



Cement-matrix composites for thermal engineering

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Abstract

Cement-matrix composites for thermal engineering are reviewed, with focus on temperature sensing, Joule heating and heat retention. These composites contain admixtures such as short electrically conducting fibers and silica fume, so that the electrical and/or thermal properties are modified. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Thermal engineering involves temperature sensing, heating, cooling, heat retention, etc. These issues are relevant to concrete structures, as they pertain to energy saving. Since buildings consume much energy, the energy saving that can result from thermal engineering of structures is tremendous.

Thermal engineering of concrete structures is conventionally achieved by the use of non-structural materials or devices, such as thermometers for temperature sensing, high thermal mass objects for heat retention, embedded heating coils for heating, hot water pipes for heating, etc. Relatively little attention has been given to the use of concrete (a cement-matrix composite) itself for thermal engineering. The use of a structural material for thermal engineering means the elimination or reduction of the need for peripheral non-structural materials for thermal engineering. As structural materials are inexpensive and durable, this results in reduced cost and enhanced durability. Furthermore, the elimination of embedded objects means the avoiding of

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mechanical property degradation, as embedded objects are like holes in the structure. In addition, the thermal engineering function provided by a structural material is everywhere – not just here and there.

Cement-matrix composites for thermal engineering are reviewed in this paper, with focus on temperature sensing, Joule heating and heat retention. The composites described are structurally superior to conventional cement-matrix composites, while exhibiting the desired functional properties. Moreover, the functional and structural properties do not degrade with time.

2. Cement-matrix composites for temperature sensing

The sensing of temperature is needed for thermal control, energy conservation, hazard mitigation and operation control. Concrete structures that benefit from temperature sensing include buildings (for temperature regulation and energy saving), as well as highways, bridges and airport runways (for hazard mitigation and deicing). Temperature sensing is conventionally achieved by thermometers, thermistors or thermocouples in the form of devices that are attached to or embedded in a concrete structure. However, the use of concrete itself for temperature sensing reduces the cost, enhances the durability and allows the sensing function to exist throughout the structure.

Cement-matrix composites for temperature sensing (as thermistors or thermocouples) contain short electrically conducting fibers which are present at a volume fraction below the percolation threshold, so that the fibers essentially do not touch one another. The fibers are not the sensors; they merely modify the composite so that the composite becomes effective for temperature sensing. Although the fiber addition raises the cost of the composite, the cost remains low compared to the use of devices for temperature sensing.

A thermistor is a thermometric device consisting of a material (typically a semiconductor, but in this case a cement paste) whose electrical resistivity decreases with rise in temperature. A cement-matrix composite containing short carbon fibers is a thermistor due to its resistivity decreasing reversibly with increasing temperature [1]; the sensitivity is comparable to that of semiconductor thermistors.

Fig. 1 [1] shows the current-voltage characteristic of carbon-fiber (5 mm long, 15 μm diameter, in the amount of 0.5% by weight of cement) silica-fume (SiO_2 particles of mean size around 0.1 μm , in the amount of 15% by weight of cement) cement paste at 38°C during stepped heating. The characteristic is linear below 5 V and deviates positively from linearity beyond 5 V. The resistivity is obtained from the slope of the linear portion. The voltage at which the characteristic starts to deviate from linearity is referred to as the critical voltage.

Fig. 2 shows a plot of the resistivity vs. temperature during heating and cooling for carbon-fiber silica-fume cement paste. The resistivity decreases upon heating and the effect is quite reversible upon cooling. That the resistivity is slightly increased after a heating-cooling cycle is probably due to thermal degradation of the cement-based material. Fig. 3 shows the Arrhenius plot of log conductivity (conductivity = 1/resistivity) vs. reciprocal absolute temperature. The slope of the plot gives the activation energy, which is 0.390 ± 0.014 and 0.412 ± 0.017 eV during heating and cooling respectively.

Results similar to those of carbon-fiber silica-fume cement paste were obtained with carbon-fiber (0.5% by weight of cement) latex (a styrene-butadiene particle dispersion, in the amount of

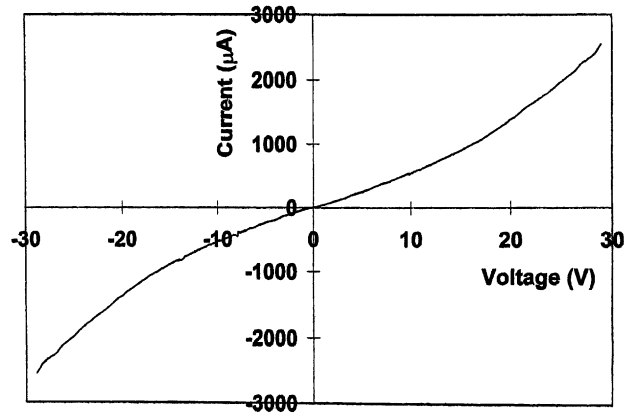


Fig. 1. Current–voltage characteristic of carbon-fiber silica-fume cement paste at 38°C during stepped heating.

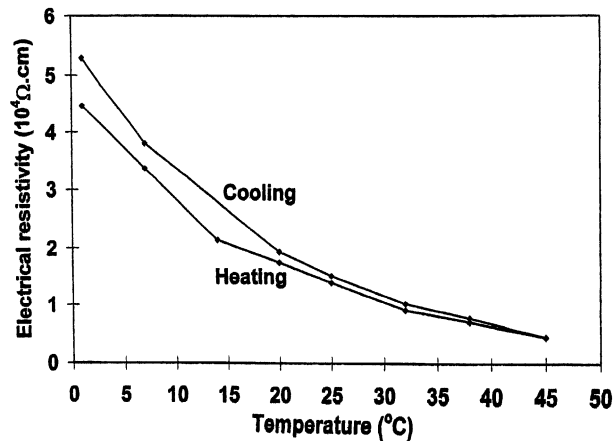


Fig. 2. Plot of volume electrical resistivity vs. temperature during heating and cooling for carbon-fiber silica-fume cement paste.

20% by weight of cement) cement paste, silica-fume cement paste, latex cement paste and plain cement paste. However, for all these four types of cement paste, (i) the resistivity is higher by about an order of magnitude, and (ii) the activation energy is lower by about an order of magnitude, as shown in Table 1. The critical voltage is higher when fibers are absent (Table 1).

The Seebeck [2–5] effect is a thermoelectric effect, which is the basis for thermocouples for temperature measurement. This effect involves charge carriers moving from a hot point to a cold point within a material, thereby resulting in a voltage difference between the two points. The Seebeck coefficient is the voltage difference per unit temperature difference between the two points. Negative carriers (electrons) make it more positive and positive carriers (holes) make it more negative.

The Seebeck effect in carbon fiber reinforced cement paste involves electrons (and/or ions) from the cement matrix [4] and holes from the fibers [3,4], such that the two contributions are equal at

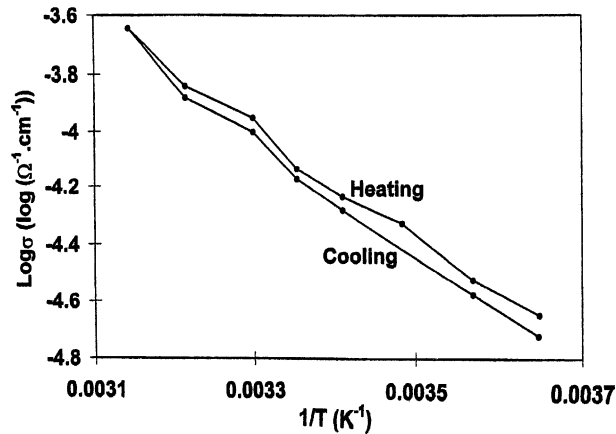


Fig. 3. Arrhenius plot of log electrical conductivity vs. reciprocal absolute temperature for carbon-fiber silica-fume cement paste.

Table 1
Resistivity, critical voltage and activation energy of five types of cement paste

Formulation	Resistivity at 20°C ($\Omega \text{ cm}$)	Critical voltage at 20°C (V)	Activation energy (eV)	
			Heating	Cooling
Plain	$(4.87 \pm 0.37) \times 10^5$	10.80 ± 0.45	0.040 ± 0.006	0.122 ± 0.006
Silica fume	$(6.12 \pm 0.15) \times 10^5$	11.60 ± 0.37	0.035 ± 0.003	0.084 ± 0.004
Carbon fibers + silica fume	$(1.73 \pm 0.08) \times 10^4$	8.15 ± 0.34	0.390 ± 0.014	0.412 ± 0.017
Latex	$(6.99 \pm 0.12) \times 10^5$	11.80 ± 0.31	0.017 ± 0.001	0.025 ± 0.002
Carbon fibers + latex	$(9.64 \pm 0.08) \times 10^4$	8.76 ± 0.35	0.018 ± 0.001	0.027 ± 0.002

the percolation threshold, a fiber content between 0.5% and 1.0% by weight of cement [4]. The hole contribution increases monotonically with increasing fiber content below and above the percolation threshold [4].

Due to the free electrons in a metal, cement containing metal fibers such as steel fibers is even more positive in the thermoelectric power than cement without fiber [5]. The attainment of a very positive thermoelectric power is attractive, since a material with a positive thermoelectric power and a material with negative thermoelectric power are two very dissimilar materials, the junction of which is a thermocouple junction. (The greater the dissimilarity, the more sensitive is the thermocouple.)

Table 2 and Fig. 4 show the thermopower results. The absolute thermoelectric power is much more positive for all the steel-fiber cement pastes compared to all the carbon-fiber cement pastes. An increase of the steel fiber content from 0.5% to 1.0% by weight of cement increases the absolute thermoelectric power, whether silica fume (or latex) is present or not. An increase of the steel fiber content also increases the reversibility and linearity of the change in Seebeck voltage with the temperature difference between the hot and cold ends, as shown by comparing the values of the Seebeck coefficient obtained during heating and cooling in Table 2. The values obtained

Table 2

Volume electrical resistivity, Seebeck coefficient ($\mu\text{V}/^\circ\text{C}$) with copper as the reference, and the absolute thermoelectric power ($\mu\text{V}/^\circ\text{C}$) of various cement pastes with steel fibers (S_f) or carbon fibers (C_f)

Cement paste	Volume fraction fibers (%)	Resistivity (Ωcm)	Heating		Cooling	
			Seebeck coefficient	Absolute thermoelectric power	Seebeck coefficient	Absolute thermoelectric power
Plain	0	$(4.7 \pm 0.4) \times 10^5$	-0.35 ± 0.03	1.99 ± 0.03	-0.38 ± 0.05	1.96 ± 0.05
SF	0	$(5.8 \pm 0.4) \times 10^5$	-0.31 ± 0.02	2.03 ± 0.02	-0.36 ± 0.03	1.98 ± 0.03
L	0	$(6.8 \pm 0.6) \times 10^5$	-0.28 ± 0.02	2.06 ± 0.02	-0.30 ± 0.02	2.04 ± 0.02
$S_f(0.5^a)$	0.10	$(7.8 \pm 0.5) \times 10^4$	51.0 ± 4.8	53.3 ± 4.8	45.3 ± 4.4	47.6 ± 4.4
$S_f(1.0^a)$	0.20	$(4.8 \pm 0.4) \times 10^4$	56.8 ± 5.2	59.1 ± 5.2	53.7 ± 4.9	56.0 ± 4.9
$S_f(0.5^a) + \text{SF}$	0.10	$(5.6 \pm 0.5) \times 10^4$	54.8 ± 3.9	57.1 ± 3.9	52.9 ± 4.1	55.2 ± 4.1
$S_f(1.0^a) + \text{SF}$	0.20	$(3.2 \pm 0.3) \times 10^4$	66.2 ± 4.5	68.5 ± 4.5	65.6 ± 4.4	67.9 ± 4.4
$S_f(0.5^a) + \text{L}$	0.085	$(1.4 \pm 0.1) \times 10^5$	48.1 ± 3.2	50.4 ± 3.2	45.4 ± 2.9	47.7 ± 2.9
$S_f(1.0^a) + \text{L}$	0.17	$(1.1 \pm 0.1) \times 10^5$	55.4 ± 5.0	57.7 ± 5.0	54.2 ± 4.5	56.5 ± 4.5
$C_f(0.5^a) + \text{SF}$	0.48	$(1.5 \pm 0.1) \times 10^4$	-1.45 ± 0.09	0.89 ± 0.09	-1.45 ± 0.09	0.89 ± 0.09
$C_f(1.0^a) + \text{SF}$	0.95	$(8.3 \pm 0.5) \times 10^2$	-2.82 ± 0.11	-0.48 ± 0.11	-2.82 ± 0.11	-0.48 ± 0.11
$C_f(0.5^a) + \text{L}$	0.41	$(9.7 \pm 0.6) \times 10^4$	-1.20 ± 0.05	1.14 ± 0.05	-1.20 ± 0.05	1.14 ± 0.05
$C_f(1.0^a) + \text{L}$	0.82	$(1.8 \pm 0.2) \times 10^3$	-2.10 ± 0.08	0.24 ± 0.08	-2.10 ± 0.08	0.24 ± 0.08

SF: silica fume; L: latex.

^a% by weight of cement.

during heating and cooling are close for the pastes with the higher steel fiber content, but are not so close for the pastes with the lower steel fiber content. In contrast, for pastes with carbon fibers in place of steel fibers, the change in Seebeck voltage with the temperature difference is highly reversible for both carbon fiber contents of 0.5% and 1.0% by weight of cement, as shown in Table 2 by comparing the values of the Seebeck coefficient obtained during heating and cooling.

Table 2 shows that the volume electrical resistivity is much higher for the steel-fiber cement pastes than the corresponding carbon fiber cement pastes. This is attributed to the much lower

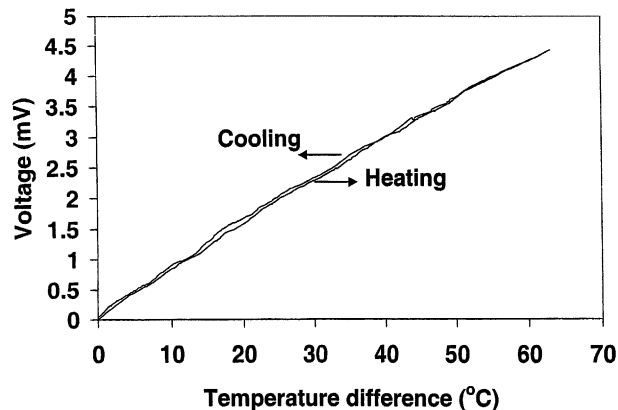


Fig. 4. Variation of the Seebeck voltage (with copper as the reference) vs. the temperature difference during heating and cooling for steel-fiber silica-fume cement paste containing steel fibers in the amount of 1.0% by weight of cement.

volume fraction of fibers in the former (Table 2). An increase in the steel or carbon fiber content from 0.5% to 1.0% by weight of cement decreases the resistivity, though the decrease is more significant for the carbon fiber case than the steel fiber case. That the resistivity decrease is not large when the steel fiber content is increased from 0.5 to 1.0% by weight of cement and that the resistivity is still high at a steel fiber content of 1.0% by weight of cement suggest that a steel fiber content of 1.0% by weight of cement is below the percolation threshold.

Whether with or without silica fume (or latex), the change of the Seebeck voltage with temperature is more reversible and linear at a steel fiber content of 1.0% by weight of cement than at a steel fiber content of 0.5% by weight of cement. This is attributed to the larger role of the cement matrix at the lower steel fiber content and the contribution of the cement matrix to the irreversibility and non-linearity. Irreversibility and non-linearity are particularly significant when the cement paste contains no fiber.

From the practical point of view, the steel-fiber silica-fume cement paste containing steel fibers in the amount of 1.0% by weight of cement is particularly attractive for use in temperature sensing, as the absolute thermoelectric power is the highest ($68 \mu\text{V}/^\circ\text{C}$) and the variation of the Seebeck voltage with the temperature difference between the hot and cold ends is reversible and linear. The absolute thermoelectric power is as high as those of commercial thermocouple materials.

By pouring dissimilar cement pastes side by side to make a junction, a cement-based thermocouple with sensitivity $70 \mu\text{V}/^\circ\text{C}$ has been attained [6]. The dissimilar cement pastes are preferably steel fiber cement paste (n-type) and carbon fiber cement paste (p-type).

3. Cement-matrix composites for Joule heating

Heating is an important part of the thermal engineering of structures, especially in relation to the heating of buildings and the deicing of bridges and airport runways. Heating can be attained by the flow of hot fluids, the radiation of heat from a space heater, the use of solar energy, etc. It is desirable to use concrete itself for the heating of concrete structures, as this would reduce cost, enhance durability and simplify design. This section describes the use of cement-matrix composites for Joule heating, i.e., resistance heating.

Joule heating requires the passage of an electric current. Due to the high electrical resistivity of conventional cement-based materials, the current tends to be low, making Joule heating ineffective. Therefore, cement-matrix composites for Joule heating are those that have relatively low resistivity, as made possible by the use of admixtures, such as short carbon fibers, which are electrically conducting.

Fig. 5 [7] gives the volume electrical resistivity of cement-matrix composites containing short carbon fibers at 7 days of curing. The resistivity decreases much with increasing fiber volume fraction, whether a second filler (silica fume or sand) is present or not. When sand is absent, the addition of silica fume decreases the resistivity at all carbon fiber volume fractions except the highest volume fraction of 4.24%; the decrease is most significant at the lowest fiber volume fraction of 0.53%. When sand is present, the addition of silica fume similarly decreases the resistivity, such that the decrease is most significant at fiber volume fractions below 1%. When silica fume is absent, the addition of sand decreases the resistivity only when the fiber volume fraction is

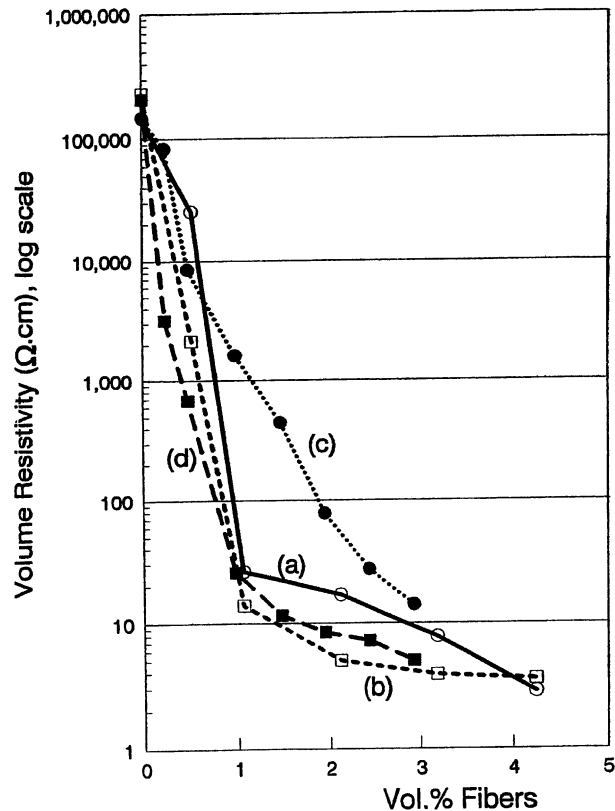


Fig. 5. Variation of the volume electrical resistivity with carbon fiber volume fraction: (a) without sand, with methylcellulose, without silica fume, (b) without sand, with methylcellulose, with silica fume, (c) with sand, with methylcellulose, without silica fume and (d) with sand, with methylcellulose, with silica fume.

below about 0.5%; at high fiber volume fractions, the addition of sand even increases the resistivity due to the porosity induced by the sand. Thus, the addition of a second filler (silica fume or sand) that is essentially non-conducting decreases the resistivity of the composite only at low volume fractions of the carbon fibers and the maximum fiber volume fraction for the resistivity to decrease is larger when the particle size of the filler is smaller. The resistivity decrease is attributed to the improved fiber dispersion due to the presence of the second filler. Consistent with the improved fiber dispersion is the increased flexural toughness and strength due to the presence of the second filler.

4. Cement-matrix composites for heat retention

Heat retention is needed for concrete structures in order to enhance temperature stability. This is particularly important for buildings, for which a high thermal mass is needed. Instead of using non-structural materials to attain a high thermal mass, it is desirable to use the concrete itself.

Table 3
Specific heat (J/g K, ± 0.001) of cement pastes^a

Formulation	As-received silica fume	Silane-treated silica fume
A	0.782	0.788
A ⁺	0.793	0.803
A ⁺ F	0.804	0.807
A ⁺ O	0.809	0.813
A ⁺ K	0.812	0.816
A ⁺ S	0.819	0.823

A: cement + water + water reducing agent + silica fume; A⁺: A + methylcellulose + defoamer; A⁺F: A⁺ + as-received fibers; A⁺O: A⁺ + O₃-treated fibers; A⁺K: A⁺ + dichromate-treated fibers; A⁺S: A⁺ + silane-treated fibers.

^aThe value for plain cement paste (with cement and water only) is 0.736 J/g K.

Since concrete is massively used in a concrete structure, the improvement of the heat retention ability of concrete can be highly effective for increasing the thermal mass of a concrete structure.

Cement-matrix composites for heat retention are those that exhibit relatively high values of the specific heat, as made possible by the use of admixtures. Table 3 [8,9] shows the specific heat of cement pastes. The specific heat is significantly increased by the addition of silica fume. It is further increased by the further addition of methylcellulose and defoamer. It is still further increased by the still further addition of carbon fibers. The effectiveness of the fibers in increasing the specific heat increases in the following order: as-received fibers, O₃-treated fibers, dichromate-treated fibers and silane-treated fibers. This trend applies whether the silica fume is as-received or silane-treated. For any of the formulations, silane-treated silica fume gives higher specific heat than as-received silica fume. The highest specific heat is exhibited by the cement paste with silane-treated silica fume and silane-treated fibers. The specific heat is 12% higher than that of plain cement paste, 5% higher than that of the cement paste with as-received silica fume and as-received fibers, and 0.5% higher than that of the cement paste with as-received silica fume and silane-treated fibers. Hence, silane treatment of fibers is more valuable than that of silica fume for increasing the specific heat.

A low value of the thermal conductivity is also desirable for the purpose of heat retention. The thermal conductivity is the product of the thermal diffusivity, specific heat and density. Table 4 [8,9] shows the thermal diffusivity of cement pastes. The thermal diffusivity is significantly decreased by the addition of silica fume. The further addition of methylcellulose and defoamer or

Table 4
Thermal diffusivity (mm²/s, ± 0.03) of cement pastes^a

Formulation	As-received silica fume	Silane-treated silica fume
A	0.26	0.24
A ⁺	0.25	0.22
A ⁺ F	0.27	0.26
A ⁺ O	0.29	0.27
A ⁺ K	0.29	0.27
A ⁺ S	0.25	0.23

A: cement + water + water reducing agent + silica fume; A⁺: A + methylcellulose + defoamer; A⁺F: A⁺ + as-received fibers; A⁺O: A⁺ + O₃-treated fibers; A⁺K: A⁺ + dichromate-treated fibers; A⁺S: A⁺ + silane-treated fibers.

^aThe value for plain cement paste (with cement and water only) is 0.36 mm²/s.

Table 5
Density (g/cm^3 , ± 0.02) of cement pastes^a

Formulation	As-received silica fume	Silane-treated silica-fume
A	1.72	1.73
A ⁺	1.69	1.70
A ⁺ F	1.62	1.64
A ⁺ O	1.64	1.65
A ⁺ K	1.65	1.66
A ⁺ S	1.66	1.68

A: cement + water + water reducing agent + silica fume; A⁺: A + methylcellulose + defoamer; A⁺F: A⁺ + as-received fibers; A⁺O: A⁺ + O₃-treated fibers; A⁺K: A⁺ + dichromate-treated fibers; A⁺S: A⁺ + silane-treated fibers.

^aThe value for plain cement paste (with cement and water only) is 2.01 g/cm^3 .

the still further addition of fibers has relatively little effect on the thermal diffusivity. Surface treatment of the fibers by ozone or dichromate slightly increases the thermal diffusivity, whereas surface treatment of the fibers by silane slightly decreases the thermal diffusivity. These trends apply whether the silica fume is as-received or silane-treated. For any of the formulations, silane-treated silica fume gives slightly lower (or essentially the same) thermal diffusivity than as-received silica fume. Silane treatments of silica fume and of fibers are about equally effective for lowering the thermal diffusivity.

Table 5 [8,9] shows the density of cement pastes. The density is significantly decreased by the addition of silica fume, which is used along with a water reducing agent. It is further decreased slightly by the further addition of methylcellulose and defoamer. It is still further decreased by the still further addition of fibers. The effectiveness of the fibers in decreasing the density decreases in the following order: as-received fibers, O₃-treated fibers, dichromate-treated fibers and silane-treated fibers. This trend applies whether the silica fume is as-received or silane-treated. For any of the formulations, silane-treated silica fume gives slightly higher (or essentially the same) specific heat than as-received silica fume. Silane treatment of fibers is more valuable than that of silica fume for increasing the density.

Table 6 [8,9] shows the thermal conductivity. It is significantly decreased by the addition of silica fume. The further addition of methylcellulose and defoamer or the still further addition of fibers has little effect on the density. Surface treatment of the fibers by ozone or dichromate

Table 6
Thermal conductivity (W/m K , ± 0.03) of cement pastes^a

Formulation	As-received silica fume	Silane-treated silica-fume
A	0.35	0.33
A ⁺	0.34	0.30
A ⁺ F	0.35	0.34
A ⁺ O	0.38	0.36
A ⁺ K	0.39	0.37
A ⁺ S	0.34	0.32

A: cement + water + water reducing agent + silica fume; A⁺: A + methylcellulose + defoamer; A⁺F: A⁺ + as-received fibers; A⁺O: A⁺ + O₃-treated fibers; A⁺K: A⁺ + dichromate-treated fibers; A⁺S: A⁺ + silane-treated fibers.

^aThe value for plain cement paste (with cement and water only) is 0.53 W/m K .

Table 7
Thermal behavior of cement pastes and mortars

	Cement paste		Mortar	
	Without silica fume ^a	With silica fume ^a	Without silica fume ^a	With silica fume ^a
Density (g/cm ³ , ±0.02)	2.01	1.73	2.04	2.20
Specific heat (J/g K, ±0.001)	0.736	0.788	0.642	0.705
Thermal diffusivity (mm ² /s, ±0.03)	0.36	0.24	0.44	0.35
Thermal conductivity ^b (W/m K, ±0.03)	0.53	0.33	0.58	0.54

^a Silane treated.

^b Product of density, specific heat and thermal diffusivity.

slightly increases the thermal conductivity, whereas surface treatment of the fibers by silane has negligible effect. These trends apply whether the silica fume is as-received or silane-treated. For any of the formulations, silane-treated silica fume gives slightly lower (or essentially the same) thermal conductivity as as-received silica fume. Silane treatments of silica fume and of fibers contribute comparably to reducing the thermal conductivity.

Sand is a much more common component in concrete than silica fume. It is different from silica fume in its relatively large particle size and negligible reactivity with cement. Sand gives effects that are opposite from those of silica fume, i.e., sand addition decreases the specific heat and increases the thermal conductivity [10].

Table 7 [10] shows the thermal behavior of cement pastes and mortars. Comparison of the results on cement paste without silica fume and those on mortar without silica fume shows that sand addition decreases the specific heat by 13% and increases the thermal conductivity by 9%. Comparison of the results on cement paste with silica fume and those on mortar with silica fume shows that sand addition decreases the specific heat by 11% and increases the thermal conductivity by 64%. That sand addition has more effect on the thermal conductivity when silica fume is present than when silica fume is absent is due to the low value of the thermal conductivity of cement paste with silica fume (Table 7).

Comparison of the results on cement paste without silica fume and on cement paste with silica fume shows that silica fume addition increases the specific heat by 7% and decreases the thermal conductivity by 38%. Comparison of the results on mortar without silica fume and on mortar with silica fume shows that silica fume addition increases the specific heat by 10% and decreases the thermal conductivity by 6%. Hence, the effects of silica fume addition on mortar and cement paste are in the same direction. That the effect of silica fume on the thermal conductivity is much less for mortar than for cement paste is mainly due to the fact that silica fume addition increases the density of mortar but decreases the density of cement paste (Table 7). That the fractional increase in specific heat due to silica fume addition is higher for mortar than cement paste is attributed to the low value of the specific heat of mortar without silica fume (Table 7).

Comparison of the results on cement paste with silica fume and those on mortar without silica fume shows that sand addition gives a lower specific heat than silica fume addition and a higher thermal conductivity than silica fume addition. Since sand has a much larger particle size than silica fume, sand results in much less interface area than silica fume, though the interface may be more diffuse for silica fume than for sand. The low interface area in the sand case is believed to be

responsible for the low specific heat and the higher thermal conductivity, as slippage at the interface contributes to the specific heat and the interface acts as a thermal barrier.

Silica fume addition increases the specific heat of cement paste by 7%, whereas sand addition decreases it by 13%. Silica fume addition decreases the thermal conductivity of cement paste by 38%, whereas sand addition increases it by 22%. Hence, silica fume addition and sand addition have opposite effects. The cause is believed to be mainly associated with the low interface area for the sand case and the high interface area for the silica fume case, as explained in the last paragraph. The high reactivity of silica fume compared to sand may contribute to causing the observed difference between silica fume addition and sand addition, though this contribution is believed to be minor, as the reactivity should have tightened up the interface, thus decreasing the specific heat (in contrast to the observed effects). The decrease in specific heat and the increase in thermal conductivity upon sand addition are believed to be due to the higher level of homogeneity within a sand particle than within cement paste.

5. Structural performance

The cement-matrix composites mentioned above for thermal engineering are structurally attractive, in addition to being thermally attractive. For example, the improved structural properties rendered by carbon fiber addition pertain to the increased tensile and flexural strengths, the increased tensile ductility and flexural toughness, the enhanced impact resistance, the reduced drying shrinkage and the improved freeze–thaw durability [11–34]. The tensile and flexural strengths decrease with increasing specimen size, such that the size effect becomes larger as the fiber length increases [35]. The low drying shrinkage is valuable for large structures and for use in repair [36,37] and in joining bricks in a brick structure [38,39].

6. Conclusion

Cement-matrix composites for thermal engineering contain admixtures such as short electrically conducting fiber and silica fume, so that the electrical and/or thermal properties are modified. Changes in the electrical properties enable the composites to provide temperature sensing by serving as thermistors or thermocouples, and to provide Joule heating. Changes in the thermal properties enable heat retention.

Acknowledgements

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