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Strain-Sensing Characteristics of Carbon Fiber-Reinforced Cement

by Sihai Wen and D. D. L. Chung

Strain sensing in carbon fiber reinforced cement, as enabled by piezoresistivity, is characterized by the gauge factor, which is defined as the fractional change in electrical resistance per unit strain. Under uniaxial compression, the gauge factor in both longitudinal and transverse directions decrease in magnitude with increasing specimen size from 13 to 51 mm, due to a slight decrease in the degree of preferred orientation of the 5 mm-long fibers. Also under uniaxial compression, the gauge factor in both directions decreases in magnitude as the fiber content increases beyond the percolation threshold.

Keywords: cement; fibers; silica fume; strain.

INTRODUCTION

The ability of a structural material to sense its own strain (without embedded or attached sensors) is attractive for smart structures. Specific applications include structural vibration control, traffic monitoring, weighing, room occupancy monitoring, and building security. The advantages of this self-sensing ability over the use of embedded or attached sensors are low cost, high durability, large sensing volume, and the absence of mechanical property loss (which occurs in the case of embedded sensors).[1]

Self-sensing cement-based materials are strongly piezoresistive due to the presence of electrically conductive fiber admixtures.[2-11] Piezoresistivity refers to the change in electrical resistivity with strain. The most effective admixture is short carbon fibers. The strain-sensing ability stems from the slight pull-out of crack-bridging fibers during tension affecting the electrical contact between fiber and cement matrix. Upon compression, fiber push-in occurs instead. This effect occurs even at very low strains in the elastic regime. Carbon fibers (15 μm diameter) are more effective than steel fibers (8 μm diameter), probably due to the fiber-fiber contact rather than the fiber-matrix contact governing the piezoresistivity in steel fiber cement.[3] The carbon fibers are low-cost ones made from isotropic pitch. In contrast, carbon nanofibers of diameter 0.1 μm are ineffective due to their tendency for clumping.[4,5]

Previous work on the strain-sensing ability of carbon fiber cement has shown that uniaxial compression causes the volume electrical resistivity to decrease in both longitudinal and transverse directions[6] and that uniaxial tension causes the resistivity to increase in both directions.[12] The strain effect is to be distinguished from the damage effect. Damage causes the resistivity to increase, whether under compression or tension.[7,13,14] The magnitude of the piezoresistive effect is described by the gauge factor, which is defined as the fractional change in resistance (not resistivity) per unit strain in the direction of the resistance measurement. If the resistivity does not change with strain, the gauge factor is around 2 (the exact value depending on the Poisson ratio). In carbon fiber cement, the gauge factor is typically 100 or more, due to the significant change of the resistivity with strain. For cement containing 0.5 vol.% carbon fibers (together with silica fume, which helps fiber dispersion), the gauge factor has been reported to be 350 ± 30 in the longitudinal direction under uniaxial compression[6] and 90 ± 10 in the longitudinal direction under uniaxial tension.[12] In the transverse direction, the gauge factor is negative because of the definition of the gauge factor and the fact that the strain is negative when the length is decreased. For cement containing 0.5 vol.% carbon fibers, the gauge factor has been reported to be –390 in the transverse direction under uniaxial compression[6] and –59 in the transverse direction under uniaxial tension.[12] Thus, in the case of uniaxial loading, strain sensing can be achieved by measuring either the longitudinal or transverse resistance. This adds flexibility to the implementation of the self-sensing technology in structures.

In spite of prior work,[6-24] questions remain concerning the strain-sensing characteristics of carbon fiber cement. Two questions in particular are addressed in this paper. They relate to the effect of the carbon fiber volume fraction and the effect of the specimen size.

Previous work conducted at 28 days of curing involved a carbon fiber volume fraction of 0.5%,[6-24] which is below the percolation threshold.[25] (The percolation threshold is the volume fraction above which the adjacent fibers touch, thereby resulting in a continuous conductive path in the composite, as shown by a decrease in the electrical resistivity by orders of magnitude.[25]) A previous investigation of the effect of carbon fiber volume fraction was limited to the study of mortar at 7 days of curing.[23] The piezoresistive behavior of carbon fiber mortar changes at a curing age between 7 and 14 days.[18] At 14 days and longer, the resistance decreases upon compression; at 7 days, the resistance increases upon compression.[18]

There has been little prior work[11] on the effect of specimen size. Reference 11 reported that the fractional change in resistance per unit stress (related to the gauge factor) increases as the specimen size increases from 20 to 40 mm in the stress direction and explained the trend by considering that the deformation was more for the larger specimen under the same compressive stress. This explanation, however, is not reasonable because the strain rather than the deformation is what governs the resistance change and the strain is independent of specimen size. Reference 11 did not consider

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the effect of fiber preferred orientation. The size effect can relate to the effect of the degree of preferred orientation of the fibers in the cement. The smaller the thickness of the specimen in the vertical direction during curing, the greater the chance of preferred orientation of the fibers. This is because the fibers tend to lie down, with a preferred orientation in the horizontal plane during curing. Preferred orientation of the fibers is expected to affect the piezoresistive behavior.

This work involves simultaneous measurement of the piezoresistive behavior in the longitudinal and transverse directions for each specimen. This simultaneous measurement in the same specimen is in contrast to prior work,[6,12] which measured the behavior in the two directions in different specimens that were different in geometry. Thus, this work provides a more reliable comparison of the piezoresistive behavior in the longitudinal and transverse directions.

RESEARCH SIGNIFICANCE

This paper provides basic data associated with the strain-sensing characteristics of carbon fiber-reinforced cement. The data relate to the effect of specimen size and of the fiber volume fraction.

EXPERIMENTAL METHODS

The carbon fibers were isotropic pitch-based and unsized, the fiber diameter was 15 μm, and the nominal fiber length was 5 mm. Fibers in the amounts of 0.50, 1.00, and 1.50% by mass of cement (corresponding to 0.48, 0.95, and 1.43 vol.%) were used. The percolation threshold was between 0.5 and 1.0 vol.%.[25] Prior to using the fibers in 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 wetability of fibers by water.[15]

The cement used was portland cement (Type I), the silica fume was used in the amount of 15% by mass of cement, and the methylcellulose was used in the amount of 0.4% by mass of cement. A defoamer was used whenever methylcellulose was used was in the amount of 0.13 vol.% (percent of sample volume).

A rotary mixer with a flat beater was used for mixing. Methylcellulose was dissolved in water and then the defoamer and fibers were added and stirred by hand for approximately 2 min. Then the methylcellulose mixture, cement, water, and silica fume were mixed for 5 min. After pouring the mixture 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. The water-cement ratio (*w/c*) was 0.35. The slump (ASTM C 143-90a) was 43 ± 5, 34 ± 4, and 25 ± 3 mm for carbon fiber contents of 0.5, 1.0, and 1.5% by mass of cement, respectively. These

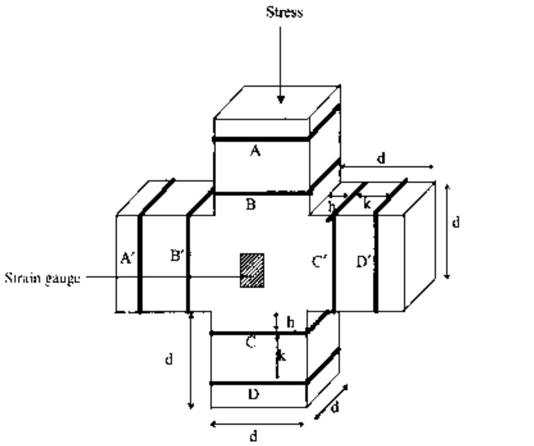

Fig. 1—Specimen configuration. d = *13, 25, or 51 mm. For case of* d = *13 mm,* h = *2 mm and* k = *8 mm. For* d = *25 or 51 mm,* h = *5 mm and* k = *10 mm.*

low slump values are due to the absence of a water-reducing agent. Six specimens of each type of cement paste were tested.

Specimens of the shape depicted in Fig. 1 were prepared by using molds of the same shape, such that the vertical direction during curing was the direction perpendicular to the page in Fig. 1. For the same shape, three specimen sizes were obtained by using three mold sizes. The three sizes correspond to *d* (specimen dimension defined in Fig. 1) being 0.5, 1.0, and 2.0 in. (that is, 13, 25, and 51 mm).

Compressive stress at increasing amplitudes was applied in the direction shown in Fig. 1. The stress, which was within the elastic regime, was provided by a hydraulic mechanical testing system. A strain gauge was applied to the center of the specimen (Fig. 1)—one on each of two opposite surfaces. One strain gauge was for measuring the longitudinal strain, whereas the other strain gauge was for measuring the transverse strain.

During repeated compression, DC electrical resistance measurement in the longitudinal direction was made by using the electrical contacts—A, B, C, and D—as shown in Fig. 1. Each contact was in the form of silver paint in conjunction with copper wire, which was wound parametrically. In accordance with the four-probe method of resistance measurement, Contacts A and D were for passing current while Contacts B and C were for measuring the voltage. As Contacts B and C were close to the central cubic portion (2 to 5 mm from the edge of the central cubic portion) of the specimen (that is, the portion experiencing the stress), the measured resistance was essentially the longitudinal resistance of the central cubic portion. Similarly, electrical resistance in the transverse direction was measured by using electrical contacts—A′, B′, C′, and D′—shown in Fig. 1. Because the strains involved were small, the fractional change in resistance was essentially equal to the fractional change in resistivity.

The severity of the piezoresistive effect was described by the gauge factor (fractional change in resistance per unit strain), which was calculated for each cycle by dividing the maximum change in resistance within the cycle (relative to the resistance at the beginning of the cycle) by the resistance at the beginning of the cycle and then dividing by the strain amplitude for the cycle. The gauge factor for a particular specimen type was obtained by averaging over the gauge factor values for all three cycles of each of the six specimens of the same type.

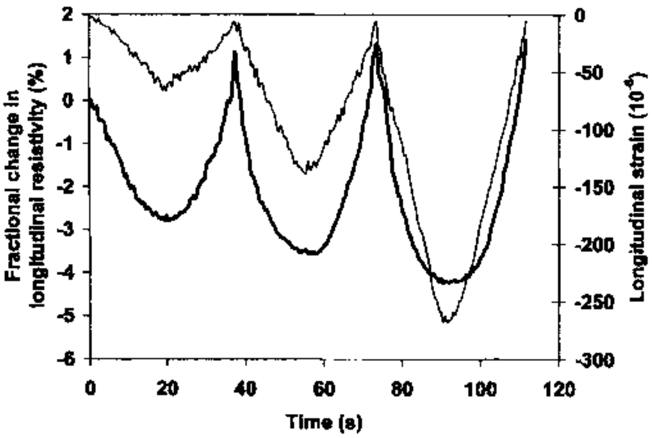

Fig. 2—Fractional change in longitudinal resistivity versus time (thick curve) and longitudinal strain versus time (thin curve) for cement paste containing 0.95 vol.% carbon fibers and small specimen size with d = *13 mm.*

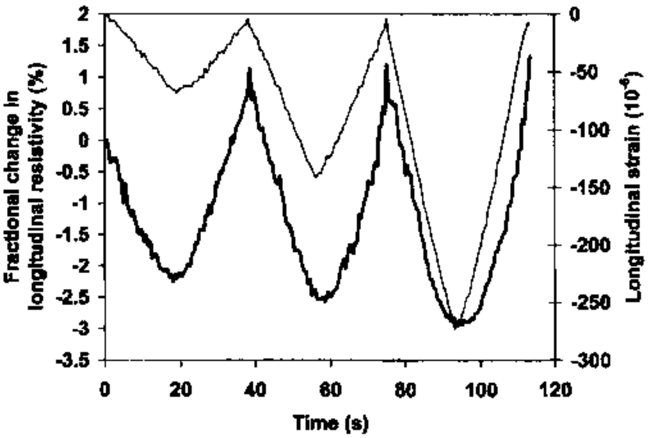

Fig. 4—Fractional change in longitudinal resistivity versus time (thick curve) and longitudinal strain versus time (thin curve) for cement paste containing 0.95 vol.% carbon fibers and large specimen size with d = *51 mm.*

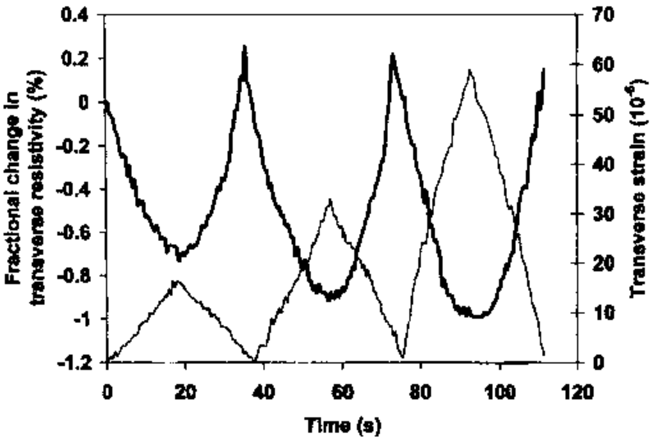

Fig. 3—Fractional change in transverse resistivity versus time (thick curve) and transverse strain versus time (thin curve) for cement paste containing 0.95 vol.% carbon fibers and small specimen size with d = *13 mm.*

Table 1—Volume electrical resistivity at no load for various combinations of fiber content and specimen size

Fiber content, vol.%	Resistivity, Ω·cm		
	Small specimen size*	Medium specimen size†	Large specimen size‡
0.48	$(1.24 \pm 0.07) \times 10^4$	$(1.33 \pm 0.10) \times 10^4$	$(1.49 \pm 0.08) \times 10^4$
0.95	$(7.38 \pm 0.62) \times 10^2$	$(7.91 \pm 0.72) \times 10^2$	$(8.25 \pm 0.49) \times 10^2$
1.43	$(3.25 \pm 0.19) \times 10^2$	$(3.88 \pm 0.23) \times 10^2$	$(4.07 \pm 0.26) \times 10^2$

*d = 13 mm (Fig. 1).
†d = 25 mm (Fig. 1).
‡d = 51 mm (Fig. 1).

The configuration in Fig. 1 also allows measurement of the resistivity at no load. The dependence of the resistivity on fiber volume fraction and specimen size was thus studied in this work. At no load, the resistivity is the same in the longitudinal and transverse directions.

RESULTS AND DISCUSSION

Table 1 shows the volume electrical resistivity at no load for various combinations of fiber content and specimen size. For each specimen size, the resistivity decreased monotonically with increasing fiber content, such that the decrease was much more from 0.48 to 0.95 vol.% fibers than that from 0.95 to 1.43 vol.% fibers. This is consistent with the prior report that the percolation threshold is between 0.5 and 1.0 vol.% carbon fibers.[18] For the same fiber content, the resistivity increased slightly with increasing specimen size. This is attributed to the decrease in the degree of preferred orientation of the fibers as the specimen size (in the vertical direction during curing) increases, because the fibers are much more conductive than the cement matrix and an increase in the degree of preferred orientation of the fibers causes the resistivity at 28 days of curing to decrease in the direction of the preferred orientation. The effects of curing age and casting direction on the preferred orientation of the fibers are beyond the scope of this paper. As the specimen shape was the same for the three sizes, the specimen shape was not a factor in this study.

Consistent with prior work,[6] both longitudinal and transverse resistivities decreased upon compression such that the resistivity after the first unloading was higher than that before loading (due to minor damage or irreversible microstructural change). Subsequent to the first loading cycle, the resistivity decrease upon loading was reversible. Also consistent with prior work[6] is the observation that the magnitude of the gauge factor is slightly higher in the transverse direction than in the longitudinal direction. The origin of this difference may relate to the much smaller strain magnitude in the transverse direction than the longitudinal direction, as shown by comparing Fig. 2 and 3 and comparing Fig. 4 and 5. The strain in the transverse direction is due simply to the Poisson effect.

Figure 2 and 3 show the results for the smallest specimen size (d = 13 mm) and a fiber content of 0.95 vol.%. Figure 4 and 5 show the corresponding results for the largest specimen size (d = 51 mm). The behavior is similar for all combinations of specimen size and fiber content, except that the gauge factor is different for the different combinations, as shown in Table 2.

The gauge factor is close for fiber contents of 0.48 and 0.95 vol.%, though the magnitude may be slightly higher for 0.95 vol.%. The slightly higher magnitude for the higher fiber volume fraction is consistent with the notion that the piezoresistivity is due to fiber pull-out (or push-in) and with the larger number of crack-bridging fibers for the higher

Table 2—Gauge factor in longitudinal and transverse directions for various combinations of fiber content and specimen size

Fiber content, vol.%	Gauge factor					
	Small specimen size*		Medium specimen size†		Large specimen size‡	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
0.48	409 ± 27	–437 ± 32	352 ± 26	–381 ± 30	327 ± 23	–363 ± 27
0.95	418 ± 22	–456 ± 25	373 ± 20	–405 ± 29	332 ± 17	–374 ± 26
1.43	309 ± 21	–317 ± 24	260 ± 16	–302 ± 18	222 ± 14	–248 ± 20

*d = 13 mm (Fig. 1).
†d = 25 mm (Fig. 1).
‡d = 51 mm (Fig. 1).

fiber volume fraction. An increase of the fiber content from 0.95 to 1.43 vol.% causes the magnitude of the gauge factor to decrease. These trends apply to both longitudinal and transverse gauge factors and to all three specimen sizes.

This effect of the fiber content is consistent with the prior report that the fractional change in resistance of carbon fiber mortar at tensile fracture did not vary much with the carbon fiber content in the range from 0.53 to 4.24 vol.%, in spite of the drop of the resistivity by orders of magnitude in this fiber content range.[25] The gauge factor was not reported, however, and the curing age was 7 days in Reference 24.

The percolation threshold is between 0.5 and 1.0 vol.%.[25] The values of the gauge factor just below and just above the percolation threshold (at 0.48 and 0.98 vol.%, respectively) are close. Thus, percolation did not affect the piezoresistive phenomenon as expected from the notion that the piezoresistivity stems from fiber pull-out (or push-in) rather than stemming from the change in connectivity among the fibers. On the other hand, an increase of the fiber content to 1.43 vol.% caused the gauge factor to drop, probably due to the proximity of the fibers causing interference of adjacent fibers to fiber push-in during compression for each fiber.

An increase in the specimen size caused the magnitude of the gauge factor to decrease. This trend applies to both longitudinal and transverse gauge factors and to all three fiber contents. It is attributed to the decrease in the degree of preferred orientation of the fibers in the plane of Fig. 1 as the specimen size increased. This explanation is based on the notion that the piezoresistivity is due to fiber pull-out (or push-in). The pull-out (or push-in) of fibers that are perpendicular to the plane of Fig. 1 is not expected to affect the resistivity in the longitudinal or transverse direction. In other words, it is the pull-out (or push-in) of fibers in the plane of Fig. 1 that mainly contributes to the observed piezoresistivity in the plane of Fig. 1.

The trend mentioned previously is opposite to that reported in Reference 11. This discrepancy is attributed to the fact that Reference 11 used the two-probe method whereas this work uses the four-probe method. The resistance of the electrical contacts is included in the measured resistance in the two-probe method, whereas it is not included in the measured resistance in the four-probe method. The larger the specimen, the greater the proportion of the measured resistance (two-probe method) that is due to the specimen (rather than the contacts), and the higher the measured gauge factor. Thus, the trend reported in Reference 11 is an artifact resulting from the two-probe method used.

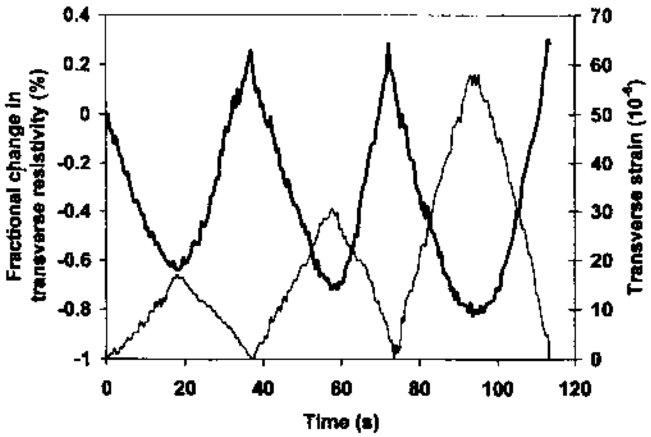

Fig. 5—Fractional change in transverse resistivity versus time (thick curve) and transverse strain versus time (thin curve) for cement paste containing 0.95 vol.% carbon fibers and small specimen size with d *= 51 mm.*

CONCLUSIONS

The strain-sensing characteristics of carbon fiber-reinforced cement, as based on piezoresistivity and described by the gauge factor, were found to depend on the fiber volume fraction and specimen size. Under uniaxial compression, the gauge factor in both longitudinal and transverse directions decreased in magnitude with increasing specimen size in the range from 13 to 51 mm, due to the decrease in the degree of preferred orientation of the 5 mm-long fibers in the horizontal plane during curing as the specimen size increased. Under uniaxial compression, the gauge factor in both longitudinal and transverse directions increased very slightly (if at all) in magnitude as the fiber content increased from 0.48 to 0.95 vol.% and decreased in magnitude as the fiber content increased from 0.95 to 1.43 vol.%. This is due to the percolation threshold being between 0.48 and 0.95 vol.% and that a fiber content beyond the percolation threshold reduces the piezoresistive effect.

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