Available online at www.sciencedirect.com
ScienceDirect
Carbon 45 (2007) 710–716
CARBON
www.elsevier.com/locate/carbon

Electrical-resistance-based damage self-sensing in carbon fiber reinforced cement

Sihai Wen, D.D.L. Chung *

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

Received 12 April 2006; accepted 30 November 2006
Available online 9 January 2007

Abstract

Damage self-sensing (to be distinguished from strain self-sensing) by electrical resistance measurement is effective in carbon fiber reinforced cement below the percolation threshold, as shown under uniaxial compression. Major damage that is accompanied by irreversible strain is indicated by irreversible resistivity increase ranging from 10% to 30%. Minor damage in the elastic regime is indicated by this increase ranging from 1% to 7%. The irreversible resistivity fractional change per unit irreversible strain is higher in the transverse direction than the longitudinal direction. The origin of the damage self-sensing ability is attributed to the fracture of fibers that bridge microcracks and the consequent resistivity increase. The fracture of a bridging fiber occurs upon microcrack opening or shear.

1. Introduction

For the purpose of hazard mitigation, it is valuable to monitor the damage in a concrete structure, whether the damage is due to earthquake, wind, ocean waves or live loads. The damage sensing is also referred to as structural health monitoring. This monitoring may be conducted occasionally, though continuous monitoring is preferred for enhanced safety.

Embedded sensors such as fiber-optic sensors have been used for damage sensing in concrete structures. Continuous carbon fiber in cement has been reported for damage sensing, due to the increase in electrical resistance of the composite upon fiber breakage [1]. However, embedded sensors and continuous fibers suffer from the high cost of installation. A less costly technique involves admixtures, which can be incorporated in the cement mix. In general, the use of a structural material (without embedded sensors) as the sensor is known as self-sensing.

Self-sensing is made possible by the effect of damage on the volume electrical resistivity of the cement-based material [2]. Damage causes the resistivity to increase, as observed for damage in the elastic regime [3], in the plastic (inelastic) deformation region [4–9], and after failure [8], though information prior to failure is more useful than that after failure. Damage effects have been reported for cement-based materials that contain electrically conductive admixtures (e.g., short carbon fiber) [10,11] and those that do not contain conductive admixtures [4], whether aggregates are present or not [12]. The occurrence of damage has been shown by acoustic emission observation during loading [11]. Although a conductive admixture is not required, its presence enhances the effectiveness for damage sensing [2,10]. In particular, the presence of short carbon fiber as an admixture enhances both damage sensing and strain sensing [2,13,14].

Sensing by AC impedance measurement [8,9,15] is less studied than that by DC resistance measurement [2–7,10–14]. The DC method is simpler for implementation than the AC method.

Strain sensing by impedance measurement using the two-probe method (i.e., a configuration involving two electrical contacts) and embedded steel electrical contacts in

* Corresponding author. Tel.: +1 716 645 2593x2243; fax: +1 716 645 3875.
E-mail address: ddlchung@buffalo.edu (D.D.L. Chung).
URL: http://alum.mit.edu/www/ddlchung (D.D.L. Chung).

0008-6223/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.carbon.2006.11.029

carbon fiber reinforced cement mortar has been reported during compression, though the absence of observation during subsequent unloading makes it not possible to distinguish between the effects of reversible strain and irreversible damage [15].

Damage sensing in carbon fiber reinforced cement by impedance measurement using the two-probe method and electrical contacts in the form of water-saturated paper towel has been reported in relation to crack propagation from a notch made in the specimen prior to tensile testing [9]. As water is an ionic conductor, the conduction involves ions. The real part of the impedance increases as the crack mouth opening displacement increases [9].

Continuous DC resistance measurement for an extended time causes electric polarization, which results in increase in the measured resistance [16,17]. However, polarization is much less in carbon fiber reinforced cement than cement without carbon fiber [16].

This work is concerned with DC resistance measurement using the four-probe method, which is a configuration involving four electrical contacts. The outer two contacts are for passing current, while the inner two contacts are for voltage measurement. The four-probe method is advantageous over the two-probe method in that the measured resistance does not include the contact resistance.

The fiber is typically used at a volume fraction below the percolation threshold, because of the need to maintain high compressive strength, high workability and low cost. Furthermore, exceeding the percolation threshold does not affect significantly the strain sensing ability [18–20]. The fiber is not a sensor, but is an additive for enhancing the sensing ability of the cement-based material. This paper is focused on carbon fiber reinforced cement below the percolation threshold.

Damage sensing is to be distinguished from strain sensing, as strain can be reversible and is not necessarily accompanied by damage. Compressive strain causes the resistivity (as obtained by the four-probe method) of carbon fiber reinforced cement to decrease reversibly, whereas tensile strain causes the resistivity to increase reversibly [21–23]. The effect of strain on the resistivity is known as piezoresistivity. The combination of damage sensing and strain sensing is valuable for understanding how the damage occurs.

Damage in cement-based materials results in an irreversible increase in the electrical resistance, as shown by measuring the resistance (four-probe method) in the stress (longitudinal) direction during loading and subsequent unloading [4,10,11]. Under compression of carbon fiber reinforced cement-based materials, reversible strain causes the resistance to decrease reversibly, whereas damage causes the resistance to increase irreversibly [10,11]. In order to distinguish between reversible and irreversible effects, the resistance needs to be measured during loading and subsequent unloading. The greater the damage, the more is the irreversible increase in resistance after unloading. These effects of compressive strain and damage have been observed in carbon fiber reinforced cement-based materials. Bontea et al. [10] reported these effects in carbon fiber reinforced concrete (with fine and coarse aggregates) containing 0.18 vol.% fiber. Chen et al. reported these effects in carbon fiber reinforced mortar (with fine aggregate) containing 0.8 vol.% fiber, which is above the percolation threshold [11].

Damage in cement-based materials is more severe when the deformation is more irreversible. The irreversible strain is a quantity that can be measured quite simply, say by using an attached strain gage. Thus, it is useful to correlate the damage (as indicated by the irreversible resistance increase) and the irreversible strain for the purpose of understanding the damage sensing characteristic. Prior work on the damage sensing ability of carbon fiber reinforced cement-based materials suffers from one or more of the following aspects: (i) not providing any strain measurement [11], (ii) not providing a sufficiently reliable measurement of the irreversible strain [10], (iii) using the two-probe method [9,15], and (iv) not making observation during unloading [9,15]. Correlation of the irreversible resistance increase and the irreversible strain is an objective of this work.

Because of the difference in damage sensitivity between the longitudinal and transverse directions for cement paste without any conductive admixture [3], it is necessary to compare the damage sensitivity between these two directions for carbon fiber reinforced cement. Such comparison is relevant to practical implementation of the sensing technology, because the transverse resistance may be more conveniently measured than the longitudinal resistance for certain configurations of the concrete structure. Furthermore, such comparison is expected to shed light on the science of the damage sensing ability.

This work involves simultaneous measurement of the damage (as indicated by the irreversible resistance increase) in the longitudinal and transverse directions for the same specimen. This is in contrast to prior work (involving no fiber) [3], which measured the behavior in the two directions in different specimens that were different in geometry. Simultaneous measurement of the resistance in the two directions in the same specimen is expected to give more reliable results than separate measurement of the resistance in the two directions in different specimens that are different in geometry. This work is also in contrast to prior work (involving carbon fiber) [10,11], which measured the behavior in the longitudinal direction only.

The scientific origin of the electrical-resistance-based damage sensing in carbon fiber cement-based materials has not been well elucidated in prior work. Bontea et al. [10] suggested that fiber fracture is a cause of the irreversible increase in resistance upon damage for carbon fiber reinforced concrete. On the other hand, based on electrical resistance results obtained during dynamic loading of carbon fiber reinforced mortar containing 0.8 vol.% fiber (above the percolation threshold), Chen et al. [11] suggested that the origin of the irreversible resistance increase is the breakdown of the electrically conductive network due to cracks. This origin is plausible for a fiber volume fraction above the percolation threshold, although it is not plausible below the percolation threshold (due to the absence of a conductive network). In contrast, this paper addresses carbon fiber reinforced cement at a fiber volume fraction below the percolation threshold.

This paper is aimed at advancing the science and technology of electrical-resistance-based damage sensing in carbon fiber reinforced cement-based materials. For this purpose, this work addresses (i) the correlation of the irreversible resistivity fractional change and the irreversible strain indicated by a conventional attached strain gage, and (ii) the comparison of the damage sensing characteristics of carbon fiber reinforced cement in the longitudinal and transverse directions.

2. Experimental methods

Silica fume in combination with methylcellulose has been shown to be the most effective admixture for promoting fiber dispersion [24–27]. Therefore, this paper uses silica fume in combination with methylcellulose in carbon fiber reinforced cement.

The carbon fibers were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, KY). The fiber diameter was 15 μm. The nominal fiber length was 5 mm. 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 wettability of fibers by water [28].

The mix used Portland cement (Type I) from Lafarge Corp. (Southfield, MI), plus silica fume (Elkem Materials Inc., Pittsburgh, PA, microsilica, EMS 965) in the amount of 15% by mass of cement, methylcellulose (Dow Chemical Corp., Midland, MI, Methocel A15-LV) in the amount of 0.4% by mass of cement, defoamer (Colloids Inc., Marietta, GA, 1010) in the amount of 0.13 vol.% (% of specimen volume), and carbon fibers in the amount of 0.50% by mass of cement (corresponding to 0.48 vol.%). The percolation threshold is between 0.5 and 1.0 vol.% [20].

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 about 2 min. Then, the methylcellulose mixture, cement, water and silica fume were mixed for 5 min. The water/cement ratio was 0.35. 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 cured at room temperature (about 22 °C) in air (relative humidity = 100%) for 28 days. Six specimens were tested.

Cross-shaped specimens (as 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. The specimen dimensions are shown in Fig. 1.

Compressive stress was applied in the direction shown in Fig. 1. The stress, which returned to zero at the end of each cycle, was provided by a hydraulic mechanical testing system (MTS Model 810). Two strain gages were applied to the center of the specimen (Fig. 1) – one on each of the two opposite surfaces. One strain gage was for measuring the longitudinal strain, while the other strain gage was for measuring the transverse strain. In the case of cubic specimens (51 × 51 × 51 mm, or 2 × 2 × 2 in.), a strain gage was applied at the center of one of the cube faces that were parallel to the stress direction.

During repeated compression at progressively increasing stress amplitudes, 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 perimetrically. In accordance with the four-probe method of resistance measurement, contacts *A* and *D* were

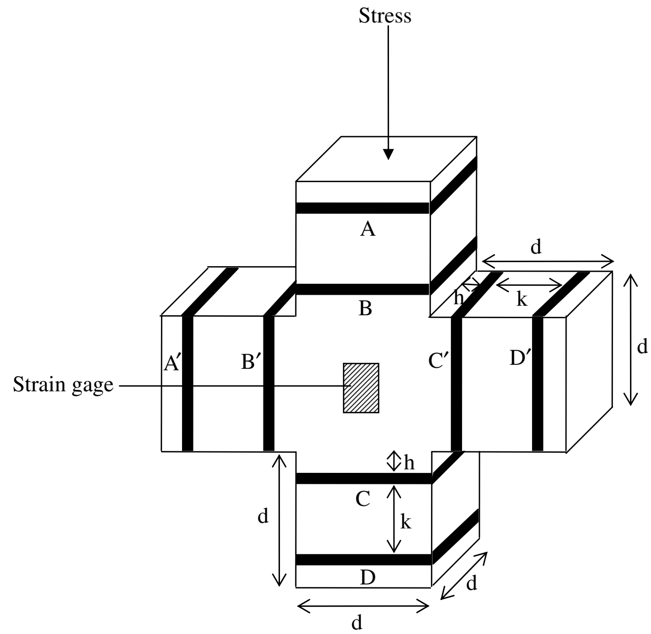

Fig. 1. Specimen configuration. $d = 51$ mm, $h = 5$ mm, and $k = 10$ mm.

used for passing current while contacts *B* and *C* were used for measuring the voltage. As contacts *B* and *C* were close to the central cubic portion (2–5 mm from the edge of the central cubic portion) of the specimen, the measured resistance was essentially the longitudinal resistance of the central cubic portion. Electrical resistance in the transverse direction was measured by using electrical contacts *A*′, *B*′, *C*′ and *D*′, as shown in Fig. 1. Because the strains involved were small, the fractional change in resistance was essentially equal to the fractional change in resistivity, as shown by simple calculation. At no load, the resistivity is the same in the longitudinal and transverse directions.

The loading (loading rate = 0.34 MPa/s) of the cubic specimens involved three cycles at progressively increasing stress amplitudes, which were close to those in the first three cycles (Fig. 2) used in testing the specimens of the cross-shaped specimens. No electrical measurement was made on the cubic specimens, which only served for measurement of the residual strength and residual modulus after compressive loading. For the residual strength/modulus testing, three specimens were tested

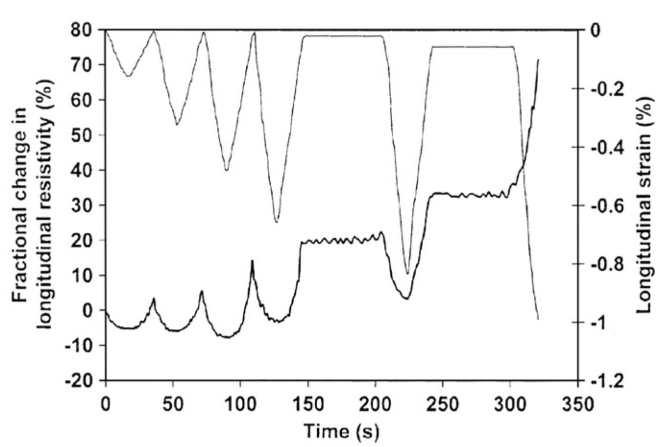

Fig. 2. Variation of the fractional change in longitudinal resistivity (thick curve) with time and of the longitudinal strain (thin curve) with time during uniaxial compression at progressively increasing stress amplitudes.

prior to any loading, and three other specimens were tested after the three compressive cycles. The residual strength/modulus testing involved monotonic compressive loading up to failure at a loading rate of 0.17 MPa/s.

3. Results and discussion

The resistivity at no load is $(1.49 \pm 0.08) \times 10^4\ \Omega$ cm. The fractional change in longitudinal resistivity, along with the longitudinal strain, is shown in Fig. 2, as a function of time during uniaxial compression at progressively increasing stress amplitudes. Fig. 3 shows the transverse resistivity and transverse strain results obtained simultaneously in the same specimen. Both longitudinal and transverse resistivities decrease upon uniaxial compression, due to piezoresistivity, as previously reported [18].

The resistivities show partial irreversibility even after the first cycle, although the strains show no partial irreversibility until after the third cycle (Table 1). The irreversible resistivity change is an increase in all cases. The higher the stress amplitude, the greater are the irreversible change in resistivity and the irreversible strain (Table 1 and Figs. 2 and 3).

In Figs. 2 and 3, the last half cycle, at the end of which failure occurs, is characterized by the resistivity increasing with increasing strain magnitude, due to the dominance of damage over strain in affecting the resistivity. In contrast, in all prior cycles, the resistivity decreases with increasing strain magnitude, due to the dominance of strain over damage in affecting the resistivity.

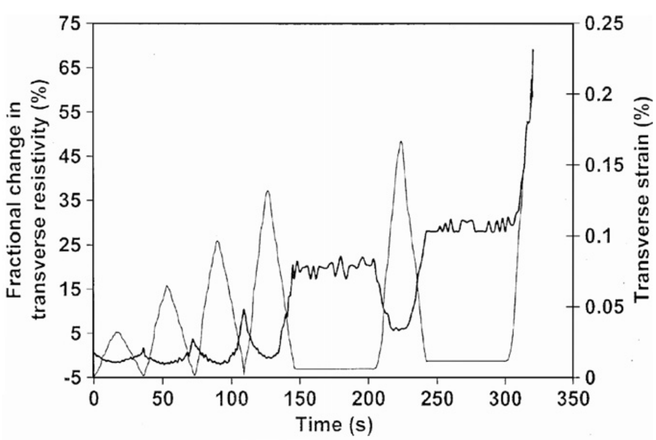

Fig. 3. Variation of the fractional change in transverse resistivity (thick curve) with time and of the transverse strain (thin curve) with time during uniaxial compression at progressively increasing stress amplitudes.

Table 1
Irreversible strain and irreversible resistivity change after various numbers of cycles of compressive loading at progressively increasing stress amplitudes up to failure, which occurs in Cycle 5

Cycle no.	Irreversible strain (10^{-4})[a]		Irreversible resistivity change[a] (%)	
	Longitudinal	Transverse	Longitudinal	Transverse
1	0	0	3.16 ± 0.23	1.64 ± 0.06
2	0	0	6.50 ± 0.28	5.45 ± 0.33
3	-2.0 ± 0.1	0.50 ± 0.02	14.3 ± 1.2	10.4 ± 0.7
4	-2.7 ± 0.2	0.60 ± 0.03	24.4 ± 0.9	20.5 ± 1.5
5	-4.3 ± 0.3	1.0 ± 0.1	32.0 ± 2.7	28.9 ± 2.1

[a] Relative to the value prior to loading.

Due to polarization, the measured resistivity increases with time, but the incremental increase diminishes with time and is mainly in the first 50 s [16]. In contrast, the incremental increase in this work increases with time, such that the increase is significant beyond the first 100 s. This means that the resistivity increase that is attributed to damage in this work has little contribution from polarization.

The small irreversible resistivity changes after the first and second cycles (Table 1) indicate minor damage in the elastic regime (irreversible strain absent). The large irreversible resistivity changes after the third, fourth and fifth cycles indicate major damage in the plastic deformation regime (irreversible strain present). The trends are the same for longitudinal and transverse resistivities, though the magnitude of the transverse irreversible strain is smaller than that of the longitudinal irreversible strain and the fractional irreversible resistivity change is accordingly lower in the transverse direction than the longitudinal direction.

Fig. 4 shows the relationship between the irreversible resistivity fractional change and the irreversible strain. The portion of the plot with negative irreversible strain corresponds to the longitudinal resistivity in relation to the longitudinal strain. The portion of the plot with positive irreversible strain corresponds to the transverse resistivity in relation to the transverse strain. Although the highest irreversible strain magnitude and the highest irreversible resistivity fractional change are smaller for the transverse direction than the longitudinal direction, the average magnitude of the slope of the curve in Fig. 4 is higher for the transverse direction than the longitudinal direction. This slope magnitude describes the damage sensing effectiveness, i.e., the irreversible resistivity fractional change per unit irreversible strain.

The resistance method of damage sensing, at least in the case of carbon fiber reinforced cement, is effective for sensing damage that is accompanied by irreversible strain as small as 0.5×10^{-4}. Both longitudinal and transverse resistivities are effective indicators of damage. Minor damage in

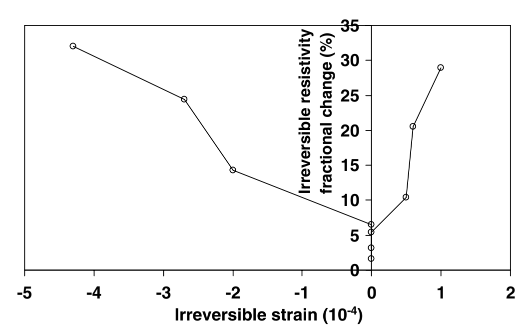

Fig. 4. Relationship of the irreversible resistivity fractional change with the irreversible strain.

the elastic regime can also be sensed by resistance measurement, but sensitivity for such minor damage is low compared to that for major damage that is accompanied by plastic (inelastic) deformation. The low sensitivity for minor damage in the elastic regime is advantageous for strain sensing in this regime. In general, damage is indicated by fractional irreversible resistivity increase.

Fig. 5 shows typical stress–strain curves for the compressive testing of cube specimens up to failure for specimens which had no previous load history and for specimens which had undergone three cycles at progressively increasing stress amplitudes up to 40 MPa. The initial strength (before loading) was 47.0 ± 5.6 MPa; the residual strength (after loading) was 41.0 ± 5.2 MPa. The initial modulus was 5.4 ± 0.4 GPa; the residual modulus was 4.6 ± 0.4 GPa. The reduction in both strength and modulus, though small, indicates the occurrence of damage, which is consistent with the irreversible increase in resistivity and the non-zero residual strain after the third cycle in both Figs. 2 and 3.

The origin of the electrical-resistance-based damage sensing in carbon fiber reinforced cement below the percolation threshold probably relates to the fiber breakage and the consequent irreversible increase in electrical resistivity of the cement-based material, as explained below. The bridging of a microcrack by a fiber is a well-known phenomenon in fiber reinforced brittle-matrix composites [29]. This phenomenon contributes largely to the ability of fibers to toughen a brittle-matrix composite. However, carbon fibers are brittle and cannot withstand bending to a small radius of curvature [30,31]. Upon shear of a microcrack, with the shear stress in the plane of the microcrack, the bridging fiber will be bent sharply at each of the two surfaces that make up the crack. As a consequence, the fiber will tend to break at one of these surfaces.

Damage sensing by resistance measurement has been reported in the elastic regime for cement paste without any conductive admixture [3]. Although the cement paste is isotropic in the electrical resistivity, its damage sensing behavior is different in the longitudinal and transverse

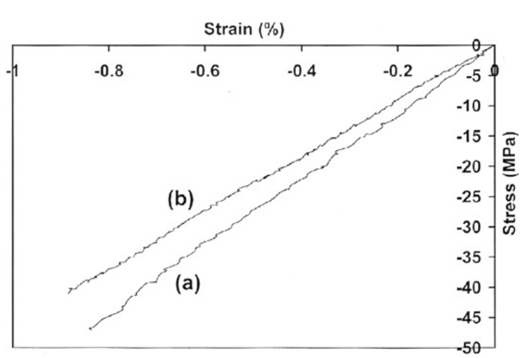

Fig. 5. Stress–strain curve for compressive testing up to failure. (a) Before loading (initial state). (b) After loading (state giving the residual strength and residual modulus).

directions. The resistance in the longitudinal direction is characterized by complex variation of the resistivity with strain; the resistivity increases upon first compressive loading, further increases upon subsequent unloading, decreases slightly during second loading up to the maximum stress of the first cycle, and then increases as the stress increases beyond this value [3]. The resistivity in the transverse direction shows little response to strain after the first cycle [3]. The damage sensing behavior is better in the longitudinal direction than the transverse direction, in spite of the Poisson effect and the consequent tension in the transverse direction; cement-based materials are more prone to damage under tension than under compression. Furthermore, that the damage sensing behavior is different in the two directions suggests that the damage does not occur simply through shear, as the shear stress is highest at an angle of 45° to the axis of the applied compressive stress and thus would have made the behavior the same in the longitudinal and transverse directions.

Comparison of the results of this paper for carbon fiber reinforced cement with those for cement paste without any conductive admixture [3] is revealing. For either the longitudinal or transverse direction, the damage sensing ability is much better and the values of the fractional changes in resistance are much higher in the presence of carbon fiber than in the absence of fiber. In addition, in the absence of fiber, the damage sensing characteristic is such that resistance in either direction increases during the first compressive loading, increases further during the subsequent unloading and decreases during subsequent loading. In contrast, in the presence of carbon fiber, the resistance decreases during loading in every cycle, due to strain, and its value at the end of a loading cycle is higher than that at the beginning of the cycle when damage occurs. These differences in behavior between the cases with and without fiber relates to the difference in mechanism behind the sensing ability. In the case without fiber, the sensing ability relates to defect generation during the first compressive loading, defect healing during subsequent loading, and defect aggravation that dominates during subsequent unloading [3]. The defects may be microcracks and precursors of microcracks. They are regions of relatively high electrical resistivity. However, due to the very low volume fraction of the defects, the dynamics of the defects has only minor effects on the electrical resistivity of the cement material. Therefore, the fractional change in resistivity due to loading is small. On the other hand, carbon fiber is more conductive than cement by about 8 orders of magnitude. The mechanism involving fiber fracture enables the fractional change in resistance due to loading to be much larger in the case with fiber than in the case without fiber.

The electrical-resistance-based damage sensing ability of cement paste without any conductive admixture is worse in the transverse direction than the longitudinal direction [3]. In the transverse direction, the sensing ability is so poor that the resistance almost does not respond to the changes in load [3]. However, the damage sensing ability of carbon fiber reinforced cement is similar (though not identical) in the two directions, as shown in this work. In the case without fiber, defect generation during loading causes the resistance to increase during first loading and the dynamics of these defects causes the resistance changes during subsequent unloading and loading [3]. Since the loading is uniaxial, the defects generated by the loading are necessarily direction dependent, i.e., they are not randomly oriented relative to the loading axis. As a result, the sensing behavior is quite direction dependent. However, in the case with fiber, the microcracks with bridging fibers are already present prior to any loading, so they are quite direction independent. As a result, the sensing behavior is similar for the longitudinal and transverse directions in the presence of fiber, but is quite different for these two directions in the absence of fiber. It should be noted that, in this work, the fibers are randomly oriented in the plane of the cross in the cross-shaped specimen (Fig. 1), since the cross-shaped specimen lies down during setting and curing.

That the damage sensing behavior is similar for the longitudinal and transverse directions for the case with fiber is consistent with the notion that damage occurs through shear and the consequent fiber breakage. However, there is a minor difference. The irreversible resistivity fractional change per unit irreversible strain is higher in the transverse direction than the longitudinal direction (Fig. 4). This difference suggests that the damage mechanism does not only involve microcrack shear with the resolved shear stress in the plane of the crack, but also involves microcrack opening upon tension in the direction perpendicular to the plane of the crack. The loading is compressive in the longitudinal direction and tensile in the transverse direction, due to the Poisson effect. The transverse tension promotes the opening of cracks that are in the longitudinal direction and that have bridging fibers in the transverse direction. Consequently, the transverse tension causes the breakage of fibers in the transverse direction, thereby increasing the resistivity in the transverse direction. Thus, for the same magnitude of strain, damage is more severe in the transverse direction than the longitudinal direction.

4. Conclusion

Damage self-sensing by resistance measurement is effective in carbon fiber reinforced cement, as shown for uniaxial compression specimens. Damage is indicated by an irreversible increase in the resistivity in the longitudinal or transverse direction. Major damage that is accompanied by irreversible strain (with the magnitude as low as 2×10^{-4} in the longitudinal direction and 0.5×10^{-4} in the transverse direction) is indicated by irreversible resistivity increase ranging from 10% to 30%. Minor damage in the elastic regime is indicated by irreversible resistivity fractional increase ranging from 1% to 7%. The irreversible resistivity fractional change per unit irreversible strain is higher in the transverse direction than the longitudinal direction.

The origin of the damage sensing ability is attributed to the fracture of fibers that bridge microcracks and the consequent resistivity increase. The fracture of a bridging fiber occurs upon shear of a microcrack, with the resolved shear stress in the plane of the crack. It also occurs upon tension of a microcrack, with the tensile stress perpendicular to the plane of the crack.

Acknowledgement

This work was supported in part by National Science Foundation.

References

[1] Wen S, Chung DDL. Piezoresistivity in continuous carbon fiber cement–matrix composite. Cem Concr Res 1999;29(3):445–9.
[2] Chung DDL. Damage in cement-based materials, studied by electrical resistance measurement. Mater Sci Eng Rev 2003;42(1):1–40.
[3] Cao J, Wen S, Chung DDL. Defect dynamics and damage of cement-based materials, studied by electrical resistance measurement. J Mater Sci 2001;36(18):4351–60.
[4] Wen S, Chung DDL. Damage monitoring of cement paste by electrical resistance measurement. Cem Concr Res 2000;30(12): 1979–82.
[5] Mao Q, Zhao B, Sheng D, Li Z. Resistance changement of compression sensible cement specimen under different stresses. J Wuhan Univ Tech 1996;11(3):41–5.
[6] Wu Y, Bing C, Keru W. Smart characteristics of cement-based materials containing carbon fibers. Mech Mater Eng Sci Exp 2003:172–5.
[7] Yao W, Chen B, Wu K. Smart behavior of carbon fiber reinforced cement-based composite. J Mater Sci Tech 2003;19(3):239–43.
[8] Reza F, Batson GB, Yamamuro JA, Lee JS. Resistance changes during compression of carbon fiber cement composites. J Mater Civil Eng 2003;15(5):476–83.
[9] Peled A, Torrents JM, Mason TO, Shah SP, Garboczi EJ. Electrical impedance spectra to monitor damage during tensile loading of cement composites. ACI Mater J 2001;98(4):313–22.
[10] Bontea D-M, Chung DDL, Lee GC. Damage in carbon fiber reinforced concrete, monitored by electrical resistance measurement. Cem Concr Res 2000;30(4):651–9.
[11] Chen B, Liu J, Wu K. Electrical responses of carbon fiber reinforced cementitous composites to monotonic and cyclic loading. Cem Concr Res 2005;35(11):2183–91.
[12] Cao J, Wen S, Chung DDL. Defect dynamics and damage of cement-based materials, studied by electrical resistance measurement. J Mater Sci 2001;36(18):4351–60.
[13] Chung DDL. Piezoresistive cement-based materials for strain sensing. J Intell Mater Syst Struct 2002;13(9):599–609.
[14] Chung DDL. Electrical conduction behavior of cement–matrix composites. J Mater Eng Perf 2002;11(2):194–204.
[15] Fu X, Ma E, Chung DDL, Anderson WA. Self-monitoring in carbon fiber reinforced mortar by reactance measurement. Cem Concr Res 1997;27(6):845–52.
[16] Wen S, Chung DDL. Electric polarization in carbon fiber reinforced cement. Cem Concr Res 2001;31(2):141–7.
[17] Cao J, Chung DDL. Electric polarization and depolarization in cement-based materials, studied by apparent electrical resistance measurement. Cem Concr Res 2004;34(3):481–5.
[18] Chen P-W, Chung DDL. Concrete as a new strain/stress sensor. Composites, Part B 1996;27B:11–23.
[19] Shi Z-Q, Chung DDL. Carbon fiber reinforced concrete for traffic monitoring and weighing in motion. Cem Concr Res 1999;29(3): 435–9.

[20] Chen P-W, Chung DDL. Improving the electrical conductivity of composites comprised of short conducting fibers in a non-conducting matrix: the addition of a non-conducting particulate filler. J Elect Mater 1995;24(1):47–51.
[21] Wen S, Chung DDL. Strain sensing characteristics of carbon fiber reinforced cement. ACI Mater J 2005;102(4):244–8.
[22] Wen S, Chung DDL. Uniaxial compression in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. Cem Concr Res 2001;31(2):297–301.
[23] Wen S, Chung DDL. Uniaxial tension in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. Cem Concr Res 2000;30(8): 1289–94.
[24] Chung DDL. Improving cement-based materials by using silica fume. J Mater Sci 2002;37(4):673–82.
[25] Chung DDL. Dispersion of short fibers in cement. J Mater Civil Eng 2005;17(4):379–83.
[26] Cao J, Chung DDL. Carbon fiber reinforced cement mortar improved by using acrylic dispersion as an admixture. Cem Concr Res 2001;31(11):1633–7.
[27] Fu X, Chung DDL. Combined use of silica fume and methylcellulose as admixtures in concrete for increasing the bond strength between concrete and steel rebar. Cem Concr Res 1998;28(4):487–92.
[28] Fu X, Lu W, Chung DDL. Ozone treatment of carbon fiber for reinforcing cement. Carbon 1998;36(9):1337–45.
[29] Sakai M, Miyajima T, Inagaki N. Fracture toughness and fiber bridging of carbon fiber-reinforced carbon composites. Compos Sci Tech 1990;40(3):231–50 [volume date 1991].
[30] Hashishin T, Kohara H, Iwanaga H, Takeuchi S. Fracture behavior of alumina and carbon fibers in the loop test, Japan. J Ceram Soc Jpn 2002;110:772–4.
[31] Furuyama M, Higuhi M, Kubomura K, Sunago H, Jiang H, Kumar S. Compressive properties of single-filament carbon fibers. J Mater Sci 1993;28(6):1611–6.