Polyethylene glycol/mesoporous calcium silicate shape-stabilized composite phase change material: Preparation, characterization, and adjustable thermal property

Tingting Qian, Jinhong Li*, Xin Min, Yong Deng, Weimin Guan, Hongwen Ma

Beijing Key Laboratory of Materials Utilization of Nonmetallic Minerals and Solid Wastes, National Laboratory of Mineral Materials, School of Materials Science and Technology, China University of Geosciences, Beijing 100083, PR China

ABSTRACT

Shape-stabilized composite phase change materials (ss-CPCMs) composed of PEG (polyethylene glycol) and MCS (mesoporous calcium silicate) were prepared by a facile blending and impregnating method. Various techniques were employed to characterize their structural and thermal properties. The supercooling extent, melting time and solidifying time of the ss-CPCM were respectively 25%, 28.2%, and 27.3% less than those of PEG. The characterization results by DSC (Differential Scanning Calorimetry) technique indicated that the PEG/MCS ss-CPCM was a good candidate for building applications due to its large latent heat, suitable phase change temperature, and good thermal reliability. The crystallinity of PEG in the ss-CPCMs decreased with the increase of MCS content. We proposed the possible formation mechanism of PEG/MCS and concluded that the thermal properties of the PEG/MCS were influenced by the adsorption confinement of the PEG molecule chains in the mesoporous structure of MCS and the interferences of MCS as an impurity in the perfect PEG crystallization. Interestingly, the melting temperature of the new ss-CPCMs could be adjusted from 34.16 °C to 58.13 °C and the solidifying temperature could be adjusted from 27.21 °C to 44.10 °C. Corresponding latent heats of the melting and solidifying processes were 97.79–128.18 J/g and 85.41–114.19 J/g, respectively.

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1. Introduction

Non-renewable resources are limited and their usage is often related to the emission of harmful gases. Therefore, the utilization of new energy has been worldwide concerned. The technique of latent heat storage employing PCMs (phase change materials) is the most concerned. PCMs (Phase change materials) have become a hotspot in the fields of solar heating system, building energy conservation, air-conditioning systems, thermal insulation and regulation, waste heat recovery, etc. due to their high energy storage density, isothermal operating characteristics, and extremely small temperature variation [1][2], and [3]. Compared with inorganic PCMs, organic PCMs can avoid some fatal flaws, such as super cooling and phase separation. More importantly, organic PCMs have numerous advantages, such as self-nucleating behavior and good thermal reliability [4] and [5].

Among various organic PCMs, polyethylene glycol (PEG) has always been viewed as the most promising one due to its suitable phase change temperatures and high latent heat storage capacity, which could be simply tuned via changing its molecular weight [6]. Besides, PEG molecules could also be directly incorporated into the carrier matrixes and own congruent melting behavior, excellent resistance to corrosion, good chemical and thermal stabilities, biodegradation, non-toxicity, low vapor pressure, and competitive price [7] and [8]. However, the actual applications of PEG inevitably face two enduring problems: phase instability in melting state and low thermal conductivity. The former, in particular, restricts its applications to a large extent. Moreover, the organic PEG PCMs also have an interfacial combination problem with surrounding materials [9,10].

To solve the problem of liquid PEG leakage, a novel kind of shape-stabilized composite phase change materials (ss-CPCMs) prepared through blending PEG with carrier matrixes have been extensively studied [11]. The powder—like and organic—inorganic ss-CPCM can maintain its solid state even when the phase-change substance is changed from solid to liquid state [10]. In other words, during the phase change process, the carrier matrixes could
make liquid PEG convenient to control and prevent PEG from adverse interactions with the surrounding materials and environment [12,13].

In this connection, various carrier matrixes, including polymers [14,15], and porous materials, have been widely reported, including silica, diatomite, bentonite, vermiculite, perlite, attapulgite, montmorillonite, expanded graphite, and metal foam [6,10,11,16–18]. However, the laborious PCMs encapsulation procedure employing polymer matrixes often increases the synthesis costs. Additionally, organic capsule shells always enlarge heat resistance, cause serious incompatibility problems and are not tough enough in the long-term to prevent the leakage of melting PCMs [19,20]. Since numerous attractive characteristics of inorganic substances naturally, e.g. chemical stability, thermal conductivity, mechanical strength and fire resistance, are always significantly higher than those of the organic polymers, finding an appropriate inorganic carrier matrix for ss-CPCMs is a prospective way to overcome their limitations shape instability and synchronously enhance their thermal performances. Moreover, those ss-CPCMs based on inorganic carrier matrixes could be easily prepared and directly applied without additional encapsulation [21,22].

In the past decades, the requirements for buildings have increased tremendously: comfortable indoor climate, the healthy environment, the sustainable and energy efficient design, and the low energy utilization rate [23]. CS (Calcium Silicate), as a pretty important inorganic material in the building industry, can be considered as a good carrier material because of its nontoxicity, high melting point, excellent thermal stability, good mechanical properties, desirable thermal conductivity, high storage capacity, and flame resistance [24]. However, based on the Feng et al. [25], the phase change properties and shape stabilization of PCMs were found to be related to the average pore size of the carrier material. In detail, if the average pore size is too small, the motion of PCM molecular will be unavoidably impeded. On the contrary, if the pores are too large, there will not be sufficient capillary force to stabilize the liquid PCMs. Py et al. [26] once reported that a mesoporous support would perform better. In this way, PEG based composite PCMs stabilized by mesoporous matrices are promising candidates for high performance heat storage systems. Thus MCS (mesoporous calcium silicate) has been first prepared and then employed to act as carrier material. However, to the best of our knowledge, the preparation of PEG/MCS ss-CPCMs based on MCS has not been reported.

In this paper, a series of novel PEG/MCS ss-CPCMs with enhanced thermal properties for thermal energy storage have been prepared via a simple blending and impregnating operation in air. The prepared PEG/MCS ss-CPCM might be used as a candidate for the application in building envelopes in the hot summer, whose temperature is often as high as 50–70 °C.

2. Experimental

2.1. Materials

PEG, as the latent heat storage substrate, was in commercial grade with an average molecular weight of 1000, 2000, 4000 and 6000, which was purchased from Beijing Chemical Reagent Ltd. Besides, all the other chemical reagents (Na2SiO3, 9H2O, CaO, etc.) were analytically pure and also purchased from Beijing Chemical Reagent Ltd. Deionized water was used throughout the experiments.

2.2. Preparation of shape-stabilized CPCMs

MCS was synthesized through a simple hydrothermal process. Na2SiO3·9H2O and CaO powders (mass ratio of 1:1) were firstly well-mixed with distilled water, then stirred, and subjected to the hydrothermal treatment at 160 °C for 8 h. Finally, the synthesized MCS powder was filtered, washed, and dried at 105 °C for 12 h before acting as the carrier matrix.

PEG/MCS ss-CPCMs were prepared using the direct blending and impregnating operation in air. The PEG and MCS with different mass ratios (4:6, 5:5, 6:4 and 7:3) were mixed in a mixing vessel. The components of the PEG/MCS composites are listed in Table 1. Absolute ethanol was added while stirring and the solution was then stirred vigorously for 2 h. After this, the mixture was dried at 80 °C for 24 h, so that the ethanol solvent would evaporate and the shape stabilization of the composites above PEG’s melting point could be investigated. In order to observe the PCM leakage from the composites, the composite PCMs were simultaneously heated during the impregnation process above the melting temperature of the PEG. The maximum absorption ratios of MCS samples for PEG were determined as the absorption amount obtained when no liquid PEG trace was observed on the surface of the mixing vessel (for example, the vessel was visually dry). Finally, four kinds of the PEG/MCS composites were obtained and respectively denoted as ss-CPCM1, ss-CPCM2, ss-CPCM3, and ss-CPCM4.

2.3. Analysis methods

The specific surface area and pore volume were determined by a N2 adsorption analyzer (Quantachrome Instruments, US). And the pore size distribution was calculated from the adsorption branches of the corresponding nitrogen isotherm using the BJH (Barrett–Joyner–Halenda) method. Scanning electronic microscope (SEM, Model HITACHI S-4800) was adopted to observe the microstructures of ss-CPCMs. The chemical compatibility of CPCMs was obtained via Fourier transform infrared spectroscopy (FT-IR, Model Frontier). Samples were ground sufficiently and mixed with KBr. The mixtures were well compacted to provide the smooth test surfaces and then pressed into pellets. FTIR spectra were obtained in the range of 400–4000 cm⁻¹. X-ray diffraction (XRD, Model XD-3) technique was applied to investigate the crystal structures and crystallization properties of PEG in ss-CPCMs. XRD patterns were collected at a scanning rate of 4°/min in the 20 range 4–70° using Ni-filtered CuKα radiation (λ = 0.1541 nm) and operating at 40 kV and 100 mA. The phase change temperature and enthalpy of the samples were obtained by using a Q100 DSC (Differential Scanning Calorimetry). The samples were heated and cooled between 0 and 100 °C at a rate of 10 °C/min in a nitrogen atmosphere.

3. Results and discussion

3.1. Characterization of MCS and PEG/MCS ss-CPCMs

3.1.1. Micro-morphology analysis

Fig. 1 shows the microstructures of MCS and ss-CPCMs prepared with different PEG mass fractions. As shown in Fig. 1(a) and (b), active MCS powder is mainly composed of crossed flower-like sheet structures and has multiple pores with many inner surfaces, which can be easily permeated with the melted PEG. As illustrated from Fig. 1(c) to (f), PEG with different mass ratios (40–70 wt.%) is
adsorbed and dispersed in the porous network of active MCS, respectively. The structure of MCS provided the good mechanical strength for the whole composite and prevented the seepage of the melted PEG due to the effect of capillary and surface tension force. Therefore, the shape-stabilized CPCMs were obtained. In this experiment, the maximum mass percentage of the PEG in the composites was determined to be 70 wt.%. There was no leakage of the PEG from the composites even when the composites were heated over the melting point of PEG. Therefore, final products were defined as shape-stabilized composite PCMs.

3.1.2. Specific surface area and pore size analysis

The BET (Brunauer Emmette Teller) and N\textsubscript{2} adsorption–desorption measurement are carried out to examine the textural properties of the as-prepared MCS and PEG/MCS powders. The corresponding adsorption–desorption isotherm and pore size distribution curve of the sample are shown in Fig. 2. In the isotherms, MCS resembled a typical type IV isotherm with a hysteresis loop of type H\textsubscript{1} in the P/P\textsubscript{0} range of 0.4–1.0, which is typical for a mesoporous solid. Applying the BJH (Barret–Joyner–Halenda) method to calculate the pore size distribution (inset of Fig. 2), the average pore diameter of MCS was found to be 10.39 nm. Moreover,

<table>
<thead>
<tr>
<th>Results</th>
<th>0%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
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</thead>
<tbody>
<tr>
<td>PEG mass fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific surface area (m\textsuperscript{2}/g)</td>
<td>91.291</td>
<td>40.425</td>
<td>0.972</td>
<td>0.532</td>
<td>0.072</td>
</tr>
<tr>
<td>Pore volume (cc/g)</td>
<td>0.237</td>
<td>0.062</td>
<td>0.031</td>
<td>0.012</td>
<td>0.004</td>
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<tr>
<td>Mean pore diameter (nm)</td>
<td>10.393</td>
<td>1.946</td>
<td>0.638</td>
<td>0.043</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 2

Textural properties of MCS and the prepared PEG/MCS ss-CPCMs.

Fig. 1. SEM pictures of: (a, b) MCS, (c) ss-CPCM1, (d) ss-CPCM2, (e) ss-CPCM3 and (f) ss-CPCM4.

Fig. 2. Nitrogen adsorption–desorption isotherms and pore size distribution (insert) of MCS sample.
the N₂ adsorption—desorption analysis results of MCS and the PEG/MCS ss-CPCMs with various PEG weight percentages are summarized in Table 2. Based on Table 2, we observe that the surface areas, pore volumes and diameters of the PEG/MCS ss-CPCMs decreased with the increase in PEG weight percentages and were far lower than those of MCS. The results are consistent with the analysis results from SEM images, indicating that PEG is uniformly distributed into MCS pores.

3.1.3. FL-IR analysis
Chemical compatibility between PEG and MCS was determined via FT-IR analysis. The spectra of (a) MCS, (b) PEG and (c) ss-CPCM4 are presented in Fig. 3. In Curve (a), the peaks from 400 to 1100 cm⁻¹ are caused by silicate ions. The peak at 966 cm⁻¹ indicates the stretching vibration of Si—O group; the peak around 447 cm⁻¹ belongs to the bending vibration of siloxane (—Si—O—Si—) group; the peak at 659 cm⁻¹ is also caused by the vibration of siloxane (—Si—O—Si—) group. In Curve (b), the typical stretching vibrations of C—H at 962 and 2888 cm⁻¹ correspond to CH₂ of PEG. And the stretching vibrations of C—O and —OH are found at 1112 and 3432 cm⁻¹, respectively. In Curve (c), except for some slight peak shifts, all the main absorption peaks of both PEG and MCS occur as predicted. According to FL-IR results, no chemical interaction occurs between PEG and MCS matrix, while some physical interactions exits, including hydrogen bonding interactions, capillary effect, and surface tension forces, which largely contribute to the shape-stabilization of the prepared CPCMs. These results are in good agreement with that of reference [10,18].

3.1.4. XRD analysis
As shown in the XRD patterns of MCS and the prepared ss-CPCMs with various PEG mass fractions (Fig. 4), two notable sharp peaks at around 19° and 23° are assigned to PEG crystal, while another two main peaks at around 6° and 29° belongs to MCS crystal. PEG and MCS have different diffraction peaks. The diffraction peaks of MCS and PEG appear in ss-CPCMs, suggesting that ss-CPCMs exhibit a composite structure formed by crystallite PEG and MCS. Besides, the 2θ positions of the PEG peaks show no significant change in ss-CPCMs, indicating that the crystal structure of PEG was not destroyed after impregnation. These findings further indicate that no appreciable interaction occurs between PEG and MCS. These results are similar to previous study results [27,28].

3.2. Phase change behavior of shape-stabilized CPCMs
The phase change temperature and latent heat of the prepared ss-CPCMs were measured with the DSC technique. Fig. 5(a) demonstrates the melting and solidifying DSC curves of pristine PEG and ss-CPCMs with various PEG mass fractions. The corresponding phase change parameters obtained from the DSC evaluation are summarized in Table 3.

As a critical factor for PCMs, the phase change enthalpy is always considered as a most reliable indicator to evaluate the thermal energy storage capacity of the prepared ss-CPCMs. In the composites, only the PEG substrate can absorb/release heat during the melting and solidifying process. Therefore, the higher PEG content will positively boost the latent heat storage capacity of the prepared ss-CPCM. Based on Table 3, ss-CPCM4 could be unquestionably chosen as the most promising latent heat storage material. In order to determine the reliability of ss-CPCM4, the 200-cycle experiment was conducted (denoted as ss-CPCM4c) and no leakage of PEG was found. As shown in Fig. 5(b) and Table 3, no significant difference can be observed in both endothermal and exothermal curves of ss-CPCM4 after cycles, indicating that ss-CPCM4 has excellent thermal reliability, which means a longer life cycle.

As known, the theoretical enthalpy of ss-CPCM could be determined by Eq. (1) [8]:

$$H_{\text{theo}} = \eta \cdot H_{\text{PCM}},$$

where the value of η is the encapsulation ratio of the PEG; $H_{\text{theo}}$ represents the theoretical phase change enthalpy of the CPCMs; $H_{\text{PCM}}$ denotes the latent heat of the pristine PEG. However, the melting and solidifying enthalpies of the prepared ss-CPCMs were lower than their theoretic values. It was likely to be the steric effect and drag effect restricted the crystal arrangement and orientation of PEG molecular chains, which led to the decline of regularities of crystal line regions and the increase of lattice defects; therefore, the actual enthalpies of ss-CPCMs were lower than the theoretical enthalpies [25]. Besides, the melting temperatures of the prepared ss-CPCMs were slightly lower than that of pristine PEG, probably due to the physical interactions between PEG and MCS, the confined phase change behaviors, or the enhancement in thermal conductivity [29]. The solidifying temperatures of the ss-CPCM2,
ss-CPCM3, and ss-CPCM4 are higher than that of the pristine PEG. The phenomenon is not consistent with previous results [12,21]. Moreover, as another important parameter in practical applications, supercooling of PCMs must be taken into account. In accordance with the DSC measurement results in Table 3, the extent of supercooling could be obtained as the difference between the melting and solidifying temperature. The corresponding evaluation results are described in Fig. 6. Compared with the supercooling extent of pristine PEG, the supercooling extents of the prepared ss-CPCM1, ss-CPCM2, ss-CPCM3, ss-CPCM4, and ss-CPCM4c are respectively reduced by 2%, 2%, 13%, 25%, and 22%. The result suggests that the supercooling extent of PEG can be favorably reduced by impregnation with MCS.

3.3. Comparison with vacuum treatment

In this paper, the ss-CPCMs were prepared by direct blending and impregnating operation in air without vacuum treatment. However, as reported by the literature [12], those prepared through the vacuum method usually have better adsorption capacities and thermal properties. Therefore, the two methods were compared and the results are shown in Fig. 7. All the experimental results were performed in duplicate and the mean values were taken with the relative error less than 3%. As shown in Fig. 7, no obvious differences between the two methods have been observed. As known, the liquid PEG can exist firmly into MCS pores mainly due to capillary forces. However, the atmosphere pressure within the pores may prevent the impregnation process. That is, if the capillary forces are smaller than the outside atmospheric pressure, the operation will turn out to be a failure. Because of the ordinary pore geometry of MCS, air within the pores may be effortlessly replaced by the PEG molecules just under the atmospheric pressure. No extra vacuum treatment is required. What is noteworthy is that those ss-CPCMs in which pores are not fully suffused with PEG molecule could not be used directly because air within the pores may expand dramatically at the elevated temperature and cause the leakage of the PEG. The results here are similar with those of our previous study [6].

3.4. Melting and solidifying characteristics of the prepared ss-CPCM

In order to investigate the melting and solidifying characteristics of the prepared ss-CPCMs, 30 g PEG and 30 g ss-CPCM4 were respectively added into two glass vessels. A thermometer with the temperature accuracy of ±0.5 °C was placed in the center of the two vessels. The two testing vessels were put into a water bath at 70 °C for complete melting and then straightway placed into another water bath with a constant temperature of 25 °C for the solidifying process. The temperature variations of the PEG and ss-CPCM4 during melting and solidifying periods were measured and recorded. The enhancement in the thermal conductivity of the prepared composite was determined through comparing its melting and solidifying time with that of pristine PEG.

Fig. 8 exhibits the melting and solidifying process curves of the PEG and ss-CPCM4. Fig. 8(a) shows the time required for the

![Fig. 5. DSC curves of (a) PEG and the prepared ss-CPCMs, (b) ss-CPCM4 before and after thermal cycle experiment.](image)

![Table 3. Thermal characteristics of PEG and the prepared PEG/MCS ss-CPCMs.](table)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Melting process (Hm)</th>
<th>Solidifying process (Hs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hm(J/g)</td>
<td>Tm (°C)</td>
</tr>
<tr>
<td>PEG</td>
<td>183.10</td>
<td>58.95</td>
</tr>
<tr>
<td>ss-CPCM1</td>
<td>28.56</td>
<td>58.02</td>
</tr>
<tr>
<td>ss-CPCM2</td>
<td>65.79</td>
<td>58.40</td>
</tr>
<tr>
<td>ss-CPCM3</td>
<td>104.60</td>
<td>58.27</td>
</tr>
<tr>
<td>ss-CPCM4</td>
<td>122.10</td>
<td>57.03</td>
</tr>
<tr>
<td>ss-CPCM4c</td>
<td>113.60</td>
<td>57.59</td>
</tr>
</tbody>
</table>

![Fig. 6. Phase change temperature of PEG and ss-CPCM4.](image)
temperature rising from 25 °C to 50 °C for PEG and ss-CPCM4 is 34.8 min and 25 min, respectively. As seen from Fig. 8(b), the time required for the temperature reducing from 50 °C to 25 °C for PEG and ss-CPCM4 is respectively 22 min and 16 min. That is, the melting and solidifying time of ss-CPCM4 is respectively 28.2% and 27.3% less than that of PEG, suggesting that the heat storage/release rate of the ss-CPCM4 is much faster than that of pristine PEG in practical applications.

3.5. The proposed formation mechanism of ss-CPCM

Fig. 9(a) simply illustrates the schematic formation mechanism of the preparation of PEG/MCS ss-CPCM. PEG segments can be adsorbed by MCS through capillary force and surface tension. However, MCS interferes with the solidifying process of PEG molecules. Since some PEG chains are inevitably embedded into the nano-sized pores, other PEG chains are adsorbed on the surface of the mesoporous matrices. The combined effects of nano-sized and mesoporous confinement and surface adsorption impede the crystal aggregation of the whole PEG chain. The influence on the solidifying of PEG becomes more significant when the content of the MCS content is increased. According to the XRD results shown in Fig. 9(b), when the weight percentage of PEG falls to a certain range (e.g. 20 wt.%), no typical peak of PEG appears, indicating that PEG in the PEG/MCS PCMs is thoroughly confined by the excess MCS and cannot form crystals. On the contrary, in the composites with the high PEG content, part of the PEG molecule chains is in the free condition and can be crystallized freely. In other words, in the prepared ss-CPCMs, the higher PEG content always means the higher fractions of the crystalline phase, thus resulting in the larger enthalpy. Although the abundant pores of MCS restrict PEG's free movement, they can also stabilize the PEG/MCS ss-CPCMs above the melting point of PEG. These results are in good agreement with previous results [30].

3.6. Adjustable thermal properties of ss-CPCMs

In ss-CPCMs prepared with PEG4000, the latent heats of its melting and solidifying processes can be respectively adjusted from 28.56 to 122.10 J/g and from 21.14 to 106.80 J/g by changing the PEG mass fractions from 40% to 70%. However, the corresponding phase change temperatures can hardly be regulated in this way. Therefore, a series of PEG/MCS ss-CPCMs with PEGs of different molecular weights were prepared under the same experimental conditions. The phase change temperatures and enthalpies could be simultaneously tuned. The mass ratio of MCS to PEG is controlled at 3:7 and their thermal values are summarized in Table 4. The phase change temperature ranges of melting and solidifying processes are respectively 34.16–58.95 °C and 27.21–43.48 °C and the latent heats of the two processes are 94.79–131.48 J/g and 85.41–110.19 J/g, respectively. In short, thermal properties of PEG/MCS composites can be tailored according the application requirements in different thermal storage fields by adjusting the molecular weight or mass ratio of PEG.

Besides, we observe that the phase change temperatures of the PEG/MCS ss-CPCMs with the same PEG weight percentage increased with the increase in PEG molecular weights. The phase change enthalpy of the PEG6000/MCS ss-CPCM was the largest one among four samples. Three significant parameters, i.e. the impregnation ratio (R), impregnation efficiency (E), and thermal storage capability (w) have been employed to quantify the phase change performance of the prepared PEG6000/MCS ss-CPCM [31], which could be calculated using the following three equations:

\[ R = \frac{H_{M, com}}{H_{M, PCM}} \times 100\%, \]

Please cite this article in press as: Qian T, et al., Polyethylene glycol/mesoporous calcium silicate shape-stabilized composite phase change material: Preparation, characterization, and adjustable thermal property, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.01.043
The obtained PEG/MCS ss-CPCMs own high exudation stability even in the liquid state of PEG. SEM results indicated that PEG was well impregnated. FT-IR, XRD, and 200-cycle experiment results proved the excellent chemical compatibility and reliability of PEG/MCS ss-PCM.

(2) PEG/MCS ss-CPCMs have the adjustable phase change temperature ranges of the melting and solidifying process for the applications in building envelopes in the hot summer. Their corresponding large latent heats could be easily tuned by changing the PEG mass fraction (40–70 wt.%) or molecular weight (1000 – 6000).

(3) The supercooling extent, and melting and solidifying time of the prepared ss-CPCM were respectively 25%, 28.2% and 27.3% less than those of the pristine PEG.

4. Conclusions

A series of novel shape-stabilized CPCMs were prepared by blending PEG with MCS via direct impregnation operation in air. Moreover, the possible formation mechanism of the ss-CPCM was proposed. It was found that the crystallinities of PEG in the composites increased with the increase of the PEG content. Based on the above discussion, the conclusions can be drawn as follows:

(1) The obtained PEG/MCS ss-CPCMs own high exudation stability even in the liquid state of PEG. SEM results indicated

$$E = \frac{H_{M,com} + H_{S,com}}{H_{M,PCM} + H_{S,PCM}} \times 100\%,$$

$$\phi = \frac{H_{M,com} + H_{S,com}}{R} \times 100\%,$$

where $H_{M,com}$ and $H_{S,com}$ denote the melting and solidifying phase change enthalpies, respectively; $H_{M,PCM}$ and $H_{S,PCM}$ respectively represent the melting latent heat and solidifying latent heat of PEG. R represents the effective impregnation of PEG within the structure of MCS, while $E$ describes an effective performance of the PEG inside the composite for latent heat storage. The prepared PEG6000/MCS composite achieved a high impregnation ratio of 66.7% and efficiency of 65.4%. Additionally, the thermal storage capability was higher than 97.9%, indicating that almost all PEG molecule chains could effectively store/release heat through phase transition.

**Table 4**

<table>
<thead>
<tr>
<th>PCM</th>
<th>Melting process</th>
<th>Solidifying process</th>
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<td></td>
<td>$H_M$(J/g)</td>
<td>$T_M$(C)</td>
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<tr>
<td>PEG1000</td>
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<td>PEG1000/MCS</td>
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<td>PEG4000/MCS</td>
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<td>57.03</td>
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<td>PEG6000/MCS</td>
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<td>58.13</td>
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**Fig. 9.** Schematic formation mechanism of PEG/MCS composite.

**References**


