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Paraffin/expanded vermiculite composite phase change material as aggregate for developing lightweight thermal energy storage cement-based composites

Biwan Xu *, Hongyan Ma, Zeyu Lu, Zongjin Li

Department of Civil and Environmental Engineering, The Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong, China

HIGHLIGHTS

- The composite PCM has onset melting temperature 27.0 °C and latent heat 77.6 J/g.
- LW-TESCCs with the composite PCM were made with bulk densities below 1500 kg/m^3.
- LW-TESCCs reveal superior thermal insulation performance and heat storage merit.

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ABSTRACT

In this study, a new paraffin/expanded vermiculite composite phase change material (PCM) was tailor-made as aggregate for developing lightweight thermal energy storage cement-based composites (LW-TESCCs). Vermiculite calcined at 800 °C for 1 h (EVM-800) can be considered as the optimum paraffin supporting matrix candidate, as it has the best expanded microstructure and crystallization. The composite PCM was fabricated at a paraffin-to-EVM-800 weight ratio of 0.6:1.0 by the vacuum impregnation method. The results of scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FT-IR) show that the paraffin can be well vacuum drawn into the expanded interlayer spaces of EVM-800, and that the paraffin and EVM-800 are chemically inert. The differential scanning calorimetry (DSC) results reveal that the composite PCM has an onset melting temperature of 27.0 ± 0.1 °C and latent heat of 77.6 ± 4.3 J/g, and good thermal stability is clearly suggested by the thermogravimetric analysis (TGA) results. Moreover, the LW-TESCCs with bulk densities below 1500 kg/m^3 were further developed by incorporating the composite PCM as sand replacement. It is found that the LW-TESCCs have significantly improved thermal resistance performance and well-endowed thermal storage capabilities. Thus, it can be expected that the potential applications of the LW-TESCCs in building envelopes would significantly contribute to reducing indoor air temperature fluctuations and in saving energy.

1. Introduction

Buildings not only consume enormous amount of energy, but also cause huge amount of greenhouse gas around the world. A large portion of building energy consumption has always been used for space heating and cooling in creating and maintaining comfortable thermal conditions. Nevertheless, much of this energy is ultimately lost through the building envelope [1]. Therefore, great effort has been dedicated to improving thermal insulation performance and the thermal mass of building envelopes [2–4]. Utilization of thermal storage walls or roof ponds incorporated with phase change materials (PCMs) is one of the popular themes [1,4]. PCMs have been well acknowledged to have prominent characteristics, such as high heat storage density, heat recovery capacity and repeatable utilization. Amongst a wide range of PCMs in the market, paraffin can be considered as the most popular one. This is because paraffin is chemically inert and has good heat storage density and little phase segregation during its melting–freezing phase change cycles [5–12]. However, like most of the PCMs with typical solid-to-liquid phase change characteristics, the sole use of paraffin leads to leakage problems during its melting phase change process, and could lead to performance deterioration of the panel materials [13]. Therefore, paraffin applications are now frequently in the

* Corresponding author. Tel.: +852 23588761; fax: +852 2358 1534.
E-mail address: xubiwan@gmail.com (B. Xu).

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form of form-stable composites that employ a variety of porous materials as supporting matrices, such as metallic foams [6], carbon foams [7], expanded graphite [8], diatomite [9–11] and expanded vermiculite [12].

Vermiculite is a hydrous phyllosilicate mineral. Accordion-like volume expansions are quite commonly observed for vermiculite during thermal treatments. The vermiculite volume expansions can be varied from 8 to 30 times its original size, depending on its texture and the thermal conditions used [14]. Thanks to the expanded microstructures, expanded vermiculites are highly porous, lightweight, and have quite low densities and thermal conductivities. They have already had wide applications, such as soil conditioners [15], sorbents of heavy metals [15] and oily water [16], and lightweight aggregates [17]. More recently, a new application using expanded vermiculite as a PCM supporting matrix has been further explored. Organic PCMs, such as paraffin [6], capric–myristic acids [18], capric–lauric acids [18], capric–palmitic acids [18], capric–stearic acids [18], and n-octadecane [18,19], have been reported as being successfully impregnated into the expanded interlayer spaces of expanded vermiculites. Moreover, these reported form-stable expanded vermiculite-based composite PCMs [6,18,19] were determined to have high heat storage capacities and thermal stabilities.

Lightweight cement-based composites with bulk density lower than 2000 kg/m^3 have been attracting great attention, as they can contribute to simplifying constructions, saving space and reducing costs [20,21]. Adoption of lightweight aggregates is one of the common ways for producing lightweight cement-based composites. Amongst a variety of lightweight aggregates, expanded vermiculites with quite low densities have been popularly used [17,22]. In this study, considering the expanded vermiculite's high porosity and low density, a new form-stable paraffin/expanded vermiculite lightweight aggregate was firstly fabricated. It was tailor-made for the further development of lightweight thermal energy storage cement-based composites (LW-TESCCs). Differing from the previously reported paraffin/expanded composite PCM that had an onset melting temperature of 48 °C [12], this newly fabricated composite PCM has a much lower onset melting temperature of around 27 °C. Ideally, composite PCMs for building interior applications have their phase change temperatures ranging from 22 °C to 28 °C [10]. Over the past few decades, normal thermal energy storage cement-based composites with bulk densities higher than 2000 kg/m^3 have already been widely reported and used in practice [23–25]. However, LW-TESCCs that could contribute to simplifying construction, saving space and costs, as well as reducing building energy consumption, have received much less attention. Therefore, the other important research intent of this study is the development of new LW-TESCCs using the above-mentioned tailor-made paraffin/expanded vermiculite composite PCM as the lightweight aggregate.

2. Experimental program

2.1. Materials

Raw vermiculite (VM-Raw) was supplied from Yuli Xinlong Vermiculite Co., Ltd., Xinjiang province, China. Its chemical compositions were determined by X-ray fluorescence (JSX-3210Z), and are given in Table 1. In order to obtain the optimum expanded vermiculite as the paraffin supporting matrix, VM-Raw was calcined at 600 °C, 800 °C and 1000 °C, respectively, for 1 h. These obtained expanded vermiculites are hereafter referred to as EVM-600, EVM-800 and EVM-1000. Paraffin with an onset melting temperature of 27.5 °C and latent heat of 201.5 J/g was used for fabricating the aimed composite PCM. The more detailed thermal property information of this paraffin is given in the authors' previous work [11]. Besides, other starting raw materials for making LW-TESCCs include ordinary Portland cement (OPC), silica fume (SF), river sand, superplasticizer (SP) and methylcellulose (MC). Specific gravities of the used OPC and SF are 3.15 and 2.10, respectively; and their chemical compositions are summarized in Table 1. Particle size distributions of the river sand, with a maximum particle size of 1 mm and the fabricated paraffin/EVM-800 composite PCM are presented in Fig. 1. The bulk densities of the river sand and the fabricated composite PCM are 1.55 g/cm^3 and 0.76 g/cm^3, respectively. In addition, the detailed experimental information of the composite PCM is given in the latter part of this paper.

Table 1
Chemical compositions of the raw materials used/wt.%.

Composition	VM-Raw	OPC	SF
SiO_2	44.54	22.17	96.43
MgO	26.14	2.06	0.70
Al_2O_3	12.90	4.22	–
Fe_2O_3	6.29	0.35	0.073
CaO	1.74	66.10	0.78
K_2O	5.35	–	1.28
TiO_2	1.39	–	–
Na_2O	1.28	–	–
Cr_2O_3	0.30	–	–
MnO	0.070	–	–
SO_3	–	5.09	0.38
P_2O_5	–	–	0.36

2.2. Preparation of form-stable paraffin/EVM-800 composite PCM and testing methods

The dehydration behavior of VM-Raw was determined by the thermogravimetric analysis (TGA, Q5000) method. This TGA test was carried out over a temperature range from 25 °C to 1000 °C, at a heat ramping rate of 10 K/min under nitrogen gas atmosphere. The mineralogical compositions of VM-Raw and the thermally expanded ones were examined by X-ray diffractometer (X'pert Pro, PANalytical). Their specific surface areas were measured by the Brunauer–Emmett–Teller method (BET, Coulter SA3100). Furthermore, the micro-morphologies of VM-Raw and EVM-800 were characterized by scanning electron microscopy (SEM) instrument (JEOL-6390).

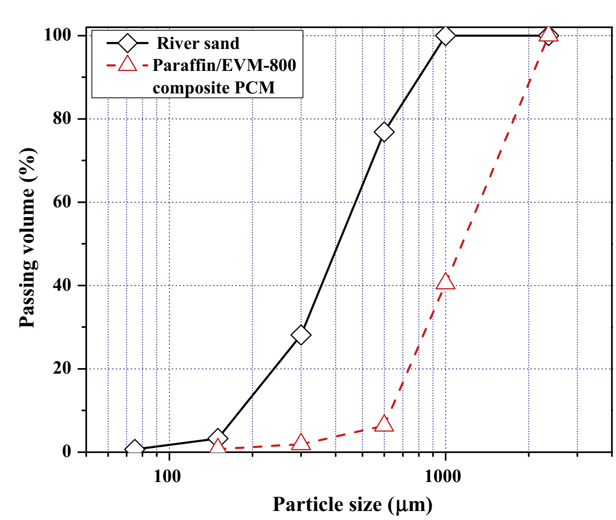

Fig. 1. Particle size distributions of the river sand and the paraffin/EVM-800 composite PCM.