Piezoresistive Cement-based Materials for Strain Sensing

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ABSTRACT: Cement-based materials that exhibit piezoresistivity with sufficient magnitude and reversibility contain electrically conductive fibers. The phenomenon allows the materials to sense their own strain. The fibers are preferably discontinuous. Carbon fibers (15 μm diameter) are most effective. Steel fibers (8 μm diameter) are less effective. Carbon filaments (0.1 μm diameter) are ineffective. The piezoresistive behavior, mechanism and materials are reviewed, including cement-based materials with continuous and discontinuous fibers.

Key Words: cement, concrete, strain sensor, piezoresistive, carbon fiber, steel fiber.

INTRODUCTION

Strain sensing (related to stress sensing, but is distinct from damage sensing) is relevant to structural vibration control, traffic monitoring and weighing. In particular, weighing pertains to (i) the weighing of trucks that may or may not be moving, (ii) the weighing of all the people in each room of a building for the purpose of room occupancy monitoring and the use of the information for controlling lighting, ventilation, air-conditioning and heating (i.e., for energy saving), (iii) the detection of people inside or outside a building for enhancing building security, and (iv) the weighing of cargo.

Cement-based materials include concrete (containing coarse and fine aggregates), mortar (containing fine aggregate but no coarse aggregate) and cement paste (containing no aggregate, whether coarse or fine). The fine aggregate is typically sand. The coarse aggregate is typically stones such as gravel. These aggregates are chosen due to their low cost and wide availability. The combination of coarse and fine aggregates allows dense packing of the aggregates, as the fine aggregate fills the space between the units of large aggregate. Both aggregates serve as fillers, while cement serves as the matrix (i.e., the binder). Hence, these materials are cement–matrix composites. Concrete is the form that is most commonly used in structures. Mortar is used in masonry (i.e., for joining bricks in a brick wall), coating and some forms of repair. Cement paste by itself is not used in structural applications, but is relevant to functional applications and is a basic component of concrete and mortar.

Conventional applications of the stress–strain sensors include pressure sensors for aircraft and automobile components, vibration sensors for civil structures such as bridges and weighing-in-motion sensors for highways. The first category tends to involve small sensors (e.g., in the form of cement paste or mortar) and they will compete with silicon pressure sensors. The second and third categories tend to involve large sensors (e.g., in the form of precast concrete or mortar) and they will compete with silicon, acoustic, inductive and pneumatic sensors.

Other than aggregates, fillers in smaller quantities can be optionally added to the cement mix to improve the properties of the resulting materials. These fillers are called admixtures, which are discontinuous, so that they can be included in the mix. They can be particles, such as silica fume (a fine particulate) and latex (a polymer in the form of a dispersion). They can be short fibers, such as polymer, steel, glass or carbon fibers. They can be liquids such as methylcellulose aqueous solution, water reducing agent, defoamer, etc.

Cement reinforced with short carbon fibers is capable of sensing its own strain due to the effect of strain on the electrical resistivity (Chen and Chung, 1993, 1995a, 1996a,b; Chung, 1995; Fu and Chung, 1996a, 1997a; Qizhao et al., 1996; Fu et al., 1997, 1998a,b; Xu et al., 1998; Shi and Chung, 1999; Wen and Chung, 2000, 2001a,c, 2003). As observed at 28 days of curing, the resistivity in the stress and transverse directions increases upon tension, due to slight fiber pull-out that accompanies crack opening, and decreases upon compression, due to slight fiber push-in that accompanies crack closing (Qizhao et al., 1996; Fu and Chung, 1996a, 1997a; Fu et al., 1997, 1998a,b; Wen and Chung, 2000, 2001a). This electromechanical phenomenon, called piezoresistivity (i.e., change of the electrical resistivity with strain), allows the use of electrical resistance measurement (DC or AC) to monitor the strain of the

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cement-based material, which is itself the sensor. This means that the cement-based material is self-sensing. In contrast to the conventional method of using embedded or attached strain sensors (Robins et al., 2001; Wang et al., 2001), self-sensing involves low cost, high durability, large sensing volume and absence of mechanical property degradation (which tends to occur in case of embedded sensors).

Piezoresistivity studies have been mostly conducted on polymer–matrix composites with fillers that are electrically conducting. These composite peizoresistive sensors work because strain changes the proximity between the conducting filler units, thus affecting the electrical resistivity. Tension increases the distance between the filler units, thus increasing the resistivity; compression decreases this distance, thus decreasing the resistivity.

Composite piezoresistive materials include polymer–matrix composites containing continuous carbon fibers (Schulte and Baron, 1989; Prabhakaran, 1990; Schulte, 1993; Kaddour et al., 1994; Muto et al., 1995; Sugita et al., 1995; Ceysson, et al., 1996; Wang and Chung, 1996b, 1997a,b, 1998; Irving and Thiagarajan, 1998; Abry et al., 1999), carbon black (Kost et al., 1984; Pramanik et al., 1990; Radhakrishnan et al., 1994), metal particles (Radhakrishnan et al., 1994), short carbon fibers (Pramanik et al., 1990; Taya et al., 1998), cement–matrix composites containing short carbon fibers (Chen and Chung, 1993, 1996a,b; Fu and Chung, 1996a; Fu et al., 1997, 1998), and ceramic–matrix composites containing silicon carbide whiskers (Ishida et al., 1994). The sensing of reversible strain had been observed in polymer–matrix and cement–matrix composites (Kost et al., 1984; Chen and Chung, 1993, 1996a,b; Radhakrishnan et al., 1994; Fu and Chung, 1996a; Wang and Chung, 1996b, 1997a,b, 1998; Fu et al., 1997, 1998; Irving and Thiagarajan, 1998; Taya et al., 1998).

The presence of electrically conductive fibers in the cement-based material is necessary for the piezoresistivity to be sufficient in magnitude and in reversibility. In the absence of conductive fibers, the piezoresistivity is weak and has substantial irreversibility, if at all observable, as shown in the case of cement-based materials without fibers (Cao et al., 2001) and with nonconductive (polyethylene) short fibers (Chen and Chung, 1996b). Although conductive fibers are important for piezoresistivity, they are preferably discontinuous (around 5 mm in length, unless stated otherwise), due to the low cost of short fibers compared to continuous fibers and the amenability of short fibers for incorporation in the concrete mix by mixing, and are typically used at a volume fraction below the percolation threshold, which refers to the volume fraction above which the fibers touch one another to form a continuous electrical path. The fibers are not the sensors; they are an additive for rendering significant piezoresistivity to the cement-based material, which is the sensor. A low fraction of fibers is preferred for the purpose of maintaining low cost, high workability and high compressive strength.

Steel fibers are even more conductive than carbon fibers. Short steel fibers are used in cement-based materials to enhance the tensile, flexural and shear properties (Chen and Chung, 1996c; Alavizadeh-Farhang and Silfwerbrand, 2000; Bayasi and Kaiser, 2001; Lotfy, 2001; Nataraja et al., 2001; Teutsch, 2001) and the abrasion resistance (Febrillet et al., 2000), decrease the drying shrinkage (Sun et al., 2001), increase the effectiveness for electromagnetic interference (EMI) shielding (Wen and Chung, 2002) and provide controlled electrical resistivity (Wen and Chung, 2001b). Moreover, stainless steel fibers of diameter 60 μm render piezoresistivity to a cement-based material, as shown under compression, though the phenomenon is noisy in that the resistivity does not vary smoothly with the strain (Chen and Chung, 1996b). The large diameter of the steel fibers compared to carbon fibers (15 μm) was believed to be the cause of the inferior performance of the steel fiber cement-based material (Chen and Chung, 1996b). However, carbon fiber (15 μm diameter) cement paste is a better piezoresistive strain sensor than stainless steel fiber (8 μm diameter) cement paste at a similar fiber volume fraction, as shown by a higher signal-to-noise ratio and better reversibility upon unloading (Wen and Chung, 2003). The difference in performance of carbon fiber cement and steel fiber cement is attributed to a difference in piezoresistivity mechanism.

EFFECT OF FIBER TYPE ON THE PIEZORESISTIVE BEHAVIOR

The experimental results presented in this section were all obtained at 28 days of curing, using Type I portland cement. For details in the materials processing, please refer to the literature cited.

Cement Paste Containing 0.72 Vol.% Short Steel Fibers

Figure 1 (Wen and Chung, 2003) shows the variation of the fractional change in resistivity with strain and stress for cement paste containing 0.72 vol.% short steel fibers (8 μm diameter) under repeated tension. Both resistivity and strain increased with increasing stress with partial reversiblity. The higher the stress amplitude, the higher were both the strain and the resistivity.

Figure 2 (Wen and Chung, 2003) shows corresponding results obtained under compression. The strain was mostly reversible, but the resistivity decrease upon compression was noisy and the resistivity showed an irreversible increase after each stress cycle.

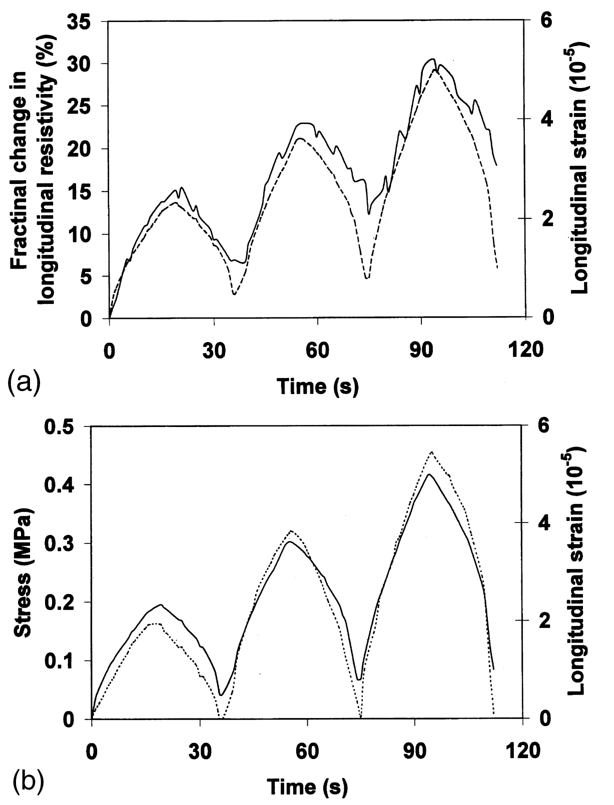

Figure 1. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0.72 vol.% steel fibers under tension.*

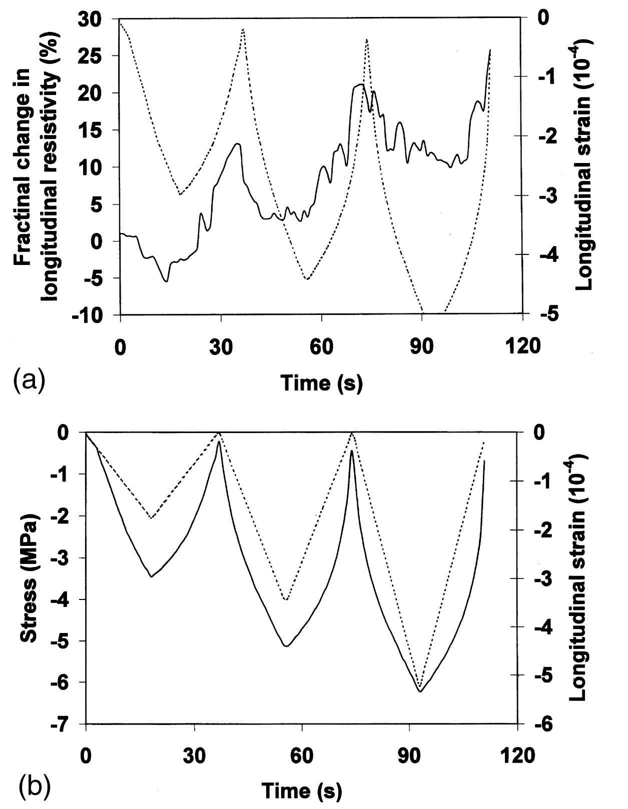

Figure 2. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0.72 vol.% steel fibers under compression.*

Cement Paste Containing 0.36 Vol % Short Steel Fibers

Figures 3 and 4 (Wen and Chung, 2003) show the piezoresistivity results for cement paste containing 0.36 vol.% short steel fibers (8 μm diameter) under tension and compression respectively. The resistivity increased upon tension and decreased upon compression, as observed for cement paste containing 0.72 vol.% steel fibers (Figures 1 and 2). However, the resistivity change and strain were more reversible, both under tension and compression.

Cement Paste Containing 0.5 Vol.% Short Carbon Fibers

Figures 5 and 6 (Wen and Chung, 2000, 2001a) show the piezoresistivity results for cement paste containing 0.5 vol.% short carbon fibers (15 μm diameter) under tension and compression respectively. The strain was totally reversible and was linearly related to the stress. The resistivity increased with tensile strain and decreased with compressive strain, such that the effect was totally reversible, except for an irreversible increase at the end of the first compression cycle. The resistivity variation was much less noisy and much more reversible than that observed for the two steel fiber cement pastes (Figures 1–4).

Cement Paste Containing 0.5 Vol.% Short Carbon Filaments

The use of carbon filaments (catalytically grown, 0.1 μm diameter > 100 μm long,) in place of conventional short carbon fibers (based on isotropic pitch, 15 μm diameter, "Cement Paste Containing 0.5 Vol. % Short Carbon Fibers") in a cement–matrix composite results in increased noise in the piezoresistive effect (Fu and Chung, 1997b). This is because of the bent morphology and large aspect ratio of the filaments, which hinder the pull-out of filaments. Thus, carbon filaments are not attractive for cement–matrix composite strain sensors.

Gage factor

The gage factor is defined as the fractional change in resistance (not resistivity) per unit strain. With the strain being positive for tension and negative for compression, the gage factor is positive for both tension and compression. Its value, as obtained from the first stress cycle, is listed in Table 1 for all three pastes.

The gage factor was higher under tension than compression for the two steel fiber cement pastes, but was lower under tension than compression for the

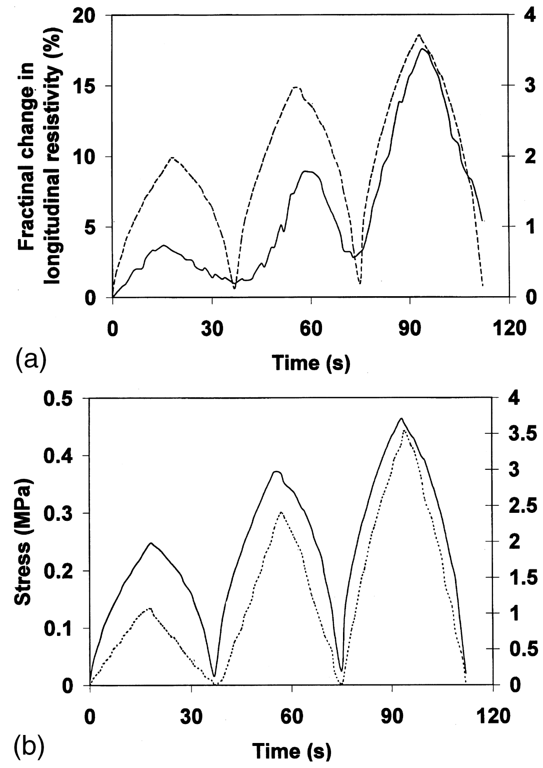

Figure 3. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0.36 vol.% steel fibers under tension.*

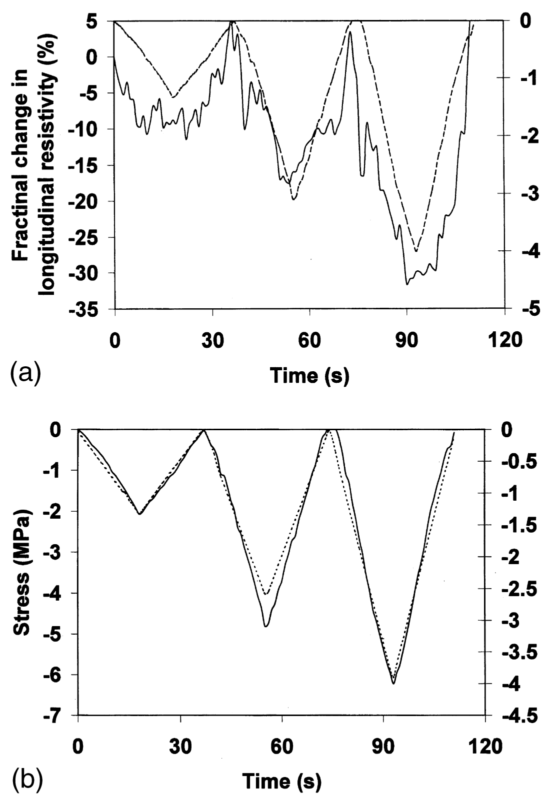

Figure 4. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0.36 vol.% steel fibers under compression.*

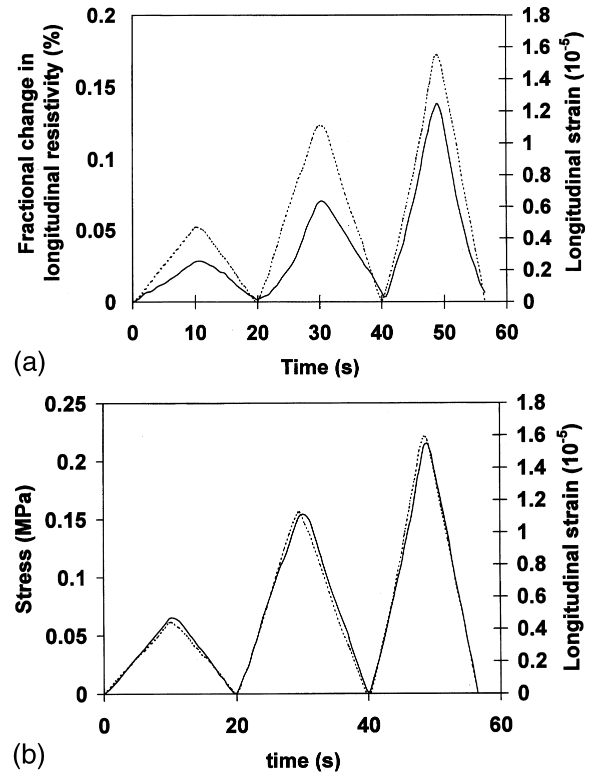

Figure 5. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0.5 vol.% carbon fibers under tension.*

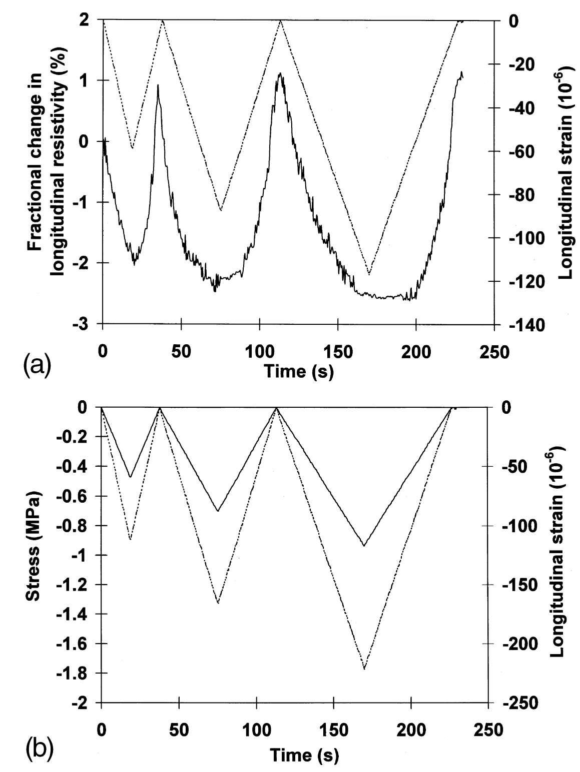

Figure 6. *Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b) for cement paste containing 0.5 vol.% carbon fibers under compression.*

carbon fiber cement paste. The gage factor under tension was much higher for the two steel fiber cement pastes than for the carbon fiber cement paste. These sharp contrasts between steel fiber and carbon fiber pastes suggest a difference in the piezoresistivity mechanism.

The gage factor is higher for the steel fiber cement pastes than the carbon fiber cement paste, except for the case of the paste with 0.72 vol.% steel fibers under compression. Between the two steel fiber pastes, the value for tension is higher and that for compression is lower for the paste with a higher fiber content.

Electrical Resistivity

The electrical resistivity of the three cement pastes of "Effect of Fiber Type on the Piezoresistive Behavior" is listed in Table 1. The two steel fiber pastes are much more conductive than the carbon fiber paste. This difference is because the steel fiber volume fractions are above the percolation threshold previously determined for the steel fiber case (between 0.27 and 0.36 vol.%) (Wen and Chung, 2002), whereas the carbon fiber volume fraction is below the percolation threshold previously determined for the carbon fiber case (between 0.5 and 1.0 vol.%) (Chen and Chung, 1995b).

Discussion

Percolation means the touching of adjacent fibers so that a continuous conducting path exists. Above the percolation threshold (i.e., when percolation occurs prior to straining), the conductivity is governed by the contact resistance at the fiber–fiber contact, which is affected by tension much more than compression. Below the percolation threshold (i.e., when percolation does not occur prior to straining), the conductivity is governed by the contact resistance at the fiber–matrix interface, in case that the matrix is not insulating, i.e., the case of the cement matrix (Chung, 1995). This interface is inherently weak and is thus affected by compression more than tension. Thus the piezoresistivity in steel fiber cement pastes is dominated by the effect of strain (particularly tensile strain) on the fiber–fiber contact, whereas that in carbon fiber cement is dominated by the effect of strain (particularly compressive strain) on the fiber–matrix contact.

Table 1. Gage factor and electrical resistivity of cement pastes containing silica fume and fibers.

Fibers	Gage Factor		Resistivity
	Tension	Compression	(Ω.cm)
0.72 vol.% steel fibers	4560 ± 640	200 ± 30	16 ± 1
0.36 vol.% steel fibers	1290 ± 160	720 ± 100	57 ± 4
0.5 vol.% carbon fibers	90 ± 10	350 ± 30	$(1.5 \pm 0.1) \times 10^4$

Steel fibers are much more ductile than carbon fibers. The ductility of the steel fibers is favorable for the change in fiber–fiber contact, which involves more movement than the change in fiber–matrix contact.

An increase in steel fiber volume fraction causes the gage factor under tension to increase, but causes that under compression to decrease. This supports the fact that, in the presence of percolation, tension has more effect on the fiber–fiber contact than compression.

Although the gage factor is relatively low for the carbon fiber cement paste than the steel fiber pastes, the signal-to-noise ratio is higher and the reversibility upon unloading is better for the former, as shown by comparing Figures 1(a)–6(a). In particular, the signal-to-noise ratio is very low for the steel fiber cement pastes under compression. Therefore, the carbon fiber cement paste is a superior strain sensor than the steel fiber counterparts. Between the two steel fiber pastes, the one with the lower fiber volume fraction (0.36%) is superior, due to better reversibility upon unloading, the higher gage factor under compression, and the better balance in gage factor between tension and compression.

The relatively higher signal-to-noise ratio and superior reversibility (upon unloading) of the carbon fiber cement paste is attributed to the relatively small movement of the fibers associated with changing the tightness of the fiber–matrix interface, compared to the relatively large movement of the fibers associated with changing the proximity between adjacent fibers.

It was previously believed that the inferior piezoresistive performance of steel fiber cement compared to carbon fiber cement was due to the large diameter (60 μm) of the steel fiber used in the previous work (Chen and Chung, 1996b). However, the steel fiber diameter (8 μm) was even less than the carbon fiber diameter (15 μm) in this work. Thus, the inferior performance of steel fiber cement is related to the difference in piezoresistive mechanism, rather than the difference in diameter.

EFFECT OF CURING AGE ON THE PIEZORESISTIVE BEHAVIOR

The piezoresistive behavior of carbon fiber reinforced mortar changes at a curing age between 7 and 14 days. At 14 days and beyond, the electrical resistance decreases upon compression, as shown in Figure 6. However, at a curing age of 7 days, it increases upon compression. The contrast is shown in Figure 7, which shows the piezoresistive behavior upon compression up to failure (Fu and Chung, 1997a). The contrast is attributed to the effect of the curing age on the fiber–cement bond strength, which diminishes with increasing curing age from 7 to 14 days, as shown for 60 μm-diameter stainless steel fiber (Fu and Chung,

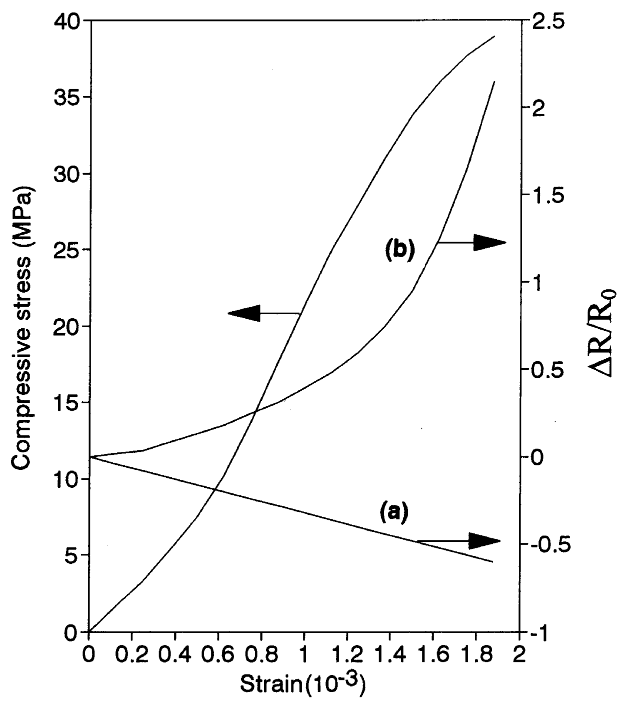

Figure 7. Fractional change in resistance ($\Delta R/R_o$) versus the compressive strain during static compression of carbon fiber reinforced mortar up to failure. (a) 28 days of curing; (b) 7 days of curing.

1996b). At 7 days, the strong bond causes the need to weaken the bond prior to fiber pull-out. At 14 days and beyond, the bond is weak to start with, so bond weakening is not necessary prior to fiber pull-out.

MECHANISM BEHIND PIEZORESISTIVITY IN SHORT FIBER CEMENT-BASED MATERIALS

The piezoresistivity in carbon fiber cement-based materials involves a mechanism in which the fibers (discontinuous and electrically conductive) are pulled out irreversibly from the cement (less conductive) matrix (Chung, 1995). The fiber pull-out is activated by straining and accompanies crack opening. The reverse, fiber push-in, accompanies crack closing. As the amount of fiber pull-out ($< 1\ \mu m$) is negligible compared to the fiber length (5 mm), the fiber–matrix interface area is essentially not affected by the fiber pull-out, but the fiber–matrix contact resistivity is increased upon fiber pull-out, thus causing the overall resistivity of the composite to increase. The reversibility of the fiber pull-out is associated with the reversibility of the crack opening. This reversibility is made possible by the fact that the fiber bridges the crack. The crack volume increase alone just cannot explain the large increase in electrical resistance.

In order for a short fiber composite to have strain sensing ability using the abovementioned mechanism, the fibers must be more conducting than the matrix, of diameter smaller than the crack length and be well dispersed. Their orientations can be random and they do not need to touch one another (i.e., percolation is not needed). Percolation refers to the situation in which the fibers touch one another, thus allowing electrical conduction to occur from one fiber directly to another fiber.

The evidence that supports the abovementioned sensing mechanism includes the following (Chen and Chung, 1996a, Chung, 1995).

- The sensing ability was present when the fibers were conducting (i.e., carbon or steel) and absent when the fibers were nonconducting (i.e., polyethylene).
- The sensing ability was absent when fibers were absent.
- The sensing ability occurred at low carbon fiber volume fractions which are associated with little effect of the fiber addition on the concrete's volume electrical resistivity.
- There was no maximum volume electrical resistivity required in order for the sensing ability to be present.
- The sensing ability was present when the carbon fiber volume fraction was as low as 0.2% – way below the percolation threshold, which was 1 vol.% or above, depending on the ingredients (e.g., silica fume vs. latex) used to help disperse the fibers.
- Fracture surface examination showed that the fibers were separate from one another.
- The fractional increase in electrical resistance ($\Delta R/R_o$) upon straining did not increase with increasing carbon fiber volume fraction, even though the increase in fiber volume fraction beyond the percolation threshold caused large decrease (by orders of magnitude) in the volume electrical resistivity.
- The electrical resistance increased upon straining, whether in tension or compression. In contrast, if the mechanism involved the change in proximity between adjacent fibers upon straining, the resistance would have increased in tension and decreased in compression at all curing ages.
- The presence of carbon fibers caused the crack height to decrease by orders of magnitude. For example, the irreversible crack height observed after deformation to 70% of the compressive strength was decreased from 100 to $1\ \mu m$ by the addition of carbon fibers in the amount of 0.37 vol.%, even though the compressive strength was essentially not affected by the fiber addition.
- The presence of carbon fibers caused the flexural toughness and tensile ductility of the composite to increase greatly.

Evidence No. 3, 4, 7 and 8 are against the change in proximity between adjacent fibers upon straining as the mechanism. Evidence 9 and 10, together with prior knowledge on fiber reinforced concrete (Li et al., 1991; Li, 1992), suggest the occurrence of fiber bridging.

Evidence No. 1, 2, 5 and 6 suggest that the electrical contact resistance between fiber and matrix plays an important role and that between fiber and fiber does not. All the pieces of evidence together support the abovementioned mechanism. However, further work is necessary to completely prove the mechanism.

PIEZORESISTIVITY IN CONTINUOUS FIBER CEMENT-BASED MATERIALS

Continuous fibers are far more effective than short fibers for reinforcement, so advanced structural composites all use continuous fibers rather than short fibers, in spite of 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 (Yoshizawa et al., 1996; Abdelrahman and Rizkalla, 1997; Ballinger, 1997; Fam et al., 1997; Missihoun et al., 1997; Norris et al., 1997; Soudki et al., 1997; Takeda et al., 1996). 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. Although numerous studies have been made on the use of short fibers in concrete (Banthia, 1994), little work has been reported on the use of continuous fibers (Saito et al., 1989; Zheng and Chung, 1989; Uomoto, 1995; Pivacek et al., 1997; Kolsch, 1998). In contrast to short fibers, continuous fibers cannot be incorporated in a cement mix. They need to be placed and made straight and parallel prior to the pouring of cement paste around it (Wen et al., 2000). Thus, the preparation of continuous fiber cement–matrix composites is much more complicated than that of short fiber cement–matrix composites.

Unidirectional continuous carbon fiber reinforcement results in cement–matrix composites that exhibit tensile strength approaching that expected by calculation based on the Rule of Mixtures (Saito et al., 1989). Due to the electrical conductivity of carbon fibers and the slight conductivity of the cement matrix, measurement of the DC electrical resistance of the composite provides a way to detect damage (Wen et al., 2000). 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 in 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} Ω.cm, whereas that of cement paste is 10^5 Ω.cm.

Figure 8 (Wen et al., 2000) 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 (continuous, 11 μm diameter). The stress–strain curve is linear up to a strain of 0.2%, at which the resistance starts to increase abruptly. Figure 9 (Wen et al., 2000) 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 increases upon loading and decreases upon unloading in every cycle, such that the resistance increase is not totally reversible. The gage factor, which is the fractional change in resistance (reversible

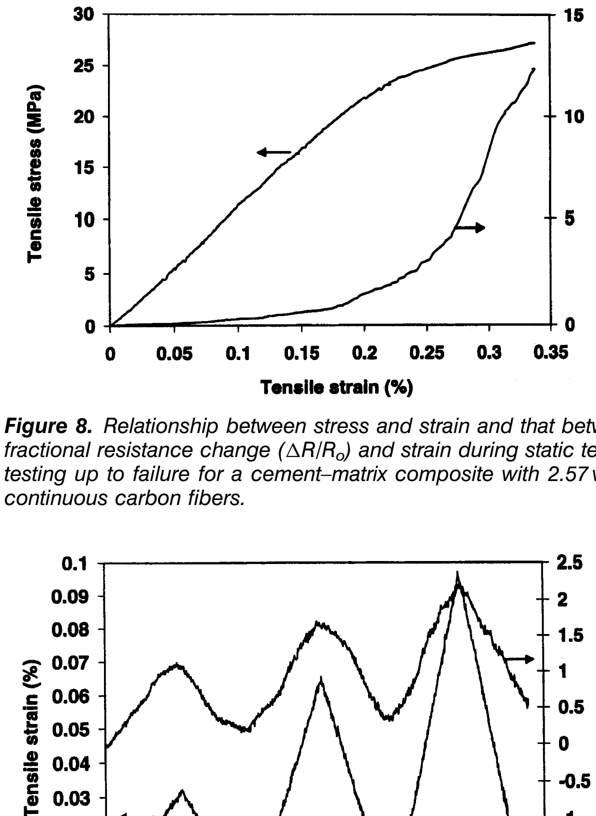

Figure 8. Relationship between stress and strain and that between fractional resistance change ($\Delta R/R_o$) and strain during static tensile testing up to failure for a cement–matrix composite with 2.57 vol.% continuous carbon fibers.

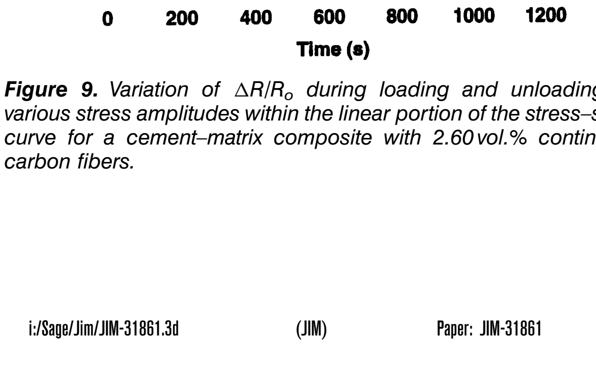

Figure 9. Variation of $\Delta R/R_o$ during loading and unloading for various stress amplitudes within the linear portion of the stress–strain curve for a cement–matrix composite with 2.60 vol.% continuous carbon fibers.

portion) per unit strain, is 28, 21 and 17 for the first, second and third cycles respectively (Figure 9). The decrease in gage factor with increasing cycle number (increasing stress amplitude) (Table 2) is attributed to the decrease in reversibility with increasing stress amplitude. It is not clear why the intermediate fiber volume fraction gives the highest gage factor. Investigation of composites with different fiber contents shows that the extent of irreversibility in resistance increase is greater when the stress amplitude as a fraction of the tensile strength is higher.

Similar piezoresistive behavior was observed for composites with various fiber contents (Wen et al., 2000). Table 3 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.

The abrupt increase in resistance at high strains is accompanied by a decrease in modulus (Figure 8), so it is attributed to fiber breakage. The smaller increase in resistance at low strains is not accompanied by any change in modulus (Figure 8), so it is attributed to fiber–matrix interface degradation. The degradation causes the fiber–matrix contact resistivity to increase, thereby affecting the measured resistance, as explained above. Figure 9 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 2 only. 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. The reversible resistance change means that the continuous carbon fiber composites are strain sensors. The mechanism 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 (Table 1) than continuous fiber composites.

In spite of the effort to align the fibers, the fiber alignment is not perfect, as shown by the low strength, low modulus and high resistivity relative to the calculated values (Table 3). 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.

Piezoresistivity also occurs in continuous carbon fiber epoxy–matrix composites (Wang and Chung, 1996). 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 (Wang and Chung, 1996), 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.

Table 2. Gage factor.

		Fiber Volume Fraction (%)		
Cycle No.	**Maximum load (lb)**	**2.60 ± 0.06**	**5.14 ± 0.25**	**7.24 ± 0.24**
1	50	32.6 ± 7.9	57.6 ± 0.06	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

Table 3. 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

PIEZORESISTIVITY IN SHORT FIBER CEMENT COATING

Because most structures are not built with carbon fiber reinforced concrete but with conventional concrete, the applicability of a cement-based material as a strain sensor can be widened by using the material as a strain sensing coating on conventional concrete. Cement paste containing short carbon fibers is an effective strain-sensing coating, as tested when the coating (with fibers) is on either the tension side or the compression side of a cement specimen (without fiber) under flexure (Wen and Chung, 2001c). The resistance is measured with surface electrical contacts on either side. The resistance increases reversibly on the tension side upon loading and decreases reversibly on the compression side upon loading. The behavior is similar whether the strain sensing coating contains silica fume or latex.

DC VERSUS AC

The data presented in all the above sections of this paper involve the use of DC electrical power, i.e., the DC electrical resistance is measured. Under AC condition, the impedance Z consists of the resistance R_s (real part of Z) and the reactance X_s (imaginary part of Z), i.e., $Z = R_s + iX_s$, where the subscript s refers to a configuration in which the sample is in series connection with the measuring circuit. AC provides both resistance and reactance information and AC is relevant to data acquisition by wireless methods. It has been found that in carbon fiber (short) reinforced mortar at 7 days of curing, the reactance X_s is a more sensitive indicator than the resistance R_s, as the fractional change in reactance exceeds the fractional change in resistance upon deformation (Fu et al., 1997). The effect of strain on the reactance relates to the effect of strain on the polarization (Wen and Chung, 2001d), i.e., the direct piezoelectric effect (Mingqing et al., 2000), which is to be distinguished from the piezoresistive effect. The piezoelectric effect is beyond the scope of this paper.

CONCLUSION

Cement reinforced with short carbon fibers (15 μm diameter) is capable of sensing its own strain, due to piezoresistivity (DC or AC), i.e., the effect of strain on the electrical resistivity. The resistivity in the stress and transverse directions increases upon tension and decreases upon compression. Short steel fibers (8 μm diameter) and continuous carbon fibers (11 μm diameter) are less effective. Short carbon filaments (0.1 μm diameter) are ineffective. In the case of short carbon fiber (15 μm diameter) reinforced cement, the piezoresistive behavior changes at a curing age between 7 and 14 days, and its mechanism involves slight fiber pull-out and push-in upon tension and compression respectively.

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