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Experimental and numerical study of shape-stable phase-change nanocomposite toward energy-efficient building constructions

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ABSTRACT

Fatty acids-based phase change material (PCM) was supported by graphite interconnected nanosheets to form a shape-stable nano-PCM composite, which complements high heat storage capacity with desired shape-stability, long-term durability, and thermal conductivity. The nano-PCM was incorporated into the gypsum wallboard using a sandwich structure, and the thermal performance of the gypsum wallboards incorporated with nano-PCM was evaluated using test cells under simulated day and night temperature change, in comparison with commercial drywall panels. Use of nano-PCM in wallboards enabled (i) reduction of the interior temperature fluctuations, and (ii) shifted (delayed) the time at which the peak temperature was reached. A numerical model was employed to investigate the contribution of nano-PCM to energy efficiency of the tests cells (representing a scaled, simplified building). Incorporation of nano-PCM into wallboards was found to reduce the energy consumption for maintaining the interior temperature within comfort zone by 79%.

1. Introduction

Thermal energy storage system benefits the building heating and cooling by diminishing indoor temperature fluctuations, and also by shifting the building energy load away from the peak hours of energy demand [1]. The technology offers significant energy and environmental benefits. Residential and commercial buildings account for about 39% of total U.S. energy consumption, and 38% of U.S. carbon dioxide (CO_2) emissions [2]. Space heating, cooling and air conditioning (HVAC) account for the largest amount of end-use energy consumption in residential and commercial buildings; they are responsible for 35% and 32% of energy end-use in these sectors, respectively [3]. Moreover, thermal energy storage systems balance out the discrepancies caused by the mismatch in the timing of energy supply and demand in alternative energy systems (solar, waste heat retrieval, etc.) [4]. In the case of solar space heating, for example, intermittent supply of solar radiation requires storage of the excess daytime supply to meet the nighttime energy demand [5].

Storage of thermal energy can be accomplished by sensible, latent or chemical heat storage. Latent heat storage, which involves (typically solid–liquid) phase transformation [6], is generally preferred due to: (i) the nearly isothermal nature of phase change; (ii) the relatively large specific heat storage capacity associated with phase change versus sensible heat storage; and (iii) the greater control and reliability offered by phase change versus chemical (reaction) heat storage [4].

An appropriate PCM for a particular application should provide a desired balance of phase change temperature, high latent heat, stability under repeated phase change cycles in service environment, thermal conductivity, non-toxicity, resistance to super-cooling, economy, sustainability (abundance and ready availability), and resistance to phase separation and evaporation. The required phase change temperatures and latent heats for building (heating/cooling) applications can be met by a number of PCMs [7,8]. Some key PCM selections for building applications include salt hydrates, fatty acids, and paraffins. Paraffins have many desired properties, including high heat of fusion, negligible super-cooling, low vapor pressure in the melt, chemical resistance, stability, self-nucleating capability, and resistance to phase segregation [9,10]. The key technical drawbacks of paraffins are their low thermal conductivity and large volume change upon melting/freezing; they are also petroleum-based and rather costly. Alternatively, fatty acids are bio-based, sustainable and environmentally friendly [11–15]. Their advantages over paraffins include lower flammability and stability of molecular structure. Fatty acids also exhibit small volume change during melting or solidification with a melting dilatation of approximately 0.1–0.2 mL/g [16]. As

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Nomenclature

ρ	density (kg/m^3)
c_p	heat capacity (J/(kg K))
λ	heat conductivity (W/(m K))
α	thermal diffusivity (m^2/s)
N	number of wall layers
ΔH	latent heat
Δt	time step (s)
Δx	grid space (m)
N_G	number of grid points
l	wall width (m)
R	gas factor
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)

far as the melting temperature is concerned, fatty acids can be easily tailored, by blending two fatty acids in eutectic combination ratios [17,18], to provide the required melting temperature (for optimum diurnal heat storage) that is 1–3 °C above the average room temperature [19]. Binary fatty acid systems with desired melting temperature offer relatively large surface tension (in the order of $2–3 \times 10^{-4}$ N/cm), and desired chemical compatibility with common inorganic building materials (facilitating their incorporation into porous inorganic building materials [20,21].

The phase change materials commonly used for latent heat storage, however, suffer from important technical drawbacks which have hampered their broader market penetration. These drawbacks include: (i) the liquid state of phase change materials (at elevated temperatures) requires costly containments (encapsulations) against seepage, which increase their cost (per unit weight) by one to two orders of magnitude [4]; (ii) the low thermal conductivity of common phase change materials (which tends to be further compromised by common encapsulation techniques [4]) leads to localized melting near the heat source, limiting effective use of their whole volume (especially in scaled-up applications) toward thermal energy storage [6]; (iii) the flammability and inadequate heat resistance of common phase change materials limit their building applications [22]; and (iv) the high (molten state) vapor pressure, supercooling, phase segregation and susceptibility to chemical attack of some phase change materials [22] further limit their effectiveness and market potential.

In this study, fatty acids-based phase change material was blended with expanded graphite interconnected nanosheets to form a nano-PCM composite, as a new class of low-cost, scalable, and shape-stable phase change materials. The nano-PCM was incorporated into gypsum wallboard using a sandwich structure, and the thermal performance of the gypsum wallboards incorporated with nano-PCM was evaluated using test cells under simulated day and night temperature change, in comparison with commercial drywall panels. Numerical models were also developed for evaluating the benefits of PCM incorporated gypsum boards.

2. Experimental work

2.1. Materials

Capric acid (CA) and palmitic acid (PA) were purchased from Sigma Aldrich, and used without further purification. Graphite interconnected nanosheets were kindly supplied by Dr. Drzal's group at Michigan State University, which has a surface area of approximately 100 m^2/g. Exfoliated graphite nanoplatelets (xGnP) were supplied by XG Sciences. Gypsum powder (SHEETROCK® Lightweight Setting Type Joint Compounds Easy Sand™90) was purchased from USG Corporation, which was used for fabrication of gypsum board, and commercial drywall panels from National Gypsum (Properties-GridMarX) were used as the control for PCM incorporated gypsum board. Sulfated poly(styrene) (SPS) was purchased from Aldrich, which has a weight average molecular weights (M_w) of 70,000.

2.2. Preparation of fatty acids nanocomposite and characterization

CA and PA were melted at their corresponding melting temperature. The CA–PA eutectic mixture was obtained by slowly adding CA to PA while stirring rapidly, with a final CA/PA (wt%) ratio of 75.2/24.8. To prepare PCM nanocomposite, the CA–PA mixture was added to graphite interconnected nanosheets with a final composition of 8 wt% graphite and 92% PCM, and sonicated in a sonic bath for 1 h, followed by cooling down to room temperature. The morphologies of graphite interconnected nanosheets and nano-PCM were studied with the scanning electron microscope (SEM) using JEOL 6400V (Japan Electron Optics Laboratories, JP) with a LaB6 emitter. The melting temperature, freezing temperature and latent heat of CA–PA and the nano-PCM were measured using a dynamic scanning calorimeter (DSC) (2920 DSC, TA Instruments) equipped with a cooling attachment at a heating and cooling rate of 5 °C/min. The weight of specimen was in the range of 5–10 mg. The thermal conductivity of nano-PCM and nano-plaster was measured with Anter Unitherm Model 2022 following ASTM E1530.

2.3. Design and fabrication of three-layered gypsum board

A sandwich wall panel was designed to incorporate CA–PA nanocomposite in the gypsum board, as shown in Fig. 1. The thickness of the nano-PCM layer was 5 mm, sandwiched in between one-layer (3 mm) of plaster, and the other 'nanoplaster' layer (5 mm) enhanced with 2 wt% xGnP for improved thermal conductivity. To improve durability of the three-layered structure, the nano-PCM layer was surrounded by a 10-mm wide gypsum to form an enclosed structure, as shown in Fig. 1. To fabricate the sandwich wall panel, xGnP was dispersed in 0.1 wt% sulfated poly(styrene) solution using tip sonication for 1 h, and then gypsum powder was mixed with xGnP suspension (with a gypsum powder to water ratio of 1.54:1) to cast the 5-mm nanoplaster layer in a plastic mold. After drying for 24 h, a 5-mm thick nano-PCM was layered on top of the nanoplaster layer, followed by adding 10-mm wide plaster edge around, and 3-mm plaster layer on the top. The wall panel was cured at room temperature for one week.

2.4. Thermal performance evaluation

Two test cells were built for experimental evaluation of the PCM effects on thermal response. Each cell was a cubic enclosure with 0.28 m internal dimension. The control cell (Fig. 2a) had typical envelope panels comprising a gypsum board, insulation, OSB backing and vinyl siding. The cell with nano-PCM (Fig. 2b) had the sandwich panel structure of Fig. 1. While five of the six envelope panels of each test cell had the layered structures shown in Fig. 1, the top face was made of an aluminum sheet with 2 mm thickness (not shown in pictures). This top (aluminum) face is an active face because of its low thermal inertia and low thermal resistance [23]. It enhances heat transfer between the exterior (temperature-controlled) environment and the interior of test cells.

The two test cells were instrumented with four thermocouples for monitoring of temperatures in the interior of the cell (T_1), on the interior face of an envelope panel (T_2), and on the exterior faces of two envelope panels (T_3–T_4), as shown in Fig. 2c. Both test cells were placed in a climatic chamber. Over a 24-h test period,