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New kinds of energy-storing building composite PCMs for thermal energy storage

Alper Biçer *, Ahmet Sarı *

Gaziosmanpaşa University, Department of Chemistry, 60240 Tokat, Turkey

A R T I C L E I N F O

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Energy storing-composite phase change materials (PCMs) are significant means of thermal energy storage in buildings. Although several building composite PCMs (BCPCMs) have been developed in recent years, the additional investigations are still required to enrich the diversity of BCPCMs for solar heating and energy conservation applications in buildings. For this purpose, the present work is focused the preparation, characterization and determination of 10 new kinds of BCPCMs. The BCPCMs were prepared by blending of liquid xylitol pentalaurate (XPL) and xylitol pentamyristate (XPM) esters with gypsum, cement, diatomite, perlite and vermiculite as supporting matrices. The scanning electron microscopy (SEM) and Fourier Transform Infrared (FT-IR) analysis showed that the ester compounds were adsorbed uniformly into the building materials due to capillary forces. The highest adsorption ratio of XPL ester into gypsum, cement, perlite, diatomite, and vermiculite were found to be 20, 19, 71, 52 and 40 wt.%, respectively while it was found to be 22, 25, 66, 50 and 41 wt.% for XPM ester, respectively. Differential scanning calorimetry (DSC) results indicated that the melting temperatures and latent heat energy storage capacities of the prepared BCPCMs are in range of about 40–55 °C and 31–126 J/g, respectively. Thermogravimetric (TG) investigations showed that the BCPCMs had good thermal endurance even above their phase change temperatures. The BCPCMs exhibited almost same chemical and phase change characteristics after 1000 thermal cycling test. It can be also concluded that especially the BCPCMs perlite, vermiculite, diatomite content were found to better candidates for thermal energy storage applications in buildings due to the fact that they have relatively higher heat storage capacity.

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1. Introduction

Heating and cooling requirements of buildings donate considerably to amplify energy consumption and CO_2 discharge. Many efforts have been spent to reduce energy expenses in buildings, as well as reduce CO_2 emission and environmental pollution. Heating and cooling of building by passive way is one of solution concepts developed for this purpose [1]. In this sense, solar energy storage in any forms like sensible heat, latent heat, reversible reaction heat, or combination of these is a basic means to match the peak times between energy supply and demand [2]. Thermal energy can be effectively stored in latent heat form by using phase change materials (PCMs) due to its advantageous properties, such as phase change (solid–liquid, solid–solid, gas–liquid) ability at almost constant temperature, absorbing or releasing high amount of latent heat, thermal and chemical stability, reducing adverse or toxic effects, and varieties of utility fields. Therefore, in last 20 years, PCMs have growing interest in different application types such as building [3–5], textiles [6–8], agriculture [9,10], medicine [11], transportation [12], and electronics [13].

PCMs can be integrated practically with building materials and the final product is described as building composite PCMs (BCPCMs). As the exterior temperature, PCM hosted by the porous building material absorbs the heat of near environment and then melts in the porous structure with the temperature increase over its phase change point. This case retards the temperature increment gradient in building structure. Conversely, the temperature of its near environment decrease, it undergoes phase change from liquid to solid state again by discharging the absorbed heat.

In last 20-years, BCPCMs have been taking into consideration for keep the temperature in the building envelope at comfortable level for a long time interval. With beginning of the utility of BCPCMs as gypsum board [14–16], wall covering material [17,18], plaster [19], concrete [20], ceiling or floor construction material [21] they have been a part of light weight-building envelopes. Thermal energy storage performance of a BCPCM depends on some factors such as its stable phase change ability, energy storage capacity per its unit mass, compatibility between the components of the composite, preparation method, application field, climatic conditions, and the amount of solar energy gain [22]. The selection of BCPCM with respect to phase change temperature is made by

* Corresponding authors. Tel.: +90 356 2521616; fax: +90 356 2521585.
E-mail addresses: alper.bicer@gop.edu.tr (A. Biçer), ahmet.sari@gop.edu.tr (A. Sarı).

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considering climatic conditions and service purpose (heating, cooling or air conditioning). The chemical and physical compatibility of PCM with building material and near environment is another essential factor. The heat storage ability of BCPCM is directly associated with the adsorption percent and heat storage capacity of PCM used in the preparation of BCPCM. The preparation method is effective on the mass fraction of PCM into building matrices. The integration of PCMs with building construction materials is carried out basically in two manner: Mixing a micro or macro encapsulated PCM into polymer matrices with a building material [23,24] or immersing PCM into typical building material [25–27]. However, the applicability, repeatability and costs of these methods should not be ignored. In practice, the immersion method has been more preferred and generally performed using two ways [28]: (i) Incorporation of PCM with building matrices by using solvent [29–31]. (ii) Impregnation of liquid PCM into the building materials by mixing, stirring, ultrasonic [25–27] and vacuum impregnation methods [32–34]. In first one, there are two disadvantageous, requirement of suitable solvent to dissolve PCM and diffuse into the matrices and evaporation necessary of residue solvent which will leads to unpleasant effects for the environment. However, the second method is simpler and does not need the use of any organic solvent.

In recent years, the porous building materials have been gain increasing interest in the preparation of BCPCMs due to their advantages of low cost, direct incorporation viability and good chemical compatibility, and extensive usage feasibility in building industries [35–37]. Therefore, most researches have been focused on the combination of porous building materials with various organic PCMs, such as paraffins [38–40], fatty acids [41–43], their mixtures [44–46], fatty acid esters [47–49], and PEGs [50–52]. These literatures indicated that the BCPCMs with organic PCM content have improved thermal energy storage capacity to meet the necessities of many energy-saving systems in an environmentally friendly approach. However, these BCPCMs are still at development stage and the research results regarding with their applications in buildings are not enough to extend in commercialize grade.

Xylitol pentalaurate (XPL) and xylitol pentamyristate (XPM) esters have been reported as potential organic PCMs in our previous study [53] since they have reasonably large energy storage density, stable phase change behaviors, good thermal and chemical reliability, non-corrosiveness and better odor properties in comparison with the fatty acids. Moreover, the synthesis processes of these PCMs are simple and do not require high temperature, specific catalyst with high cost and long reaction time. Thus, these advantages make XPL and XPM esters feasible candidates for thermal energy storage in building envelopes. On the other hand, gypsum and cement are known as usual construction materials. Perlite [39,43], vermiculite [46] and diatomite [31,48,50] are also porous, ultra-lightweight, environmentally safe and low cost (e.g.: in Turkish markets, the selling price is about 0.07 $/kg for cement, 0.29 $/kg for perlite, 2.8 $/kg vermiculite, 0.35 $/kg diatomite and 0.06 $/kg for gypsum). In addition, the cost of production BCPCMs is very low since they are prepared by using impregnation method that is known as directly mixing liquid PCM with porous building material. On the other hand, to the best of our knowledge, there is no study about the thermal energy storage properties of the BCPCMs prepared by incorporation of these esters with gypsum, cement, diatomite, perlite and vermiculite. For this purpose, the present work is aimed to (1) prepare 10 new kinds form-stable BCPCMs, (2) chemically and morphologically characterize the prepared BCPCMs using SEM and FT-IR techniques, (3) measure the energy storage properties using by DSC analysis, (4) compare their energy storage capacities with literature, (5) establish their thermal reliability and chemical stability after 1000 heating–cooling cycles and (6) investigate their thermal durability performances using TG analysis method.

2. Materials and methods

2.1. Materials

The XPL and XPM esters were synthesized in our previous study [53]. Gypsum and cement, diatomite, perlite and vermiculite were supplied from Turkish company. The chemical compositions of these materials providing by the manufacturer company were presented in our previous study [18].

2.2. Preparation of the BCPCMs

The BCPCMs were prepared using blending method [25,27]. Firstly, the XPL and XPM esters were liquefied above their melting temperatures. The liquid ester compounds was then separately added to the porous building materials at different mass fractions in a 300 mL-beaker. The mixture was blended at 300 rpm for 45 min by using a magnetic stirrer with temperature controller. During the preparation process, the temperature of the BCPCM was kept over the melting temperatures of the ester compound in order to observe the liquid leakage form the BCPCM surface. Then, the mixture was dried in an oven at 70 °C for 6 h.

The mass fractions of PCMs were altered between 10% and 30% (w/w) during the preparation of gypsum and cement based-BCPCMs and 30% and 80% (w/w) for the preparation of perlite, vermiculite and diatomite-based BCPCMs. The mass percentage of PCMs adsorbed into building materials is increased by 2 wt.% at the next stage. As shown in Table 1, the prepared form-stable BCPCMs, they were denoted as BCPCM-1, BCPCM-2, BCMPCM-3, BCPCM-4, BCPCM-5, BCPCM-6, BCPCM-7, BCPCM-8, BCPCM-9, and BCPCM-10.

2.3. Characterization of the BCPCMs

The microstructures of the prepared form-stable BCPCMs were investigated by using a LEO 440 model SEM instrument. The chemical structures of the BCPCMs were characterized by using a JASCO 430 model FT-IR spectrophotometer. The FT-IR analyses were carried out using KBr pellets between 400 and 4000 cm^{-1} wavenumber.

DSC instrument (Perkin Elmer JADE model) was used to measure solid–liquid phase change temperatures and latent heat capacities of the BCPCMs at a heating rate of 2 °C/min. The measurements were repeated three times for each sample and the mean values were taken into account. Thermal durability of the prepared BCPCMs was determined by using a TG analyzer (Per-

Table 1
The prepared BCPCMs and their abbreviations in the text.

Prepared building composite PCMs	Abbreviation
XPL(20%)/gypsum	BCPCM-1
XPL(19%)/cement	BCPCM-2
XPL(71%)/perlite	BCPCM-3
XPL(52%)/diatomite	BCPCM-4
XPL(40%)/vermiculite	BCPCM-5
XPM(22%)/gypsum	BCPCM-6
XPM(25%)/cement	BCPCM-7
XPM(66%)/perlite	BCPCM-8
XPM(50%)/diatomite	BCPCM-9
XPM(41%)/vermiculite	BCPCM-10

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