Characteristic and Properties of Ternary Shape-Stabilized Composite Phase Change Materials Based on Expanded Graphite

Hua Fei,* Jiahong Zhou, Qian He, Linya Wang, Ximei Liang, and Yucheng Pan

ABSTRACT: Myristic acid-palmitic acid-tetradecanol/expanded graphite (MA-PA-TD/EG) and myristic acid-stearic acid-lauric acid/expanded graphite (MA-SA-LA/EG) were obtained. MA-PA-TD/EG and MA-SA-LA/EG for the optimum mass ratio of 8:1 were investigated by DSC, FT-IR, TG, and SEM, and it was shown that MA-PA-TD and MA-SA-LA phase change materials were evenly distributed in expanded graphite through capillary force. Phase transition temperatures of MA-PA-TD/EG and MA-SA-LA/EG before and after cooling and heating cycles were 34.14, 34.39 °C and 30.21, 30.33 °C, respectively, and MA-PA-TD/EG and MA-SA-LA/EG had good stability. On the other hand, MA-PA-TD/EG was 67% faster than that of MA-PA-TD during solid−liquid phase change, and MA-SA-LA/EG was 63% faster than that of MA-SA-LA. Meanwhile, MA-PA-TD/EG and MA-SA-LA/EG had good thermal stability and heat storage according to thermogravimetric experiments. Therefore, MA-PA-TD/EG and MA-SA-LA/EG are suitable for practical application in buildings.

1. INTRODUCTION

Latent heat storage technology can store solar energy, geothermal energy, and other energies and use the temperature difference to absorb or release latent heat through phase change of phase change materials (PCMs), so as to realize heat energy storage.1−3 Fatty acid alcohols have good stability and are non-toxic and corrosion-free,4−7 but they are prone to liquid leakage and have low thermal conductivity. It can be improved by a physical adsorption method to combine liquid organic phase change materials with inorganic porous media. Expanded graphite is a kind of vermicular material with high thermal conductivity,8−11 and it has a wide range of sources and low prices. The composite of expanded graphite and a phase change material can improve its thermal conductivity and adsorption capacity and prevent leakage.12−14 Also, recent studies showed that relatively cheap additives (such as carbon black) can significantly improve the thermal conductivity of PCMs.15−18 The preparation of composite phase transition material is mainly microcapsules, physical adsorption, heating co-melting, etc. The preparation process of a microcapsule method is complex with poor thermal conductivity, and the heating co-melting method is only applicable for materials with a large melting point gap, while the physical adsorption preparation process is simple and has low cost, which overcomes the defects such as liquid phase leakage and poor thermal conductivity of PCMs.19

At present, many kinds of PCMs are used in energy-saving buildings. Relevant research has confirmed that ternary PCMs have similar thermal and physical properties to binary phase change materials and have certain application potential in engineering practice.20−22 Fatty acids and alcohols are prospective PCMs.23 Nevertheless, single fatty acid has high phase transition temperature,24 and single fatty alcohol will undergo crystallization transformation duringsolidification,
resulting in the formation of multiple freezing points. Fatty acids and alcohols can help prepare binary or multicomponent eutectic composite phase change materials (CPCMs) to contents required by applications. Huang et al. studied capric-palmitic-stearic acid/EG (CA-PA-SA/EG) ternary CPCM, and the latent heat and phase transition temperature were 37.38 J/g and 128.93 °C, respectively. Zhang et al. studied capric-palmitic-stearic acid/EG (CA-PA-SA/EG) ternary CPCM, and the latent heat and phase transition temperature were 131.7 J/g and 21.33 °C, respectively. Liu et al. prepared lauric-myristic-stearic acid/EG (LA-MA-SA/EG) CPCM, and the latent heat and phase transition temperature were 137.1 J/g and 29.05 °C, respectively. Li et al. studied decanoic-lauric-stearic acid/EG (DA-LA-SA/EG) ternary CPCM, and the latent heat and phase transition temperature were 123 J/g and 38.6 °C, respectively. Zhong prepared lauric-myristic-palmitic acid/EG (LA-MA-PA/EG) ternary CPCM, and the latent heat and phase transition temperature were 153.5 J/g and 30.79 °C, respectively. In addition, there are a few studies on the compound of fatty acids and fatty alcohols. Therefore, it is of great significance to further study whether PCMs are suitable for the requirements of different fields such as solar energy utilization and building energy conservation.

In this paper, two kinds of ternary shape-stabilized CPCMs were obtained by using expanded graphite as adsorption materials. The best mass ratio, phase transformation performance, and thermal stability were investigated by FT-IR, SEM, DSC, TG, and other experiments.

2. RESULTS AND DISCUSSION

2.1. Step Cooling Curves of MA-PA-TD and MA-SA-LA. Figure 1 shows the step cooling curves of MA-PA-TD and MA-SA-LA CPCM. It can be seen that the temperature of the "horizontal platform" is the lowest when the mass ratio of MA-PA:TD is 54:46. The mass fractions of TD are 45, 46, and 47%, and the crystallization temperatures are 28.8, 28.6, and 28.9 °C. The T-X phase diagram for MA-PA-TD and MA-SA-LA ternary eutectic mixtures is shown in Figure 2. The eutectic temperature of MA-PA-TD reduces with the rise in TD content. The eutectic temperature reaches the lowest value when the content of TD is 46%, and then increases. Therefore, the minimum eutectic temperature of MA-PA-TD (MA-PA:TD) is 28.6 °C, and the optimum mass ratio is 54:46. The mass fractions of LA are 62, 63, and 64%, and the crystallization temperatures of MA-SA-LA are 29.3, 29.0, and 29.4 °C. It is observed from Figure 2 that as the mass fraction of MA-SA increases, the eutectic temperature of MA-SA-LA decreased gradually. The eutectic temperature reaches the lowest value when the content of MA-SA is 37% and then increases. The minimum eutectic temperature of MA-SA-LA (MA-SA:LA) is 29.0 °C. Therefore, the optimum mass ratio is 37:63, and the phase transition temperature is 29.0 °C.

2.2. FT-IR Characteristics of MA-PA-TD and MA-SA-LA. The FT-IR curves of TD, LA, MA-SA, MA-PA, MA-PA-TD, and MA-SA-LA CPCM are displayed in Figure 3. As shown in Figure 3, feature absorption peaks of MA-PA grow at 718, 939, 1285, 1426, 1694, 2843, and 2911 cm⁻¹. The infrared spectra of TD show that the main feature peaks are at 2848, 2921, and 3430 cm⁻¹, which are the symmetrical and antisymmetric stretching vibration absorbed peaks of −CH₂ and the stretching vibration of −OH, respectively. The stretching vibration of C−O, the symmetrical bending vibration of −CH₃, and the stretching vibration of C==O occurred at 1056, 1465, and 1639 cm⁻¹, respectively. The feature absorption peaks of MA-PA-TD occurred at 715, 1057, 1282, 1468, 1697, 2842, and 2908 cm⁻¹. There are only feature absorption peaks of MA-PA and TD and no new feature absorption peaks appeared, indicating that there is no chemical reaction in MA-PA-TD PCMs. In Figure 3, the feature absorption peaks of MA-SA occurred at 2910, 2843, 1694 cm⁻¹, the medium intensity feature peaks were at 1470 and 1295 cm⁻¹, and the weak sharp feature absorbed peaks were at 942 and 718 cm⁻¹. MA-SA-LA produced feature peaks at 2909, 2844, 1692, 1428,
1300, 930, and 719 cm\(^{-1}\), respectively, and there is no new feature peak, indicating that no chemical reaction occurred during the melting process.

### 2.3. Optimal Mass Ratio of MA-PA-TD/EG and MA-SA-LA/EG

MA-PA-TD/EG CPCMs with ratios of MA-PA-SA to EG of 5:1, 10:1, 15:1, and 20:1 and MA-SA-LA/EG CPCMs with ratios of MA-SA-LA to EG of 5:1, 10:1, 15:1, 20:1, and 25:1 were prepared. The samples were weighed 0.200 g on qualitative filter paper and labeled A\(_1\)–A\(_8\) and B\(_1\)–B\(_9\), respectively. The samples were dried in a constant temperature drying oven with a set temperature of 70 °C for 1.5 h and then taken out. After 20 min of stabilization, the leakage of PCMs on the qualitative filter paper was observed, and the quality before and after drying was weighed for comparison. There was no obvious phase change material on A\(_1\) filter paper, the mass loss rate was 0.5%, and the content of MA-PA-TD was not enough to dominate the adsorption of EG. The mass loss rates of A\(_2\)–A\(_8\) were 2, 5.5, and 6%, respectively, the mass loss rates were all higher than 1.5%, and there was obvious leakage of PCM, which exceeded the adsorbed capacity of EG. There was no obvious phase change material on B\(_1\) filter paper, and the mass loss rate was 0.5%. The mass loss rates of B\(_2\)–B\(_8\) were 1.5, 2, 5, and 7.5%, respectively, which were higher than 1.5%, and there was obvious phase change material leakage on the qualitative filter paper. Thus, 0.200 g of MA-PA-TD/EG CPCMs with ratios of 6:1, 7:1, 8:1, and 9:1 was prepared, and 0.200 g of MA-SA-LA/EG CPCMs with ratios of 6:1, 7:1, 8:1, and 9:1 was prepared. On the filter paper of samples A\(_1\)–A\(_8\) of MA-PA-TD/EG and B\(_1\)–B\(_9\) of MA-SA-LA/EG, the mass loss rates of A\(_2\)–A\(_8\) were 0.5, 1.0, 1.0, and 1.5%, respectively, while the mass loss rates of B\(_2\)–B\(_8\) were 0.5, 1.0, 1.0, and 1.5%, respectively. As a result of the latent heat of phase transition being proportional to the phase transition temperature, the quality loss ratios for A\(_1\)–A\(_8\), A\(_9\), B\(_1\)–B\(_9\), and B\(_9\) are 1%, the optimal quality ratios for MA-PA-TD, MA-SA-LA, and EG are 8:1, and the specific experimental results are shown in Table 1.

### 2.4. DSC Characteristics of MA-PA-TD/EG and MA-SA-LA/EG

Figure 4 shows the DSC curves of MA-PA-TD, MA-PA-TD/EG, MA-SA-LA, and MA-SA-LA/EG CPCMs. In Figure 4, the latent heat of phase transition temperature of MA-PA-TD and MA-PA-TD/EG are 29.64, 28.17 and 34.14, 38.86 °C, and the melting–solidification latent heats are 162.0, 168.4 and 65.6, 154.8 J/g, respectively. The melting–solidification temperatures of MA-SA-LA and MA-SA-LA/EG are 28.81, 27.44 and 30.21, 30.96 °C, and the melting–solidification latent heats are 143.3, 143.9 and 129.8, 124.9 J/g, respectively. The difference of melting–solidification temperature between MA-PA-TD/EG and MA-PA-TD is 4.5 and 10.69 °C respectively. The differences of melting–solidification temperature between MA-SA-LA/EG and MA-SA-LA are 1.4 and 3.52 °C, respectively. This may be due to the temperature change caused by the force in the pores of EG during melting and solidification. The latent heat of MA-PA-TD/EG is proportional to the content of MA-PA-TD, and the latent heat of MA-SA-LA/EG is smaller than that of MA-SA-LA because there is no phase transition for EG. The result shows that the theoretical latent heat value of MA-PA-TD/EG is more than the measured value, which may be due to the abnormal interaction between PCMs, measurement errors, and the weak adsorption of EG on PCMs during the coating and solidification of CPCMs, resulting in the loss of some phase change materials.

### 2.5. Characteristics of MA-PA-TD/EG and MA-SA-LA/EG Heat Storage and Release

Figure 5 shows the melting and solidification curves of MA-PA-TD, MA-PA-TD/EG, MA-SA-LA, and MA-SA-LA/EG CPCMs. It takes 3647 s for MA-PA-TD/EG to rise from 5 to 44.5 °C, and the time for MA-PA-TD is 1309 s longer than that for MA-PA-TD/EG. It takes 3340 s for MA-SA-LA/EG to rise from 5 to 44.5 °C, and the time of MA-SA-LA is 1361 s longer than that of MA-SA-LA/EG. MA-PA-TD takes 1590 s for the endothermic process, while MA-PA-TD/EG only takes 531 s, which is 67% shorter than that of MA-PA-TD. MA-SA-LA takes 2481 s, while MA-SA-LA/EG only takes 926 s, which is 63% shorter than MA-SA-LA. The times required for MA-SA-LA and MA-SA-LA/EG are 338 and 80 s, and the time consumed by MA-SA-LA/EG decreased by 76%. Due to the high thermal conductivity of EG, the heat storage and release rates of MA-PA-TD/EG and MA-SA-LA/EG are much higher than those of MA-PA-TD and MA-SA-LA, respectively. MA-PA-TD/EG and MA-SA-LA/EG have excellent properties of heat storage and release.

### 2.6. Thermal Reliability and Stability of MA-PA-TD/EG and MA-SA-LA/EG

It is necessary for composite phase change materials to keep good thermal reliability in the application of building energy saving. 0.5 g of MA-PA-TD/EG and MA-SA-LA/EG CPCMs was weighed and placed in a qualitative filter paper. The samples were dried at 80 °C for 48 h and then taken out. After stabilizing for 20 min, the leakage of PCMs in the qualitative filter paper was observed, and the quality before and after drying was weighed for comparison. The results indicated that the masses of MA-PA-TD/EG and MA-SA-LA/EG after heat treatment were 0.495 and 0.496 g, respectively, which had little change with the mass of the original sample, and there was no obvious leakage on the filter paper. It can be shown that MA-PA-TD/EG and MA-SA-LA/EG CPCMs have superior thermal reliability.

Figure 6 shows the TG curves of MA-PA-TD/EG, MA-SA-LA/EG, and MA-SA-LA/EG. In Figure 6, the weight loss of MA-PA-TD/EG lasts from 150 to 347 °C, and the rate of weight loss is

### Table 1. Mass Change of MA-PA-TD/EG, MA-SA-LA/EG during Heat Treatment

| samples | mass ratio | quality before heat treatment (g) | quality after heat treatment (g) | quality variation (g) | quality loss rate (%) |
|---------|------------|---------------------------------|---------------------------------|----------------------|----------------------|
| A\(_1\) | 5:1        | 0.200                           | 0.199                           | 0.001                | 0.5                  |
| A\(_2\) | 10:1       | 0.200                           | 0.196                           | 0.004                | 2.0                  |
| A\(_3\) | 15:1       | 0.200                           | 0.189                           | 0.011                | 5.5                  |
| A\(_4\) | 20:1       | 0.200                           | 0.188                           | 0.012                | 6.0                  |
| A\(_5\) | 6:1        | 0.200                           | 0.199                           | 0.001                | 0.5                  |
| A\(_6\) | 7:1        | 0.200                           | 0.198                           | 0.001                | 1.0                  |
| A\(_7\) | 8:1        | 0.200                           | 0.198                           | 0.002                | 1.0                  |
| A\(_8\) | 9:1        | 0.200                           | 0.197                           | 0.003                | 1.5                  |
| B\(_1\) | 5:1        | 0.200                           | 0.199                           | 0.001                | 0.5                  |
| B\(_2\) | 10:1       | 0.200                           | 0.197                           | 0.003                | 1.5                  |
| B\(_3\) | 15:1       | 0.200                           | 0.196                           | 0.004                | 2.0                  |
| B\(_4\) | 20:1       | 0.200                           | 0.190                           | 0.010                | 5.0                  |
| B\(_5\) | 25:1       | 0.200                           | 0.185                           | 0.015                | 7.5                  |
| B\(_6\) | 6:1        | 0.200                           | 0.199                           | 0.001                | 0.5                  |
| B\(_7\) | 7:1        | 0.200                           | 0.198                           | 0.002                | 1.0                  |
| B\(_8\) | 8:1        | 0.200                           | 0.198                           | 0.002                | 1.0                  |
| B\(_9\) | 9:1        | 0.200                           | 0.197                           | 0.003                | 1.5                  |
90%. When the temperature is below 80 °C, there is little loss of quality, and when the mass loss is 10%, the temperature is as high as 240 °C. Meanwhile, the weight loss process of MA-SA-LA/EG lasts from 130 °C to 285 °C. When the temperature is below 80 °C, the mass loss is almost zero. When the mass loss is 10%, the temperature is as high as 180 °C. However, there is almost no mass loss of EG during the whole heating process, indicating that MA-PA-TD/EG and MA-SA-LA/EG CPCMs have excellent thermostability at working temperature (<80 °C).

The service life of CPCMs is affected by thermal cycle stability. The DSC curves of MA-PA-TD/EG and MA-SA-LA/EG after thermal cycling are shown in Figure 7. As shown in Figure 7a, the latent heat and phase transition temperature of MA-PA-TD/EG after 300 accelerated cooling and heating cycles are 63.99 J/g and 34.39 °C, respectively. The latent heat and solidification temperature after cycles are 173.1 J/g and 38.85 °C, respectively. Compared with the temperature indicated by DSC of MA-PA-TD/EG, the phase transition temperature of MA-PA-TD/EG rose by 0.25 °C and the latent heat of phase transition reduced by about 1.574 J/g after the thermal cycling. As shown in Figure 7b, the latent heat and phase transition temperature of MA-SA-LA/EG after 300 cycles are 135.1 J/g and 30.33 °C, respectively, and the latent heat and solidification temperature after cycles are 132.6 J/g and 31.16 °C, respectively. The phase transition temperature of MA-SA-LA/EG increases by 0.12 °C, and the latent heat of phase transition increases by about 5.3 J/g, which are within the error range; thus, MA-PA-TD/EG and MA-SA-LA/EG CPCMs have excellent thermostability.

2.7. Structural Analysis of MA-PA-TD/EG and MA-SA-LA/EG. Figure 8 shows the micromorphology of EG, MA-PA-TD/EG, and MA-SA-LA/EG. In Figure 8a, EG has many natural scales, such as flake and flake scales, and is filled with a large number of pores. As shown in Figure 8b,c, MA-PA-TD and MA-SA-LA are adsorbed by EG through physical action, and the pores of EG are uniformly filled by MA-PA-TD and
MA-SA-LA. The MA-PA-TD and MA-SA-LA will not leak out as a result of the fixation of porous material. The surface of the MA-PA-TD/EG and MA-SA-LA/EG material is compact. The MA-PA-TD/EG and MA-SA-LA/EG CPCMs have excellent qualitative effects.

2.8. FT-IR Analysis of MA-PA-TD/EG and MA-SA-LA/EG. Figure 9 shows the FT-IR curves of EG, MA-PA-TD, MA-PA-TD/EG, MA-SA-LA, and MA-SA-LA/EG CPCMs. The FT-IR curve of EG shows a bending vibration peak of $\text{H}_2\text{O}$ at $3443 \text{ cm}^{-1}$, a bending vibration peak of $\text{CH}_2$ adsorbed water at $1630 \text{ cm}^{-1}$, and a stretching vibration peak of C=O at $1044 \text{ cm}^{-1}$, which may be due to the absorption of a small amount of water by EG. The feature adsorption peaks of MA-PA-TD are at 715, 1057, 1282, 1468, 1697, 2842, and $2908 \text{ cm}^{-1}$ for the FT-IR curve of MA-PA-TD, which are the out-of-plane bending feature absorption peak of C-H, the stretching vibration absorption peaks of C-O at 1057 and $1282 \text{ cm}^{-1}$, the symmetrical bending vibration absorption peak of $\text{CH}_3$, the stretching vibration absorption peak of C=O, the symmetrical stretching vibration absorption peak of $\text{CH}_2$, and the asymmetrical stretching vibration absorption peak of $\text{CH}_2$. The FT-IR curves of MA-PA-TD/EG CPCMs show feature absorption peaks at 2922, 2849, 1698, 1466, 1303, 933, and $724 \text{ cm}^{-1}$. In Figure 9b, the FT-IR curves of MA-SA-LA indicate the antisymmetric stretching vibration absorption peak and symmetrical stretching vibration absorption peak of $\text{CH}_2$ at 2909 and $2844 \text{ cm}^{-1}$ and asymmetrical bending vibration absorption peak of $\text{CH}_3$ and stretching vibration absorption peak of C-O at 1692, 1428, and 1300 cm$^{-1}$; the feature absorption peaks at 935 and 719 cm$^{-1}$ are produced by the bending vibration of $\text{OH}$ and the out-of-plane bending vibration of C-H, respectively. The feature absorption peaks of MA-SA-LA/EG composites appear at 2919, 2853, 1706, 1465, 1300, 1060, 933, and $725 \text{ cm}^{-1}$. The results indicate that MA-PA-TD/EG has the feature absorption peaks of MA-PA-TD and EG, while MA-SA-LA/EG has the characteristic
absorption peaks of MA-SA-LA and EG, and no new characteristic absorption peaks arise, which indicates that chemical reactions do not happen between MA-PA-TD, MA-SA-LA, and EG, which is the combination of surface physical tension.

3. CONCLUSIONS

In this work, the melting–solidification temperatures of MA-PA-TD and MA-SA-LA CPCMs were 34.14, 38.86 and 30.21, 30.96 °C, respectively. The phase transition temperatures of MA-PA-TD/EG and MA-SA-LA/EG after thermal cycling were 34.39 and 30.33 °C, respectively. There was no significant change in temperature, indicating that MA-PA-TD/EG and MA-SA-LA/EG CPCMs have good chemical and thermal stability. The thermal stability of materials is a crucial factor for the long-term stable use of PCMs in practical applications. On the other hand, because of the promoting effect of EG with high thermal conductivity, the heat storage and release rates of MA-PA-TD/EG and MA-SA-LA/EG are much faster than those of MA-PA-TD and MA-SA-LA. The consumption time in the liquid–solid process was 74% less than that of MA-PA-TD, and those for MA-SA-LA/EG in solid—liquid and liquid—solid processes were reduced by 63 and 76%, respectively. Moreover, there was almost no mass loss below 80 °C for the thermal stability of MA-PA-TD/EG and MA-SA-LA/EG. MA-PA-TD/EG and MA-SA-LA/EG have good thermal reliability, thermal stability, heat storage, and release performance and have excellent potential and prospect in building energy saving.

4. EXPERIMENTAL SECTION

4.1. Materials. Expanded graphite, MA, PA, TD, SA, and LA were used as raw materials to prepare the expanded graphite CPCMs for energy storage. MA-PA-TD with mass ratios of 4:1, 3:2, 2:3, 1:4, and 1:1 and MA-SA-LA with mass ratios of 4:1, 3:2, 1:1, 2:3, 7:3, and 1:4 were weighed with an electronic balance, put into beaker, recorded with a label paper number, and sealed. The sample was heated to melting in a constant temperature drying oven and stirred with a magnetic stirrer, and the heating temperature was set to 80 °C. The ternary PCMs were put into test tubes and sealed. After sufficient cooling, MA-PA-TD and MA-SA-LA were obtained. The best mass ratio of the ternary eutectic system was obtained by a step cooling curve method, and the lowest eutectic temperature was obtained by a DSC test. Then, a certain quality of EG in a beaker was weighed and placed in a constant temperature drying oven at 80 °C for 24 h. 0.5 g was weighed with an electronic balance, placed in a ceramic dish and evenly dispersed, and then expanded in a microwave oven for 38 s. The liquid ternary eutectic mixtures of MA-PA-TD and MA-SA-LA with different mass ratios were evenly mixed with EG, and then the samples were dried for 24 h to make them fully mixed. The temperature of the drying oven was set at 68 °C, and the ternary eutectic mixture of MA-PA-TD and MA-SA-LA stirred once every 12 h to evenly absorb into the pores of EG and then cooled to room temperature to obtain MA-PA-TD/EG and MA-SA-LA/EG CPCMs. Moreover, Figure 10 is an illustration of the experimental device.

4.2. Characterization of MA-PA-TD/EG and MA-SA-LA/EG. The characterization of MA-PA-TD/EG and MA-SA-LA/EG CPCMs was investigated using a DSC, which was preheated and calibrated. The temperature range was 10–80 °C in a nitrogen flow rate of 50 mL/min, and the cooling rate was 20 °C/min. On the other hand, the thermal resistance of EG, MA-PA-TD/EG, and MA-SA-LA/EG CPCMs was investigated by TG. The thermogravimetric analyzer was preheated and calibrated. The room temperature was raised to 400 °C with a heating rate of 10 °C/min in a nitrogen atmosphere. When the mass change range of the sample loaded in a crucible balance device was almost zero, the instrument was started to investigate the weight loss features of the samples, and the mass change curve for the CPCM was obtained.

The heat storage and exothermic conditions of MA-PA-TD/EG and MA-SA-LA/EG were obtained by heat storage and exothermic experiments. The test tube containing the sample was put in the 75 °C constant temperature water tank to melt. After the sample in the test tube was completely melted, the temperature sensor was put in the test tube and the probe was immersed in the liquid material, ensuring that the probe was located in the middle of the test tube without making contact with the wall of the test tube. After the temperature of the sample was stable, it was put in a constant temperature and humidity incubator for cooling. When the temperature became stable at 5 °C, the sample was taken out and put in a constant temperature drying oven for heating and melting. When the temperature remained stable, the sample was put in the incubator with constant temperature and humidity for cooling connected to a computer to output the temperature change. In order to determine whether the CPCMs with expanded graphite have good thermal cycle stability, the accelerated thermal cycle test was carried out. The experimental step was to put the prepared sample into the test tube, melt it in the constant temperature water tank at 75 °C, then cool it in a constant temperature and humidity incubator for 20 min, and take it out. The above steps were repeated 300 times, and DSC experiments were carried out to compare the thermal properties of thermal cycling.

The microstructures of EG, MA-PA-TD/EG, and MA-SA-LA/EG CPCMs were observed by scanning electron microscopy. The experimental steps were as follows: First, the sample was adhered to conductive adhesive, then the conductive adhesive was evenly attached to the copper sheet and sealed, and the sample was scanned and analyzed by the instrument. The structure and functional groups of MA-PA-TD/EG and MA-SA-LA/EG were determined by FT-IR.

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Notes

The authors declare no competing financial interest.

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