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Effect of Moisture on Piezoresistivity of Carbon Fiber-Reinforced Cement Paste

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Piezoresistivity, as exhibited by carbon fiber-reinforced cement-based material, allows a structural material to sense its strain or stress through electrical resistance measurement. This paper addresses the worst scenario associated with the effect of moisture on the piezoresistivity of carbon fiber-reinforced cement paste. This scenario is associated with both water saturation and a fiber content below the percolation threshold. For this scenario relative to the condition after drying at room temperature, the gauge factor (fractional change in resistance per unit strain) is decreased by at least 12% and the variability of the gauge factor with the strain amplitude and with the strain history is increased. These negative effects are attributed to the water at the fiber-matrix interface. The water interferes with the electronic conduction across the interface. Nevertheless, the piezoresistivity remains strong, the signal-to-noise ratio of the resistance remains high, and the relationship between resistivity and strain remains quite linear.

Keywords: carbon; electrical resistivity; fibers; moisture; piezoresistivity; strain.

INTRODUCTION

Piezoresistivity is a phenomenon in which the electrical resistivity changes with strain.[1-3] It allows the detection of strain through electrical resistance measurement. Such detection is needed for structures for the purpose of vibration control, stress monitoring, and load scaling. Examples of load scaling are weighing (including weighing in motion) and room occupancy monitoring (for the purpose of building facility management or evacuation monitoring).

The ability of a structural material to sense its own strain is to be distinguished from the attainment of the sensing function by the use of embedded or attached devices. Compared with the latter, the former is attractive for its low cost, high durability, large sensing volume, and absence of mechanical property loss (which tends to occur in the case of embedded devices).[1]

A cement-based material reinforced with short carbon fibers has a strong effect of piezoresistivity. The electrical resistivity increases reversibly in an element with uniaxial tension[4,5] and decreases reversibly with uniaxial compression.[6-8] Under flexure, the surface resistance of the tension side increases whereas that of the compression side decreases upon loading.[9] The fractional change in DC electrical resistance per unit strain (a figure of merit known as the gauge factor) is in the hundreds for carbon fiber-reinforced cement paste,[4-13] in contrast to a value of approximately 2 for metal strain gauges. The piezoresistive behavior is relatively weak for cement-based materials reinforced with steel fibers or carbon nanofibers.[2,3]

The electrical conductivity of cement-based materials is affected by moisture, as water provides ions that contribute to ionic conduction. Due to a decrease in the amount of free water (which is to be distinguished from water trapped in the hydrate that is formed during the curing reaction), the electrical conductivity of carbon fiber-reinforced cement paste decreases with time during curing.[14,15] The effect is much smaller than that in the case without the fiber reinforcement,[15] however, due to the mainly electronic nature of the electrical conduction in carbon fiber-reinforced cement paste.[16] Furthermore, the effect is less at a higher fiber content[15] due to the diminished role of the cement matrix when the fiber content is higher. In addition, the conductivity of carbon fiber-reinforced cement paste decreases after heating at 80 °C (176 °F) for 24 hours subsequent to curing,[17] due to moisture loss. With the increase in the amount of free water, the conductivity of carbon fiber-reinforced cement paste increases after water absorption that is conducted subsequent to curing.[16]

The dielectric effect in a cement-based material relates to the flow of ions in response to an applied electric field and the consequent electric polarization. The lower is the electrical resistivity of the material, the less is the polarization. As a result, the dielectric effect is less in carbon fiber-reinforced cement than cement that contains no conductive admixture.[18] The effect is enhanced by moisture, which provides ions.[19] It also depends on the stress.[20]

Although there has been considerable study on the effect of moisture on the electrical conductivity[14-17] and dielectric behavior[19] of cement-based materials, little attention has been given to the effect of moisture on the piezoresistive behavior. It has been reported that the relative humidity during curing has a negligible effect on the fractional change in resistance (relative to the resistance in the unloaded state) at compressive/tensile fracture of carbon fiber-reinforced cement paste at 7 days of curing.[21] It has also been reported that the electrical resistivity of carbon fiber-reinforced cement paste decreases upon compression at either 14 or 28 days of curing, but increases upon compression at 7 days of curing.[22] This means that the piezoresistivity mechanism changes between 7 and 14 days of curing, though the mechanism at 7 days of curing has been little studied. The behavior at 14 days of curing is more relevant to practical applications. In spite of the report on the effect of curing age on the piezoresistivity, the effect of water absorption (after curing) on the piezoresistivity has not been previously reported.

Moisture is encountered by cement-based structures due to rain, flooding, underwater use, and other environmental conditions. Therefore, the effect of moisture on the piezoresistivity of carbon fiber-reinforced cement paste is relevant to

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the practical application of this type of material as a piezoresistive structural material.

Electrical conduction in carbon fiber-reinforced cement paste is dominated by electronic conduction rather than ionic conduction[16] due to the electronic nature of the conduction in carbon fibers. In this context, electronic conduction relates to conduction by electrons and/or holes. Even at a fiber content below the percolation threshold (volume fraction above which the fibers touch one another to form a continuous, electrically conductive path),[23] electronic conduction dominates in carbon fiber-reinforced cement paste.[16] Piezoresistivity in carbon fiber-reinforced cement paste involves the slight pullout of crack-bridging fibers and the consequent increase in the contact resistivity of the fiber-matrix interface upon tension.[24] The reverse occurs upon compression. As water absorption is expected to affect the fiber-matrix interface, it is expected to affect the piezoresistivity of carbon fiber-reinforced cement paste.

This paper is focused on investigating the effect of moisture (free water due to water absorption after curing) on the piezoresistivity of carbon fiber-reinforced cement paste. The investigation involves comparison of the piezoresistive behavior in the dry state (the state after drying at room temperature) and in the wet state (the state after water absorption to saturation). States with water content higher than that of the dry state and lower than that of the wet state are not addressed, even though such intermediate states are more commonly encountered in practice than the wet state. The intermediate states are expected to exhibit piezoresistive behavior that is intermediate between those of the dry and wet states. Although the wet state is not commonly encountered in practice, it represents an extreme state that is useful for providing an upper bound to the effect of moisture on the piezoresistive behavior.

The carbon fiber-reinforced cement paste analyzed in this study is at a fiber content below the percolation threshold. The higher the fiber volume fraction, the lower the cement matrix volume fraction, and the less the amount of water absorption. This trend is expected in spite of the low fiber volume fraction in this work and the consequent small effect of the fiber volume fraction. Furthermore, at a fiber content above the percolation threshold, the conduction path does not involve the cement matrix, so that the effect of water absorption by the cement matrix on the electrical conduction is expected to be less than the corresponding case of fiber contents below the percolation threshold. Although the workability decrease associated with increasing the fiber content may cause increased air void content and, hence, increased water absorption, this effect can be made small by the use of a water-reducing agent, which is used in this work. Furthermore, the fiber may decrease the amount of shrinkage cracks, thereby decreasing the water absorption. By considering both a fiber content below the percolation threshold and the state of water saturation, this paper addresses the worst scenario in terms of the possible negative effect of moisture uptake. The assessment of this upper bound condition is the objective of this paper.

Table 1—Properties of carbon fibers used in cement-matrix composites

Filament diameter	15 ± 3 μm ([5.9 ± 1.2] × 10^{-4} in.)
Tensile strength	690 MPa (1.0 × 10^5 psi)
Tensile modulus	48 GPa (7.0 × 10^6 psi)
Elongation at break	1.4%
Electrical resistivity	3.0 × 10^{-3} Ω.cm (1.2 × 10^{-3} Ω.in.)
Specific gravity	1.6 g cm^{-3} (100 lb/ft^3)
Carbon content	98 wt.%

Aggregates affect both the electrical conductivity[13,14,23,25-27] and the piezoresistivity[21] of carbon fiber-reinforced cement-based materials. The effect of aggregates is not addressed in this paper, however, which is directed at a fundamental study of the effect of moisture on the piezoresistive behavior. Nevertheless, the effect of moisture in the presence of aggregate is expected to be smaller than that in the absence of aggregate because the piezoresistive phenomenon is associated with the cement paste rather than the aggregate, and the moisture enters the cement paste rather than the nonporous aggregate. This work involving cement paste provides the foundation for future work involving aggregates.

RESEARCH SIGNIFICANCE

Water is commonly encountered by concrete structures. This paper provides the first study of the effect of moisture on the piezoresistivity of a carbon fiber-reinforced cement-based material. By addressing the worst scenario, which is associated with both water saturation (by absorption after curing) and a fiber content below the percolation threshold, this study provides the upper bound for the effect of moisture (free water). The worst scenario and the corresponding state after drying at room temperature are compared in terms of the sensitivity, accuracy, and repeatability of the piezoresistivity-based strain sensing. This information is useful for practical application of the phenomenon.

EXPERIMENTAL METHODS

Materials

The cement-based material used in the study is carbon fiber-reinforced cement paste. In other words, there is no aggregate. The paste contains ozone-treated carbon fiber and silica fume.

The carbon fiber is isotropic pitch-based, unsized, with a diameter of 15 μm and a nominal length of 5 mm (0.2 in.). The fiber properties are shown in Table 1.[28] The amount of fibers is 0.5% by mass of cement (corresponding to 0.5 vol.% of the composite). The volume fraction is obtained by consideration of the density of the fiber and the volume of the composite. This fiber content is below the percolation threshold, which is between 0.5 and 1.0 vol.%.[23] For the effect of the carbon fiber volume fraction on the resistivity, refer to Reference 23. The conduction is dominated by the fibers.[16] The silica fume essentially does not contribute to the conduction; it mainly contributes to improving the fiber dispersion.

The fiber content used has been extensively used in previous research on the piezoresistivity in carbon fiber-reinforced cement paste.[4,6,8,9,16,28,29] For the behavior at

other fiber contents, please refer to Reference 7. For the behavior in the absence of fiber, please refer to Reference 30.

The ozone treatment of the fibers was conducted prior to incorporating the fibers in the cement mixture to improve the hydrophylicity of the fibers.[4] This process involves drying the fibers at 110 °C (230 ºF) in air for 1 hour and then treating the surface with ozone by exposure to ozone gas (0.6 vol.% in oxygen) at 160 °C (320 °F) for 10 minutes.

The cement was Type I portland cement. The water-cement ratio (*w*/*c*) was 0.35. No aggregate was used. A water-reducing agent was used in the amount of 1.0% by mass of cement.[7]

Due to its submicron particle size, silica fume was used to help the dispersion of the fibers.[31] As in previous work on carbon fiber-reinforced cement, it was in the amount of 15% by mass of cement.[7] The silica fume served to enhance the fiber distribution, in contrast to the conventional functions of silica fume in cement-based materials.

Methylcellulose in the amount of 0.4% by mass of cement is used along with the silica fume.[7] Both silica fume and methylcellulose solutions, when used separately, help the fiber dispersion, but the combined use of silica fume and methylcellulose solution is even more effective.[31] The defoamer was in the amount of 0.13 vol.% (percent of specimen volume) and was used along with the methylcellulose,[7] due to the foam that is generated by the use of methylcellulose. A rotary mixer with a flat beater was used for mixing. Methylcellulose was dissolved in water and then the defoamer was added and stirred by hand for approximately 2 minutes. Then the methylcellulose solution, cement, water, silica fume, and fibers were mixed in the mixer for 5 minutes. After pouring into molds, an external vibrator was used to achieve the compaction and decrease the amount of air bubbles. The specimens were demolded after 24 hours and then cured in air at room temperature with a relative humidity of nearly100% (attained in a moisture chamber) for 28 days.[7] The hydration reaction occurs during curing.

Specimens in the dry state were obtained by removing them from the moisture chamber and drying in air at room temperature for a few days. Specimens in the wet state were obtained by putting the specimens that were initially in the dry state into a moisture chamber with a relative humidity of nearly 100% for approximately 3 days. The testing of a wet specimen was conducted while the specimen was still saturated (or nearly saturated) with water. Three specimens were tested. Each specimen was tested in the dry state and then in the wet state to study the effect of water absorption.

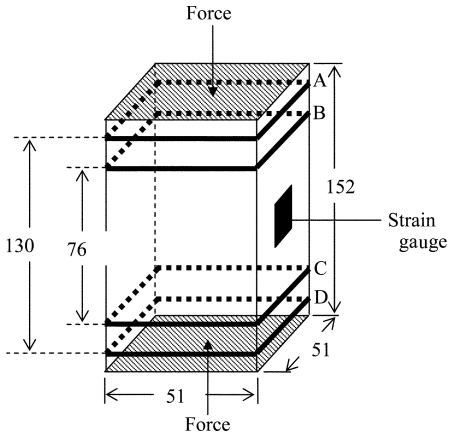

Fig. 1—Specimen configuration for piezoresistivity testing. Four electrical contacts are embedded steel in planes indicated by A, B, C, and D. (Note: All dimensions are in mm.; 1 mm = 0.0394 in.)

Testing

Each specimen has a dimension of 6 in. (150 mm) tall with a square (2 x 2 in. [51 x 51 mm]) cross section (Fig. 1).[8] Compressive stress is applied along the long axis of the specimen. The column shape is chosen due to the need to apply four electrical contacts at four planes that are perpendicular to the length of the column for the purpose of measuring the electrical resistance along the axis of the column. The DC electrical resistance is continuously measured using a multimeter while repeated compressive loading at various strain amplitudes is applied along the length of the specimen using a hydraulic mechanical testing system. The loading is all within the elastic range, which is characterized by the return of the strain to zero upon unloading. The strain at the elastic limit is approximately 0.5%, beyond which damage occurs, as previously reported for carbon fiber-reinforced cement of the same composition.[29] The stress-strain curve is linear up to failure.[29] Damage causes an irreversible increase in the electrical resistivity, thereby allowing damage sensing,[29] which is beyond the scope of this paper. The strain in the longitudinal direction is measured by using a metallic strain gauge that has been adhesively attached to the center of a vertical face of the specimen when the specimen is in the dry state. Evaluation is conducted, including measurement of the electrical resistivity, the gauge factor (the fractional change in resistance per unit strain, that is, a measure of the strain sensitivity), the data divergence (as shown by testing three specimens), and the possible effect of strain history.

Each electrical contact is made of an embedded stainless steel foil. Although copper is more conductive than steel, the surface oxidation by a copper element with moisture could be a problem. Besides, steel is commonly embedded in cement-based materials for the purpose of providing reinforcement, so its use in cement is well established. Stainless steel is even more favorable due to its corrosion resistance. It is seldom used, however, as a reinforcement due to its high cost. Steel is an electronic conductor (not an ionic conductor), so the use of steel electrical contacts allows both electronic and ionic conduction in the cement-based material.[16]

Electrical contacts made of ionic conductors are widely used for studying the electrical conduction in cement-based materials, as they allow ionic conduction. They are commonly in the form of water (or aqueous solutions) being held in a sponge, paper towel, or other water absorbing media. From the viewpoint of implementation of piezoresistive strain sensing in cement-based structures, the use of a volatile form of electrical contact is not practical. In contrast, electrical contacts in the form of metals are suitable for practical implementation.

The four-probe method was used in this work. The inner two electrical contacts were 3 in. (76 mm) apart from one another. The outer two electrical contacts were 5 in. (130 mm) apart from one another, such that each contact was at a distance of 0.5 in. (13 mm) from an end of the column. Hence, the adjacent current and voltage contacts were 1 in. (25 mm) apart.

An embedded stainless steel contact was installed in the specimen during the placement of the cement. Each steel

contact was in the form of a stainless steel foil (0.06 mm [0.002 in.] thick) that had punched holes of a diameter of 3 mm (0.1 in.), such that the edges of adjacent holes were apart by a distance ranging from 2 to 3 mm (0.08 to 0.12 in.) and the holes were arranged in a square array and they occupied 17.4% of the 2 x 2 in. (51 x 51 mm) embedded foil area. The holes allowed mechanical interlocking between the foil and the cement.

RESULTS AND DISCUSSION

Figures 2 and 3 show the fractional change in longitudinal resistance during repeated loading at various strain amplitudes in the elastic regime for the dry and wet states, respectively. The series of strain amplitudes used in the 10 cycles, as designed to investigate if there is any effect of the strain history, is the same for the dry and wet states. The strain returns to zero at the end of each stress cycle. In every cycle, the resistance decreases reversibly upon loading. Examination of the fractional change in resistance for the series of stress cycles in Fig. 2 and 3 shows that there is no dependency on the strain history, as explained in the following. Cycles 1, 3, and 10 have essentially the same strain amplitude of -0.27×10^{-4}; Cycles 2 and 5 have essentially the same strain amplitude of -0.52×10^{-4}; Cycles 4 and 7 have essentially the same strain amplitude of -0.85×10^{-4}; Cycles 6 and 9 have essentially the same strain amplitude of -1.1×10^{-4}. In spite of the difference in strain history among the cycles in each of these groups, different cycles at essentially the same strain amplitude give essentially the same fractional change in resistance. The absence of strain history dependence adds to the feasibility of strain sensing using this multifunctional cement-based material. A comparison of Fig. 2 and 3 shows that the signal-to-noise ratio is similar for the dry and wet states.

The initial resistivity (prior to any loading) is $(1.22 \pm 0.18) \times 10^4$ Ω.cm [$(4.8 \pm 0.7) \times 10^3$ Ω.in.] and $(4.10 \pm 0.62) \times 10^3$ Ω.cm [$(1.6 \pm 0.2) \times 10^3$ Ω.in.] for the dry and wet states, respectively. The conductivity is substantially higher for the wet state than the dry state. This is expected because the water in the wet state promotes ionic conduction.

Table 1 shows that the gauge factor (fractional change in resistance per unit strain) is lower for the wet state than the dry state. Both states, however, provide effective sensing. For both the dry and wet states, the gauge factor has a scatter of up to 17% among the three specimens of each type tested.

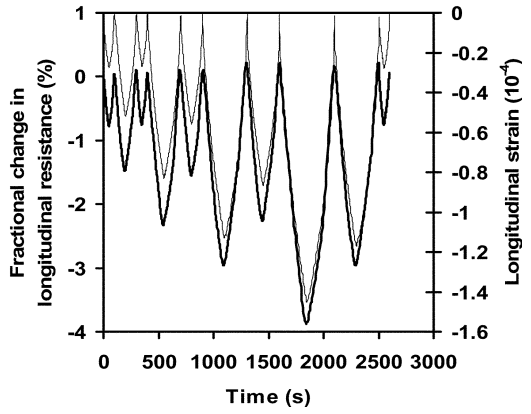

Fig. 2—Curves of fractional change in longitudinal resistance (thick curve) versus time and of longitudinal strain (thin curve) versus time using repeated compression at various strain amplitudes, for dry state.

In real structural application, this variability in the gauge factor is less of an issue because a particular structure is always a particular piece of cement-based material (unless the structure is dismantled) and the strain sensing calibration is conducted for that particular piece of material. The gauge factor has more variability among the cycles for the wet state (gauge factor ranging from 218 to 262, that is, 20% variation) than the dry state (gauge factor ranging from 267 to 291, that is, 9% variation). Thus, the dry state is superior to the wet state for strain sensing.

Table 2 shows the resistivity at the peak strain averaged over the three specimens of each state. To investigate the dependence of the resistivity at the peak strain with the strain amplitude, it is better to consider this variation for a single specimen rather than considering the variation of the average resistivity of three specimens. This is because the variation among specimens may overshadow the variation with the strain amplitude. Therefore, it is revealing to consider the variation of a single specimen in each experiment. Figures 4

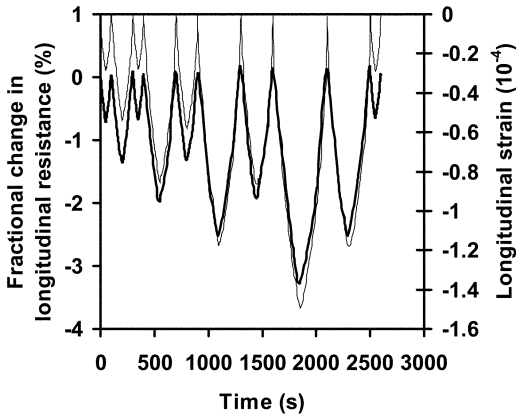

Fig. 3—Curves of fractional change in longitudinal resistance (thick curve) versus time and of longitudinal strain (thin curve) versus time using repeated compression at various strain amplitudes, for wet state.

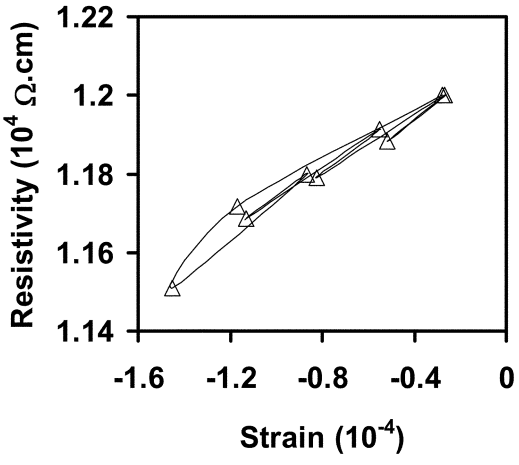

Fig. 4—Variation of resistivity at peak strain versus strain amplitude for single specimen of dry state. Data points are connected with line drawn to indicate order in which various strain amplitudes are imposed. Order is as shown in Fig. 2. Data correspond to those of Fig. 2. (Note: 1.00×10^4 Ω.cm = 3.94×10^3 Ω.in.

and 5 show the variation for a single specimen of the dry and wet states, respectively.

The resistivity at the peak strain decreases monotonically with increasing magnitude of the strain amplitude for both dry and wet states, as shown in Fig. 4 and 5, respectively. Both methods give a roughly linear relationship between the resistivity at the peak strain and the strain amplitude. The roughly linear behavior indicates that the gauge factor is essentially independent of the strain amplitude. It is effective for strain sensing.

Table 2 shows essentially no systematic effect of the strain amplitude on the gauge factor. It is more revealing, however, to study the effect in a single specimen rather than consider the average value of the gauge factor for three specimens of each electrical contact configuration. As shown in Fig. 6 for one specimen of each state, the gauge factor decreases with increasing magnitude of the strain amplitude for both states. Based on Fig. 6, the fractional decrease in gauge factor per unit strain is 600 for the dry state and 1100 for the wet state. The extrapolated value of the gauge factor at zero strain is decreased by 12% in going from the dry state to the wet state. The extrapolated value of the gauge factor at a strain magnitude of 1.6×10^{-6} is decreased by 20% in going from the dry state to the wet state. The dependence of the gauge factor on the strain amplitude is not desirable for practical application. The dependence is small for the dry state compared with the wet state. Due to the decrease of the gauge factor with increasing strain amplitude, strain sensing based on the piezoresistivity is preferably performed at low strain amplitudes. The elastic limit of approximately 0.5% strain[30] is the ultimate strain limit for the strain sensing. In addition, Fig. 6 shows that the gauge factor depends on the strain history. The dependence is smaller for the dry state than the wet state. Thus, the strain sensing in the wet state is less accurate than that in the dry state.

In summary, in the wet state, the gauge factor is lower, varies more with the strain amplitude, and depends more on the strain history in comparison with the dry state. The signal-to-noise level in the resistivity variation, however, is similar for both states. In spite of the drawbacks of the wet state compared with the dry state, the piezoresistive effect of the wet state remains strong and the relationship between resistivity and strain remains quite linear. Therefore, carbon fiber-reinforced cement can provide strain sensing regardless of its free water content, although the performance is better when the free water content is low.

The wet state is the state of water saturation and represents the worst scenario that is seldom encountered in practice (unless a marine environment is encountered). The effect of moisture at levels below water saturation is expected to exhibit a gauge factor that is between the values of the dry

Table 2—Strain amplitude and corresponding gauge factor for each cycle of uniaxial compression imposed on carbon fiber-reinforced cement in dry and wet states*

Cycle no.	Strain amplitude (10^{-4})		Gauge factor		Resistivity (10^4 Ωcm) (3.94×10^3 Ωin.)	
	Wet	Dry	Wet	Dry	Wet	Dry
1	–0.27 ± 0.02	–0.27 ± 0.01	262 ± 39	287 ± 42	0.407 ± 0.052	1.20 ± 0.16
2	–0.54 ± 0.03	–0.52 ± 0.03	253 ± 41	285 ± 40	0.405 ± 0.061	1.19 ± 0.14
3	–0.28 ± 0.02	–0.27 ± 0.01	244 ± 32	286 ± 37	0.407 ± 0.052	1.20 ± 0.16
4	–0.84 ± 0.02	–0.82 ± 0.03	241 ± 33	278 ± 46	0.402 ± 0.059	1.18 ± 0.17
5	–0.56 ± 0.02	–0.55 ± 0.02	242 ± 30	291 ± 41	0.405 ± 0.058	1.19 ± 0.14
6	–1.15 ± 0.03	–1.13 ± 0.04	226 ± 35	267 ± 33	0.400 ± 0.060	1.17 ± 0.15
7	–0.86 ± 0.02	–0.87 ± 0.03	236 ± 36	286 ± 43	0.402 ± 0.059	1.18 ± 0.14
8	–1.51 ± 0.04	–1.45 ± 0.03	218 ± 34	278 ± 45	0.397 ± 0.060	1.15 ± 0.14
9	–1.18 ± 0.03	–1.17 ± 0.04	224 ± 35	285 ± 35	0.401 ± 0.061	1.17 ± 0.13
10	–0.29 ± 0.02	–0.28 ± 0.01	233 ± 40	278 ± 39	0.408 ± 0.054	1.20 ± 0.18

*Initial resistivity is $(1.22 \pm 0.18) \times 10^4$ Ω.cm ($[4.80 \pm 0.71] \times 10^3$ Ω.in.) and $(4.10 \pm 0.62) \times 10^3$ Ωcm ($[1.61 \pm 0.24] \times 10^3$ Ω.in.) for dry and wet states, respectively. Three specimens were tested for each state.

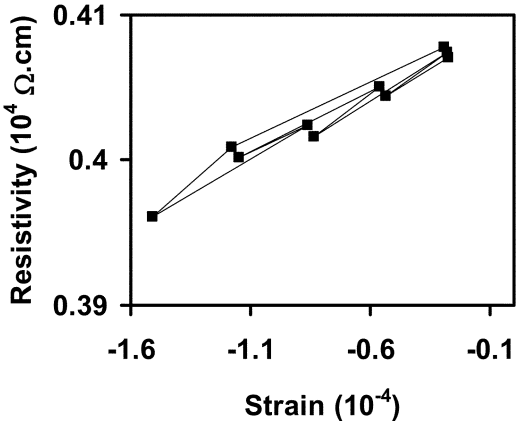

Fig. 5—Variation of resistivity at peak strain versus strain amplitude for single specimen of wet state. Data points are connected with line drawn to indicate order in which various strain amplitudes are imposed. Order is as shown in Fig. 3. Data correspond to those of Fig. 3. (Note: 1.00 × 10^4 Ω.cm = 3.94 × 10^3 Ω.in.

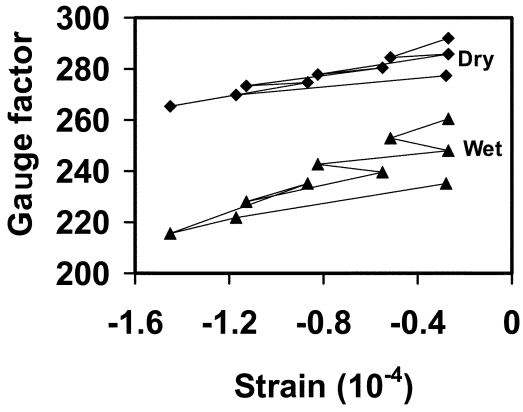

Fig. 6—Effect of strain amplitude on gauge factor, as shown for one specimen of dry state and one specimen of wet state. Data points for each state are connected with line drawn to indicate order in which various strain amplitudes are imposed. Data and order are as shown in Fig. 2 and 3 for the dry and wet states, respectively.

and wet states and that varies with the strain amplitude to a degree that is intermediate between those of the dry and wet states. Future work should address the intermediate states of wetness.

The initial resistivity values correspond to conductivity values of 8.4×10^{-5} $\Omega^{-1}.cm^{-1}$ (2.1×10^{-4} $\Omega^{-1}.in.^{-1}$) and 2.5×10^{-4} $\Omega^{-1}.cm^{-1}$ ($6.4 \times 10^{-4}\Omega^{-1}.in.^{-1}$) for the dry and wet states, respectively. The fractional electronic contribution to the conductivity of the dry state is 0.99.[16] Thus, it can be assumed that the conductivity is all electronic in the dry state and the additional conductivity for the wet state is due to ionic conduction. This means that, in the wet state, electronic conduction contributes 0.34 of the conductivity, while ionic conductivity contributes 0.66 of the conductivity. The large contribution of ionic conduction in the wet state is consistent with the fact that the wet state corresponds to a state of near saturation by water.

In spite of the high conductivity of the wet state, the gauge factor is lower for the wet state than the dry state. In other words, for the same strain amplitude, the fractional change in resistance is lower for the wet state than the dry state. The low value of the gauge factor of the wet state reflects interference of the ions to the piezoresistivity, which involves conduction across the fiber-matrix interface.[24] Carbon is an electronic conductor (not an ionic conductor), although conduction in cement can have both ionic and electronic contributions. Due to the electronic nature of the conduction in carbon fibers, conduction across the fiber-matrix interface must be electronic (not ionic). Water is an ionic conductor rather than an electronic conductor. Therefore, it interferes with the conduction across the fiber-matrix interface. In other words, the presence of water at areas of the interface causes these parts of the interface not to contribute to the piezoresistivity. As a result, the piezoresistive effect is diminished. Furthermore, the variability in the spatial distribution of water at the fiber-matrix interface may contribute to causing variability in the gauge factor. As a consequence, the gauge factor has more variability in the wet state than the dry state. In addition, the spatial distribution of water at the interface may depend on the strain history. This dependence may contribute to causing the gauge factor in the wet state to depend on the strain history to a degree that exceeds that in the dry state.

The piezoresistivity results of this work have been fitted with an analytical model that has been previously reported for the piezoresistivity phenomenon of carbon fiber-reinforced cement.[24] The model is based on the assumption that the piezoresistivity is due to the slight pullout of crack-bridging fibers during crack opening and the consequent increase in the contact electrical resistivity of the fiber-matrix interface (Fig. 7). The adjustable parameter in this model is the product of a and t, where a is the length of the major axis of an elliptical crack and t is the crack width. Figures 8 and 9 show the measured and calculated piezoresistive data for the dry and wet states, respectively. The curve fitting provides at values of 81.2 μm^2 (1.26×10^{-7} $in.^2$) and 18.9 μm^2 (2.93×10^{-8} $in.^2$) for the dry and wet states, respectively. The smaller size of the cracks for the wet state is consistent with the presence of water. In other words, the moisture makes the effective crack size smaller.

By considering both a fiber content below the percolation threshold and the state of water saturation, this paper addresses the worst scenario in terms of the negative effect of moisture uptake. This analysis shows that, even for this worst scenario, the negative effect of moisture on the piezoresistivity is small enough that the piezoresistivity remains strong.

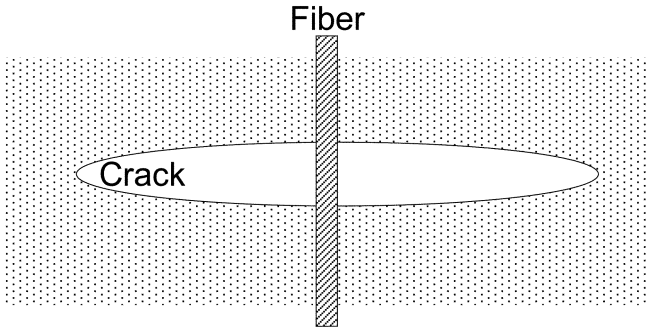

Fig. 7—Model of piezoresistivity mechanism, involving slight pullout of crack-bridging fibers during crack opening and consequent increase in contact electrical resistivity of fiber-matrix interface.

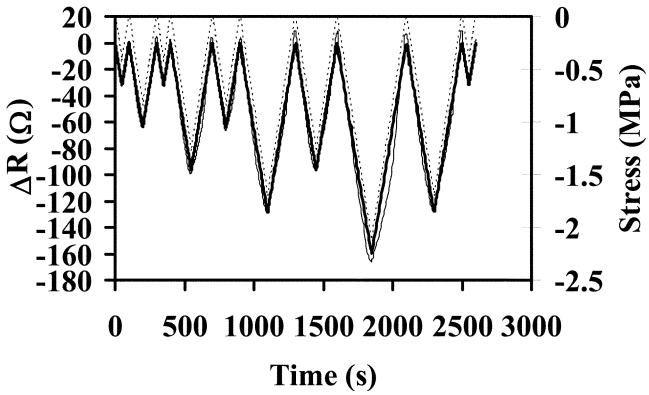

Fig. 8—Variation of measured and calculated values of change in electrical resistance (ΔR) with time and of applied stress with time under uniaxial compression for dry state. Thick solid line, thin solid line, and dashed line indicate measured ΔR, calculated ΔR, and stress, respectively. (Note: 1.00 MPa = 145 psi.)

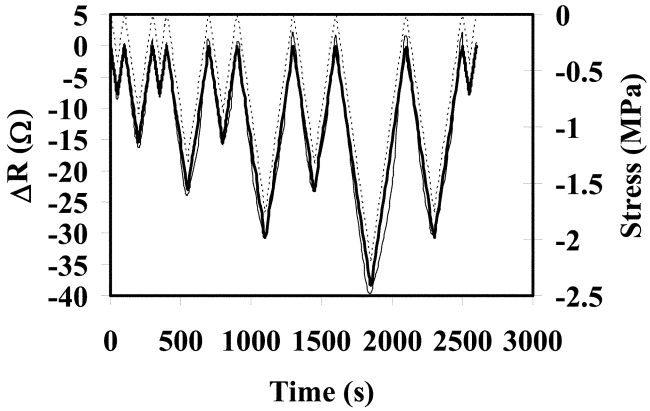

Fig. 9—Variation of measured and calculated values of change in electrical resistance (ΔR) with time and of applied stress with time under uniaxial compression for wet state. Thick solid line, thin solid line, and dashed line indicate measured ΔR, calculated ΔR, and stress, respectively. (Note: 1.00 MPa = 145 psi.)

The piezoresistive behavior can be used for the sensing of strain or stress, although this paper emphasizes strain effects. The relation between stress and strain of carbon fiber-reinforced cement paste under compression has been previously reported.[29]

CONCLUSIONS

This paper addresses the worst scenario associated with the effect of moisture on the piezoresistivity of carbon fiber-reinforced cement paste. The worst scenario is associated with both the extreme moisture content corresponding to water saturation and a fiber content below the percolation threshold. For this worst scenario, moisture diminishes the piezoresistivity. It decreases the gauge factor by at least 12% and increases the variability of the gauge factor with the strain amplitude and with the strain history, although it increases the electrical conductivity. The diminished piezoresistivity is because of the water at the fiber-matrix interface interfering the electronic conduction. In spite of the lower piezoresistive performance of the water-saturated state, the piezoresistivity remains strong, the signal-to-noise ratio of the resistance remains high, and the relationship between resistivity and strain remains quite linear. These findings mean that carbon fiber-reinforced cement-based materials can be used as strain sensors irrespective of their state of wetness.

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