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ARTICLE

Preparation and thermal properties of shape-stabilized composite phase change materials based on polyethylene glycol and porous carbon prepared from potato

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A shape-stabilized composite phase change material (ss-CPCM) comprising polyethylene glycol (PEG) and porous carbon was prepared by absorbing PEG into porous carbon, assisted by ultrasound. In the composite, PEG served as a phase change material for thermal energy storage, and the porous carbon, which was prepared from fresh potato via freeze drying followed by heat treatment, was used as an absorbant that also acted as the supporting material. Various analytical techniques were used to investigate the chemical composition, microstructure, and thermal properties of the prepared PEG/ porous carbon ss-CPCMs. Scanning electron microscopy, X-ray diffraction and Fourier transform infrared spectroscopic results indicated that PEG was well absorbed and encapsulated in the porous structure of the carbon and that there was no chemical reaction between them during the phase change process. The shape and exudation stability test results indicated that the PEG/ porous carbon ss-CPCMs have excellent shape stability, compared to pristine PEG. The contact angle test suggested that the melting PEG has good level of wettability on the carbon so that melting PEG could be well protected from exudation in the porous carbon by surface tension effect, even if the temperature is higher than melting point of PEG. Differential scanning calorimetric results showed that the PEG/ porous carbon ss-CPCMs have considerable phase change enthalpies and thermal storage capabilities. In addition to this, the latent heats of ss-CPCMs increased with increasing contents of the PEG in the composites and achieved the highest value when the amount of PEG was 50 %. Moreover, the thermogravimetric analysis results showed that the composites had excellent thermal stabilities. Based on the above analyses, the prepared ss-CPCM with 50 % PEG content proved to be a promising candidate for thermal energy storage applications.

Introduction

The entire world is facing a serious crisis of energy consumption. Hence, improving the efficiency of energy utilization and preventing its depletion as a crucial solution has received more and more attention throughout the world.[1,2]

As a highly efficient method for utilization of energy, thermal energy storage technology plays an important role in improving the imbalance between energy demand and supply.[3] Amongst all the materials, phase change materials (PCMs) have attracted a lot of interest in many fields, because of their safety, stability, low price, high energy storage density, and constant phase change temperatures.[4] A large amount of latent heat could be stored and released during the phase transition of PCMs at a nearly constant temperature. Depending on different phase change temperatures, phase change materials find applications in various fields such as solar heating systems,[5] thermal insulation materials,[6] building

energy conservation[7,8] and so on.

A wide range of promising inorganic and organic PCMs, including ice,[9] salt hydrates,[10] fatty acids,[11] paraffin waxes,[12] and n-carboxylic acids,[13] have been studied for latent heat storage applications. Amongst the various candidates for PCMs, polyethylene glycol (PEG), an organic macromolecular polymer, is endowed with excellent characteristics, such as high latent heat, congruent melting behavior, good chemical and thermal reliability, lower vapor pressure in the melt, biodegradability, and is commercial available at competitive prices.[14] Moreover, PEG can be easily manipulated by changing its molecular weight so that a suitable phase change temperature could be chosen.[15]

However, the direct application of PEG is limited due to some limitations. Because of low thermal conductivity, which is a common disadvantage of all the organic PCMs, the efficiency of heat transfer decreases. In addition, the leakage of the PCMs occurs when the application temperature is above the melting point.[16,17] In order to solve the problems, a process of encapsulation and shape stabilization of PCMs using supporting materials, was developed, which enable the retention of the solid state during the phase-change process of PCMs.[18-21] In the past decades, owing to some attractive features of porous carbonaceous materials, e.g. chemical and thermal stabilities, high surface areas, porous structures, and excellent thermal conductivities, many studies on the preparation

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and characterization of the shape stabilized PCMs using porous carbon materials, such as graphite,[22] expanded graphite,[23] graphene oxide,[24] carbon nanospheres,[25] and carbon nanotubes,[26] were conducted.

The methods for preparation of porous carbon materials have been extensively investigated.[27-29] It is noteworthy that these studies unexceptionally utilized industrial raw materials, such as starch, sucrose, phenolic resins, etc. as the source of carbon. Due to the toxicity of phenolic resins and the high cost of pure starch and sucrose, the large-scale industrial manufacture and applications of PCMs have been restricted. Therefore, it is very meaningful to develop a green and cheaper alternative route to prepare porous carbon materials with desirable properties.

Nowadays, agricultural byproducts and renewable plant resources have become excellent sources for preparing carbon materials for their high yields, low cost, and most importantly due to their unique biological cell structures.[30-32] Potato is one of the most important high yielding crops. It is one of the primary raw materials for starch in industrial manufacturing because of its high starch content (14 % - 20 %).[33] Additionally, the porous cellular structure of potato makes it an ideal candidate for the preparation of porous carbon materials, without the need of any additional foaming reagents. Hence, the use of potato as a raw material for the direct preparation of porous carbon materials is promising.

In this paper, the synthesis and properties of a shape-stabilized composite phase change material based on polyethylene glycol/ porous carbon for thermal energy storage is presented. A novel form of porous carbon material was used as the supporting material in the composite, which was directly prepared from fresh potato, rather than industrial starch, through freeze drying followed by heat treatment, whereas PEG was used as a phase change material for thermal energy storage. In this research, the thermal properties and shape stabilities of the composite were all improved compared to pure PEG. This was the result of a synergistic effect between the porous carbon and PEG. Therefore, the shape-stabilized PEG/ porous carbon composites proved to be promising candidates for thermal energy storage, which can be applied in the fields, whose application temperatures conform to the phase change temperature of PEG, such as solar heating and building envelopes, during hot summers.

Experimental

Materials

Fresh potato was used as the starting material for porous carbon powder. PEG, which was purchased from Beijing Chemical Reagent Ltd, and used as the phase change material for thermal energy storage, was of commercial grade with an average molecular weight of 4000 and a phase change temperature of 53-56 °C. Absolute ethyl alcohol was analytically pure and purchased from Beijing Chemical Reagent Ltd.

Preparation of porous carbon powder

The scheme for preparation of porous carbon powder and the SEM images (a, b, c) at different stages of preparation of the powder are shown in Fig. 1. Rectangular pieces having a thickness of 10 mm were cut from fresh potatoes and were frozen at -30 °C for 24 h. These pieces were freeze dried for 24 h in a vacuum freeze dryer, to obtain dehydrated specimens. Subsequently, the specimens were pyrolyzed at 900 °C for 2 h in a resistance furnace under argon atmosphere. In order to protect the porous structure, the specimen samples were slowly heated at a heating rate of 1 °C/ min up to 500 °C. During this heating process, the biopolymers (hemicellulose, cellulose, starch), which were present in the potato samples, completely decomposed to carbon. This was followed by heating at a higher heating rate of 2 °C/ min up to 900 °C. Finally, porous carbon powder with a mesh size of 100- 200 was obtained after grinding in an agate mortar.
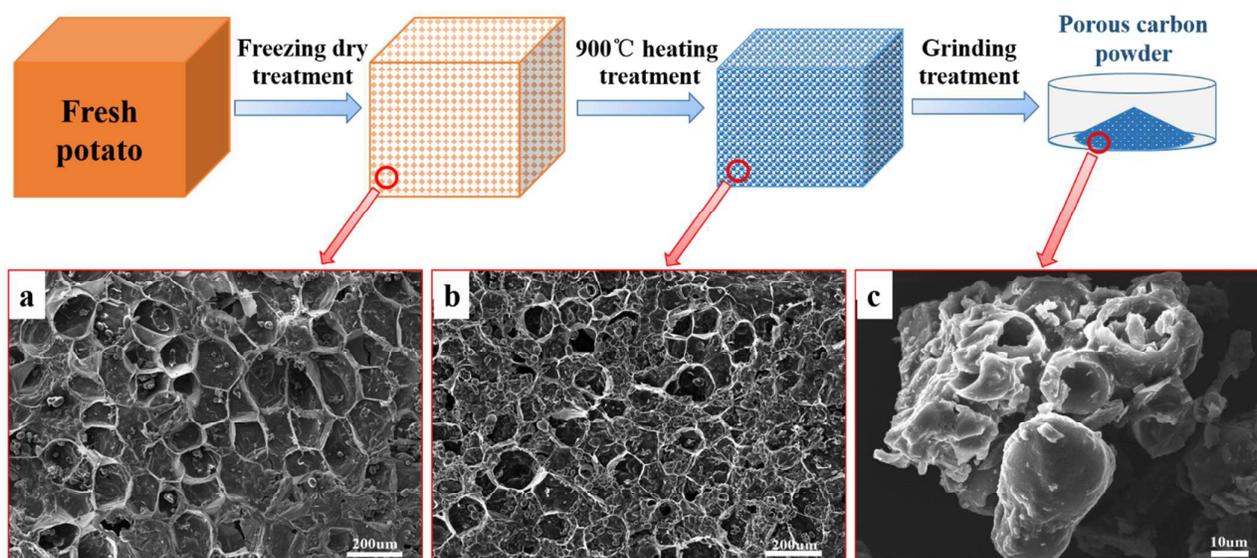
Fig. 1. Schematic route for the preparation of porous carbon powder and its SEM images (a, b, c).

Figs. 1a and 1b represent the SEM images of porous carbon specimens before and after heat treatment at 900 °C, respectively. It was clear that the faveolate structure was perfectly retained and was benefited by the appropriate heating rate, however, heating reduced the bore diameter. As shown in the Figs. 1b and 1c, numerous hollow coacervate granules of carbon were formed which appeared like many houselets and were beneficial for the absorption and storage of the phase change materials.

The mercury porosimetry was applied to test the pore size distribution and surface area of the prepared porous carbon. The textural parameters are summarized in Table 1. As shown in the Fig. 2a, the porous carbon possesses a hierarchical pore structures. These pores are irregularly distributed in a large range from several nanometers to several micrometers. The porous carbon has an average pore diameter of 204.7 nm and a porosity of 73.4%. Fig. 2b shows the contribution of differently sized pores on the specific surface area. From the figure, the specific surface areas of the porous carbon mainly originate from the nanopores in the range of 3–100 nm. Additionally, the porous carbon has a specific surface area of 42.6 m^2/g. Considerable special surface area and high porosity enabled the porous carbon to be used as a promising supporting materials for PCMs.

Table 1. Textural parameters of the porous carbon

Average pore diameter (nm)	204.7
Porosity (%)	73.4
Special surface area (m^2/g)	42.6
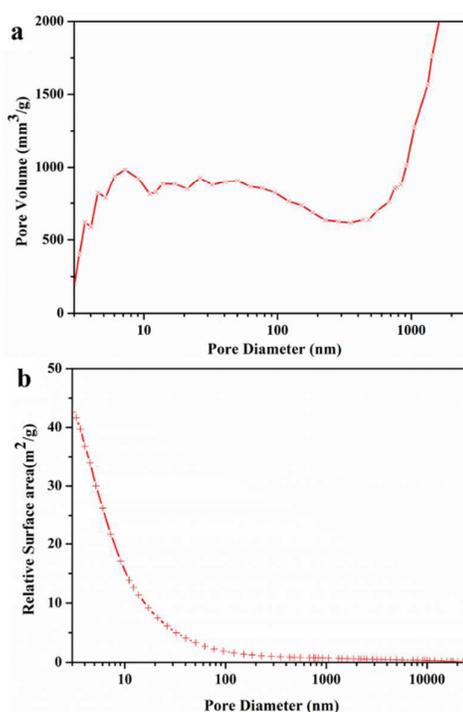
Fig. 2. Pore distributions of porous carbon (a) and contributions of different sized pore on the surface area (b)
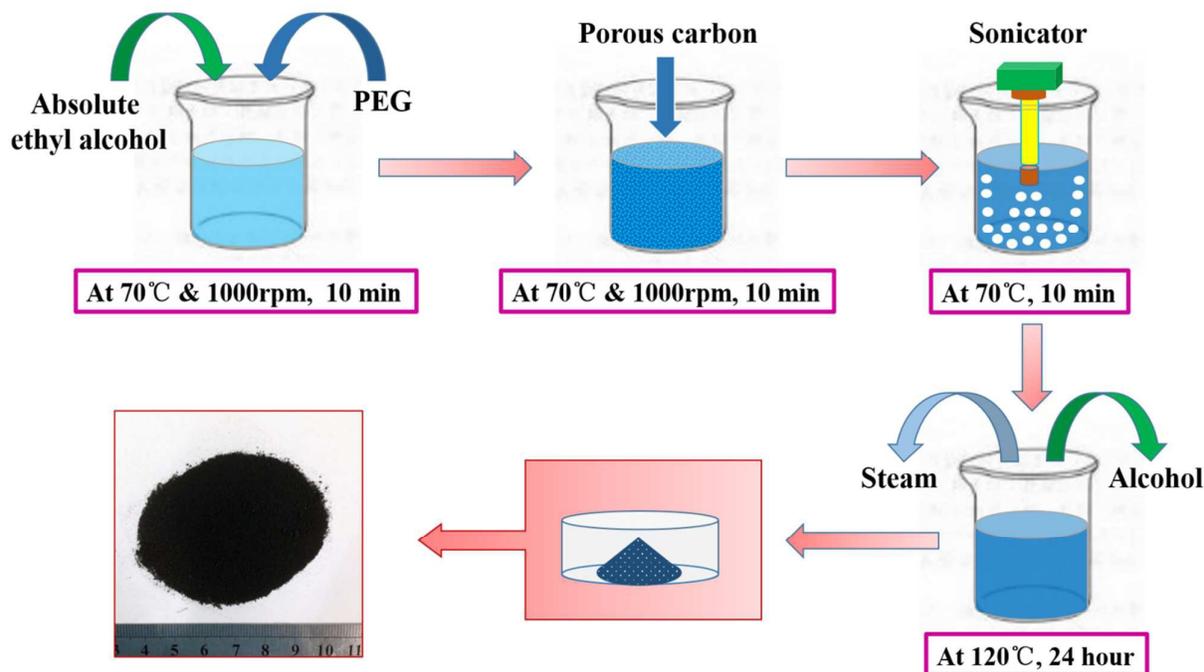
Fig. 3. Schematic route for the preparation of the ss-CPCM samples.
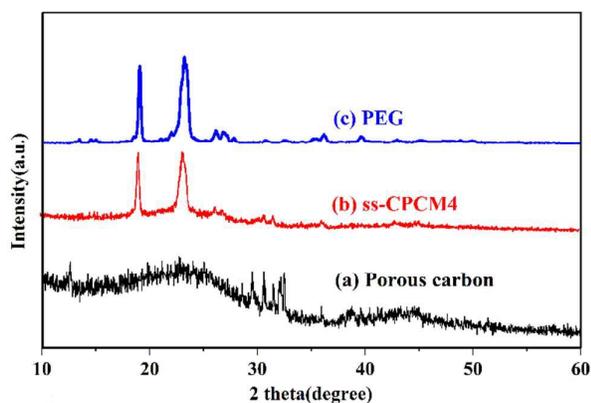
Fig. 4. XRD patterns of (a) porous carbon, (b) prepared ss-CPCM4, and (C) PEG
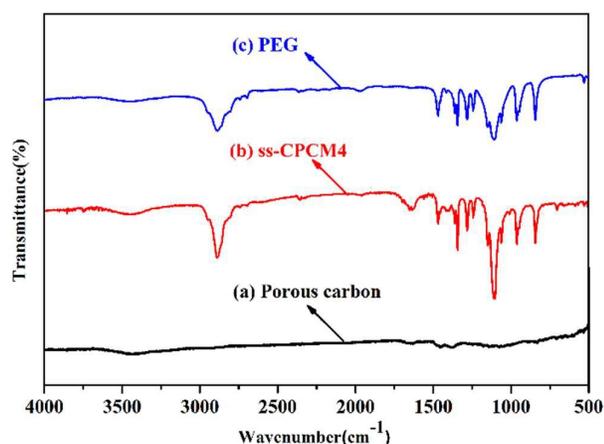
Fig. 5. FT-IR spectra of (a) porous carbon, (b) prepared ss-CPCM4, and (C) PEG.

Preparation of PEG/ porous carbon ss-CPCMs

The stoichiometries of reactants and the route for the preparation of the PEG/ porous carbon composites are shown in Table 2 and Fig. 3, respectively. 1 g of PEG was melted in a beaker containing 50 mL absolute ethyl alcohol at 70 °C and then appropriate quantities of the porous carbon powder, as mentioned in the table, were added to the solution. The mixture was sonicated for 30 min at 150 W to break down the PEG aggregates, using a constant temperature sonifier cell disruptor. The compound was then dried in an oven at 120 °C for 24 h to release alcohol and water molecules absorbed in the pores of the carbon. Finally, four samples of the PEG/ porous carbon composites were obtained, and were designated as ss-CPCM1, ss-CPCM2, ss-CPCM3, and ss-CPCM4.

Table 2. Proportions of reactants for the preparation of PEG/ porous carbon composites.

Samples	PEG(g)	Porous carbon(g)
ss-CPCM1	1.0	3.0
ss-CPCM2	1.0	2.0
ss-CPCM3	1.0	1.5
ss-CPCM4	1.0	1.0

Analytical methods

The powder X-ray diffraction patterns of the ss-CPCM samples were recorded using an X-ray diffractometer (XRD, XD-3 model) at a scanning speed of 8° min[-1], to investigate the crystalloid phase of the PEG/ porous carbon ss-CPCMs. The chemical composition was determined by Fourier transform infrared spectroscopy (FT-IR, Frontier model). The exudation stabilities of the PEG/ porous carbon ss-CPCMs were analyzed by diffusion-oozing circle test.[34] The contact angle tests was proceed to investigate the wettability of PEG to porous carbon. The microstructures of the composites were studied by scanning electron microscopy (SEM, Hitachi model S-4800). Besides these, the thermal properties of the composites, such as latent heat and phase change temperature, were determined by differential scanning calorimetry (DSC, Q2000). The thermal stabilities of PCMs were investigated by thermogravimetric analysis (TGA, Q50).

Results and discussion

XRD patterns of the PEG/ porous carbon composites

The XRD patterns of porous carbon, PEG, and ss-CPCM4 are shown in Fig. 4. The pattern for porous carbon powder (Fig. 4(a)) showed a broad peak at around 23° and several peaks of impurities at 2ϑ = 29.5°, 30.6°, 31.4°, 32.2°, and 32.5°, which indicated that the porous carbon was non-crystalline in nature and impure. Fig. 4(c) shows the XRD pattern of PEG with diffraction peaks at 2ϑ = 15.0°, 19.0°, 22.0°, 23.2°, 26.1°, and 26.8°, which corresponded exactly to the characteristic peaks reported for polyethylene glycol 4000 (JCPDS 49-2095) and proved that PEG, used in the present study, was pure with an average molecular weight of 4000. After impregnation of PEG into the porous carbon, it could be seen from Fig. 4(b) that the ss-CPCM4 sample showed diffraction peaks of PEG along with the broad peaks of the porous carbon, which suggested that PEG was successfully loaded into the porous carbon structure and also that the crystal structure of PEG in the composite was not affected during the synthesis.

FT-IR analysis of the PEG/ porous carbon composite

Fig. 5 shows the FT-IR spectra of (a) porous carbon, (b) ss-CPCM4, and (c) PEG. The FTIR spectrum of porous carbon (Fig. 5(a)) showed the characteristic absorption peaks at 1631 cm^{-1} and 3480 cm^{-1}, corresponding to the stretching vibrations of C=O and –OH respectively. It suggested that there was adsorbing water in the structure of porous carbon. As shown in the Fig. 5(c), the peaks at 960 and 2869 cm^{-1} in the spectrum of PEG were due to the typicalstretching vibrations of the –CH$_2$ group. The symmetrical stretching vibrations of C–O and –OH appeared at 1107 and 3480 cm^{-1}, respectively. In Fig. 5(b), all the main absorption peaks of both PEG and porous carbon at 960, 2869, 1107, and 3480 cm^{-1} appeared as expected. Although some peaks shifted slightly, no obvious new peak was observed. The FT-IR spectra of ss-CPCM4 possesses all primary absorption peaks of the PEG. It indicated that only physical absorption and no chemical interaction existed between PEG and the porous carbon.
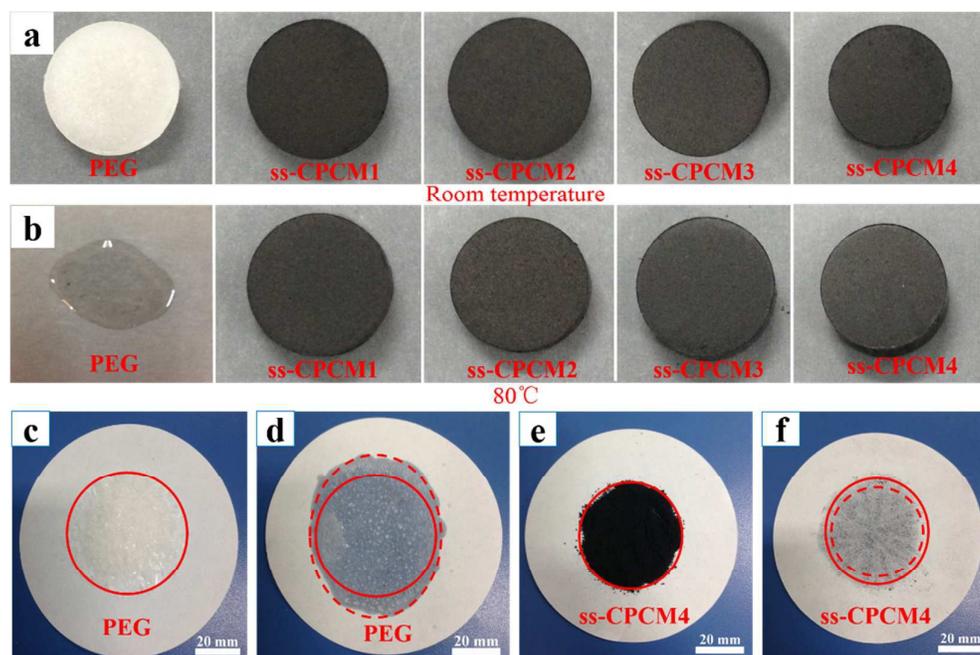
Fig. 6. Photographs of the samples (a) at room temperature and (b) at 80℃; diffusion-oozing circle test, (c) pristine PEG on filter paper (d) melting PEG on filter paper (e) ss-CPCM4 on filter paper, and (f) PEG leakage of ss-CPCM4 on filter paper.

Shape and exudation stability of the PEG/ porous carbon composites

The PEG/ porous carbon composite powders were uniaxially compressed into circular pieces, with each piece having a thickness of 2 mm, using a steel mold with dimensions of φ = 13 mm under a pressure of 30 MPa. Then, the prepared samples were heated to 80 °C, which is higher than the melting point of the PEG, in order to investigate their shape stability. The macroscopic photographs of the ss-CPCMs and pure PEG at room temperature and at 80 °C are shown in Figs. 6a and 6b, respectively. Comparison of the photographs showed that at 80 °C, pure PEG was in a molten state and the primary form was totally changed. Liquid PEG was not present on the surface of the PEG/ porous carbon composites and all of them perfectly retained their primary shapes even when the temperature was much higher than the melting point of PEG.

In order to investigate the exudation stabilities of the ss-CPCMs, diffusion-oozing circle test was carried out.[34] In this test, a filter paper (90 mm) was used to check the exudation of PEG from ss-CPCM4 sample, which absorbed the highest amount of PEG. 3 g of pristine PEG and 3 g of ss-CPCM4 powder were placed in the center of the filter paper respectively, which had a test area of 50 mm^2, and heated at 80 °C for 2 h. As seen in Figs. 6c-f, obvious large-scale diffusion blot was appeared on the filter paper with pristine PEG, while only a faint exudation blot was observed on the filter paper with ss-CPCM4 samples and it was restricted to the primary area of 50 mm^2, which indicated that there was no leakage during the heating process of ss-CPCM4.
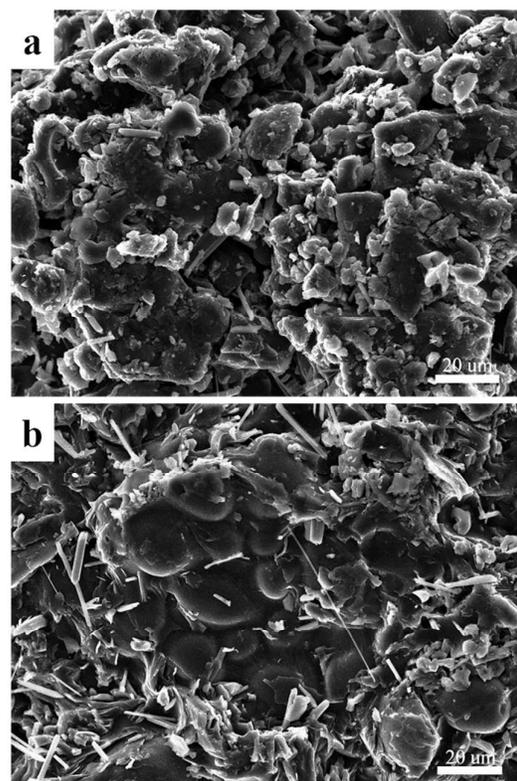
Fig. 7. SEM images of the prepared ss-CPCM4 before (a) and after (b) shape and exudation stability tests.

The SEM images of ss-CPCM4 before and after shape and exudation stability experiment are shown in the Figs. 7a and 7b. The ss-CPCM4 was still porous before the shape and exudation stability test However, the ss-CPCM4 became much more compacted after the shape and exudation stability experiment. This is due to the melting PEG filled into the pores of ss-CPCM4 during the process of melting. The SEM images indicated that the heating treatment would beneficial for ss-CPCMs compacting.

The results of the above tests suggested that the shape and exudation stability of the PEG/ porous carbon composites prepared in this study were quite good.

The wettability analysis of PEG to porous carbon

The contact angle tests was proceed to investigate the wettability of PEG to porous carbon. Figs. 8a-d shows the spreading extent of the melting PEG on porous carbon at different temperatures (70–100 °C) and the degree of corresponding contact angles are shown in the Fig. 9. The degree of contact angles between PEG and carbon were 87.1°, 79.5°, 68.3°, 65.2° at 70 °C, 80 °C, 90 °C, 100 °C, respectively. It is indicated that the contact angles degrees were declined with the increase in temperature. The cause probably is the reduction of viscosity of melting PEG. Moreover, the degree of contact angles at the temperature above 70 °C were all lower than
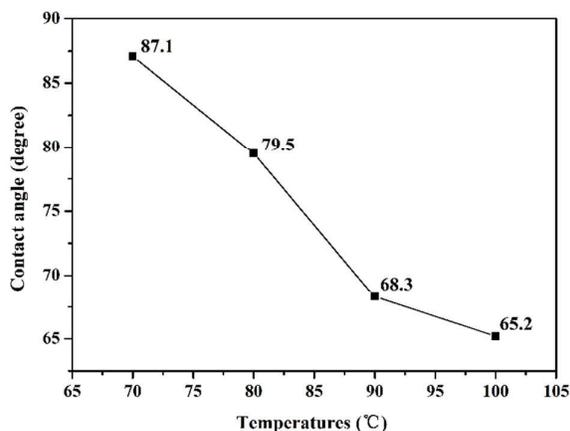
Fig. 9 The degree of contact angles between melting PEG and porous carbon at different temperatures.

90°, which suggested that the melting PEG has good level of wettability on the carbon. And the well wettability between PEG and carbon is an important factor of excellent shape and exudation stability of the PEG/ porous carbon composites at the temperature above the melting point.
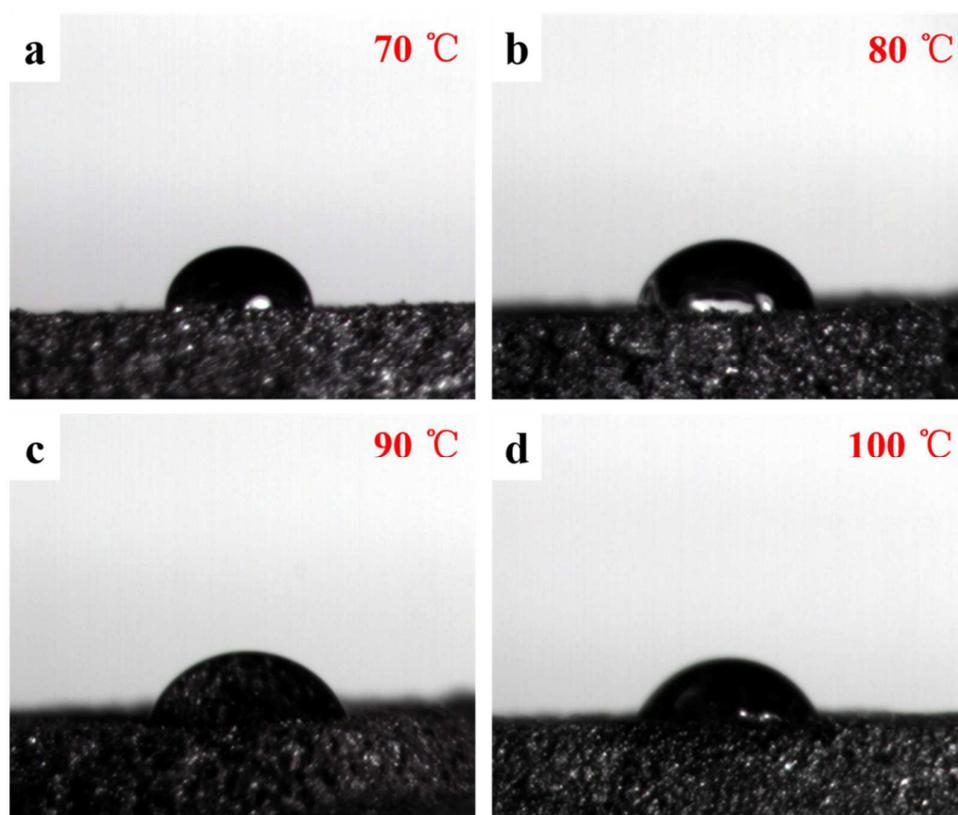
Fig. 8 Photographs of the melting PEG on the porous carbon at 70 °C (a), 80 °C (b), 90 °C (c) and 100 °C (d).
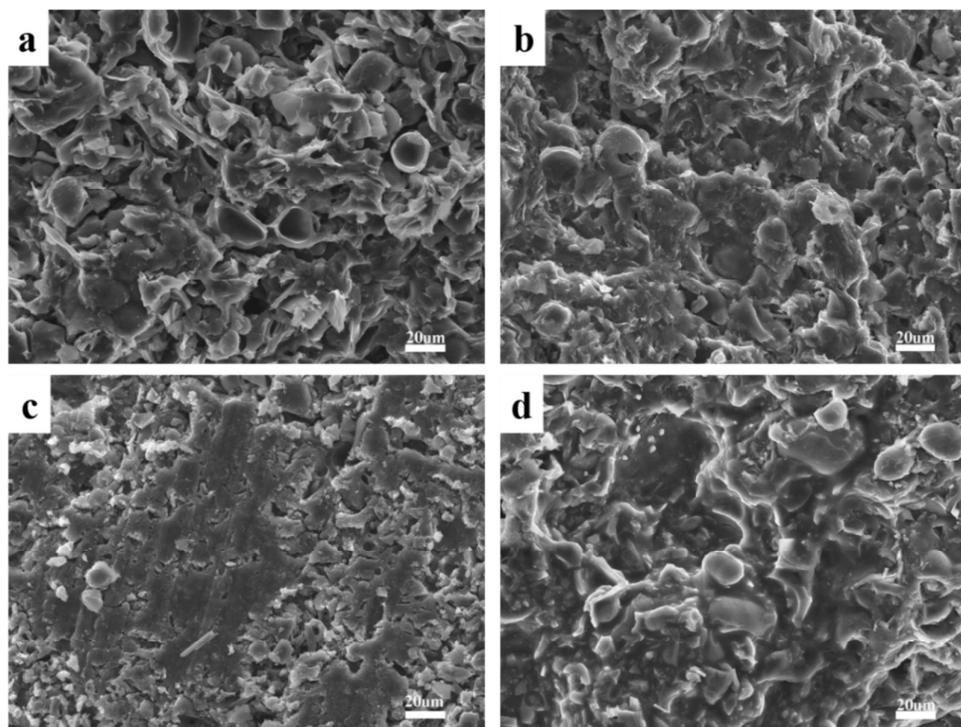
Fig. 10. SEM images of the prepared ss-CPCM1(a), ss-CPCM2(b), ss-CPCM3(c) and ss-CPCM4(d).

Morphology of the PEG/ porous carbon composite

As seen in Figs. 10a-d, PEG, present in different proportions (1 : 3, 1 : 2, 2 : 3, and 1 : 1) in the composites, was equably absorbed and dispersed in the porous carbon network. PEG was stably and uniformly distributed in the network, constituting the carbon skeleton and granules, under the effect of the capillary and surface tension forces. The porous nature of carbon could provide a reasonable mechanical strength for the whole composite to retain its settled form and prevent leakage of the molten PEG. Hence, there was no deformation and leakage of PEG in the composites as shown in Fig. 6, even at a temperature above the melting point of PEG. Comparing the SEM images of the different ss-CPCMs, it was evident that the microstructures of ss-CPCM1 and ss-CPCM2 had higher porosities relative to the other two composites. PEG was in a hard and dense form in ss-CPCM3 and 4, especially in ss-CPCM4 (Fig. 6d), where there were hardly any pores. This was proportional to the different loading amounts of PEG in the PCM composites.

Phase change behavior of the PEG/ porous carbon composites

DSC technique was used to investigate the phase change temperatures and latent heats of pure PEG and ss-CPCMs. The DSC curves, comparison of the melting and crystallization enthalpies, and the phase change temperatures of pristine PEG and ss-CPCMs are shown in Figs. 11 (a, b, and c) and data are presented in Table 3. The melting and solidifying temperatures were determined to be 58.27 °C and 39.04 °C for PEG, respectively. This was consistent with the literature values.[35, 36] The melting temperatures of ss-CPCMs with different proportions of PEG (ss-CPCM1 to ss-CPCM4) were 56.67 °C, 56.69 °C, 56.30 °C, and 56.35 °C respectively, whereas the solidifying temperatures were 38.91 °C, 38.80 °C, 38.60 °C, and 39.81 °C, respectively. In short, the melting and crystallization temperatures of the prepared PEG/ porous carbon ss-CPCMs were slightly lower than those of pure PEG. This was probably due to the fact that the addition of porous carbon enhanced the thermal conductivity of the composites or interfered with the crystallization of PEG through physical interactions.[35, 37]

Table 3. Thermal characteristics of pristine PEG and the prepared ss-CPCMs

Samples	PEG/porous carbon ratio	Melting process		Crystallization process	
		T_M(°C)	H_M(J/g)	T_C(°C)	H_C(J/g)
ss-CPCM1	1:3	56.35	47.42	39.81	42.22
ss-CPCM2	1:2	56.30	62.40	38.60	56.61
ss-CPCM3	2:3	56.69	74.35	38.80	66.36
ss-CPCM4	1:1	56.67	91.80	38.91	81.80
PEG	1:0	58.27	183.42	39.04	166.81
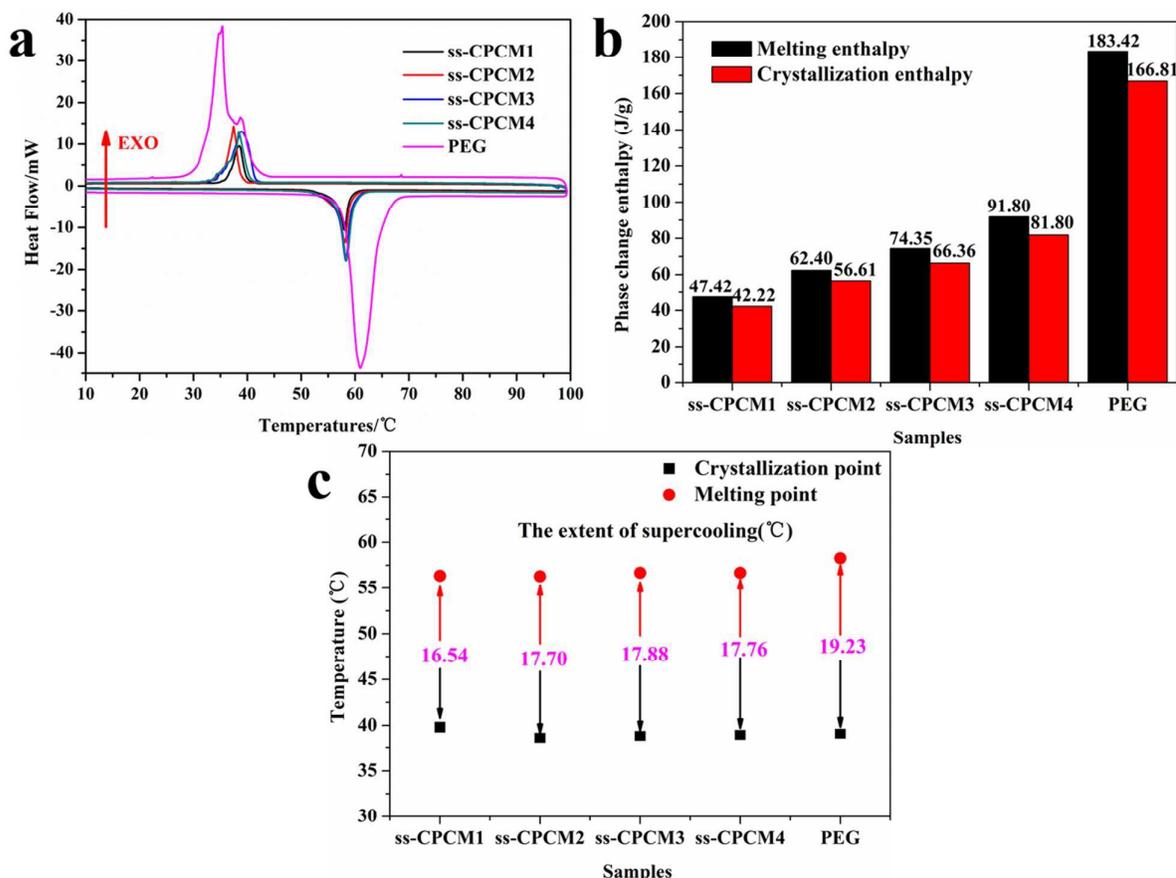
Fig. 11. DSC curves (a), comparison of the melting and crystallization enthalpies (b) and the phase change temperatures (c) of the pristine PEG and ss-CPCMs.

The melting and solidifying latent heats of pristine PEG and prepared ss-CPCMs are shown in the Fig. 11b. The measured melting and solidifying latent heats for PEG were found to be 183.4 J/g and 166.8 J/g, respectively, and for ss-CPCM4, they were 91.80 J/g and 81.80 J/g respectively. This was proportional to the proportion of PEG in ss-CPCM4, as well as with other ss-CPCMs. From Figs. 11a, it is evident that with the increase in PEG content, the area of the heat storage and release peaks increased, which implied that a high PEG content would result in a high latent heat storage capacity. Carbon, being an inert material, the latent heat could be stored or released only by PEG, during the melting and solidifying processes. Hence, a higher content of phase change material resulted in a high latent heat storage capacity. Therefore, ss-CPCM4 proved to be a promising thermal energy storage material, which not only ensured the highest latent heat storage

capacity, which was 91.8 J/g, when the mass ratio of the PEG to porous carbon was 1 : 1, but also prevented the exudation of PEG and could retain its stable shape.

An important parameter to be considered for practical application of phase change materials is supercooling. As shown in Fig. 11c, the extents of supercooling were calculated, based on the differences between melting and solidifying temperatures of pure PEG and the prepared ss-CPCMs, which are presented in Table 3. The supercooling temperatures were 19.23 °C, 16.54 °C, 17.70 °C, 17.88 °C, and 17.76 °C (PEG, ss-CPCM1 to ss-CPCM4), respectively. This result indicated that the degrees of supercooling for the ss-CPCMs were smaller than that of the PEG, which also suggested that the addition of porous carbon could reduce the degree of supercooling of the composites due to the porous nature of the carbon, which acted as a nucleation agent.[38]

Table 4. TGA data of the pristine PEG and the prepared PEG/ porous carbon ss-CPCMs

Samples	Onset (°C)	Peak (°C)	Endpoint (°C)	Residual mass (%)
ss-CPCM1	365.3	385.1	405.1	69.1
ss-CPCM2	367.4	387.3	405.9	60.2
ss-CPCM3	368.8	387.2	406.1	54.1
ss-CPCM4	369.5	390.3	407.0	44.0
PEG	375.5	397.4	412.2	0.1
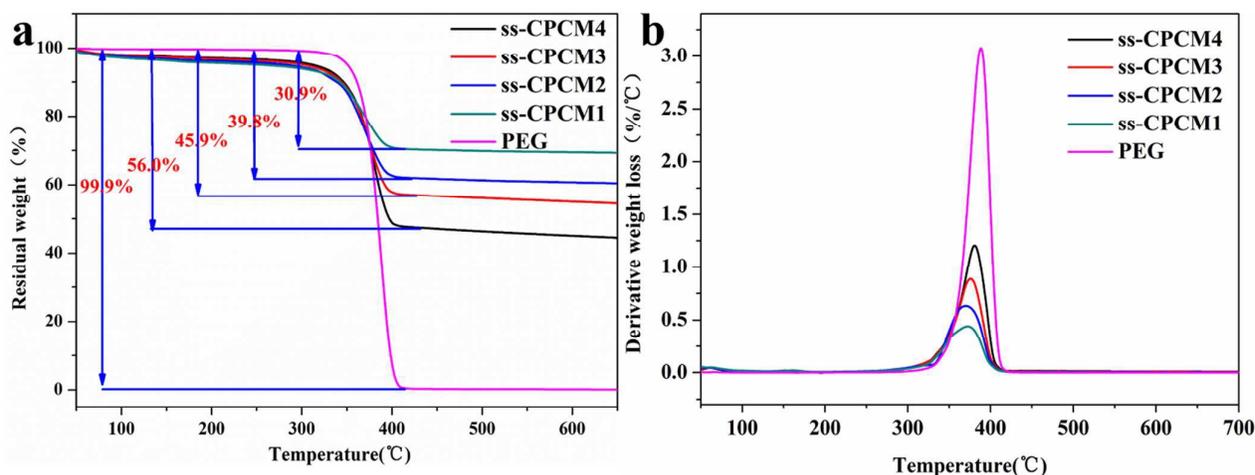
Fig. 12. TGA (a) and DTG (b) curves of pristine PEG and ss-CPCM1 to ss-CPCM4.

Thermal stabilities of the PEG/ porous carbon composites

A crucial parameter of ss-CPCM for its applications is its thermal stability. Thermal stability is a very important property compared to all other properties, since it has a direct influence on the service life and the scope of application of the composites. Fig. 12 present the TGA (a) and DTG (b) curves, respectively, of pure PEG and PCM1 to PCM4. The amount of charred residue at 700 °C and the residual mass at the endpoint temperature are presented in Table 4. From Fig. 12b and Table 4, it is clear that sharply weight loss processes of pure PEG and PEG/ porous carbon composites occurred during 360 °C to 410 °C. Only 0.1 wt% of residue remained behind for PEG, whereas the residual masses of ss-CPCMs were 69.1 wt%, 60.2 wt%, 54.1 wt%, 44.0 wt% for PCM1, PCM2, PCM3, and PCM4, respectively. The proportions of weight loss were all litter larger than that of PEG in corresponding ss-CPCMs. It is probably because some water was absorbed into the ss-CPCMs unavoidably.

It can be seen in Fig. 12, the weight loss occurred twice during the heating process. The first weight loss occurred between 100°C - 200 °C, in which the little weight loss that occurred was ascribed to the removal of water. The second weight loss at around 390 °C was a sharp one due to the degradation of the PEG molecular chains. Therefore, no significant reaction or weight loss occurred between 25 °C and 365 °C, indicating that PEG/ porous carbon ss-CPCM had a good thermal stability below 365 °C.

It is obvious from Fig. 12b and Table 4 that the endpoint temperatures of ss-CPCMs were lower compared to pure PEG, during the process of thermal degradation. The residual masses of ss-CPCMs were all slightly higher than that of pristine PEG. The reason for this is that the molten PEG was absorbed and dispersed in the porous structure of carbon, which could also be seen in the SEM images. Additionally, the porous carbon formed a physical protective barrier around PEG, which confined the transfer of flammable molecules to the gas phase and the transfer of heat from the flame to the condensed phase.[39] Therefore, the thermal stability of the composites was improved due to the addition of porous carbon.

Conclusion：

In summary, shape-stabilized PEG/ porous carbon composites were prepared under super ultrasonic conditions. The composites contained porous carbon, prepared from fresh potato by freezing dry followed by high temperature treatment, which was used as an absorbent and acted as a supporting material. The proportions of PEG used were 25 %, 33 %, 40 %, and 50 % in ss-CPCMs, which were used as phase change materials for thermal energy storage. The structures, morphologies, thermal properties of the ss-CPCMs and the wettability of PEG to porous carbon were fully investigated in this paper. The SEM images, XRD, and FT-IR results proved that PEG was successfully loaded and evenly dispersed in the porous network of carbon without any chemical reaction between them. The prepared ss-CPCMs exhibited excellent shape and exudation stabilities even when the temperature was much higher than the melting point of PEG, and it is due to the well wettability of melting PEG to porous carbon. The results of DSC analysis indicated that when the maximum mass percentage of PEG in the composites was 50 %, the ss-CPCM melted at 56.67 °C with a latent heat of 91.8 J/g and solidified at 38.91°C with a latent heat of 81.80 J/g. The extent of supercooling of ss-CPCM4 was 7.64 % less than that of pristine PEG. Due to the addition of porous carbon, ss-CPCMs had good thermal stabilities at temperatures below 365 °C, as indicated by TGA analysis. In conclusion, the prepared PEG/ porous carbon ss-CPCM can be considered as a promising PCM for application in fields at low temperatures, due to its good shape stability, satisfying latent heat capacity, and excellent thermal stability.

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Acknowledgments

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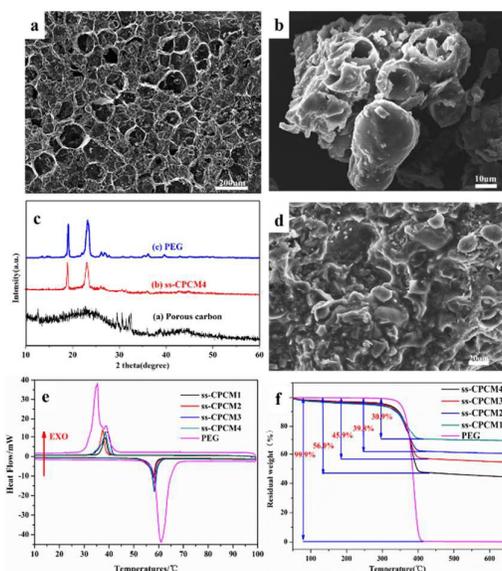
Highlight:

A shape-stabilized composite phase change material comprising PEG and porous carbon was prepared by absorbing PEG into porous carbon.