Advances in Cement Research, 2003, **15**, No. 3, July, 119–128

A comparative study of steel- and carbon-fibre cement as piezoresistive strain sensors

Sihai Wen* and D. D. L. Chung*

University at Buffalo

Carbon-fibre (15 μm diameter) cement is a better piezoresistive strain sensor than stainless steel-fibre (8 μm diameter) cement at a similar fibre volume fraction, as shown by a higher signal-to-noise ratio and better reversibility upon unloading, albeit having a lower gauge factor (particularly under tension). Steel-fibre cement containing 0·36 vol% fibres is a better piezoresistive strain sensor than that containing 0·72 vol% fibres, as shown by better reversibility upon unloading and the higher gauge factor under compression. The difference in performance of carbon- and steel-fibre cement is attributed to a difference in piezoresistivity mechanism.

Introduction

Strain sensing in the elastic regime (which is the regime for safe service of a structure) is relevant to structural vibration control, traffic monitoring and weighing in motion. Cement reinforced with short carbon fibres is capable of sensing its own strain due to the effect of strain on the electrical resistivity.[1–7] The resistivity in both the stress direction and the transverse direction increases upon tension, due to slight fibre pull-out that accompanies crack opening, and decreases upon compression, due to slight fibre push-in that accompanies crack closing.[3–7] 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 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,[8,9] self-sensing involves low cost, high durability, large sensing volume and absence of mechanical property degradation (which tends to occur with embedded sensors).

The presence of electrically conductive fibres in the cement-based material is necessary for the piezoresistivity to be sufficient in magnitude and reversible. In the absence of conductive fibres, the piezoresistivity is weak and has substantial irreversibility, if at all observable, as shown in the case of a cement-based material without fibres[10] and with non-conductive (polyethylene) fibres.[11] Although conductive fibres are important for piezoresistivity, they are discontinuous and are typically used at a volume fraction below the percolation threshold; this refers to the volume fraction above which the fibres touch one another to form a continuous electrical path. Thus, the fibres are not the sensors. Rather, they are an additive for rendering significant piezoresistivity to the cement-based material, which is the sensor. A low fraction of fibres is preferred for the purpose of maintaining low cost, high workability and high compressive strength.

The cement matrix is electrically attractive due to its electrical conductivity, which is in contrast to the non-conductive behaviour of most polymers. Due to the conductivity of the cement matrix, an electrically conductive admixture (i.e. a conductive filler) in a cement-matrix composite can enhance the conductivity of the composite even when the volume fraction of the admixture is below the percolation threshold. The percolation threshold is determined from the variation of the electrical resistivity with the volume fraction of the conductive admixture: the electrical resistivity abruptly decreases by orders of magnitude as the percolation threshold is exceeded.[12] In most cases, the percolation threshold decreases with increasing aspect ratio and with decreasing unit size of the admixture. In

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

(ACR 432) Paper received 31 January 2003; last revised 22 April 2003; accepted 8 May 2003

0951-7197

the case of short carbon fibres (7 μm diameter) in cement, the percolation threshold decreases with increasing fibre length from 1 to 10 mm.[13] However, the percolation threshold also depends on the unit size of the non-conductive or less conductive components in the composite. Thus, the presence of sand (a non-conductive component) affects the percolation threshold.[12] In the absence of sand, the percolation threshold is between 0·5 and 1·0 vol% when the conductive admixture in cement is short carbon fibre (15 μm diameter, 5 mm in length).[12]

The curing age has relatively minor influence on the electrical resistivity, although it has major influence on the mechanical properties. From a curing age of 1 to 28 days, the resistivity is increased by 63% for plain mortar, by 18% for latex mortar, by 18% for carbon fibre (0·53 vol%) latex mortar, and by 4% for carbon fibre (1·1 vol%) latex mortar.[14] Since the resistivity is a quantity that can vary by orders of magnitude, the percentage increases mentioned above do not reflect a large effect. Nevertheless, the effect in the absence of conducting fibres, especially in terms of the impedance, is sufficient for use in studying the curing process.[15–18] An increase in the carbon-fibre content, 0·53–1·1 vol%, diminishes the effect of curing age significantly, because the fibres become more dominant in governing the resistivity as the fibre content increases. The addition of latex also diminishes the effect of curing age.

Cement paste is electrically conducting, with DC resistivity at 28 days of curing around 5×10^5 Ω/cm at room temperature. The resistivity is increased slightly (to 6×10^5 Ω/cm) by the addition of silica fume (SiO_2 particles around 0·1 μm in size, in the amount of 15% by mass of cement), and is increased more (to 7×10^5 Ω/cm) by addition of latex (20% by mass of cement); latex is a styrene–butadiene co-polymer physically in the form of ~0·2 μm particles.[19] The higher the latex content, the higher is the resistivity.[20] In case of mortars (with fine aggregate, e.g. sand), the transition zone between the cement paste and the aggregate enhances the conductivity.[21] Whether aggregates (sand and stones) are present or not, the AC impedance spectroscopy technique for characterising the frequency-dependent electrical behaviour is useful for studying the microstructure.[21–24]

The non-conductive admixture effects on the resistivity, as mentioned above, are small compared to the effect of adding short conductive fibres. Nevertheless, the non-conductive admixtures can help the fibre dispersion, thereby causing the resistivity of cement-based materials containing conductive short fibres to be lower. At a volume fraction below the percolation threshold, the electrical conductivity of a composite is highly dependent on the degree of fibre dispersion. The greater the degree of fibre dispersion, the higher is the conductivity of the composite. This is because of the relatively long length of conduction path within the matrix in the case of poor fibre dispersion, as illustrated in Fig. 1. At the same carbon fibre (15 μm diameter) volume fraction (0·35 vol%, below the percolation threshold), the resistivity of cement mortar is lower when silica fume is present along with the fibres, due to the effectiveness of silica fume in helping the fibre dispersion;[25] it is further lowered when both methylcellulose and silica fume are present in addition to the fibres.[25,26] The use of acrylic, styrene acrylic or latex dispersions in place of the methylcellulose solution is less effective.[25] At the same steel fibre (60 μm diameter) volume fraction (0·05 vol%, much below the percolation threshold), the resistivity of cement mortar is lower when silane is present along with the fibres, due to the effectiveness of silane in achieving fibre dispersion.[27]

The electrical conductivity of a cement-based material containing a conductive admixture is governed by the conductivity of the admixture itself, the degree of dispersion of the admixture and the contact electrical resistivity of the interface between the admixture and the cement matrix. Due to the conductivity of the cement matrix, this contact resistivity is important, particularly when the admixture volume fraction is below the percolation threshold. The contact electrical resistivity between stainless steel fibre (60 μm diameter) and cement paste is around 6×10^6 Ω/cm^2 and is smaller if the fibre has been acid washed.[28]

Steel fibres are even more conductive than carbon fibres. Short steel fibres are used in cement-based materials to enhance the tensile, flexural and shear properties[29–34] and abrasion resistance,[35] decrease the drying shrinkage,[36] increase the effectiveness for electromagnetic interference (EMI) shielding[37] and provide controlled electrical resistivity.[38] Moreover, stainless steel fibres of diameter 60 μm have been shown to render piezoresistivity to a cement-based material tested under compression, though the phenomenon is noisy in that the resistivity does not vary smoothly with the strain.[11] The large diameter of the steel fibres compared to carbon fibres (15 μm) was believed to be the cause of the inferior performance of the steel-fibre cement-based material.[11] On the other hand, steel fibres of diameters less than 60 μm are commercially available. Therefore this paper addresses

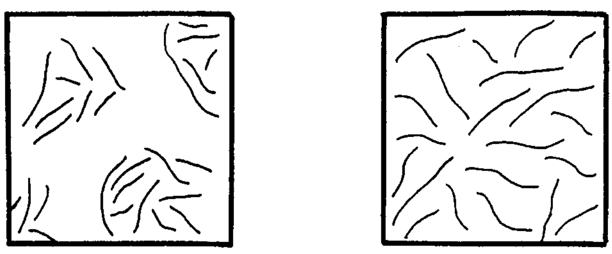

Fig. 1 Fibre dispersion below the percolation threshold: (a) poor dispersion; (b) good dispersion[27]

the piezoresistivity of cement containing stainless steel fibres (diameter 8 μm, length ~6 mm) and provides a comparison of the piezoresistivity of this material and that of the carbon-fibre (diameter 15 μm, length ~ 5 mm) counterpart. The motivation of this work is the development of improved self-sensing cement-based materials and better understanding of the mechanism for the piezoresistivity phenomenon.

Experimental method

Materials

Cement pastes were made using cement (Portland cement, type I, from Lafarge Corp., Southfield, MI), water (w/c ratio = 0·35), silica fume (15% by mass of cement, Elkem Materials, Inc., Pittsburgh, PA, EMS 965, for helping the fibre dispersion) and fibres.

The steel fibres (Beka-Shield) were made of No. 304 austenitic stainless steel, as obtained from Bekaert Fibre Technologies (Marietta, GA). The fibre diameter was 8 μm. The fibre length was 6 mm. The fibres included 10 wt% (47 vol%) of a polyvinyl alcohol (PVA) binder, which was hydrophylic and dissolved in water during cement mixing, thus allowing fibre dispersion.

The steel fibres consisted of fibres and PVA amounting to either 2·0 or 4·0% by mass of cement, corresponding to fibres without PVA in the amount of either 0·36 or 0·72 vol%. For example, a fibre content (including PVA) of 4% by mass of cement in cement paste corresponded to fibres (excluding PVA) in the amount of 3·6% by mass of cement, or 0·72 vol%, and PVA in the amount of 0·4% by mass of cement, or 0·64 vol%.

The carbon fibres were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, KY). The fibre diameter was 15 μm. The nominal fibre length was 5 mm. Fibres in the amount of 0·5% by mass of cement (corresponding to 0·5 vol%) were used. Prior to using the fibres in the 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 improved the wettability of fibres by water.[4]

Methylcellulose instead of PVA was used to help the dispersion of the carbon fibres. The methylcellulose used, at 0·4% by mass of cement, was from Dow Chemical Corp., Midland, MI, Methocel A15-LV. The defoamer (Colloids Inc., Marietta, GA, 1010) was used together with methylcellulose at 0·13 vol% (percentage of sample volume).

Each batch was large enough to cast six specimens for tensile testing, six for compressive testing and six for electrical resistivity measurement. A rotary mixer with a flat beater was used for mixing. For steel-fibre mixes, cement, water, silica fume and fibres were mixed for 5 min. For carbon-fibre mixes, methylcellulose was dissolved in water, and then the defoamer and fibres were added and stirred by hand for about 2 min. Then, the methylcellulose mixture, cement, water and silica fume were mixed for 5 min. For both steel- and carbon-fibre mixes, 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 demoulded after 1 day and then allowed to cure at room temperature in air (relative humidity = 100%) for 28 days.

Three types of cement paste were studied: (*a*) steel-fibre cement paste containing 0·72 vol% fibres; (*b*) steel-fibre cement paste containing 0·36 vol% fibres; and (*c*) carbon-fibre cement paste containing 0·5 vol% fibres.

Test method

Piezoresistivity testing was conducted by measuring the electrical resistance in the stress direction during repeated application of tensile or compressive stress at various amplitudes in essentially the elastic regime. The resistance, stress and strain in the stress direction (e.g. the longitudinal direction) were simultaneously measured. Resistance measurement used a Keithley 2001 multimeter (with a current of around 1 mA).

Dog-bone shaped specimens of the dimensions shown in Fig. 2 were used for tensile testing. The specimen cross section was 30 × 20 mm in the narrow part of the dog-bone shape. They were prepared by using moulds of the same shape and size. Tensile testing was performed using a screw-action mechanical testing system under repeated loading (applied by gripping on the sides near the two ends) at various stress magnitudes. During tensile testing the longitudinal strain was measured by using a strain gauge (3 mm in length) attached to the centre of a side at the narrow part of the dog-bone shaped specimen (Fig. 2). Simultaneously with mechanical testing, the longitudinal electrical resistance was measured using the four-probe method. The electrical contacts were made by applying silver paint along the whole perimeter in four parallel planes perpendicular to the stress axis, as illustrated in Fig. 2. The inner two contacts (typically 70 mm apart) were for voltage measurement, while the outer two contacts (typically 80 mm apart) were for passing a current.

Samples for compressive testing were in the form of cubes of size 51 × 51 × 51 mm. During repeated compression at increasing stress amplitudes, provided by a hydraulic mechanical testing system, electrical resistance measurements were made in the axial stress axis, using the four-probe method, in which silver paint in conjunction with copper wires served as electrical contacts. Four contacts were perimetrically placed around the specimen at four planes, all perpendicular to the stress axis, and symmetric with respect to the mid-point along the height of the specimen. The outer two contacts (typically 40 mm apart) were for passing

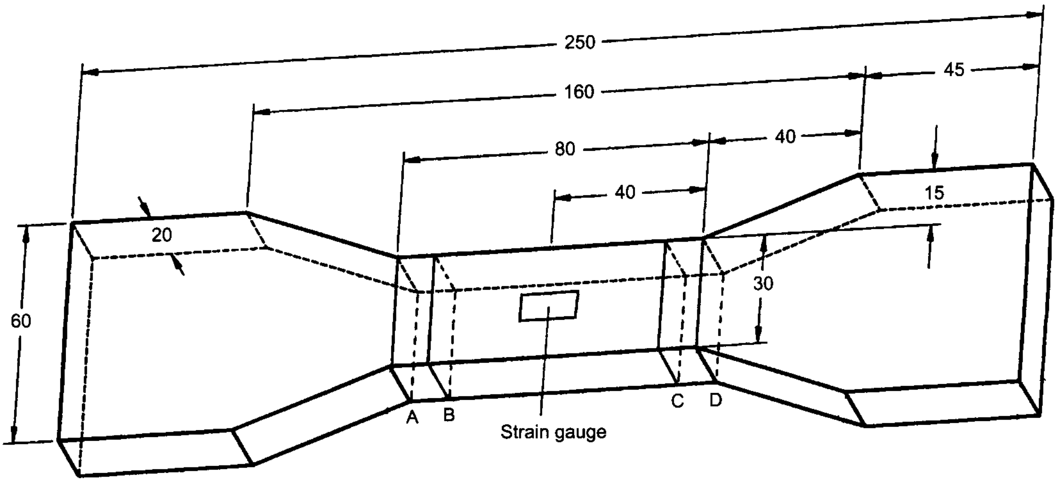

Fig. 2 Specimen configuration for tensile testing. Dimensions are in mm. The four electrical contacts are labelled A, B, C and D. The outer contacts (A and D) are for passing current. The inner contacts (B and C) are for voltage measurement

current and the inner two contacts (typically 30 mm apart) were for measuring the voltage. The longitudinal strain was measured by using a strain gauge (3 mm long) attached to the middle of one of four side surfaces of a specimen. The strain gauge was centred on the side surface and was parallel to the stress axis. As the resistance measured was that between the two inner contacts, the effect of friction at the ends of the specimen on the resistance was expected to be negligible.

Although the spacing between the electrical contacts changed upon tensile or compressive deformation, the change was so small that the measured resistance remained essentially proportional to the volume resistivity. Nevertheless, the resistivity, ρ, was obtained from the resistance, R, distance, d, between the inner contacts, and the cross-sectional area, A, by following the equation

$$\rho = R\frac{A}{d} \quad (1)$$

Six specimens of each of three types of paste were tested to ascertain reproducibility of the piezoresistivity behaviour.

DC volume electrical resistivity (as distinguished from its variation with stress) was measured using the Keithley 2001 multimeter (with a current that depended on the resistance measured, namely 9·2 mA, 0·98 mA and 89 μA for 0·72 vol% steel-fibre cement, 0·36 vol% steel-fibre cement and 0·5 vol% carbon-fibre cement respectively) and the four-probe method. In this method, four electrical contacts were applied by silver paint around the whole perimeter at four planes perpendicular to the length of the specimen (150 × 12 × 11 mm). The four planes were symmetrical around the mid-point along the length of the specimen, such that the outer contacts (for passing current) were 70 mm apart and the inner contacts (for measuring the voltage in relation to resistivity determination) were 50 mm apart. Six specimens of each composition were tested.

The gauge factor is defined as the fractional change in resistance (not resistivity) per unit strain in the same direction. It is a dimensionless number that describes the extent of the piezoresistive effect. For a metal which is conventionally used for strain gauges, the gauge factor is 2.

Results

The weak piezoresistivity in cement-based materials without fibres is described in Cao *et al.*[10] This paper only addresses the strong piezoresistivity in cement-based materials containing fibres, particularly steel fibres and carbon fibres.

Cement paste containing 0·72 vol% steel fibres

Figure 3 shows the variation of the fractional change in resistivity with strain and stress for cement paste containing 0·72 vol% steel fibres under repeated tension. Both resistivity and strain increased with increasing stress with partial reversibility. The higher the stress amplitude, the higher were both the strain and the resistivity. However, the correlation between resistivity and strain depended on the load history. This dependence is undesirable for practical strain sensing.

Figure 4 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.

Cement paste containing 0·36 vol% steel fibres

Figures 5 and 6 show the piezoresistivity results for the cement paste containing 0·36 vol% steel fibres under tension and compression respectively. The resistivity increased upon tension and decreased upon com-

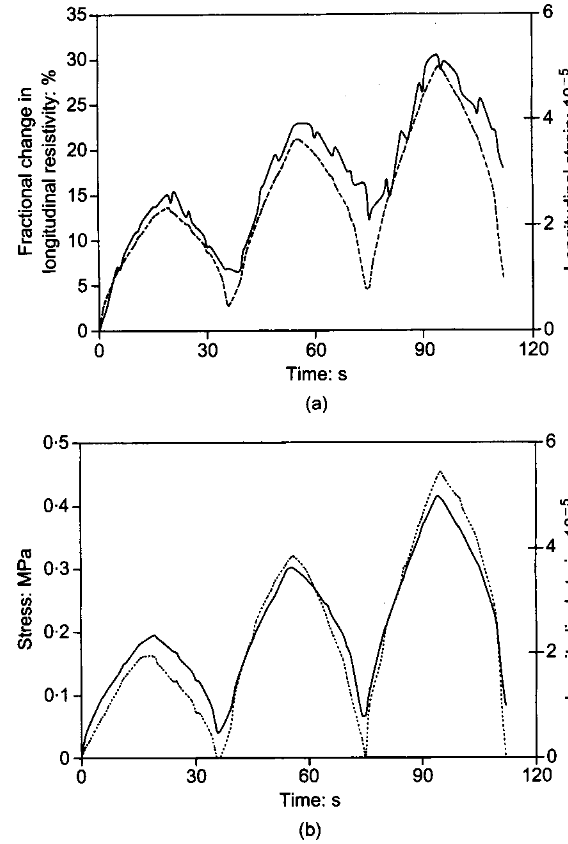

Fig. 3 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0·72 vol% steel fibres under tension

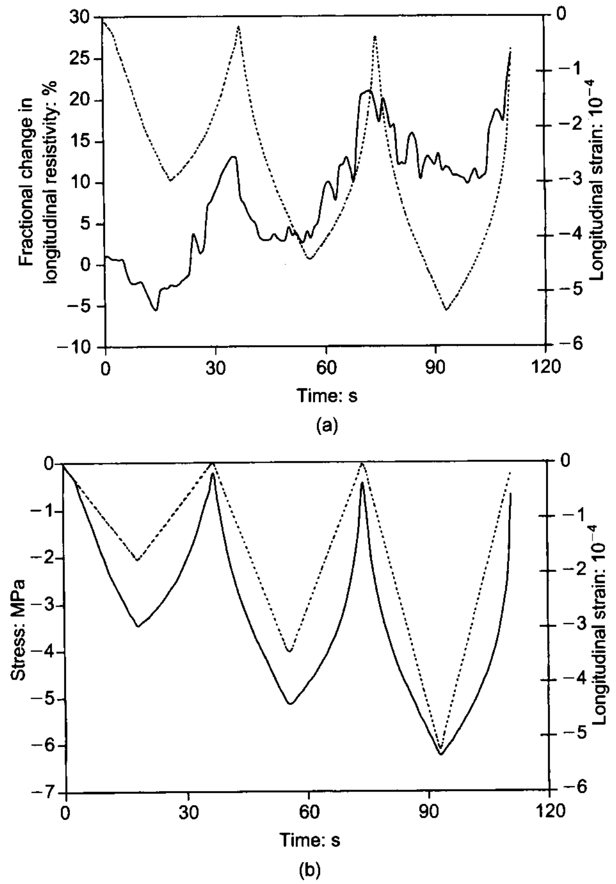

Fig. 4 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0·72 vol% steel fibres under compression

pression, as observed for cement paste containing 0·72 vol% steel fibres (Figs 3 and 4). The resistivity change and strain were more reversible, both under tension and compression, but the resistivity change was still fairly noisy in compression (Fig. 6(a)).

Cement paste containing 0·5 vol% carbon fibres

Figures 7 and 8 show the piezoresistivity results for the cement paste containing 0·5 vol% carbon fibres 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 fibre cement pastes (Figs 3–6).

Gauge factor

The gauge factor is defined as the fractional change in resistance per unit strain. With the strain being positive for tension and negative for compression, the gauge 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 gauge factor was higher under tension than compression for the two steel-fibre cement pastes, but was lower under tension than compression for the carbon-fibre cement paste. The gauge factor under tension was much higher for the two steel-fibre cement pastes than for the carbon-fibre cement paste. These sharp contrasts between steel- and carbon-fibre pastes suggest a difference in the piezoresistivity mechanism.

The gauge factor is higher for the steel-fibre cement pastes than the carbon-fibre cement paste, except for the case of the paste with 0·72 vol% steel fibres under compression. When comparing the two steel fibre pastes, the value for tension is higher and that for compression is lower for the paste with a higher fibre content.

Electrical resistivity

The electrical resistivity of the three cement pastes is listed in Table 1. The two steel-fibre pastes are much

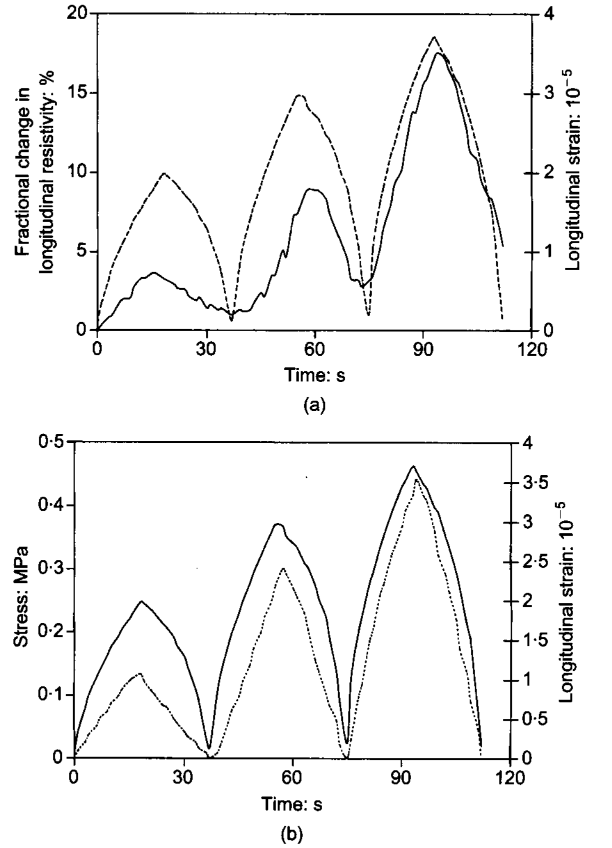

Fig. 5 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0·36 vol% steel fibres under tension

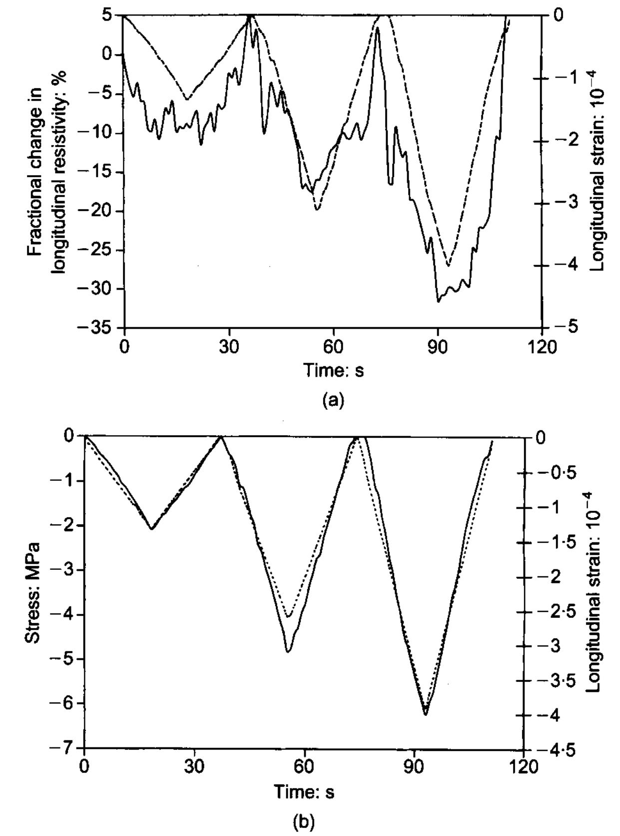

Fig. 6 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0·36 vol% steel fibres under compression

more conductive than the carbon-fibre paste. This difference is because the steel-fibre volume fractions are above the percolation threshold previously determined for steel fibre (between 0·27 and 0·36 vol%),[37] whereas the carbon-fibre volume fraction is below the percolation threshold previously determined for carbon fibre (between 0·5 and 1·0 vol%).[12]

Stress–strain relationships

Figures 9–11 show the nearly linear stress–strain relationships, as obtained from Figs 3–8 for both tension and compression in the third stress cycle during loading and unloading, for 0·72 vol% steel-fibre cement paste, 0·36 vol% steel-fibre cement paste and 0·5 vol% carbon-fibre cement paste, respectively. The apparent non-linearity suggested by the curves plotted over time in Figs 3–6 (particularly those obtained under tension) is due to slight slippage at the grips.

Table 2 shows the elastic moduli under tension and compression, as obtained from Figs 9–11. Both moduli are higher for the carbon-fibre paste than the two steel-fibre pastes. The steel-fibre paste with a higher fibre content exhibits lower moduli than at the lower fibre content. For each material, the moduli under tension and compression are quite close.

Discussion

Percolation in this instance, of electrons, results from contact between adjacent fibres so that a continuous conducting path exists. Above the percolation threshold (e.g. when percolation occurs prior to straining), the conductivity is governed by the contact resistance at the fibre–fibre contact, which is affected by tension much more than compression. Below the percolation threshold (e.g. when percolation does not occur prior to straining), the conductivity is governed by the contact resistance at the fibre–matrix interface when the matrix is conductive, i.e. in a cement matrix. This interface is inherently weak (loose) and is thus affected by compression (which tends to diminish the gap at the interface) more than tension (which tends to expand the gap). The size of the gap is not expected to affect the

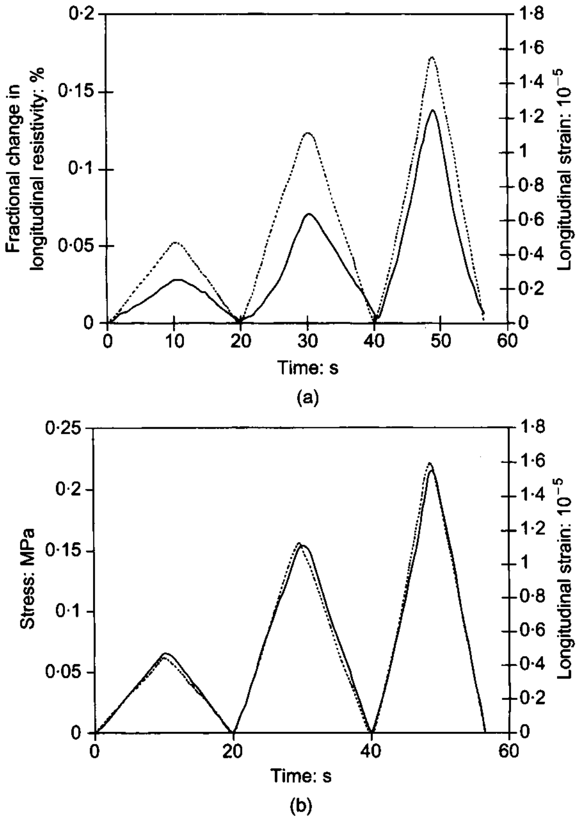

Fig. 7 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b), for cement paste containing 0·5 vol% carbon fibres under tension

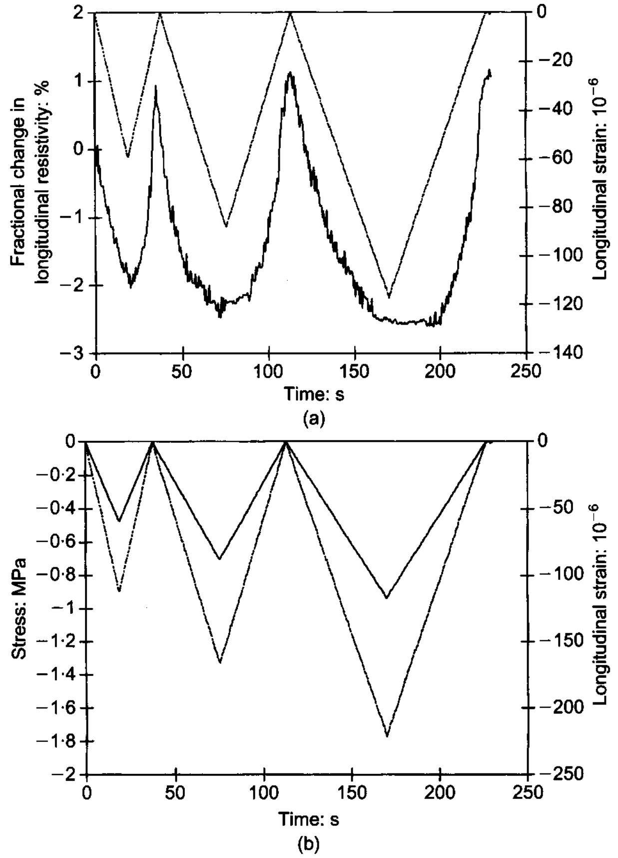

Fig. 8 Variation of the fractional change in electrical resistivity (solid curve) with strain (dashed curve) (a), and of the strain (solid curve) with stress (dashed curve) (b) for cement paste containing 0·5 vol% carbon fibres under compression

contact resistivity of the interface very much, as electron tunnelling is limited to small distances. Thus the piezoresistivity in the steel-fibre pastes is dominated by the effect of strain (particularly tensile strain) on the fibre–fibre contact, whereas that in carbon-fibre paste is dominated by the effect of strain (particularly compressive strain) on the fibre–matrix contact.

Steel fibres are much more ductile than carbon. The ductility of the steel fibres is favourable for the change in fibre–fibre contact, which involves more movement than the change in fibre–matrix contact. Although the movement associated with a change in fibre–fibre contact is relatively large, the actual movement needed to affect the resistivity is small. This is due to the small distances associated with electron tunnelling.

An increase in steel-fibre volume fraction causes the gauge factor under tension to increase, conversely causing it decreases under compression. This supports the fact that, in the presence of percolation, tension has more effect on the fibre–fibre contact than compression.

Although the gauge factor is relatively low for the carbon-fibre paste compared to the steel-fibre pastes, the signal-to-noise ratio is higher and the reversibility upon unloading is better for the former; compare the (a) parts of Figs 3–8. In particular, the signal-to-noise ratio is very low for the steel-fibre pastes under compression. Therefore, the carbon-fibre paste is a superior strain sensor than the steel-fibre counterparts. Comparing the two steel-fibre pastes, that with the

Table 1. Gauge factor and electrical resistivity of cement pastes containing silica fume and fibres

Fibres	Gage factor		Resistivity: Ω cm
	Tension	Compression	
0·72 vol% steel fibres	4560 ± 640	200 ± 30	16 ± 1
0·36 vol% steel fibres	1290 ± 160	720 ± 100	57 ± 4
0·5 vol% carbon fibres	90 ± 10	350 ± 30	$(1{\cdot}5 \pm 0{\cdot}1) \times 10^4$

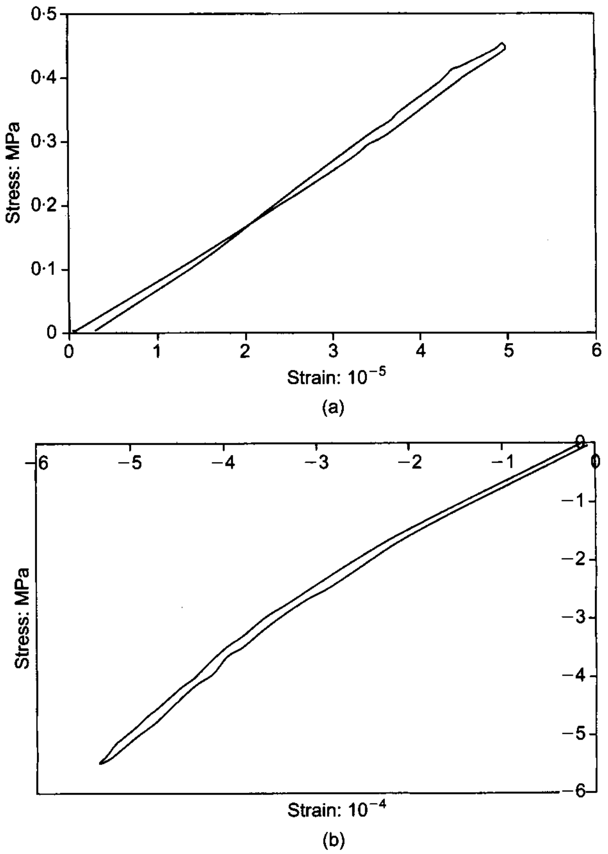

Fig. 9 Stress–strain curves of 0·72 vol% steel-fibre cement paste in the third stress cycle: (a) tension; (b) compression

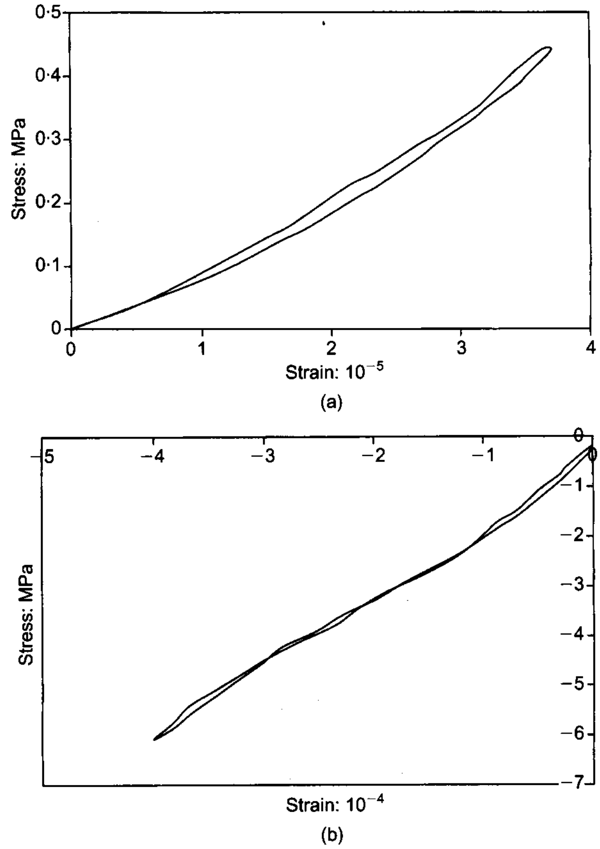

Fig. 10 Stress–strain curves of 0·36 vol% steel-fibre cement paste in the third stress cycle: (a) tension; (b) compression

lower fibre volume fraction (0·36%) is superior, due to better reversibility upon unloading, the higher gauge factor under compression, and the better balance in gauge factor between tension and compression.

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

It was previously believed that the inferior piezoresistive performance of steel-fibre cement compared to carbon-fibre cement was due to the large diameter (60 μm) of the steel fibre used in the previous work.[35] However, the steel-fibre diameter (8 μm) was smaller than the carbon-fibre diameter (15 μm) in this work. Thus the inferior performance of steel-fibre cement is related to difference in piezoresistive mechanism, rather than the difference in diameter. However, further work is needed to understand the difference in origin of the piezoresistive behaviour between steel- and carbon-fibre cements.

The pieozoresistive behaviour reported in this paper pertains to that of cement pastes. However, structural cement-based materials involve aggregates, as in concretes. As shown previously for carbon-fibre cement-based materials, the presence of aggregates diminishes the piezoresistive behaviour, though the behaviour remains strong enough for application in sensing.[39,40]

Conclusion

Carbon-fibre (15 μm diameter, below the percolation threshold) paste is a better piezoresistive strain sensor than stainless steel-fibre (8 μm diameter, above the percolation threshold) paste at a similar fibre volume fraction, as shown by a higher signal-to-noise ratio and better reversibility upon unloading. However, the gauge factor is higher for the steel-fibre pastes, particularly under tension. The steel-fibre paste containing 0·36 vol% fibres is superior to that containing 0·72 vol% fibres as a piezoresistive strain sensor, as shown by better reversibility upon unloading and the higher gauge factor under compression. The mechanism behind the piezoresistivity relates to the effect of strain on the fibre–fibre contact in the case of the steel fibre

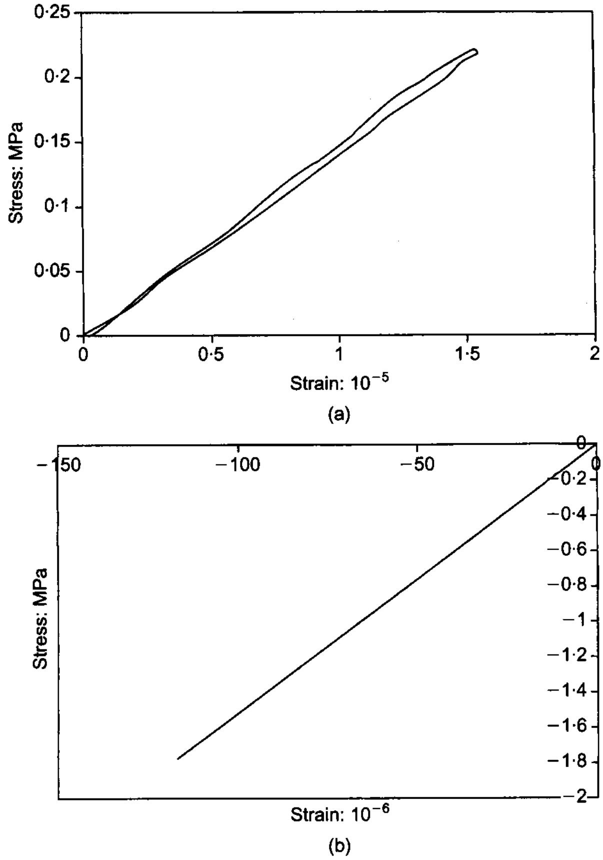

Fig. 11 Stress–strain curves of 0·5 vol% carbon-fibre cement paste in the third stress cycle: (a) tension; (b) compression

Table 2. Elastic moduli of cement pastes containing silica fume and fibres

Fibres	Modulus: GPa	
	Tension	Compression
0·72 vol% steel fibres	10·3 ± 1·5	10·3 ± 1·1
0·36 vol% steel fibres	12·4 ± 1·6	14·0 ± 1·3
0·5 vol% carbon fibres	14·4 ± 2·3	15·1 ± 2·1

paste, but relates to the effect of strain on the fibre–matrix contact in the case of the carbon-fibre paste.

References

1. Chen P.-W. and Chung D. D. L. Concrete reinforced concrete as a smart material capable of non-destructive flaw detection. *Smart Materials & Structures*, 1993, **2**, 22–30.
2. Chen P.-W. and Chung D. D. L. Carbon fibre reinforced concrete as an intrinsically smart concrete for damage assessment during static and dynamic loading. *ACI Materials Journal*, 1996, **93**, No. 4, 341–350.
3. Fu X. and Chung D. D. L. Self-monitoring of fatigue damage in carbon fibre reinforced cement. *Cement & Concrete Research*, 1996, **26**, No. 1, 15–20.
4. Fu X., Lu W. and Chung D. D. L. Ozone treatment of carbon fibre for reinforcing cement. *Carbon*, 1998, **36**, No. 9, 1337–1345.
5. Qizhao M., Binyuan Z., Darong S. and Zhuoqiu L. Resistance changement of compression sensible cement specimen under different stresses. *Journal of the Wuhan University of Technology*, 1996, **11**, No. 3, 41–45.
6. Wen S. and Chung D. D. L. Uniaxial compression in carbon fibre reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. *Cement & Concrete Research*, 2001, **31**, No. 2, 297–301.
7. Wen S. and Chung D. D. L. Uniaxial tension in carbon fibre reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions. *Cement & Concrete Research*, 2000, **30**, No. 8, 1289–1294.
8. Robins P., Austin S., Chandler J. and Jones P. Flexural strain and crack width measurement of steel-fibre-reinforced concrete by optical grid and electrical gauge methods. *Cement & Concrete Research*, 2001, **31**, No. 5, 719–729.
9. Wang C. S., Wu F. and Chang F.-K. Structural health monitoring from fibre-reinforced composites to steel-reinforced concrete. *Smart Materials & Structures*, 2001, **10**, No. 3, 548–552.
10. Cao J., Wen S. and Chung D. D. L. Defect dynamics and damage of cement-based materials, studied by electrical resistance measurement. *Journal of Materials Science*, 2001, **36**, No. 18, 4351–4360.
11. Chen P.-W. and Chung D. D. L. Carbon fibre reinforced concrete as an intrinsically smart concrete for damage assessment during static and dynamic loading. *ACI Materials Journal*, 1996, **93**, No. 4, 341–350.
12. Chen P.-W. and Chung D. D. L. Improving the electrical conductivity of composites comprised of short conducting fibres in a non-conducting matrix: the addition of a non-conducting particulate filler. *Journal of Electronic Material*, 1995, **24**, No. 1, 47–51.
13. Wang X., Wang Y. and Jin Z. Electrical conductivity characterization and variation of carbon fibre reinforced cement composite. *Journal of Materials Science*, 2002, **37**, No. 1, 223–227.
14. Fu X. and Chung D. D. L. Carbon fibre reinforced mortar as an electrical contact materials for cathodic protection. *Cement & Concrete Research*, 1995, **25**, No. 4, 689–694.
15. Morsy M. S. Effect of temperature on electrical conductivity of blended cement pastes. *Cement & Concrete Research*, 1999, **29**, 603–606.
16. Wilson J. G. and Gupta N. K. Assessment of structure formation in fresh concrete by measurement of its electrical resistance. *Building Research Information*, 1996, **24**, No. 4, 209–212.
17. Abo El-Enein S. A., Kotkata M. F., Hanna G. B., Saad M. and Abd El Razek M. M. Electrical conductivity of concrete containing silica fume. *Cement & Concrete Research*, 1995, **25**, No. 8, 1615–1620.
18. Kim H. C., Kim S. Y. and Yoon S. S. Electrical properties of cement paste obtained from impedance spectroscopy. *Journal of Material Science*, 1995, **30**, No. 15, 3768–3772.
19. Wen S. and Chung D. D. L. Carbon fibre-reinforced cement as a thermistor. *Cement & Concrete Research*, 1999, **29**, No. 6, 961–965.
20. Fu X. and Chung D. D. L. Degree of dispersion of latex particles in cement paste, as assessed by electrical resistivity measurement. *Cement & Concrete Research*, 1996, **26**, No. 7, 985–991.
21. Tumidajski P. J. Electrical conductivity of portland cement mortars. *Cement & Concrete Research*, 1996, **26**, No. 4, 529–534.

22. PING G., PING X. and BEAUDOIN J. J. Microstructural characterization of the transition zone in cement systems by means of AC impedance spectroscopy. *Cement & Concrete Research*, 1993, **23**, No. 3, 581–591.
23. MASON T. O., FORD S. J., SHANE J. D., HWANG J.-H. and EDWARDS D. D. Experimental limitations in impedance spectroscopy of cement-based materials. *Advances in Cement Research*, 1998, **10**, No. 4, 143–150.
24. MACPHEE D. E., SINCLAIR D. C. and STUBBS S. L. Electrical characterization of pore reduced cement by impedance spectroscopy. *Journal of Material Science Letters*, 1996, **15**, No. 18, 1566–1568.
25. CAO J. and CHUNG D. D. L. Carbon fibre reinforced cement mortar improved by using acrylic dispersion as an admixture. *Cement & Concrete Research*, 2001, **31**, No. 11, 1633–1637.
26. CHEN P.-W., FU X. and CHUNG D. D. L. Microstructural and mechanical effects of latex, methylcellulose and silica fume on carbon fibre reinforced cement. *ACI Materials Journal*, 1997, **94**, No. 2, 147–155.
27. CAO J. and CHUNG D. D. L. Improving the dispersion of steel fibres in cement mortar by the addition of silane. *Cement & Concrete Research*, 2001, **31**, No. 2, 309–311.
28. FU X. and CHUNG D. D. L. Single fibre electromechanical pull-out testing and its application to studying the interface between steel fibre and cement. *Composite Interfaces*, 1997, **4**, No. 4, 197–211.
29. CHEN P.-W. and CHUNG D. D. L. A comparative study of concretes reinforced with carbon polyethylene and steel fibres and their improvement by latex addition. *ACI Materials Journal*, 1996, **93**, No. 2, 129–133.
30. TEUTSCH M. Development of ductile, steel-fibre-reinforced, high-performance concretes. *Betonwerk und Fertigteil-Technik*, 2001, **67**, No. 4, 56–63.
31. BAYASI Z. and KAISER H. Steel fibres as crack arrestors in concrete. *Indian Concrete Journal*, 2001, **75**, No. 3, 215–222.
32. NATARAJA M. C., DHANG N. and GUPTA A. P. Splitting tensile strength of SFRC. *Indian Concrete Journal*, 2001, **75**, No. 4, 287–290.
33. ALAVIZADEH-FARHANG A. and SILFWERBRAND J. Responses of plain and steel fibre-reinforced concrete beams to temperature and mechanical loads: experimental study. *Transportation Research Record*, 2000, No. 1740, 25–32.
34. LOTFY B. Behaviour of steel fibre reinforced concrete subjected to direct shear load. *Journal of Engineering & Applied Science*, 2001, **48**, No. 3, 455–471.
35. FEBRILLET N., KIDO A., ITO Y. and ISHIBASHI K. Strength and abrasion resistance of ultra-high strength steel fibre reinforced concrete. *Transactions of the Japan Concrete Institute*, 2000, **22**, 243–252.
36. SUN W., CHEN H., LUO X. and QIAN H. The effect of hybrid fibres and expansive agent on the shrinkage and permeability of high-performance concrete. *Cement & Concrete Research*, 2001, **31**, No. 4, 595–601.
37. WEN S. and CHUNG D. D. L. Electromagnetic interference shielding reaching 70 dB in steel fibre cement. *Cement & Concrete Research*, in press.
38. WEN S. and CHUNG D. D. L. Cement-based controlled electrical resistivity materials. *Journal of Electronic Materials*, 2001, **30**, No. 11, 1448–1451.
39. CHEN P.-W. and CHUNG D. D. L. Concrete reinforced with up to 0·2 vol% of short carbon fibres. *Composites*, 1993, **24**, No. 1, 33–52.
40. BONTEA D.-M., CHUNG D. D. L. and LEE G. C. Damage in carbon fibre reinforced concrete, monitored by electrical resistance measurement. *Cement and Concrete Research*, 2000, **30**, No. 4, 651–659.

Discussion contributions on this paper should reach the editor by 1 January 2004