaxial compression of carbon fiber-reinforced cement pastes in the elastic regime caused reversible decreases in both longitudinal and transverse electrical resistivities. In contrast, uniaxial tension had been previously reported to cause reversible increases in both resistivities. The fractional change in resistivity per unit strain is higher in magnitude for carbon fiber silica fume cement paste than carbon fiber latex cement paste.

Keywords: Electrical properties; Strain effect; Cement paste; Fiber reinforcement; Silica fume

1. Introduction

Cement reinforced with short carbon fibers is capable of sensing its own strain due to the effect of strain on the electrical resistivity [1–12]. As observed at 28 days of curing, the resistivity in the stress direction increases upon tension, due to slight fiber pull-out that accompanies crack opening, and decreases upon compression, due to slight fiber push-in that accompanies crack closing [6–11]. However, little attention has been previously paid to the resistivity in directions other than the stress direction. In practical use of carbon fiber-reinforced cement for strain sensing, the resistivity is not necessarily measured in the stress direction. Furthermore, how the resistivity changes in directions other than the stress direction provides valuable insight on the mechanism behind the piezoresistive effect. Therefore, for both technological and scientific reasons, it is important to investigate the resistivity in directions other than the stress direction. For simplicity, this paper is focused on the resistivity in the transverse direction (i.e., a direction perpendicular to the stress axis) for the case of uniaxial compression. However, for the sake of comparison, investigation was also conducted in this work for the resistivity in the longitudinal direction.

* Corresponding author. Tel.: +1-716-645-2593 ext. 2243; fax: +1-716-645-3875.

E-mail address: ddlchung@acsu.buffalo.edu (D.D.L. Chung).

2. Experimental methods

The carbon fibers were isotropic pitch-based and unsized, as obtained from Ashland Petroleum (Ashland, KY). The fiber diameter was 15 μm. The nominal fiber length was 5 mm. Fibers in the amount of 0.5 mass% of cement were used. Prior to using the fibers in the cement, they were dried at 110°C in air for 1 h and then surface-treated with ozone by exposure to O_3 gas (0.6 vol.%, in O_2) at 160°C for 10 min. The ozone treatment was for improving the wettability of fibers by water [10]. The cement used was Portland cement (Type I) from Lafarge (Southfield, MI). The silica fume (Elkem Materials, Pittsburgh, PA, microsilica, EMS 965) was used in the amount of 15 mass% of cement. The methylcellulose, used in the amount of 0.4 mass% of cement, was Dow Chemical, Midland, MI, Methocel A15-LV. The defoamer (Colloids, Marietta, GA, 1010) used whenever methylcellulose was used was in the amount of 0.13 vol.% (percent of sample volume). The latex, used in the amount of 20 mass% of cement, was styrene butadiene copolymer (Dow Chemical, 460NA) with the polymer making up about 48% of the dispersion and with styrene and butadiene in the mass ratio 66:34, such that the latex was used along with an antifoam (Dow Corning, Midland, MI, #2410, 0.5 mass% of latex).

A rotary mixer with a flat beater was used for mixing. Methylcellulose (if applicable) was dissolved in water and then the defoamer (if applicable) and fibers (if applicable)

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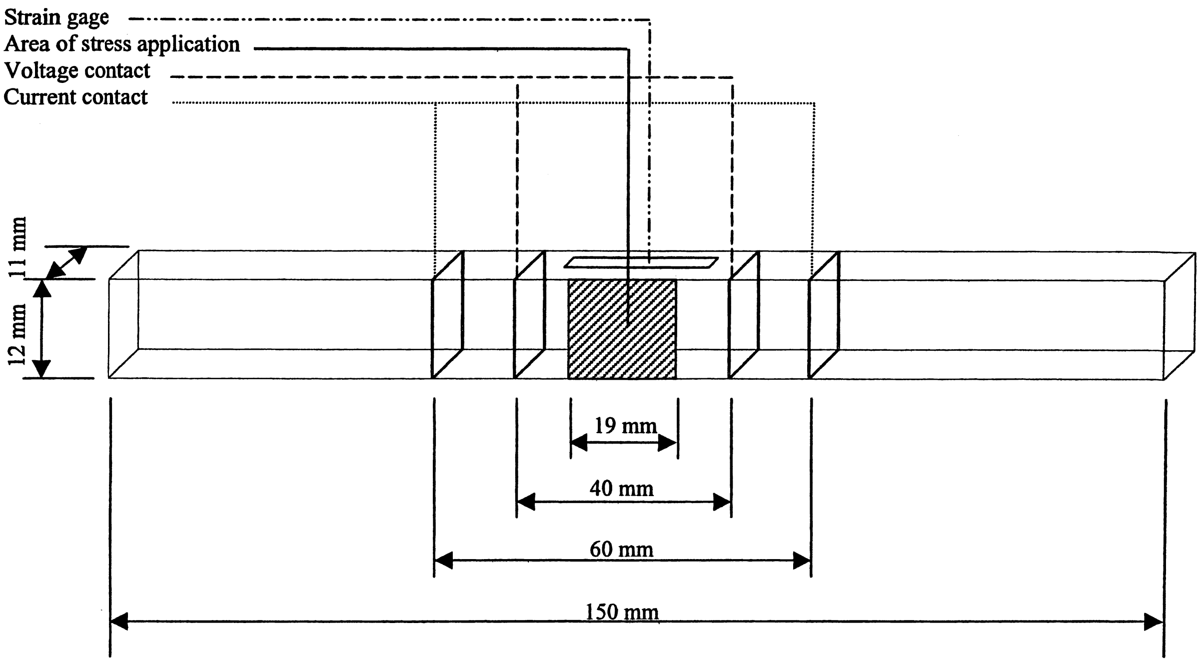

Fig. 1. Sample configuration for measuring the transverse electrical resistivity during uniaxial compression.

were added and stirred by hand for about 2 min. Latex (if applicable) was mixed with the antifoam agent and fibers (if applicable) by hand for about 1 min. The methylcellulose mixture (if applicable), the latex mixture (if applicable), cement, water, silica fume (if applicable) were mixed in the mixer for 5 min. After pouring the mix into oiled molds, an external electric vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (relative humidity = 100%) for 28 days.

Two types of cement paste were studied, namely (a) carbon fiber silica fume cement paste (consisting of cement, water, silica fume, methylcellulose, defoamer, and carbon fibers) and (b) carbon fiber latex cement paste (consisting of cement, water, latex, carbon fibers, and antifoam agent). The

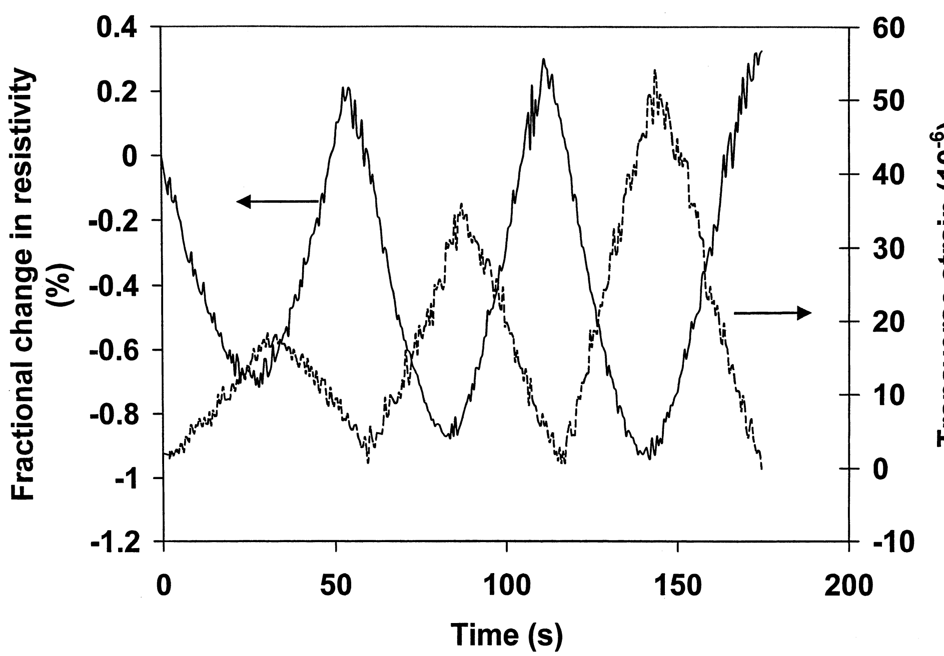

Fig. 2. Fractional change in resistivity and strain in the transverse direction for carbon fiber silica fume cement paste.

water/cement ratio was 0.35 for paste (i) and was 0.23 for paste (ii). Six specimens of each of the two types of paste were tested.

Electrical resistivity measurements were conducted using the four-probe method, with silver paint in conjunction with copper wires for electrical contacts. A Keithley (Cleveland, OH) 2001 multimeter was used.

Samples for transverse resistivity measurement were in the form of rectangular bars of size 150 × 12 × 11 mm. Each electrical contact was applied around the entire 12 × 11 mm perimeter of the bar. The voltage contacts were at two parallel cross-sectional planes that were 40 mm apart. Thus, the resistivity was measured along the length of the rectangular bar. During the resistivity measurement, compressive stress was applied to the middle portion (19 × 12 mm) of the rectangular sample (Fig. 1), such that the electrical contacts were away from the stressed portion and the stress was in a direction perpendicular to the direction of resistivity measurement. The stress (repeated loading at increasing stress amplitudes) was provided by a hydraulic mechanical testing system (MTS Model 810). The transverse strain was measured using a strain gage attached to a side of the specimen, as shown in Fig. 1.

Samples for longitudinal resistivity measurement were in the form of cubes of size 51 × 51 × 51 mm (2 × 2 × 2 in.). During repeated compression at increasing stress amplitudes, electrical resistance measurement was made in the stress axis, using the four-probe method, in which silver paint in conjunction with copper wires served as electrical contacts. Four contacts were perimetrically placed around the specimen at four planes that were all perpendicular to the stress axis and that were symmetric with respect to the midpoint along the height of the specimen. The outer two contacts (typically 40 mm apart) were for passing current. The inner two contacts (typically 30 mm apart) were for measuring the voltage. The longitudinal strain was measured by using a strain gage attached to the middle of one of four side surfaces of a specimen. The strain gage was centered on the side surface and was parallel to the stress axis.

3. Results and discussion

Figs. 2 and 3 show the fractional change in resistivity and strain in the transverse and longitudinal directions, respectively, during uniaxial compression for carbon fiber silica fume cement paste. Figs. 4 and 5 show the fractional change in resistivity and strain in the transverse and longitudinal directions, respectively, during uniaxial compression for carbon fiber latex cement paste. Both transverse and longitudinal resistivities of either paste decrease upon compression reversibly, except for some irreversible increase in both transverse and longitudinal resistivities primarily at the end of the first stress cycle. The irreversible increase is attributed to minor damage inflicted primarily in the first cycle. The greater the strain amplitude, the more is the reversible resistivity decrease upon straining. Both transverse and longitudinal strains are reversible. The gage factor (fractional change in resistivity per unit strain, essentially equal to the fractional change in resistance per unit strain) is listed in Table 1. The gage factor magnitude in either direction is higher for the carbon fiber silica fume

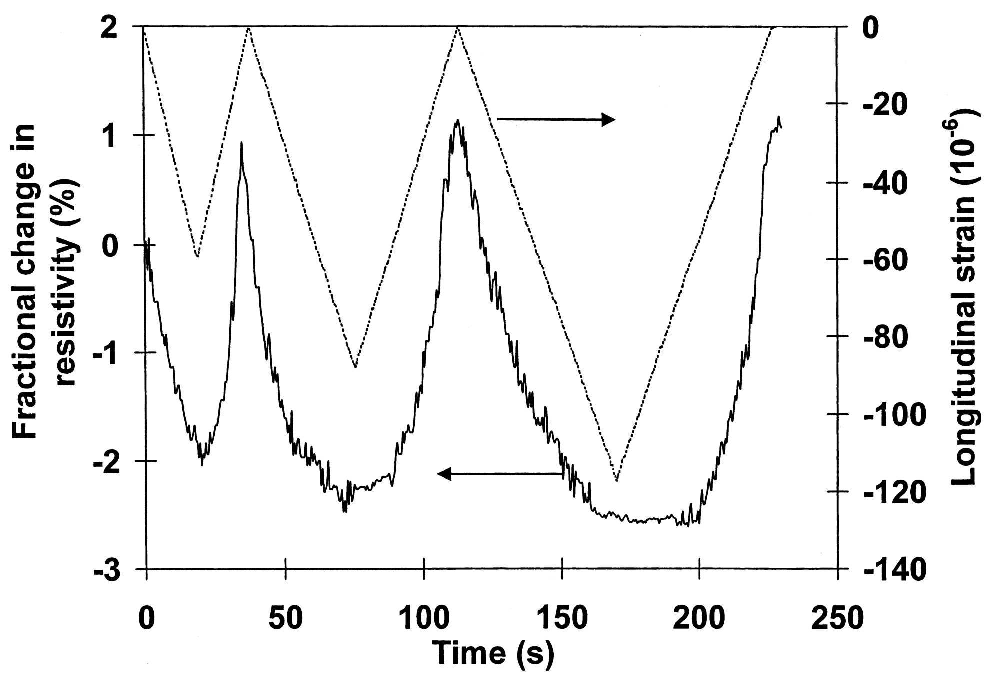

Fig. 3. Fractional change in resistivity and strain in the longitudinal direction for carbon fiber silica fume cement paste.

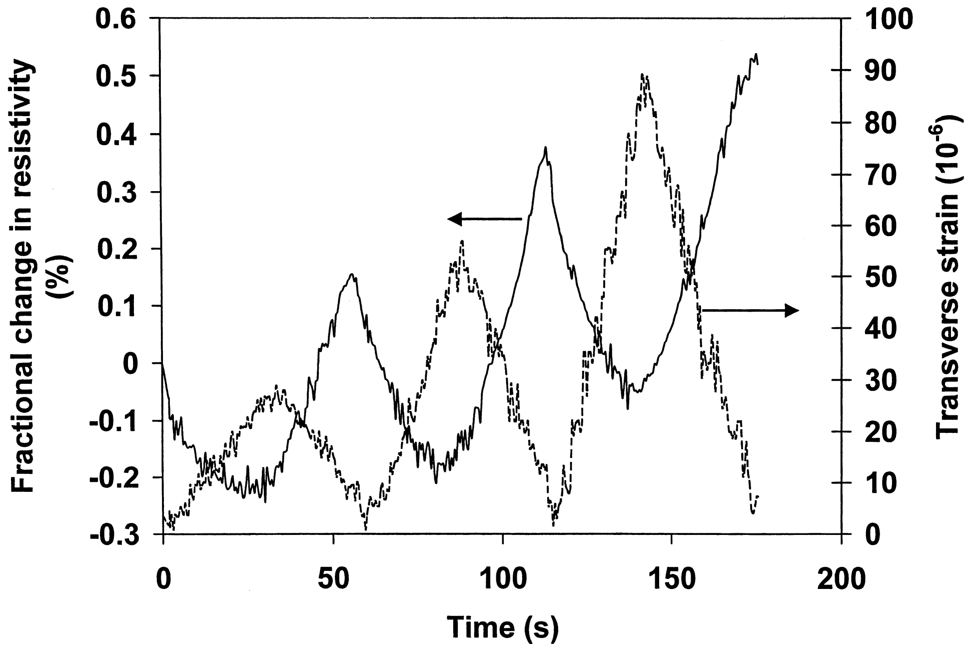

Fig. 4. Fractional change in resistivity and strain in the transverse direction for carbon fiber latex cement paste.

cement paste than for the carbon fiber latex cement paste, as suggested by the superior fiber dispersion in the former [13] and as previously reported for the case of uniaxial tension [14]. The gage factor magnitude is comparable for the two directions for carbon fiber silica fume cement paste, but is lower in the transverse direction than the longitudinal direction for carbon fiber latex cement paste. The small value for carbon fiber latex cement paste in the transverse direction was as previously reported for the case of uniaxial tension [14].

In a companion paper [14], we report that both transverse and longitudinal resistivities increase upon uniaxial tension for carbon fiber cement paste. In this paper, we report that both transverse and longitudinal resistivities decrease upon

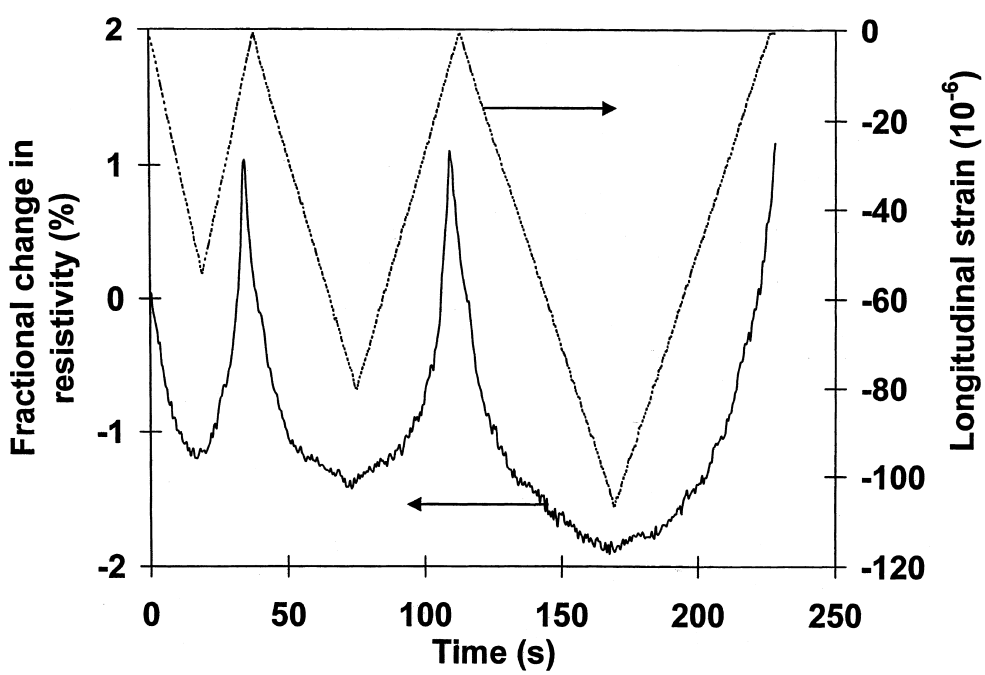

Fig. 5. Fractional change in resistivity and strain in the longitudinal direction for carbon fiber latex cement paste.

Table 1
Gage factor of carbon fiber cement pastes under uniaxial compression and under uniaxial tension

	Carbon fiber silica fume cement paste	Carbon fiber latex cement paste	References
Compression			
Longitudinal	+ 350	+ 210	This work
Transverse	− 390	− 80	
Tension			
Longitudinal	+ 89	+ 51	[14]
Transverse	− 59	− 36	

uniaxial compression. Hence, in spite of the Poisson effect, the microstructural effect of compression/tension affects similarly the resistivities in the transverse and longitudinal directions. This means that the resistivity in any direction relative to the stress axis can be used to indicate strain or stress in the stress axis, though the much larger value of the fractional change in resistivity in the longitudinal direction than in the transverse direction (due to the much larger strain magnitude in the longitudinal direction) makes it more convenient to use the longitudinal resistivity to indicate strain or stress.

The gage factor magnitude is larger under uniaxial compression (this work) than under uniaxial tension [14] for the same paste and the same direction (Table 1), as previously reported for the longitudinal case [15].

4. Conclusion

Uniaxial compression of carbon fiber-reinforced cement paste in the elastic regime caused reversible decreases in both longitudinal and transverse electrical resistivities. In contrast, uniaxial tension caused reversible increases in both resistivities [14]. The gage factor magnitude is higher for carbon fiber silica fume cement paste than carbon fiber latex cement paste, whether under uniaxial compression or uniaxial tension. The gage factor magnitude is comparable in the longitudinal and transverse directions, especially for the case of carbon fiber silica fume cement paste.

Acknowledgments

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