Enhancement of Thermo-Physical Properties of Expanded Vermiculite-Based Organic Composite Phase Change Materials for Improving the Thermal Energy Storage Efficiency

Shuang Song, Jinhong Li, Zhiwei Yang, and Chengdong Wang

ABSTRACT: In this work, expanded vermiculite (EVM) was modified by acid leaching with different concentrations (0.01, 0.05, and 0.1 mol/L) of HCl solution to obtain three kinds of acid-modified EVM (AEVM-1, AEVM-2, and AEVM-3, respectively). In the composite, polyethylene glycol (PEG) was served as a phase change material (PCM), while EVM and AEVM were served as supporting matrices. Then, graphite was served as an additive to enhance thermal conductivity, and a series of shape-stabilized composite PCMs (PEG/EVM, PEG/AEVM-1, PEG/AEVM-2, PEG/AEVM-3, and PEG-C/AEVM-3 ss-CPCMs) were prepared by physical impregnation. The latent heats of PEG/AEVM-3 and PEG-C/AEVM-3 in the melting process were 154.8 and 144.7 J/g, respectively, which increased by 22.7 and 14.7%, respectively, compared with that of PEG/EVM, indicating that acid modification effectively enhanced the heat storage capacity. The thermal conductivity of PEG-C/AEVM-3 was 0.43 W/mK, which was 65.4 and 48.3% higher than that of PEG and PEG/EVM, respectively. The results of Fourier transform infrared spectroscopy, X-ray diffraction, thermogravimetric analysis, and the thermal cycle test indicated that PEG-C/AEVM-3 reflected favorable chemical stability, thermal stability, and thermal reliability. Therefore, the prepared PEG-C/AEVM-3 with high latent heat and acceptable thermal conductivity was a promising composite PCM in the field of building energy storage.

1. INTRODUCTION

With the rapid growth of the global economy and population, building energy consumption has played an important role in the total energy consumption. According to the research statistics, building energy consumption takes up 38% of the global CO₂ emission and 39% of the global energy consumption. Therefore, the application of new environmentally friendly and energy-saving building materials is the most important way for building energy storage. Thermal energy storage (TES) has become one of the most rational and resultful methods for building energy storage. Latent heat TES (LHTES) is the most promising method in this field due to excellent phase change behavior and high heat storage capacity. Up to now, phase change materials (PCMs) for the LHTES have been widely investigated in building energy storage, such as building insulation walls, phase change cement boards, and solar space cooling and heating applications in buildings.

According to the material properties, the PCMs could be divided into two main categories: inorganic and organic PCMs. Polyethylene glycol (PEG) as a solid–liquid organic PCM, characterized by extensive phase-transition temperatures (30–65 °C), high phase-transition latent heat, a large energy storage density, and excellent phase change cycle reliability, has been widely concerned by researchers. However, it is limited by a number of shortcomings, such as the flowability during the melting process and low thermal conductivity, which would directly affect the safety and stability of the TES system and energy charging/discharging rates. In order to solve the problem of leakage, PEG is impregnated into porous materials to prepare shape-stabilized composite PCMs (ss-CPCMs) by surface tension and capillary forces. Recently, numerous clay mineral-based ss-CPCMs have been extensively reported, including expanded graphite, diatomite, expanded perlite, graphene oxide, and expanded vermiculite (EVM).
EVM has satisfactory physical properties, such as the porous structure, fire resistance, and low density. In view of the above factors, EVM is considered as one of the most economical and suitable supports to prepare ss-CPCMs for building energy storage. When EVM is used to directly encapsulate PEG, the encapsulation ratio of PEG/EVM is not very satisfactory (∼65 wt %), so the thermal storage capacity (<130 J/g) is also limited. The encapsulation material EVM plays crucial roles in offering large TES capacity of PEG/EVM ss-CPCMs. Based on the current reports for the package of PEG, if the encapsulation ratio of PCMs is larger than PEG/EVM, the application of ss-CPCMs would be more widespread. Changing the mineral structure could enhance the adsorption capacity of EVM for PCMs, which is conducive to increase the package ratio, thereby improving TES efficiency. Hence, the encapsulation performance of ss-CPCMs needs to be further enhanced.

In recent years, many organic PCMs have been directly encapsulated by EVM, but modified EVM is used to encapsulate PCMs infrequently. EVM is a layered clay mineral that could exchange cations between layers. Acid leaching is one of the effective means of modification of EVM. Proper concentration of inorganic strong acids could dissolve the tetrahedral cation, octahedral cation, and interlayer cation in the structure of EVM without destroying the pore structure to achieve the purpose of increasing the adsorption capacity of EVM. In this way, the surface energy of EVM and the ability to adsorb the PCMs would be enhanced, thereby improving the encapsulation ratio and heat storage performance of the ss-CPCMs. Therefore, it is necessary to carry out acid modification research on EVM, which has a positive impact on the ss-CPCMs.

In this work, PEG was selected as the PCM due to the broad phase change temperature and higher latent heat. Acid-modified EVM (AEVM) was prepared by acid modification of EVM with three different concentrations of HCl. Then, a series of ss-CPCMs were prepared by means of physical impregnation. Moreover, the sample with the optimal thermal storage performance was selected to add suitable graphite to enhance thermal conductivity. Therefore, a novel ss-CPCM with good thermal storage performance, excellent thermal stability, and acceptable thermal conductivity was further prepared. This ss-CPCM was expected to become a potential high-performance material in the field of building energy efficiency.

### 2. RESULTS AND DISCUSSION

#### 2.1. Composition Analysis of AEVM

Table 1 displays the cation content in the leaching solution obtained by treating EVM with different concentrations of HCl solution.

| HCl/(mol/L) | Si⁴⁺/mg | Al³⁺/mg | Fe³⁺/mg | Mg²⁺/mg | Ca²⁺/mg | Na⁺/mg |
|------------|---------|---------|---------|---------|---------|---------|
| 0.01       | 16.486  | 0.0215  | 0.0017  | 4.5450  | 60.634  | 3.3128  |
| 0.05       | 38.771  | 5.8005  | 1.8026  | 28.751  | 195.02  | 4.6263  |
| 0.1        | 73.671  | 37.330  | 11.018  | 70.585  | 279.80  | 4.7954  |

Figure 1. Photographs of EVM, PE, PAE, and PAEC.

Table 1. Cation Content in the Leaching Solution Obtained by Treating EVM with Different Concentrations of HCl Solution
extent, acid modification could improve the layer charge of EVM and enhanced the adsorption capacity of EVM, which was beneficial for encapsulating PEG.

2.2. Shape Stability of ss-CPCMs. The pictures of ss-CPCMs after the thermal stability test are displayed in Figure 1. As shown in Figure 1, EVM or AEVM exhibited no obvious change after impregnation. It could be seen that all the ss-CPCMs could maintain their form even when the temperature was higher than the melting point of PEG, and there was no obvious leakage trace on the filter paper. Thus, all the ss-CPCMs demonstrated excellent shape stability. The form stabilization of ss-CPCMs owing to the special porous structure of EVM, which could adequately adsorb the melting PEG to keep it from leakage when suffering the endothermic process, was attributed to the impact of surface tension and capillary forces. Furthermore, the encapsulation ratios of ss-CPCMs could be calculated according to eq 1

\[ \eta = \frac{(M - M_0)}{M} \]

where \( \eta \) stands for the mass fraction of PEG, \( M \) represents the final weight of the ss-CPCMs, and \( M_0 \) is the weight of EVM or AEVM before encapsulation.

It could be seen from Table 2 that the encapsulation ratio of PEG/EVM(PE) was 66.4 wt %. The encapsulation ratios of PEG/AEV1(PAE-1), PEG/AEV2(PAE-2), and PEG/AEV3(PAE-3) were 71.8, 73.8, and 75.4 wt %, respectively, which were respectively 5.4, 7.4, and 9.0% higher than that of EVM. The reason for the increase in the encapsulation ratio of AEVM compared with that of EVM was that acid modification increased the surface charge and interlayer charge of EVM, thereby improving the adsorption capacity and package capability of AEVM. Moreover, the increase in the encapsulation ratio was proportional to the concentration of HCl solution. With the increase of HCl concentration, the encapsulation ratio was proportional to the concentration of PEG. The reason for the increase in the encapsulation ratio of AEVM was that the increase in the concentration of the HCl solution was matched with the increase in the adsorption capacity of AEVM, thereby improving the adsorption capacity and package capability of AEVM. Moreover, the increase in the encapsulation ratio was proportional to the concentration of the HCl solution. With the increase of HCl concentration, the adsorption capacity of AEVM was enhanced. The encapsulation ratio of PEG-C/AEVM(PE) declined slightly owing to the addition of graphite, but it still attained 73.8 wt %. Therefore, acid modification had a positive influence on enhancing the heat storage capacity.

2.3. Pore Size Distribution of EVM and AEVM. The mercury intrusion meter was employed to measure the pore diameter and porosity of EVM and AEVM. Figure 2 demonstrates the pore size distribution and pore volume of EVM and AEVM, and the corresponding pore parameters are listed in Table 3, in which it could be seen that AEVM owned higher porosity and a larger pore diameter than EVM. The total porosity of EVM was 77.90%, and the porosity of AEVM increased to 83.85, 87.80, and 90.59% with the increase in acid concentration. It could also observed that the pore size distribution range was approximately 0.01–100 μm, and the most likely pore distribution was approximately 1–10 μm. The distribution was bimodal with two peaks at the pore diameters of 1–3 and 4–6 μm. The uppermost peaks of AEVM moved right compared to the highest peak of EVM, and the second topmost peaks of samples moved up slowly with the augment in acid leaching concentration, which showed that the most possible pore size became larger and the porosity became higher owing to the increase of acid concentration. Therefore, the pores of AEVM provided a larger package volume for PEG than the pores of EVM, which was useful to improve the TES capability of ss-CPCMs.

2.4. TES Performance of ss-CPCMs. The latent heat and the melting temperature are important properties for PCMs to be used in building energy storage. The differential scanning calorimetry (DSC) curves of PEG and the composite PCMs during the endothermic and exothermic processes are displayed in Figure 3, and the phase change parameters determined by DSC are summarized in Table 4. As shown in Figure 3 and Table 4, the DSC curves of PEG, PE, PAE, and PAEC involved an exothermic peak and endothermic peak, which demonstrated similar TES behavior. However, the DSC curves of PE, PAE, and PAEC were obviously moved to the lower-temperature direction compared to PEG. Therefore, EVM and AEVM had a significant effect on the phase-transition behavior of PEG. As seen from Table 4, the melting and solidification temperatures were respectively 64.2 and 36.2 °C for PEG, 60.4 and 30.5 °C for PE, 58.7 and 29.8 °C for PAE, 58.9 and 29.6 °C for PAE-2, and 60.1 and 29.2 °C for PAE-3. The weak attractive interactions between PEG molecules and the inner surface wall of the porous supporting matrixes led to the decrease of the phase change temperature.36 Moreover, according to the heterogeneous nucleation theory, EVM possessed a large specific surface area, which could provide more nucleation sites for the crystallization of

![Figure 2. Distribution of pore diameter in EVM and AEVM.](image)

Table 3. Pore Parameters of EVM and AEVM Obtained by Mercury Porosimetry

| samples     | average pore diameter (μm) | median pore diameter (μm) | specific pore volume (mL/g) | specific surface area (m²/g) | porosity (%) |
|-------------|---------------------------|--------------------------|-----------------------------|------------------------------|--------------|
| EVM         | 0.80                      | 1.77                     | 3.45                        | 17.22                        | 77.90        |
| AEVM-1      | 1.34                      | 2.90                     | 3.54                        | 10.55                        | 83.85        |
| AEVM-2      | 1.43                      | 3.33                     | 3.45                        | 9.66                         | 87.80        |
| AEVM-3      | 1.57                      | 3.20                     | 4.46                        | 11.36                        | 90.59        |
PEG, thereby accelerating the crystallization of PEG. It also limited the migration and diffusion of PEG molecular chains and led to the smaller grain size of PEG, which would decrease the phase change temperature. Compared with PE, the latent heats of PAE-1, PAE-2, and PAE-3 in the melting process were increasing 11.7, 12.8, and 22.7%, respectively, and in the solidification process, they were increasing 13.6, 15.2, and 20.0%, respectively, which were attributed to the fact that acid leaching increased the charge of EVM and enhanced its adsorption capacity, thus improving the encapsulation ratio and latent heat of PAE. However, the slight decline in the latent heat of PAEC was mainly due to the fact that graphite in the layers of AEVM occupied some layer space and resulted in reducing the absorbed amount of PEG, whereas the added graphite could improve the thermal conductivity. Therefore, PAEC had the optimal phase change behavior. In this study, the prepared PAEC was chosen to be the most suitable ss-CPCM for improving the TES efficiency.

### Table 4. Phase Change Parameters of PEG, PE, PAE, and PAEC ss-CPCMs

| samples | $T_M$ (°C) | $H_M$ (J/g) | $T_s$ (°C) | $H_s$ (J/g) |
|---------|-----------|-------------|-----------|-------------|
| PEG     | 64.2      | 199.9       | 36.2      | 175.0       |
| PE      | 60.4      | 126.2       | 30.5      | 113.5       |
| PAE-1   | 58.7      | 141.0       | 29.8      | 128.9       |
| PAE-2   | 58.9      | 142.4       | 29.6      | 130.8       |
| PAE-3   | 60.1      | 154.8       | 29.2      | 136.2       |
| PAEC    | 60.3      | 144.7       | 30.5      | 132.8       |

### 2.5. Crystallinity Characterization of ss-CPCMs

The X-ray diffraction (XRD) patterns of EVM, AEVM-3, PEG, C, and PAEC are shown in Figure 4. The pure PEG owned two strong diffraction peaks at 2$\theta$ = 19.1 and 23.3°. The typical diffraction peak of pure graphite was observed at 2$\theta$ = 26.4°. In the pattern of EVM, three major diffraction peaks at 2$\theta$ = 9.3, 27.8, and 28.7° were attributed to the feature peak of phlogopite. The characteristic peaks of AEVM-3 were consistent with EVM. Therefore, acid modification had a positive impact on the pore structure of EVM and did not change its characteristic diffraction peaks. It was showed that the diffraction peaks of PEG and AEVM-3 were observed in the XRD pattern of PAEC, demonstrating that PEG was successfully packaged into the pores of AEVM-3 and maintained a good crystal structure.

Because the addition of graphite in PAEC was very low, its typical reflection was not obvious. Moreover, no new characteristic peak appeared, indicating that there was no chemical reaction between PEG and AEVM-3. Thus, the prepared PAEC had good chemical stability.

### 2.6. Chemical Compatibility of ss-CPCMs

The Fourier transform infrared (FT-IR) spectra of EVM, AEVM-3, PEG, C, and PAEC are shown in Figure 5. In the FT-IR spectra of EVM, the absorption peaks at 449 and 1002 cm$^{-1}$ corresponded to the Si–O–Mg bending vibration and Si–O–Si and Si–O–Al stretching vibrations, respectively. The absorption peaks of AEVM-3 were consistent with EVM. In the FT-IR spectrum of PEG, the absorption peaks at 831, 960, and 2877, 1111 and 1237, and 1273, 1344, and 1465 cm$^{-1}$ were assigned to the $\text{CH}_2$– vibration, C–H stretching vibration, C–O stretching vibration, and C–H bending vibration, respectively. It could be seen that no characteristic absorption peak appeared in the infrared spectrum of graphite. All the main characteristic absorption peaks of AEVM-3 and PEG could be clearly seen in the FT-IR spectrum of PAEC. Furthermore, new functional groups were not generated for no other characteristic peaks, which indicated...
that the interaction among graphite, AEVM-3, and PEG was a physical effect rather than chemical reaction, demonstrating that PAEC possessed good chemical compatibility.

2.7. Morphologies of ss-CPCMs. Figure 6 displays the scanning electron microscopy (SEM) pictures of EVM, PE, AEVM-3, PAE-3, and PAEC. It could be seen from Figure 6a that EVM displayed a typical non-uniform lamellar pore structure and the pore diameter ranged from several hundred nanometers to several microns. After modification with HCl, the numerous lamellae of AEVM-3 were delaminated to form a highly porous microstructure (Figure 6c). Thus, it also showed that the pore diameter of AEVM-3 became larger than that of EVM, which was attributed to a large amount of cations dissolved from the tetrahedron, octahedron, and interlayer of EVM. It was consistent with the results of the mercury intrusion test. With strong surface tension and capillary forces, both EVM and AEVM-3 possessed high absorption capability. As shown in Figure 6b,d, the pores of EVM and AEVM-3 were almost completely filled with PEG after impregnation, indicating that PEG was successfully encapsulated in pores and on surfaces of EVM and AEVM-3. In Figure 6e,f, graphite wrapped tightly by PEG was evenly dispersed in the pores and surfaces of AEVM-3. Graphite was helpful for improving the thermal conductivity of PAEC. Furthermore, graphite could absorb a large amount of PEG, which might be related to its large specific surface area. Therefore, both graphite and AEVM-3 could prevent the leakage of PEG. These morphologies showed the morphological stability of the ss-CPCMs, further illustrating that physical impregnation was a very effective method.

2.8. Thermal Stability Analysis of ss-CPCMs. The thermal stability of ss-CPCMs is usually evaluated by thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG). The TGA and DTG curves of PEG, PE, PAE-3, and PAEC are shown in Figure 7. PEG was almost decomposed completely within the test temperature range (<650°C), and its mass loss ratio reached 99.75 wt %. PEG, PE, PAE-3 and PAEC exhibited similar thermal stability characteristics, and only showed a thermal weight loss platform (Figure 7a). The onset decomposition temperature range was 160–220 °C, and the final decomposition temperature range was 450–500 °C. The temperature range of the maximum mass loss rate was about 400–405 °C (Figure 7b). Moreover, the onset decomposition temperatures of PE, PAE-3, and PAEC were delayed compared with that of PEG. The mass loss ratios of PE, PAE-3, and PAEC were 65.71, 77.60, and 70.04 wt %, respectively, mainly from the thermal decomposition of PEG, which was almost consistent with the results of the package ratios in Table 2, further indicating that PEG was evenly dispersed in the pore structure of EVM and AEVM-3. In addition, the phase change temperature of PAEC was lower than 65 °C, and the application temperature range was usually lower than 100 °C, which was lower than the mass loss start temperature, and there was almost no mass loss in the application temperature range. Therefore, the prepared PAEC possessed excellent heat storage performance and great thermal stability.
2.9. Thermal Conductivity of ss-CPCMs. Thermal conductivity is an important parameter to characterize the heat-transfer efficiency of composite PCMs, and it determined the rate of heat storage and release. Figure 8 displays the thermal conductivity of PEG, PE, and PAEC at 25 °C. The specific heat capacity and thermal diffusivity were tested using a laser thermal conductivity meter, and the thermal conductivity was calculated according to eq 2

\[ \lambda = \alpha \cdot C_p \cdot \rho \] (2)

where \( \lambda \) is the thermal conductivity, \( \alpha \) represents the thermal diffusivity, \( C_p \) denotes the specific heat capacity, and \( \rho \) stands for the density.

The results show that the thermal conductivities of PEG, PE, and PAEC were 0.26, 0.29, and 0.43 W/mK, respectively. Compared with PEG and PE, the thermal conductivity of PAEC increased by 65.4 and 48.3%, respectively, indicating that graphite had improved thermal conductivity, which was mainly owing to the high thermal conductivity and effective dispersion of graphite. The addition of graphite reduced the scattering degree of phonons in the interface area and increased the electron propagation path, thereby effectively reducing the thermal resistance and strengthening the uniform heat-transfer effect of PAEC. Therefore, graphite effectively enhanced the thermal conductivity of PEG.

2.10. Thermal Reliability Analysis of ss-CPCMs. Outstanding thermal reliability and excellent chemical stability are the prerequisites for the application of ss-CPCMs. Figure 9 represents the DSC curves and FT-IR spectra before and after 100 cycles. It could be seen from Figure 9a that the DSC curves before and after the cycle are almost consistent. The latent heat of phase change during the melting process before and after the cycle was 144.2 and 140.6 J/g (Table 5), respectively, and the loss ratio of latent heat was only 2.5%, which indicated that PAEC owned outstanding thermal reliability. The FT-IR spectra of PAEC before and after the cycle are shown in Figure 9b. It could be seen that the spectrograms before and after the cycle are almost the same, and no new absorption peak appeared, which revealed that PAEC possessed excellent chemical stability before and after the cycle and further demonstrated the advantages of PAEC in the application of building energy storage.

| samples           | melting process | solidification process |
|-------------------|-----------------|------------------------|
|                  | \( T_m \) (°C) | \( H_m \) (J/g) | \( T_s \) (°C) | \( H_s \) (J/g) |
| PAEC (before cycles) | 66.3          | 144.2          | 33.0          | 134.2          |
| PAEC (after cycles)  | 65.9          | 140.6          | 33.6          | 128.4          |

3. CONCLUSIONS

In this study, a novel PAEC ss-CPCM applied in the field of building energy storage was successfully prepared. The original EVM was modified by three different concentrations of HCl solution to obtain the acid-modified matrix with the largest porosity and encapsulation ratio. Then, graphite enhanced thermal conductivity to obtain PAEC with the excellent thermal storage performance and enhanced thermal conductivity by physical impregnation. Compared with PE, the increase in the package ratio of PAE and PAEC was ascribed to the increased adsorption capacity of acid modification. The latent heats in the melting process of PAE-3 and PAEC were 154.8 and 144.7 J/g, which were 22.7 and 14.7% higher than...
that of PE, respectively. The thermal conductivity of PAEC was 0.43 W/mK, which was 65.4 and 48.3% higher than those of PEG and PE, respectively. The results of FT-IR, XRD, TGA, and the thermal cycle test indicated that the prepared PAEC owned great chemical compatibility, thermal stability, and thermal reliability. In conclusion, the prepared PAEC exhibited high latent heat and acceptable thermal conductivity, great chemical stability, thermal stability, and thermal reliability, which was a promising composite PCM in the field of building energy storage.

4. EXPERIMENTAL SECTION

4.1. Materials. PEG (Mw = 4000) and hydrochloric acid (HCl, AR) were obtained from China National Medicines Co., Ltd., China. Graphite (C.P.) was supplied by Sinopharm Chemical Reagent Co., Ltd. EVM was purchased from Lingshou County, Hebei Province, China. The average pore diameter and specific surface area of EVM were measured to be 800.7 nm and 7.494 m²/g, respectively.

4.2. Preparation of AEVM. The acid modification procedure of EVM is displayed in Figure 10a. EVM was modified by leaching in HCl solution of different concentrations (0.01, 0.05, and 0.1 mol/L). The leaching process included putting 5 g of EVM into 100 mL of HCl solution of a certain concentration, with stirring for 2 h at 70 °C in a water bath. Then, EVM was immediately filtered and washed with distilled water to pH > 6. Finally, it was dried in an oven for 12 h to obtain AEVM. The prepared samples were named AEVM-1, AEVM-2, and AEVM-3, respectively.

4.3. Preparation of ss-CPCMs. The preparation process of PEG/EVM, PEG/AEVM-1, PEG/AEVM-2, PEG/AEVM-3, and PEG-C/AEVM-3 ss-CPCMs is shown in Figure 10b. The ss-CPCMs were prepared by means of physical impregnation. First, EVM and AEVM and PEG were put into an enclosed beaker. Then, the beaker was heated in a water bath at 70 °C so that the melting PEG could be fully absorbed into the pores of EVM and AEVM. After the impregnation, the ss-CPCMs were taken from the liquid PEG. Then, the ss-CPCMs were put in an oven at 70 °C to remove the excess PEG on the surface of ss-CPCMs. The filter paper was continuously replaced until the leakage trace was not observed. Finally, the mass of the final ss-CPCMs was recorded. The prepared samples were named PE, PAE-1, PAE-2, and PAE-3. According to the mercury intrusion test, AEVM with the largest porosity was selected as the matrix of ss-CPCMs, which also had the largest package ratio and latent heat after encapsulating PEG. Thus, the ss-CPCMs were chosen to add graphite to enhance thermal conductivity. Graphite and PEG (1:49) were mixed in a beaker, with heating and stirring in a water bath at 70 °C for 4 h. AEVM was put into the mixture, and the temperature was kept above the melting point of PEG at 70 °C for 2 h. The filter paper was replaced in succession until no leakage trace was noticed. The sample was obtained and denoted as PAEC.

4.4. Characterization. An inductively coupled plasma emission spectrometer (Agilent ICPES730) was used to detect the cation content of the AEVM leaching solution. SEM (ZEISS SUPRA55) was applied to observe the morphologies of EVM, AEVM, and the ss-CPCMs. FT-IR (Nicolet iS10, wavenumber: 4000–400 cm⁻¹) examined the chemical compatibility of ss-CPCMs. XRD (Bruker D8 Advance, Cu Kα radiation, 2θ: 3–90°, scanning rate: 6°/min) patterns were employed to investigate the crystal phases of PEG, AEVM, C, and PAEC ss-CPCMs. The distribution of pore diameter and porosity of EVM and AEVM were analyzed using a mercury intrusion meter (Micromeritics, AutoPore IV 9500). TES properties of PEG and the ss-CPCMs were determined by using DSC (NETZSCH Q20, heating and cooling rate: 5 °C/min, atmosphere: N₂). Each sample of PEG and ss-CPCMs was measured three times to use the average value as the result. Thermal stability of PEG and ss-CPCMs was tested by using TGA and DTG (Q5000, TA, USA, test range: 30–650 °C, heating rate: 10 °C/min, atmosphere: N₂). The thermal conductivity of samples was determined by using a laser thermal conductivity tester (LFA-427, NETZSCH, Germany) at 25 °C. Each sample was tested three times under the same conditions, and the mean value was demonstrated in here. The thermal reliability of ss-CPCMs was tested by DSC and FT-IR after 100 cycles.

■ AUTHOR INFORMATION

Corresponding Author

Jinhong Li — 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
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c05739

Notes
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