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Piezoresistivity in continuous carbon fiber cement-matrix composite

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Abstract

Piezoresistivity was observed in cement-matrix composites with 2.6–7.4 vol% unidirectional continuous carbon fibers. The direct-current electrical resistance in the fiber direction increased upon tensile loading in the same direction, such that the effect was mostly reversible when the stress was below that for the tensile modulus to decrease. The gage factor was up to 60. The resistance increase was due to fiber-matrix interface degradation, which was mostly reversible. Above the stress at which the modulus started to decrease, the resistance increased with stress/strain abruptly, due to fiber breakage. The tensile strength and modulus of the composites were 88% and 84%, respectively, of the calculated values based on the rule of mixtures.

Keywords: Cement; Fiber reinforcement; Composite; Electrical properties; Mechanical properties

Continuous fibers are far more effective than short fibers for reinforcement, so advanced structural composites all use continuous fibers rather than short fibers, despite the high cost of continuous fibers compared to short fibers. Advanced structural composites are predominantly polymer-matrix composites, due to the low density and adhesive ability of polymers. The polymer-matrix composites are widely used for lightweight structures, such as aircraft and sporting goods. Less commonly, they are used for the repair and strengthening of concrete structures [1–8]. However, polymers are much more expensive than cement, and the adhesion of polymers to concrete and the long-term durability of polymers inside concrete are of concern. Therefore, continuous fiber cement-matrix composites deserve attention. Although numerous studies have been made on the use of short fibers in concrete [9], little work has been reported on the use of continuous fibers [10–14].

Saito et al. [11] showed that unidirectional continuous carbon fiber reinforcement results in cement-matrix composites exhibiting tensile strength approaching that expected by calculation based on the rule of mixtures. The tensile stress-strain curve reported by Saito et al. is a straight line up to failure. However, Saito et al. did not report on the effect of unloading from various stress levels and did not investigate the damage, if any, before failure. Before these composites can be used as structural materials, their damage behavior must be investigated.

The absence of a change in tensile modulus does not mean no damage, as fiber-matrix bond degradation is a form of damage that may not cause a decrease in the modulus. Fiber breakage would cause a modulus decrease, but it is a more severe type of damage. Fiber-matrix bond degradation is detrimental to the flexural strength and longitudinal compressive strength, so it is relevant to the mechanical behavior of the composite. Both fiber breakage and fiber-matrix bond degradation are addressed in this paper.

Due to the electrical conductivity of carbon fibers and the slight conductivity of the cement matrix, measurement of the direct-current electrical resistance of the composite provides a way to detect damage. Fiber breakage obviously causes the longitudinal resistance to increase irreversibly. Fiber-matrix bond degradation obviously increases the transverse resistance, but it also increases the longitudinal resistance when the electrical current contacts are on the surface (e.g., perimetrically around the composite in a plane perpendicular to the longitudinal direction). When the transverse resistivity is increased, the electrical current has more difficulty penetrating the entire cross-section of the specimen, thereby resulting in an increase in the measured longitudinal resistance. Note that the electrical resistivity of carbon fibers is $10^{-4}\ \Omega \cdot$ cm, whereas that of cement paste is $10^{5}\ \Omega \cdot$ cm.

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In this work, the longitudinal electrical resistance of unidirectional continuous carbon fiber cement-matrix composites was measured during static tensile loading up to failure and during repeated tensile loading at various stress amplitudes, while the stress-strain relationship was monitored. Increase in resistance with a concomitant decrease in modulus indicates fiber breakage. Increase in resistance without a concomitant decrease in modulus indicates fiber-matrix degradation.

Piezoresistive behavior refers to the effect of stress/strain on the electrical resistivity. This behavior provides the basis for stress/strain sensors. The piezoresistive behavior of short carbon fiber cement-matrix composites has been previously reported [15–20]. This paper provides the first report of the piezoresistive behavior of continuous carbon fiber cement-matrix composites. The behavior is relevant to smart structures that are rendered smart by the self-sensing concrete.

1. Experimental

The continuous carbon fibers used were pitch-based, Thornel P-25, 2000 fibers per tow, without sizing, without twist, from Amoco Performance Products, Inc. (Ridgefield, CT). The fiber properties are shown in Table 1. Before 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 is for improving the wetting of the fibers by water [21]. Cement paste made from Portland cement (type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material.

Water and cement in the weight ratio 0.45 were mixed by hand to form a cement paste. A weighed amount of continuous carbon fiber tow was immersed in the cement paste for 60 min to impregnate the fiber tow with cement paste. After this, the fiber tow was taken out and a fraction of the cement paste on the outer surface of the tow was removed by using tweezers. For the purpose of straightening the tow, the tow was stretched and wound around a glass cylinder of diameter 12 cm and allowed to remain wound for 7–10 min. After this, the tow was unwound and cut into 180-mm lengths. Then the cut lengths were laid one by one into the rectangular cavity of a steel mold (Fig. 1) and the ends of each tow were fastened through small steel plates at the ends of the mold. The inner edges of the small steel plates were 150 mm apart, thus forming a mold cavity that was 150 mm long and 14 mm wide. A steel piston of the size of the cavity was lowered into the cavity. A pressure of 32 MPa was applied to the cavity through the piston. After holding the pressure for 24 h, demolding took place and curing was performed at 100% relative humidity for 7 days. After this, the specimen was dried at 50°C for 1 h. The specimen then was weighed. The previously determined weight of the bare carbon fibers divided by the weight of the specimen gave the weight fraction of fibers in the specimen. Using the density of the fibers (Table 1), the weight fraction was converted to volume fraction. The specimen was cut and mechanically polished to size 150 × 12 × 5 mm for tensile testing. Specimens with different fiber contents (Table 2) were obtained by varying the amount of cement paste that was removed by tweezers from the impregnated fiber tow. Six specimens of each fiber content were prepared and tested. Among the six, three were for static loading and the other three were for repeated loading.

Table 1
Fiber properties

Tensile strength	1.40 GPa
Tensile modulus	160 GPa
Elongation at break	0.90%
Electrical resistivity	$1.3 \times 10^{-4}\ \Omega \cdot$ cm
Density	1.9 g/cm^3
Diameter	11 μm

The direct-current electrical resistance in the stress direction was measured during tensile testing. For the resistance measurement, a Keithley 2002 multimeter and the four-probe method were used. In this method, four electrical contacts were applied by silver paint around the whole perimeter at four planes perpendicular to the length of the specimen. The four planes were symmetrical around the mid-point along the length of the specimen, such that the two outer contacts (for passing current) were 70 mm apart and the two inner contacts (for measuring voltage) were 50 mm apart.

To facilitate the gripping of the specimens during tensile testing, glass fiber epoxy-matrix composite end caps were adhesively applied to the ends (15 mm length at each end) of each specimen. The stress direction during tensile testing was along the length of the specimen. The strain in the stress direction during tensile testing was measured by using a strain gage, which was attached to the mid-point along the length of the specimen, i.e., between the two inner electrical contacts. Tensile testing under load control was performed using a hydraulic mechanical testing system (MTS model 810). Testing was conducted under static loading up to failure and under repeated loading at various stress amplitudes, which correspond to load amplitudes of 50, 100,

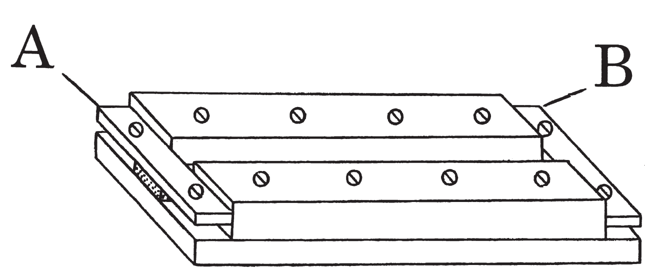

Fig. 1. Steel mold for specimen preparation. The piston above the mold cavity is not shown. The impregnated fiber tows (dotted region corresponding to the fiber ends) are in the cavity and are fastened at both ends by small steel plates A and B. The circles are screws for fastening.

Table 2
Fiber content and density

Fiber content				Density (g/cm^3)	
Weight fraction (%)		Volume fraction (%)			
Static loading	Repeated loading	Static loading	Repeated loading	Static loading	Repeated loading
2.20 ± 0.21	2.24 ± 0.14	2.57 ± 0.42	2.60 ± 0.06	2.23 ± 0.15	2.21 ± 0.09
4.61 ± 0.74	4.55 ± 0.44	5.19 ± 1.35	5.14 ± 0.25	2.16 ± 0.21	2.15 ± 0.13
7.02 ± 0.69	6.67 ± 0.43	7.37 ± 1.17	7.24 ± 0.24	2.00 ± 0.12	2.06 ± 0.05

and 150 lb. The loading rate was 2.45–6.25 lb/s for static loading and 0.125–0.375 lb/s for repeated loading.

2. Results

Fig. 2 shows the relationship between stress and strain and that between fractional resistance change ($\Delta R/R_o$) and strain during static tensile testing up to failure for a composite with 2.57 vol% carbon fibers. The stress-strain curve was linear up to a strain of 0.2%, at which the resistance started to increase abruptly. Fig. 3 shows the variation of $\Delta R/R_o$ during loading and unloading for various stress amplitudes within the linear portion of the stress-strain curve for a specimen with essentially the same fiber content. The resistance increased upon loading and decreased upon unloading in every cycle, such that the resistance increase was not totally reversible. The gage factor, which is the fractional change in resistance (reversible portion) per unit strain, is 28, 21, and 17 for the first, second and third cycles, respectively (Fig. 3). The decrease in gage factor with increasing cycle number (increasing stress amplitude) was observed in all samples (Table 3). It is attributed to the decrease in reversibility with increasing stress amplitude. It is not clear why the intermediate fiber volume fraction gave the highest gage factor. Investigation of composites with different fiber contents showed that the extent of irreversibility in resistance increase was greater when the stress amplitude as a fraction of the tensile strength was higher.

Similar piezoresistive behavior was observed for composites with various fiber contents. Table 4 lists the tensile properties and resistivity of composites with various fiber contents. The tensile strength and modulus approach the values calculated based on the rule of mixtures. The resistivity is higher than that calculated from the rule of mixtures. The ductility, strength, and modulus all increase with increasing fiber volume fraction.

3. Discussion

The abrupt increase in resistance at high strains is accompanied by a decrease in modulus (Fig. 2), so it is attributed to fiber breakage. The smaller increase in resistance at low strains is not accompanied by any change in modulus (Fig. 2), so it is attributed to fiber-matrix interface degradation. The degradation causes the fiber-matrix contact resistivity to increase, thereby affecting the measured resistance,

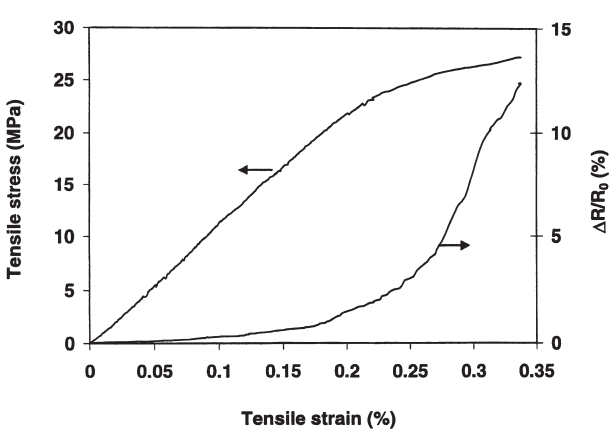

Fig. 2. Relationship between stress and strain and that between fractional resistance change ($\Delta R/R_o$) and strain during static tensile testing up to failure for a cement-matrix composite with 2.57 vol% carbon fibers.

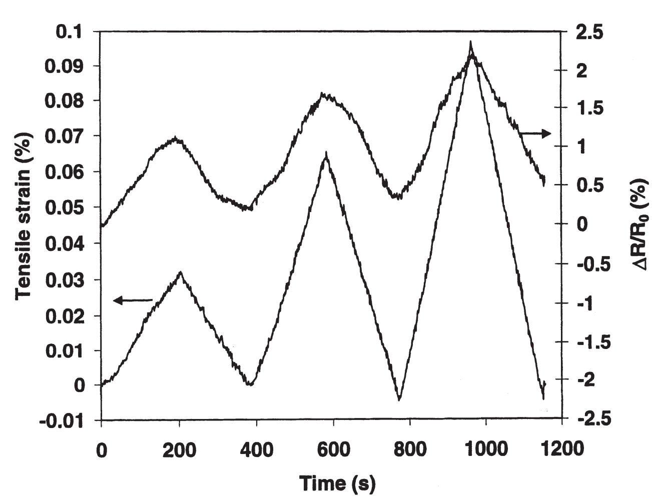

Fig. 3. Variation of $\Delta R/R_o$ during loading and unloading for various stress amplitudes within the linear portion of the stress-strain curve for a cement-matrix composite with 2.60 vol% carbon fibers.

Table 3
Gage factor

Cycle no.	Maximum load (lb)	Fiber volume fraction (%)		
		2.60 ± 0.06	5.14 ± 0.25	7.24 ± 0.24
1	50	32.6 ± 7.9	57.6 ± 2.8	33.7 ± 6.5
2	100	24.6 ± 6.9	41.7 ± 2.6	24.0 ± 2.0
3	150	16.3 ± 1.3	40.9 ± 1.7	23.4 ± 3.6

as explained in the Introduction. Fig. 3 shows that the resistance increase due to fiber-matrix interface degradation is mostly reversible. The large gage factor means that the resistance increase cannot be explained by the dimensional change, which would have resulted in a gage factor of only 2. The partly reversible fiber-matrix interface degradation probably involves reversible slight loosening of the interface. The irreversible part of the resistance increase is associated with irreversible degradation of the interface. The reversibility is consistent with that observed in short carbon fiber cement-matrix composites [15–20]. The reversible resistance change means that the continuous carbon fiber composites are strain sensors. The mechanisms of reversible resistance increase is fiber-matrix interface loosening for both short fiber and continuous fiber composites. However, the gage factor is much higher for short fiber than continuous fiber composites.

Because a broken fiber acts as an open circuit, the increase in resistance in the regime of static testing associated with fiber breakage yields the fraction of fibers broken, as shown in Fig. 4 for the sample of Fig. 2. At failure, 12% of the fibers were broken. This fraction is similarly low for continuous carbon fiber epoxy-matrix composites [22].

The method of composite fabrication in this work involved impregnation followed by curing of the impregnated fiber tows under slight tension. Saito et al. [11] involved impregnation followed by lay-up of the impregnated tows without tension. Our composites exhibit tensile strength equal to 88 ± 1% of the calculated value based on the rule of mixtures, whereas those of Saito et al. [11] exhibit tensile strength equal to 75% of the calculated value. We have made composites without tension on the impregnated fiber tows. The resulting composites are poor in strength and modulus due to the poor alignment of the fibers.

Despite the effort to align the fibers in this work, the fiber alignment is still not perfect, as shown by the low strength, low modulus, and high resistivity relative to the calculated values (Table 4). Nevertheless, the tensile strength, which reaches 86 MPa, makes these composites attractive for structural applications related to tension members, repair, surface strengthening, and lightweight structures.

Although piezoresistivity has not been previously observed in continuous fiber cement-matrix composites, it has been reported for continuous carbon fiber epoxy-matrix composites [23]. However, the resistance of the epoxy-matrix composites in the fiber direction decreases upon tension in the fiber direction, whereas that of the cement-matrix composites increases upon tension in the fiber direction. This difference in behavior is due to the difference in mechanism. The resistance decrease in the epoxy-matrix composites is due to the increase in the degree of fiber alignment [23], whereas that in the cement-matrix composites is due to the fiber-matrix interface degradation. The fiber-matrix bond is much stronger for epoxy than cement and the fiber content is much higher for epoxy- than cement-matrix composites. Moreover, epoxy is much more ductile than cement under tension. These differences in characteristics between epoxy and cement probably cause the difference in piezoresistive behavior.

4. Conclusion

Piezoresistivity with gage factor up to 60 was observed in continuous carbon fiber cement-matrix composites with fiber volume fractions in the range from 2.6% to 7.4%. The electrical resistance in the fiber direction, as measured using

Table 4
Tensile properties and electrical resistivity

	Carbon fiber volume fraction (%)		
	2.57 ± 0.42	5.19 ± 1.35	7.37 ± 1.17
Tensile strength (MPa)			
Measured	27.2 ± 1.2	57.3 ± 1.1	85.7 ± 1.32
Calculated*	30.8	64.4	98
Tensile modulus (GPa)			
Measured	11.1 ± 0.52	14.6 ± 0.86	17.3 ± 0.92
Calculated*	13.1	17.1	20.8
Ductility (%)	0.341 ± 0.011	0.468 ± 0.008	0.485 ± 0.008
Resistivity (Ω·cm)			
Measured	$(1.10 \pm 0.11) \times 10^{-1}$	$(8.40 \pm 0.94) \times 10^{-2}$	$(4.56 \pm 1.32) \times 10^{-2}$
Calculated*	5.91×10^{-2}	2.83×10^{-2}	1.86×10^{-2}

* Based on the rule of mixtures.

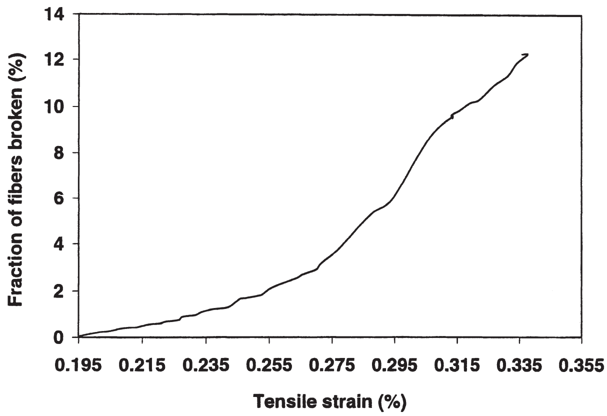

Fig. 4. Fraction of fibers broken vs. tensile strain, as obtained from Fig. 2.

surface electrical contacts, increases upon tension in the same direction. The resistance increase is mostly reversible, such that the irreversible portion increases with the stress amplitude. The effect is attributed to fiber-matrix interface degradation, which is partly irreversible. At higher strains at which the modulus is decreased, the resistance increases with strain abruptly, due to fiber breakage. The tensile strength of the composites is 88 $\pm$ 1% of the calculated value based on the rule of mixtures. The tensile modulus is 84 $\pm$ 1% of the calculated value based on the rule of mixtures.

Acknowledgments

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