Advances in Cement Research, 2004, **16**, No. 4, October, 161–166

Resistance heating using electrically conductive cements

S. Wang*, S. Wen* and D. D. L. Chung*

University at Buffalo, The State University of New York

Steel fibre (8 μm diameter, 0·72 vol.%)-reinforced cement was found to be effective for resistance heating. A DC electrical power input of 5·6 W (7·1 V, 0·79 A) resulted in a maximum temperature of 60°C (initial temperature = 19°C) and a time of 6 min to reach half the maximum temperature. Efficiency of energy conversion increased with time of heating, reaching 100% after 50 min. The heat power output per unit area was 750 W/m² for steel fibre cement, compared with 340 W/m² for a metal wire with the same resistance. The use of carbon fibres or graphite particles in place of steel fibres resulted in less effective heating, due to the higher resistivity.

Introduction

Electrical heating includes resistance heating (i.e., Joule heating) and induction heating, in addition to heating by the use of electric heat pumps, plasmas and lasers.[1,2] It should be distinguished from solar heating[3–7] and the use of fossil fuels such as coal, fuel oil and natural gas.[2] Due to the environmental problem associated with the use of fossil fuels and due to the high cost of solar heating, electrical heating is increasingly important. Although electric heat pumps are widely used for the electrical heating of buildings, resistance heating is a complementary method which is receiving increasing attention. Resistance heating is the focus of this paper.

Resistance heating involves passing an electric current through a resistor, which is the heating element. In relation to the heating of buildings, resistance heating typically involves the embedding of heating elements in the structural material, such as concrete.[8–10] The materials of heating elements cannot be too low in electrical resistivity, as this results in the resistance of the heating element being too low and a high current would be needed to attain a certain power. The lower limit of the resistance depends on the current capability of the power source. The materials of heating elements cannot be too high in resistivity either, as this results in the current in the heating element being too low (unless the voltage was very high). The upper limit of the resistance depends on the voltage capability of the power source. Materials of heating elements include metal alloys (such as nichrome), ceramics (such as silicon carbide[11]), graphite,[12,13] polymer-matrix composites,[14–16] carbon–carbon composites,[17] asphalt[18] and concrete.[19]

Resistance heating is not only useful for the heating of buildings, it is useful for the deicing of bridge decks,[20] driveways and aircraft,[14] and for the demolition of concrete structures.[21,22]

A less common form of resistance heating involves eddy current heating which accompanies induction heating,[23] but the requirement of induction heating makes this form of resistance heating relatively expensive and it is not addressed herein. Furthermore, the paper does not address the various electrical and solar methods of heating that can be used to hasten the curing of concrete.[24–27]

Conventional concrete (i.e., concrete without conductive admixtures) is electrically conductive, primarily due to ions, which originate mainly from the water in the concrete. Removal of water from concrete increases the resistivity. However, even without the removal of water, the resistivity of conventional concrete is too high for resistance heating to be effective. In fact, the resistivity is so high that it must be decreased by orders of magnitude before the material can be effective for this application. Thus, in the development of cement-based materials for resistance heating, low resistivity is not a matter for concern as the lower the resistivity, the better is the material for resistance heating.

The resistivity of concrete can be diminished by using an electrically conductive admixture, such as

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

(ACR 3455) Paper received 23 July 2003; last revised 11 May 2004; accepted 22 June 2004

discontinuous carbon fibres,[28–32] discontinuous steel fibres,[20,33] steel shaving[20] and graphite particles.[34,35] The steel shaving is better considered as a fine aggregate than an admixture, because of its large particle size (0·15 – 4·75 mm)[20] and high proportion (20 vol.%).[20] The combined use of conductive fibres and conductive particles is also effective. For example, the combined use of steel shaving (20 vol.%) and steel fibre (1·5 vol.%, fibre diameter, which is larger than that of this study by a few orders of magnitude) gives an electrical resistivity of 100 Ω cm.[20] Yet another way to diminish the resistivity involves using an alkaline slag binder.[19]

The objective of this paper is to evaluate the effectiveness of conductive cements for resistance heating, since such evaluation has received little prior attention and prior evaluation has been limited to heating in the temperature range for deicing.[20,36,37] In contrast, this work addresses heating above room temperature. In this evaluation, cements containing discontinuous carbon fibres (15 μm diameter, 1·0 vol.%), discontinuous stainless steel fibres (8 μm diameter, 0·7 vol.%) and graphite particles (< 45 μm size, 37 vol.%) were compared. Due to the lowest resistivity (0·85 Ω cm) being attained by the use of the steel fibres, the effectiveness for heating was highest for the cement with steel fibres. Therefore, this paper is focused on the evaluation of steel-fibre-reinforced cement as a heating element.

The cement matrix is slightly conductive, with electrical resistivity around 5×10^5 Ω cm.[38] The conductive admixtures used in this work involve electrons and/or holes in the conduction and they dominate the conduction in the cement–matrix composites of this work, as shown by the fact that the resistivity of these composites is lower than that of the cement matrix by a few orders of magnitude. The occurrence of percolation has been previously shown by measurement of the resistivity at various volume fractions of the conductive admixture (carbon fibre)[30] both above and below the percolation threshold. That the conductive admixtures dominate the conduction in the cement–matrix composites of this work is advantageous for the stability of the resistivity of the composites at elevated temperatures for a long time, as the cement matrix itself is limited in thermal stability. As the resistivity of cement-based materials decreases reversibly with increasing temperature,[28] the effectiveness of the cement-based materials for resistance heating is expected to improve slightly, even though moisture loss occurs as the temperature increases.[39]

Experimental methods

No aggregate (fine or coarse) was used. The cement used was Portland cement (type I).

Three types of conductive admixtures were used for the sake of comparison. They were steel fibres, carbon fibres and graphite particles.

The steel fibres were made of 304 austenitic stainless steel. 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.

Cement pastes containing steel fibres were made by using cement, water (water/cement ratio = 0·35), silica fume (15% by mass of cement, to help the fibre dispersion) and the steel fibres (fibres + PVA amounting to 4·0% by mass of cement, corresponding to fibres without PVA amounting to 3·6% by mass of cement, or 0·72 vol.%, and PVA amounting to 0·4% by mass of cement, or 0·64 vol.%).

The carbon fibres were isotropic pitch based, unsized, 15 μm in diameter and approximately 5 mm in length, as obtained from Ashland Petroleum Co. (Ashland, KT, USA). The carbon fibre content was 1·0% by mass of cement. This corresponds to a fibre volume fraction of 1·0%. The water/cement ratio was 0·35. Silica fume (Elkem Materials, Inc., Pittsburgh, PA, USA; EMS 965) was used in the amount of 15% by mass of cement in order to help the fibre dispersion. Methylcellulose, used along with carbon fibres amounting to 0·4% by mass of cement, was Methocel A15-LV (Dow Chemical Corp., Midland, MI, USA). The defoamer (Colloids, Inc., Marietta, GA, USA; 1010) was in the amount of 0·13 vol.%.

The graphite powder (flakes) were < 45 μm in size, as provided by Fisher Chemical Co., Fair Lawn, NJ, USA. The graphite/cement weight ratio was 1·0. This corresponds to a graphite volume fraction of 37%, as calculated from the densities of the components. The water/cement ratio was 0·45.

A rotary mixer with a flat beater was used for mixing. Cement, water, silica fume (if applicable) and conductive fibres (or powder) were mixed for 5 min. After pouring into oiled moulds, an external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were taken out of the moulds after 1 day and cured in air at room temperature (relative humidity = 100%) for 28 days.

Evaluation of the steel-fibre-reinforced cement as a heating element was conducted by passing a fixed DC current (ranging from 0·14 to 0·79 A, corresponding to power ranging from 0·19 to 5·64 W) along the length of the specimen (150 mm × 12 mm × 12 mm, put on a refractory brick) by using electrical contacts (150 mm apart) in the form of silver paint in conjunction with copper foil at the two end surfaces of the specimen. The silver paint was applied between each end of the specimen and a copper foil which covered the entire 12 mm × 12 mm surface of the specimen end. Two copper wires were soldered to each of the two copper foils, as illustrated in Fig. 1. One wire from each of the two ends of the specimen served as a current contact; the other wire from each end served as a voltage contact. Hence, there were two contacts for passing current and two other contacts for voltage measurement. The voltage drop along the length of the specimen ranged from 1·34 to 7·14 V. The room temperature was 18·7°C. The temperature of the specimen was measured as a function of time during constant current application and in the subsequent period in which the current was off by using a T-type thermocouple located in the middle of the top surface of the specimen. The constant current period was long enough for the temperature to essentially stabilise to a maximum.

The evaluation of the carbon-fibre-reinforced cement was conducted in the same way as that of the steel-fibre-reinforced cement, except that the current was 0·065 A and the power was 1·806 W. The evaluation of the graphite-particle-reinforced cement was also conducted in the same way, except that the current was 0·009 A and the power was 0·27 W. The differences in current and power were due to differences in resistivity.

Results and discussion

Figure 2 shows the change in temperature with time, which is proportional to the electrical energy because the power (product of voltage and current) is constant, for a power level of 5·6 W. The temperature increased with time, as expected, but it stabilised gradually. When the current was subsequently turned off the temperature dropped, as expected. Similar effects were obtained at all power levels. Table 1 shows a quantitative comparison of the results obtained at five power levels. The higher the power, the higher was the maximum temperature and the longer was the time to reach the maximum temperature. Due to the asymptotic nature of the temperature rise toward the maximum temperature, the time to reach half the maximum temperature rise is a better indicator of the response time than the time to reach the maximum temperature. Both the time to reach half the maximum temperature rise during heating and the time to cool to half the maximum temperature rise during cooling decreased with increasing power, except when the power was below 0·91 W. The electrical energy input to heat by 1°C in the initial portion of rapid temperature rise ranged from 90 to 117 J. The heat output (i.e., heat going to the environment, whether by convection, radiation or conduction) is given by the electrical energy input minus the heat absorbed by the heating element (i.e., specimen). The heat absorbed is given by the product of the specific heat, mass and temperature change. Assuming that the specific heat is constant at 1000 J/kg K,[40] the heat output was calculated, as shown in Table 1 for the heat released during the first 300 s of heating (i.e., the initial period of rapid temperature rise). This heat output ranged from 34 to 860 J, which corresponded to a heat power output ranging from 0·11 to 2·86 W during the first 300 s of heating.

The ratio of the heat power output to the electrical power input is the efficiency (η) of the conversion from electrical energy to thermal energy. It is given by

$$\eta = \frac{IV\Delta t - C_p m \Delta T}{IV\Delta t} \qquad (1)$$

where ΔT is the change in temperature in time Δt, C_p is the specific heat, m is the mass, I is the current and V is the voltage. As the heating time progresses, ΔT approaches zero and hence η approaches 100%, irrespective of the value of C_p. The C_p value just affects the time it takes for η to reach 100%.

Figure 3 shows a plot of η versus time for the case of $I = 0{\cdot}48$ A (one of the cases in Table 1). The curves almost overlap for all of the five cases in Table 1. The efficiency was about 45% at the start of heating. It increased with the time of heating, reaching 100% after 3000 s of heating.

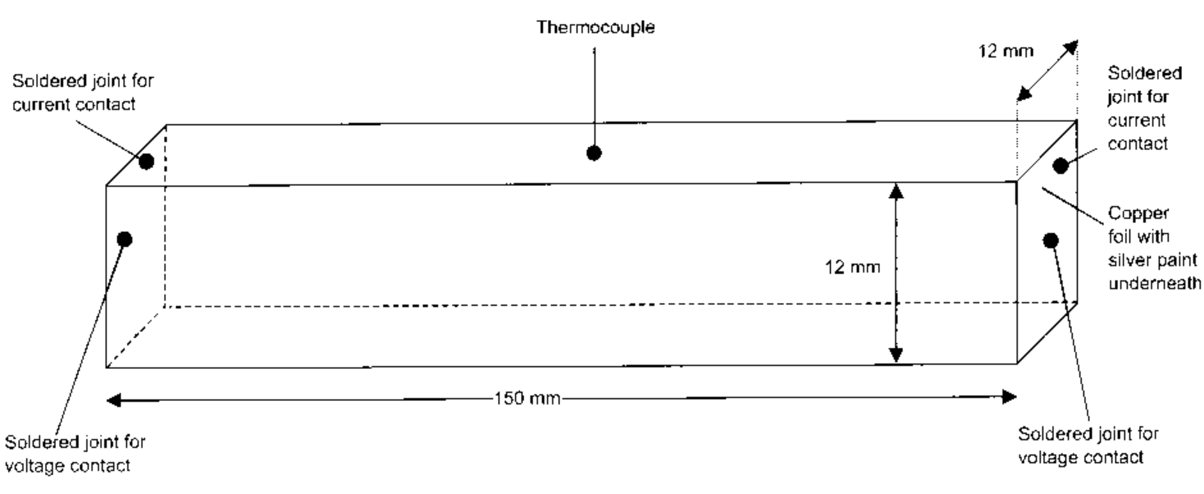

Fig. 1. Specimen configuration for evaluation of resistance heating effectiveness

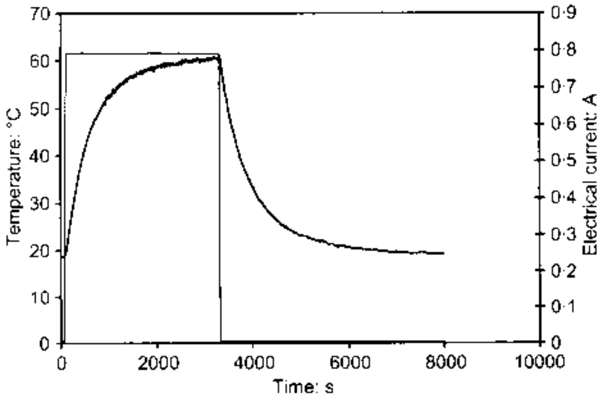

Fig. 2. Temperature variation during heating (current on) and subsequent cooling (current off). Thick curve, temperature; thin curve, current

The power of 5·6 W (highest value in Table 1) corresponds to a power per unit area of the surface of the rectangular specimen of 750 W/m^2. (The area of all six faces of the rectangular specimen bar was considered.) This value is close to the highest value of 855 W/m^2 previously reported for the power dissipation from the top and bottom faces of a slab of concrete containing carbon fibres and carbonaceous particles.[36] Because of the difference in geometry, comparison of the power per unit area of this work and that of Ref. 36 is not very meaningful.

The use of carbon fibres (1·0 vol.%, 15 μm diameter, 5 mm long) instead of steel fibres (0·72 vol.%, 8 μm diameter, 6 mm long) resulted in a maximum temperature of 56°C and a time of 256 s to reach half the maximum temperature when the electrical power input was 1·806 W (28 V, 0·065 A). The need for a high voltage (28 V, compared with 7 V in the steel-fibre-reinforced cement case) is disadvantageous.

The use of graphite particles (37 vol.%, $< 45\ \mu$m size) instead of steel fibres (0·72 vol.%) resulted in a maximum temperature of 24°C and a time of 220 s to reach half the maximum temperature rise when the electrical power input was 0·27 W (30 V, 0·009 A). The high voltage and the low maximum temperature are undesirable.

The electrical resistance of the steel-fibre-reinforced cement specimen (Fig. 2, Table 1) was 8·99 Ω. This corresponds to a resistivity of 0·85 Ω cm. In contrast, the resistivity was 407 and 104 Ω cm, respectively, for graphite (37 vol.%) cement and carbon fibre (1·0 vol.%) cement. The exceptionally low resistivity of the steel-fibre-reinforced cement is due to the high conductivity and large aspect ratio of the steel fibres used. The relatively high resistivities of the graphite cement and carbon fibre cement are due to the relatively low aspect ratio and the relatively low conductivity of the graphite and carbon fibres. Increasing the steel fibre volume fraction from 0·72 to 0·90% did not decrease the resistivity, probably due to poorer dispersion of the fibres at a higher volume fraction. The highest effectiveness for resistance heating attained by using steel-fibre (0·72 vol.%)-reinforced cement was due to the lowest resistivity.

An alternate concrete technology involves using steel shavings as the conductive aggregate, in conjunction with low-carbon steel fibre as the conductive admixture.[20] The use of 20 vol.% steel shavings together with 1·5 vol.% steel fibre resulted in an electrical resistivity of 100 Ω cm.[20] This resistivity is much higher than that of the steel-fibre-reinforced cement of the present study. Furthermore, the resistivity of the material of Ref. 20 increased with time, reaching 350 Ω cm in 6 months,[20] probably due to corrosion of the steel shavings and fibre. Of practical importance is that the material used in the present study does not require any special mixing equipment or procedure and does not require any special aggregate.

The effectiveness of a cement-based heating element is governed by the resistance, which depends on the resistivity and the dimensions. The resistances of the steel-fibre cement, carbon-fibre cement and graphite-cement specimens used in this work were 8·99, 434 and 3620 Ω, respectively, showing that a resistance of around 10 Ω is sufficiently low. In order to reach a resistance that is sufficiently low for effective use as a heating element, either the resistivity needs to be low or the ratio of the length in the current direction to the cross-sectional area perpendicular to the current direction needs to be small.

In practice, electrically conductive cements compete with metals for use in resistance heating. For the sake of comparison, let us consider the most common heating element in the form of a metal wire (say, resistivity $= 10^{-4}$ Ω cm and diameter = 0·5 mm). A length of 1·76 m is needed to attain a resistance of 8·99 Ω, which is the value for the steel-fibre-reinforced cement bar used in the present study. Thus, the use of a cement-based heating element does not require a long length. In contrast, a metal-based heating element requires a long length and consequently the winding of the long length to make a heater coil is necessary. Due to its bulkiness, a metal coil is intrusive when it is embedded in a structure. Furthermore, the air gap within the coil and between the coil and the structural material is a thermal insulator that reduces the effectiveness of heat transfer from the coil to the structure.

For the same current of 0·79 A and the same voltage of 7·1 V, the heat power output per unit area attained in the steel-fibre-cement bar of the present study (750 W/m^2) is much higher than that attained by the metal wire (340 W/m^2).

Conclusion

Steel-fibre (8 μm diameter, 0·72 vol.%)-reinforced cement is effective for use as a resistance heating

Table 1. Effectiveness of steel-fibre-reinforced cement for resistance heating. The initial temperature before heating was 18·7°C (room temperature)

Current: A	Electrical power input: W	Maximum temperature: °C	Time to reach maximum temperature: s	Time to reach half of the maximum temperature rise during heating: s	Time to drop to half of the maximum temperature rise during cooling: s	Electrical energy input to heat by 1°C during the first 300 s: J/°C	Heat energy released during the first 300 s: J	Heat power output during the first 300 s: W
0·14	0·19	20·4	2400	386	382	117	33·7	0·112
0·32	0·91	26·8	2550	478	470	91·1	133·5	0·445
0·48	2·1	35·9	2620	454	482	91·4	308·1	1·027
0·64	3·7	47·2	2770	434	454	90·3	537·3	1·791
0·79	5·6	60·3	2950	382	418	94·5	857·6	2·859

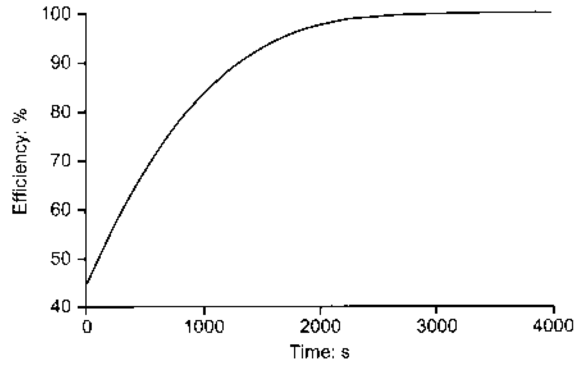

Fig. 3. Efficiency versus time during heating at a current of 0·48 A

element. An electrical power input of 5·6 W (7·1 V, 0·79 A) resulted in a maximum temperature of 60°C (initial temperature = 19°C) and a time of 6 min to reach half of the maximum temperature rise. Decreasing the electrical power input decreased the maximum temperature and increased the time to reach half the maximum temperature rise. The efficiency of conversion from electrical energy to thermal energy was about 45% at the start of heating. It increased with the time of heating, attaining 100% after 3000 s of heating. The use of carbon fibres (15 μm diameter, 1·0 vol.%) or graphite particles (< 45 μm, 37 vol.%) instead of steel fibres resulted in lower effectiveness for resistance heating, due to the higher voltage requirement associated with the higher electrical resistivity. The heat power output per unit area attained by steel-fibre-reinforced cement is 750 W/m^2, compared with 340 W/m^2 for a metal wire having the same resistance.

References

1. Perkins A. and Guthrie A. New approaches in electric heating. *Metallurgia*, 1982, **19**, No. 12, 605–621.
2. Ebeling K. Energy saving with concrete — new old heating techniques. *Betonwerk und Fertigteil- Technik*, 1994, **60**, No. 12, 70–76.
3. Lazzari F. and Raffellini G. Solar heating system with annual storage. *International Journal of Ambient Energy*, 1981, **2**, No. 3, 141–149.
4. Kumar A., Singh U., Srivastava A. and Tiwari G. N. Thermal design of a roof as an inexpensive solar collector/storage system. *Applied Energy*, 1981, **8**, No. 4, 255–267.
5. Seth S. P., Sodha M. S. and Seth A. K. Use of a thermal trap for increasing solar gains through a roof or a wall. *Applied Energy*, 1982, **10**, No. 2, 141–149.
6. Kaushik N. D. and Rao S. K. Non-convective roof pond for passive space heating. *Applied Energy*, 1982, **12**, No. 1, 21–36.
7. Fanney A. H., Dougherty B. P. and Dramp K. P. Field performance of photovoltaic solar water heating systems. *Proceedings of the 1997 International Solar Energy Conference*, 1997, pp. 171–182.
8. Ramadan B. H. Design sensitivity analysis for optimal temperature control of a radiant electric slab. *ASHRAE Transactions*, 1994, **100**, No. 1, 160–167.
9. Fomin B.G. Embedded electric heating system. *Gidrotekhnicheskoe Stroitel'Stvo*, 1999, No. 5, 12–14.

10. SANCHEZ-ROMERO M. and ALAVEDRA-RIBOT P. Experimental study of the thermal behaviour of radiant floors. *Building Research & Information*, 1996, **24**, No. 6, 369–373.
11. PELISSIER K., CHARTIER T. and LAURENT J. M. Silicon carbide heating elements. *Ceramics International*, 1998, **24**, No. 5, 371–377.
12. DOS SANTOS F. S. G. and SWART J. W. Rapid thermal flow of PSG films in vacuum using a graphite heater. *Journal of the Electrochemical Society*, 1990, **137**, No. 4, 1252–1255.
13. CATTELINO M. J., MIRAN G. V. and SMITH B. Fast- and super-fast-warm-up cathodes using novel APG/APBN heaters. *IEEE Transactions on Electron Devices*, 1991, **38**, No. 10, 2239–2243.
14. HUNG C.-C., DILLEHAY M. E. and STAHL M. Heater made from graphite composite material for potential deicing application. *Journal of Aircraft* 1987, **24**, No. 10, 725–730.
15. XIE J., WANG J., WANG X. and WANG H. Research and development of polymer material used as self-controlled heater. *Hecheng Shuzhi Ji Suliao/Synthetic Resin & Plastics*, 1996, **13**, No. 1, 50–54.
16. SANDBERG C., WHITNEY W., NASSAR A. and KUSE G. Intelligent distributed heater used for industrial applications. *Proceedings of the 1995 IEEE International Conference on Systems, Man and Cybernetics*, 1995, **4**, 3346–3351.
17. PROKUSHIN V. N., SHUBIN A. A., KLEJMENOV V. V. and MARMER Eh. N. Carbon heater elements for high temperature furnaces. *Khimicheskie Volokna*, 1992, **24**, No. 6, 50–51.
18. LONG H. W. and LONG G. E. Asphaltic compositions and uses therefore. US Patent 6, 193, 793 (2001).
19. AVTONOMOV I. V. and PUGACHEV G. A. Resistive composite material based on an alkaline slag binder. *Izvestiya Sibirskogo Otdeleniya Akademii Nauk Sssr, Seriya Tekhnicheskikh Nauk*, 1987, **21**, No. 6, 110–114.
20. YEHIA S., TUAN C. Y., FERDON D. and CHEN B. Conductive concrete overlay for bridge deck deicing: mixture proportioning, optimization, and properties. *ACI Materials Journal*, 2000, **97**, No. 2, 172–181.
21. KASAI Y. Demolition of concrete structure by heating. *Concrete International: Design & Construction*, 1989, **11**, No. 3, 33–38.
22. NAKAGAWA W., NISHITA K. and KASAI Y. Stripping demolition of reinforced concrete by electric heating method. *Proceedings of the 2nd ASME-JSME Nuclear Engineering Joint Conference*. 1993, pp. 871–876.
23. CHUTE F. S., VERMEULEN F. E. and CERVENAN M. R. On the electromagnetic heating of low loss materials using induction coils. *Canadian Electrical Engineering Journal*, 1981, **6**, No. 1, 20–28.
24. WADHWA S. S., SRIVASTAVA L. K., GAUTAM D. K. and CHANDRA D. Direct electrical curing of concrete: development and applications. *Indian Concrete Journal*, 1986, **60**, No. 12, 319–322, 327.
25. WADHWA S. S., SRIVASTAVA L. K., GAUTAM D. K. and CHANDRA D. Direct electric curing of in situ concrete. *Batiment International/Building Research & Practice*, 1987, **20**, No. 2, 97–101.
26. CAMPBELL H. S., GUPTA N. K. and WILSON J. G. Concrete 2000: curing of concrete using electrical power. *Proceedings of the Universities Power Engineering Conference*, 1998, **1**, 65–68.
27. PODGORNOV N. I. Direct heating of concrete by solar radiation. *Geliotekhnika*, 1992, **28**, No. 2, 14–16.
28. WEN S. and CHUNG D. D. L. Carbon fibre-reinforced cement as a thermistor. *Cement and Concrete Research*, 1999, **29**, No. 6, 961–965.
29. WEN S. and CHUNG D. D. L. Seebeck effect in carbon fibre reinforced cement. *Cement and Concrete Research*, 1999, **29**, No. 12, 1989–1993.
30. CHEN P. 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 Materials*, 1995, **24**, No. 1, 47–51.
31. SHUI Z., LI J., HUANG F. and YANG D. Study on the electrical properties of carbon fibre-cement composite (CFCC). *Journal of Wuhan University Technology*, 1995, **10**, No. 4, 37–41.
32. 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.
33. 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.
34. ZALESKI P. L., DERWIN D. J. and FLOOD W.H. JR Electrically conductive paving mixture and pavement system. US Patent 5, 707, 171 (1998).
35. XIE P., GU P., FU Y. and BEAUDOIN J. J. Conductive cement-based compositions. US Patent 5, 447, 564 (1995).
36. XIE P. and BEAUDOIN J. J. Electrically conductive concrete and its application in deicing. *ACI SP 154-21*. In *Advances in Concrete Technology*, (MALHOTRA V. M. (ed.)). 1995, American Concrete Institute, Detroit, pp. 399–417.
37. TUMIDAJSKI P. J., XIE P., ARNOTT M. and BEAUDOIN J. J. Overlay current in a conductive concrete snow melting system. *Cement and Concrete Research*, 2003, **33**, No. 11, 1807–1809.
38. CHUNG D. D. L. Electrical conduction behavior of cement-matrix composites. *Journal of Materials Engineering Performance*, 2002, **11**, No. 2, 194–204.
39. FU X. and CHUNG D. D. L. Effect of admixtures on the thermal and thermomechanical behavior of cement paste. *ACI Materials Journal*, 1999, **96**, No. 4, 455–461.
40. CALLISTER W. D. JR *Materials Science and Engineering*, 5th edn. 2000, Wiley, New York, p. 811.

Discussion contributions on this paper should reach the editor by 1 April 2005