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Thermal conductivity of cementitious composites containing microencapsulated phase change materials

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ABSTRACT

This paper investigates the effects of adding microencapsulated phase change materials (PCM) on the thermal conductivity of cement paste and cement mortar composites. Embedding cementitious composites with microencapsulated PCM has been considered a promising method for increasing the thermal mass of buildings to achieve greater energy efficiency and for reducing the risks of thermal cracking in pavements. Cement paste and cement mortar samples were synthesized with a constant water to cement ratio of 0.45. Both contained microencapsulated PCM with diameter ranging from 17–20 μm, volume fraction up to 30%, and a melting temperature around 24 °C. The cement mortar also contained quartz grains 150–600 μm in diameter such that the sum of the volume fractions of quartz and microencapsulated PCM was fixed at 55%. All samples were aged for more than 28 days. Their effective density and free moisture content were systematically measured. A guarded hot plate apparatus was designed, assembled, and validated according to the ASTM C177-13 to measure the effective thermal conductivity of the aged specimens of cement paste and cement mortar without and with microencapsulated PCM. Measurements were performed between 10 and 40 °C, encompassing the entire PCM phase change temperature window. The effective thermal conductivity of both the cement paste and the cement mortar composites was found to be nearly independent of temperature in the range considered. It also decreased as the volume fraction of microencapsulated PCM increased. Finally, excellent agreement was obtained between experimental data and the effective medium approximation derived by Felske (2004) for core–shell–matrix composites. These results can be used to design cementitious composite materials containing microencapsulated PCMs for energy efficient buildings and crack-resistant pavements.

1. Introduction

Embedding phase change materials (PCMs) in a concrete matrix has been proposed as a means to improve building energy efficiency [1–3] and to reduce the risk of thermal cracking [4,5]. PCMs achieve such beneficial actions by increasing the thermal mass (i.e., heat capacity) and thermal resistance by lowering the effective thermal conductivity of the cementitious composite materials [1–3]. Indeed, PCMs can store and release thermal energy in the form of latent heat through a reversible phase transition between solid and liquid states, actions which superimpose onto the sensible heat capacity of the concrete [6–9].

The thermophysical properties of cementitious composites, such as the heat capacity and thermal conductivity, are critical input variables required for modeling their thermal behavior and engineering performance for design purposes. For example, these properties determine the heat flow into and out of the building as well as the time lag in the building thermal load [10,11]. Similarly, it is important to understand the development of temperature and restrained stress gradients in cementitious composites to estimate the risk of thermal cracking [4,5]. From thermodynamic considerations, the effective volumetric heat capacity of cementitious composite materials with embedded microencapsulated PCM can be expressed as [10]

$$(\rho c_p)_{eff}(T) = \phi_c(\rho c_p)_c(T) + \phi_s(\rho c_p)_s + (1 - \phi_c - \phi_s)(\rho c_p)_m \qquad (1)$$

where ϕ_c and ϕ_s are the volume fractions of the core and shell materials, while $(\rho c_p)_c$, $(\rho c_p)_s$, and $(\rho c_p)_m$ are the volumetric heat

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Nomenclature

A_{gap}	area of the gap between the metered and guard heaters, mm^2
A_m	area of the metered heater, mm^2
c_p	specific heat, J/(kg·K)
e	thermal effusivity, $W{\cdot}s^{1/2}/(m^2{\cdot}K)$
k	thermal conductivity, W/(m·K)
L_i	vertical distance between thermocouples in sample i, m
m	mass, g
$\dot{m}$	coolant mass flow rate, g/s
q_m	heat transfer rate from the metered heater, W
q_{loss}	estimated heat loss, W
$q_{w,i}$	heat transfer rate removed by cold plate i, W
q''_i	incoming heat flux in sample i, W/m^2
Q_i	coolant volumetric flow rate, mL/min
R_g	resistance of the guard heater wire, Ω
R_m	resistance of the metered heater wire, Ω
$T_{j,i}$	temperature measured by thermocouple j in sample i,°C
U_g	voltage across the guard heater wire, V
U_m	voltage across the metered heater wire, V
V	volume, mm^3
w/c	water to cement mass ratio

Greek symbols

α	thermal diffusivity, m^2/s
Δx	associated systematic error in measurement x
ϕ_p	volume fraction of phase p in the cementitious composite
ϕ_{c+s}	volume fraction of microcapsules in the cementitious composite, $\phi_{c+s} = \phi_c + \phi_s$
$\phi_{c/s}$	volume fraction of core in the microcapsule, $\phi_{c/s} = \phi_c/(\phi_c + \phi_s)$
ϕ_w	free moisture content
ρ	density, g/cm^3
σ_q	standard deviation of the heat transfer rate q_i, W

Subscripts

c	refers to core
$c + s$	refers to core–shell particle
$cold, i$	refers to the cold plate in contact with sample i
dry	refers to fully dry free moisture content
eff	refers to effective properties
i	refers to sample A or B
m	refers to matrix
q	refers to quartz sand
s	refers to shell
sat	refers to fully saturated free moisture content
w	refers to the chiller coolant
$w, 1, i$	refers to chiller coolant entering cold plate i
$w, 2, i$	refers to chiller coolant exiting cold plate i

capacities of the core, shell, and matrix materials, respectively. On the other hand, the effect of PCM on the thermal conductivity of cementitious composites is non-trivial and limited reports are available [1–3,7,12].

This paper aims to quantify the effect of incorporating microencapsulated PCM inclusions on the effective thermal conductivity of Type I ordinary Portland cement (OPC) pastes and mortars. A guarded hot plate apparatus was designed and fabricated, and its measurement performance rigorously validated. The effective thermal conductivity of cement pastes and mortars with various volume fractions of cement paste, mineral aggregates (e.g., quartz inclusions), and functional inclusions (microencapsulated PCMs) was measured. The results also provided experimental validation of effective medium approximation (EMAs) for three-phase cementitious composites.

2. Background

2.1. Thermal conductivity measurement methods

Experimental methods available to measure the thermal conductivity of bulk solid materials can be categorized as either transient or steady-state. Transient methods include the plane source [13], hot strip [14], hot wire [15], hot bridge [16], and laser flash methods [17]. The first four methods involve temperature measurements collected over a time period ranging from 10 ns to 100 s during which the sample is heated [14–16]. A thin sensor is used to generate a pulse of thermal energy dissipated by the sample while simultaneously measuring the associated change in temperature at the sample surface [14–16]. The measured rate of thermal dissipation and change in sample temperature are used to calculate the thermal effusivity defined as $e = \sqrt{\rho c_p k}$ where ρ, c_p, and k are density, specific heat, and thermal conductivity of the sample, respectively [18]. The hot bridge method offers greater accuracy than the other three methods by using multiple sensors aligned in a Wheatstone bridge to collect sample surface temperature measurements with enhanced sensitivity [16]. Alternatively, the flash method [17] infers the thermal diffusivity α, defined as $\alpha = k/\rho c_p$. A pulse of thermal energy is applied to the front face of a parallel plane sample while the change in temperature on the back face is measured over a period of time [17]. The thermal diffusivity is then calculated based on the thickness of the sample and the time required for the back surface to reach half of its maximum temperature measured over the duration of testing [17]. Since these transient methods do not measure thermal conductivity directly, uncertainty is introduced if the density ρ and specific heat c_p are not measured independently [19].

Steady-state methods, such as the hot plate and the guarded hot plate methods, measure the temperature difference across a sample maintained between a hot and a cold surface and subjected to one-dimensional (1D) steady-state heat conduction [20]. The thermal conductivity of the sample is determined from Fourier's law, based on the imposed heat flux and the measured temperature gradient across the sample [20,21]. The hot plate method features simple measurement and analysis [20,21]. However, radial heat losses in the hot plate make it difficult to achieve 1D steady-state conditions, thus introducing uncertainty in the measured thermal conductivity [20]. To mitigate these heat losses and to ensure 1D heat conduction, the guarded hot plate method includes a heated "guard" ring concentric to the center "metered" section of the heating element [20,21]. The gap is filled with either air or a thermally insulating material to enhance radial thermal resistance around the hot plate. In addition, the guard ring is maintained at the same temperature as the metered section.

Overall, steady-state methods offer a direct measurement of thermal conductivity k, whereas transient methods require prior knowledge of the sample's density ρ and specific heat c_p. Steady-state methods are also simpler in terms of apparatus design and fabrication, experimental procedure, and data analysis [16]. However, they require longer experimental time than transient methods [13,17,22]. In this study, thermal conductivity