



# Effect of sand addition on the specific heat and thermal conductivity of cement

Yunsheng Xu, D.D.L. Chung\*

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

Received 21 May 1999; accepted 17 September 1999

## Abstract

Sand addition was found to decrease the specific heat and increase the thermal conductivity of cement, in contrast to the opposite effects of silica fume addition. The thermal conductivity increase due to sand addition was much greater when silica fume was present. The thermal conductivity decrease due to silica fume addition was much smaller when sand was present. © 2000 Elsevier Science Ltd. All rights reserved.

**Keywords:** Physical properties; Cement paste; Silica fume; Aggregate; Thermal conductivity

## 1. Introduction

The thermal behavior of cement-based materials is relevant to the use of these materials for buildings, bridges, and other structures. In particular, a high value of the specific heat is desirable due to the associated ability to retain heat. Moreover, a low value of the thermal conductivity is desirable due to the associated ability to provide thermal insulation. On the other hand, a high value of the thermal conductivity can be desirable due to the associated ability to reduce the temperature gradient, and hence the thermal stress, in a structure.

Cement-based materials are composite materials typically containing aggregates (such as sand) and admixtures (such as silica fume, which serves as a fine particulate additive, in addition to providing a cementitious function).

The addition of silica fume (silane-treated) to cement paste has been shown to increase the specific heat by 7% and decrease the thermal conductivity by 38% relative to the cement paste without silica fume [1]. Without the surface treatment using silane, the effects of silica fume on both specific heat and thermal conductivity are in the same directions, but less remarkable [1]. These effects of silica fume, either with or without surface treatment, are attributed partly to the interface (however diffuse) between silica fume and the cement matrix, although the chemical effect related to the reactivity of silica fume may also contribute to causing these effects. The interface allows some degree of

interface slippage (however slight), thus providing a mechanism of absorbing energy and increasing the specific heat. The interface also acts as a thermal barrier due to its high thermal resistance, thereby causing the thermal conductivity to decrease. The reactivity results in chemical bonds, the movement of which may absorb energy. The bonds may also affect the thermal conductivity. The surface treatment of silica fume using silane results in covalent couplings, the movement of which is expected to absorb energy and cause the specific heat to increase. The molecular nature of the covalent couplings is expected to be associated with a poor thermal conductivity, thus decreasing the thermal conductivity of the cement-based material.

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. However, the effects of sand addition on the specific heat and thermal conductivity of cement have not been previously investigated. In this paper, we report that sand gives effects that are opposite from those of silica fume (i.e., sand addition decreases the specific heat and increases the thermal conductivity). Furthermore, this paper reports on the effects of silica fume addition on the specific heat and thermal conductivity of mortar (i.e., cement paste + sand). Previous work pertains to the effects of silica fume addition on the specific heat and thermal conductivity of cement paste [1,2].

## 2. Methods

The cement used was Portland cement (Type I) from Lafarge Corp. (Southfield MI, USA). The silica fume

\* Corresponding author. Tel.: 716-645-2593, ext. 2243; fax: 716-645-3875.

E-mail address: ddchung@acsu.buffalo.edu (D.D.L. Chung)

(Elkem Materials Inc., Pittsburgh, PA, USA, EMS 965) was used in the amount of 15% by weight of cement. The silane coupling agent used was 1:1 (by weight) mixture of Z-6020 ( $\text{H}_2\text{NCH}_2\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ ) and Z-6040 ( $\text{OCH}_2\text{CHCH}_2\text{OCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ ) from Dow Corning Corp. (Midland, MI, USA). The amine group in Z-6020 serves as a catalyst for the curing of epoxy and consequently allows the Z-6020 molecule to attach to the epoxy end of the Z-6040 molecule. The trimethylsiloxy ends of the Z-6020 and Z-6040 molecules then connect to the  $-\text{OH}$  functional group on the surface of silica fume. The silane was dissolved in ethylacetate. Surface treatment of silica fume was performed by immersing the silica fume in the silane solution, heating to  $75^\circ\text{C}$  while stirring, and holding at  $75^\circ$  for 1 h, followed by filtration and drying. After this, the silica fume was heated in a furnace at  $110^\circ\text{C}$  for 12 h.

The fine aggregate used for mortars was natural sand (all passing #4 US sieve, 99.9%  $\text{SiO}_2$ ); the particle size analysis of the sand is shown in Fig. 1 of an earlier work [3]; no coarse aggregate was used; the sand/cement ratio was 1.0. The water/cement ratio was 0.35. A water-reducing agent (TAMOL SN, Rohm and Haas Co., Philadelphia, PA, USA; sodium salt of a condensed naphthalenesulphonic acid) was used in the amount of 2% of cement weight. All ingredients were mixed in a rotary mixer with a flat beater. After pouring into molds, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 24 h and then cured in air at room temperature and a relative humidity of 100% for 28 days.

The thermal conductivity (in  $\text{W/m} \cdot \text{K}$ ) was given by the product of the thermal diffusivity (in  $\text{cm}^2/\text{s}$ ), specific heat (in  $\text{J/g} \cdot \text{K}$ ) and density (in  $\text{g/cm}^3$ ). For measuring the thermal diffusivity, the laser flash method was used. In this method, a pulsed laser (Coherent General, Inc., Sturbridge, MA, USA) and a computer with Labtech software and data acquisition board were used. The specimen was in the form of a disc with diameter of 13 mm and thickness of 2 mm. Sample preparation for laser diffusivity measurement involved (a) polishing both sides of the sample, (b) coating both sides of the sample with gold for thermal contacts, and (c) coating one of the sides (the side on which the laser beam would hit) with carbon (to avoid reflection of the laser beam, since carbon is black). The temperature of the specimen at the side without carbon coating was measured after the laser flash as a function of time by using a thermocouple. From the temperature vs. time curve, the thermal diffusivity was calculated. Four specimens of each type were tested.

A Perkin-Elmer Differential Scanning Calorimeter (Norwalk, CT, USA) (DSC-7) with UNIX Specific Heat Software was used for measuring the specific heat. A three-curve analysis method was used; it involved obtaining a differential scanning calorimeter sample, baseline, and reference material data. Sapphire was selected as a reference material. The specimen was in the form of a disc 6 mm in diameter and 1 mm thick. Four specimens of each type were tested.

The density was measured by weight and volume (di-

mensions) measurements. Four specimens of each type were tested.

### 3. Results and discussion

Table 1 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%. The fact that sand addition has greater 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 1).

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%, as previously reported [1]. 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 directions. The effect of silica fume on the thermal conductivity is much weaker for mortar than for cement paste, which is mainly due to the fact that silica fume addition increases the density of mortar but decreases the density of cement paste (Table 1). The fractional increase in specific heat due to silica fume addition is higher for mortar than cement paste, which is attributed to the low value of the specific heat of mortar without silica fume (Table 1).

Comparison of the results on cement paste with silica fume and those on mortar without silica fume shows that

Table 1  
Thermal behavior of cement pastes and mortars

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

<sup>a</sup> Silane treated.

<sup>b</sup> From Xu and Chung [1].

<sup>c</sup> Product of density, specific heat, and thermal diffusivity.

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 smaller interface area than silica fume, though the interface may be more diffuse for silica fume than for sand. The smaller 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 smaller interface area for the sand case and the larger interface area for the silica fume case, as explained in the previous 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 since 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.

#### 4. Conclusions

Sand addition was found to decrease the specific heat and increase the thermal conductivity, in contrast to the opposite effects of silica fume addition. The thermal conductivity increase due to sand addition was much greater when silica fume was present. The thermal conductivity decrease due to silica fume addition was much less when sand was present. These effects are mainly attributed to the small area of the interface between sand and cement matrix, the large area of the interface between silica fume and cement matrix, and the contribution of the interface to decreasing the thermal conductivity and increasing the specific heat.

#### References

- [1] Y. Xu, D.D.L. Chung, Increasing the specific heat of cement paste by admixture surface treatments, *Cem Concr Res* 29 (7) (1999) 1117–1121.
- [2] X. Fu, D.D.L. Chung, Effects of silica fume, latex, methylcellulose and carbon fibers on the thermal conductivity and specific heat of cement paste, *Cem Concr Res* 27 (12) (1997) 1799–1804.
- [3] P.-W. Chen, D.D.L. Chung, Carbon fiber reinforced concrete as a smart material capable of non-destructive flaw detection, *Smart Mater Struct* 2 (1993) 22–30.