Novel Sugar Alcohol/Carbonized Kapok Fiber Composites as Form-Stable Phase-Change Materials with Exceptionally High Latent Heat for Thermal Energy Storage

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ABSTRACT: The development of form-stable phase-change materials (FSPCMs) with large latent heat, excellent thermal stability, and recyclability is essential for their practical applications in thermal or solar energy saving. In this paper, we first report the FSPCM composites with exceptional latent heat by employment of sugar alcohol, in this case erythritol (Ery) and mannitol (Man), as organic phase-change materials (PCMs) and carbonized kapok fiber (KKF) with a high Brunauer–Emmett–Teller surface area of up to 3396 m² g⁻¹ as porous supporting materials. The unique hollow tubelike structure of KKF makes it possible to load the organic PCMs inside and outside the KKF tubes, and a high load value of 93% was achieved. The carbonized KKF could not only endow itself robust thermal stability but also significantly decrease supercooling while enhancing the thermal conductivity of the PCM composites by over 130% compared with pure Ery and Man. Compared with these reported PCM composites for low and medium temperature usually having latent heat ranges from 150 to 258 J g⁻¹, our PCM composites display exceptionally high latent heat ranging from 297 to 350 J g⁻¹, owing to the inherent large latent heat of sugar alcohols. Notably, as a kind of natural plant fiber with abundant availability, the employment of kapok fiber as the supporting material via physical incorporation with sugar alcohols thus makes the approach simple, green, and cost-effective, which is of great technological significance for their real energy-saving applications owing to their high energy storage performance, high loading values, and enhanced thermal conductivity.

INTRODUCTION

The huge amount of global energy consumption each year has led to a number of severe issues, including the energy crisis of fossil fuels, emerging ecological concerns, global warming, and so forth.¹⁻³ Accordingly, there is an increasing interest for the development of clean, renewable, and sustainable energy resources and techniques.⁴ In this regard, though traditional energy resources such as solar energy,⁵ hydro energy, wind energy,⁶ biomass energy, and nuclear energy have long been exploited to maintain the development of human society and modern industry, a big gap between supply and demand such as energy intermittence, geographical restrictions, and so forth still remains a challenge.⁷ Therefore, it is of great importance to construct advanced energy-saving strategies or highly efficient materials/devices to address these issues.

Phase-change materials (PCMs) are a kind of energy-storage material which can store and release latent heat from the solid to the liquid state or vice versa.⁸ Compared with traditional energy resources, PCMs have great advantages, such as their high energy storage density, low temperature changes, and considerable economic benefit properties, and they have been considered as one of the frontier emerging materials for solar and waste heat storage.⁹ Up to now, a number of PCMs or PCM composites have been created, including inorganic salts or hydrated salts,₆ paraffin,₁₀ fatty acids,₁₁ and polyethylene glycol.₁₂–₁₆ Generally, inorganic salts possess high latent heat and, in most cases, were used as a thermal energy storage medium under working condition ranges from moderate temperature to high temperature.¹₇ Comparatively, organic PCMs have great advantages of low corrosion and melt/freeze cycles without phase segregation,¹⁸,¹⁹ and these have been extensively studied because of their promising energy-saving applications. However, several essential issues still remain an obstacle to their commercial use at large scale.²₀ First, the leakage of organic PCMs may occur between melt/freeze cycles when they are directly applied, so packaging them into polymeric microcapsules to form a core/shell structure or incorporating them into porous supporting materials to manufacture a composite is therefore a common approach for their real workable operation.²¹ This, however, in turn results in a multistep and complicated process with high manufacturing costs or low PCM loading and poor thermal stability, especially for the PCM composites discussed in this study.²² Second, the low thermal conductivity of organic
PCMs, which originated from their organic nature, would dramatically decrease their performance.\(^{23}\) This situation is much worse for those PCM microcapsules where their polymeric shell serves as a barrier to impede thermal transfer. Though great efforts have been made and huge progress has been achieved to address these issues, the fabrication of a thermal energy medium based on PCMs with desired thermal conductivity, high latent heat, better thermal stability, and a simple and cost-effective process still remains a challenge.

In our previous studies, several kinds of form-stable phase-change material (FSPCM) composites have been developed by incorporation of organic PCMs into porous supporting materials including graphene-coated nickel foam,\(^ {24}\) MnO\(_2\) nanowire and nanotubes,\(^ {25}\) and polyethylene nanofoam.\(^ {9}\) In these cases, both the porosity and the wettability (e.g., to be superlipophilic) of porous supporting materials were modified to achieve a better PCM loading and high thermal conductivity by physical or chemical methods. However, the difficulty in the fabrication of such nanoporous supporting materials may also cause other issues such as high product cost or industrial scaled-up problems. Kapok fiber (untreated kapok fiber named as Kf) is a kind of natural, tubelike hollow fiber with an internal diameter of ca. 15 \(\mu\)m and a length of about 25 ± 5 mm.\(^ {26}\) In view of its unique tubular morphology and easy commercial availability, Kf should be ideal candidate as porous supporting materials for preparation of PCM composites. To the best of our knowledge, however, few investigations involving Kf as supporting materials have been reported so far. In this regard, we report the design and preparation of novel FSPCM composites employing erythritol (Ery) and mannitol (Man) as PCMs and the carbonized kapok fiber treated with potassium hydroxide at 800 °C (KKf) as porous supporting materials via a simple and “green” method (no chemicals were used during the whole process). As a proof-of-concept study, the resulting FSPCM composites possess enhanced thermal conductivity and high latent heat. Furthermore, the manufacturing process is easy to be scaled up for industrialization, which may open up a new way for fabrication of high-performance PCM composites based on natural products as a heat-storage medium for real applications.

### RESULTS AND DISCUSSION

In this work, kapok fiber (Kf), which has a distinct hollow structure and characteristics such as low-cost, being environmentally friendly, and being rich for carbon production, was used as the raw material for preparation of the porous support material to fabricate the PCM composites. The tremendously large specific surface area (3396 m\(^2\) g\(^{-1}\)) of carbonized kapok fiber treated with potassium hydroxide at 800 °C (KKf) revealed KOH plays a vital role in this process by maintaining the collapse of pores and can also be used to expand interior porosity after subsequent acid leaching, leading to production of a much more interconnected pore structure with a high number of micro- and mesopores. These characteristics provide possibilities to load large PCMs and enhance the thermal conductivity of PCM composites. The schematic procedure is shown in Scheme 1. The liquid PCMs were in contact with the KKf when the temperature was above the melting point of the PCMs. Because of the large specific surface area of KKf, the liquid PCMs permeated inside the KKf and filled the entire tube. It is worth noting that the PCMs were also trapped on the outer surface of the KKf, with the load rate up to over 93%; thus, KKf would be a promising candidate for preparing FSPCM composites. The morphologies of Kf before and after corrosion were observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). As shown in Figure 1a,b, the SEM images of Kf have a hollow tubular structure with a smooth surface, owing to the coverage of inherent plant wax. Macroscopically, they are connected with each other to form a network structure. Figure 1c,d is the TEM image of the Kf; the presence of the cylindrical shaped structure of kapok fibers is apparent, and such an observation is consistent with the previous literature results.\(^ {27}\) Such a unique hollow tubular structure of Kf facilitates the loading of PCMs; Kf facilitates the loading of PCMs inside and outside the tubes of Kf. The KKf SEM images (Figure 1e,f) show that the etched kapok fibers maintain a tubular structure, whereas the wall of the tube is rough and a number of pores present on the wall were observed, which indicates an obvious corrosion, and the waxy coating has been removed from the fiber surface. The corresponding TEM images (Figure 1g,h) indicate that the tube wall of kapok fibers after potassium hydroxide treatment is significantly thinned, confirming that the impurities and pectin on the fiber surface have been removed. Figure 1i–k shows the SEM images of KKf after loading of PCMs, in this case, sugar alcohols. It can be seen that almost all KKf surfaces are covered with sugar alcohols both outside and inside the tubes. Also, the PCM-loaded KKf tubes stack and connect closely with each other to form a loose architecture, which along with their hollow tubular structure is also favorable for the loading of sugar alcohols.

Elemental mapping of typical single KKf combined with Man (the sample named as KKf/Man) was further investigated by EDS, and results are shown in Figure 2. As can be seen, the red and orange in the energy-dispersive X-ray (EDX) mapping, belonging to C−K and O−K, respectively, distribute the average along the surface of kapok fibers, which indicates the presence of C and O originating from organic PCMs, confirming successful loading of sugar alcohols onto the KKf. Interestingly, a secondary porous network structure also apparently appeared along the wall of tubes (marked as the red arrow in Figure 2), which may also be responsible for its...
extremely large specific Brunauer–Emmett–Teller (BET) surface area (see porosity analysis in Figure 3).

The porosity properties of the KKf were evaluated by nitrogen gas adsorption and desorption measurement at 77.3 K. As shown in Figure 3a, the KKf exhibits type IV adsorption and desorption isotherms. The BET surface area of the KKf was calculated to be 3396 m² g⁻¹, based on the t-plot method. All of the experimental data are summarized in Table 1. The estimated pore volume of KKf is 1.94 cm³ g⁻¹. These microspores are obtained from the inherent voids formed by evaporation of less stable substances and gas during pyrolysis and activation processes. Apparently, the KOH activation contributes to the large specific surface area. The pore size distribution of KKf obtained through Barrett–Joyner–Halenda (BJH) analysis is shown in Figure 3b. From the analysis of Figure 3b, the pore size distribution diagram shows that KKf consists of micro pores. The average porosity of adsorption is 2.29 nm. It can be seen that KKf is mainly composed of micro pores (1.7–2 nm).

Fourier transform infrared (FTIR) spectra are used to further confirm the changes in chemical compositions for the initial Kf, carbonized Kf (CKf), and sodium hydroxide solution-treated Kf (KKf), as shown in Figure 4. The KKf, as well as CKf, has an obvious peak at 3415 cm⁻¹, which is the stretching vibration peak of surface –OH. In addition, CKf shows the vibrations of the aliphatic CH groups at 2920 cm⁻¹. Compared with CKf and KKf, Kf reveals more different peaks, ranging from 1744 to 1047 cm⁻¹. The peak at 1741 cm⁻¹ for Kf corresponds to the carboxylic group. The assignment of other peaks for Kf is summarized in Table 2. The analysis on the FTIR spectra of Kf, by comparison with CKf and KKf, fully confirmed that the wax and impurities on the fiber surface have

**Table 1. Pore Performance of KKf**

| sample | S_BET (m² g⁻¹) | S_micro (m² g⁻¹) | V_micro (cm³ g⁻¹) | V_total (cm³ g⁻¹) | D_BJH (nm) |
|--------|----------------|-----------------|-----------------|------------------|------------|
| KKf    | 3396           | 884             | 0.48            | 1.94             | 2.29       |

Figure 1. SEM images of (a,b) Kf, TEM images of (c,d) Kf, SEM images of (e,f) KKf, TEM images of (g,h) KKf, and SEM images of KKf/PCMs (i–k). Scale bar: (a) 1, (b) 10, (c,d) 2, and (e–j) 1 μm.

Figure 2. TEM–EDX mapping of KKf/Man.

Figure 3. (a) Nitrogen adsorption and desorption isotherms of KKf measured at 77.3 K and (b) pore size distribution for KKf, calculated according to desorption data.
been moved in view of the disappearance of the oxygen-containing groups after carbonization and KOH etching.

The detailed degree of graphitization in CKf and KKf was investigated by Raman spectroscopy, and the results are shown in Figure 5. It is well known that Raman spectra of carbon materials generally have sharp peaks at 1346 and 1587 cm\(^{-1}\), which are referred to as D and G bands, respectively. The D band (defect band) is a disorder from the graphitized structure due to in-plane defects such as defects and heteroatoms. The G band due to the stretching vibration mode having E\(_{2g}\) symmetry in the aromatic layer of the crystalline graphite represents the degree of order of the graphite structure. In general, the intensity ratio recorded as \( R = I_D/I_G \) is commonly used to estimate the degree of disorder in graphite.\(^{29}\) As shown in Figure 5a, both of the samples display two distinctive peaks at around 1326 and 1578 cm\(^{-1}\), corresponding to D and G band, respectively. Figure 5b,c presents the R values 3.04 and 1.19, which implies KKf has a higher graphitic structure.

Figure 6 shows the X-ray diffraction (XRD) patterns of KKf, pure Man, and KKf/Man. As shown in Figure 6, the XRD pattern of hollow KKf shows a characteristic peak at 22.37° corresponding to the (002) crystallographic planes of cellulose. Pure Man has distinct peak shapes at 14.79°, 18.65°, and 23.62°, which are basically consistent with the data mentioned in the previous literature.\(^{30}\) Compared with the XRD peak shape of the pure material, no new peak appeared in KKf/Man, which indicates the PCMs are physically loaded onto KKf. Though the shape is similar, both the position and the peak intensity slightly changes, indicating that the crystal size of sugar alcohols changes slightly when combined with KKf in a confined space.

The phase-change behavior, including the phase-change latent heat and the phase-change temperature, is essential to the PCM and was measured by the differential scanning calorimetry (DSC) technique. Figure 7a displays the DSC curves of pure Man, KKf/Man, and KKf/Man after 500 cycles, whereas DSC curves of pure Ery, KKf combined with Ery (KKf/Ery), and KKf/Ery after 500 cycles are shown in Figure

| bond type     | kapok fiber (cm\(^{-1}\)) | bond type     | kapok fiber (cm\(^{-1}\)) |
|---------------|---------------------------|---------------|---------------------------|
| \(-\)OH stretching | 3415                      | C–H bending   | 1385                      |
| C–H vibration | 2920                      | C–C stretching| 1058                      |
| C=O stretching | 1744                      | C–H stretching| 898                       |
| C=C stretching | 1596                      |               |                           |
Moreover, the PCM latent heat percent of pure PCMs and PCM composites can be calculated by the following equation:

\[
\omega = \frac{\Delta H_{\text{PCM composite}}}{\Delta H_{\text{pure PCM}}} \times 100\%
\]

where \(\Delta H_{\text{PCM composite}}\) refers to the latent heat of the PCM composite and \(\Delta H_{\text{pure PCM}}\) refers to the latent heat of the relevant pure PCM. A higher \(\omega\) value suggests more preservation of the crystalline phase in the composites.

The phase change parameters and enthalpy of pure sugar alcohols and composites are listed in the Table 3. As shown in Table 3, the mass fraction of pure Man and Ery in the KKf/Man and KKf/Ery, and that in KKf/Man and KKf/Ery after 500 cycles of heating and cooling was found to be 92.54 and 77.29, and 94.41 and 87.42, respectively, indicating a large loading capacity of Man and Ery in the composites.

Moreover, it was observed from the DSC curves that the freezing temperatures of Man and Ery in composites (KKf/Man and KKf/Ery) increase compared with those of pure Man and Ery.

In previous literatures, common cotton has been investigated as a PCM supporting material. In that case, three kinds of microcapsules were prepared from common cotton, and the encapsulation ratio is measured to be 35.62, 41.47, and 35.09%. The low incorporation ratio may be due to the fact that the cotton is not hollow in appearance. In this case, in view of its unique tubular morphology and easy commercial availability, Kf should be an ideal candidate as porous supporting materials for preparation of PCM composites. The latent heat storage values of Man, KKf/Man, and KKf/Man after 500 cycles of heating and cooling were measured to be 321.86, 297.84, and 248.75 J g\(^{-1}\), respectively, whereas for Ery, KKf/Ery, and KKf/Ery after 500 cycles of heating and cooling, the latent heat corresponded to 341.53, 322.46, and 298.54 J g\(^{-1}\), respectively. Similar observations have been documented in several recent investigations on composite PCMs. On the other hand, clearly, the latent heat of Man (321.86 J g\(^{-1}\)) and Ery (341.53 J g\(^{-1}\)) are larger than that of a number of conventional organic PCMs used in the medium temperature range, including paraffin wax (250 J g\(^{-1}\)), high-density polyethylene (160 J g\(^{-1}\)), phthalic anhydride (321 J g\(^{-1}\)), and hydroquinone (258 J g\(^{-1}\)), as shown in Figure 8. Though a number of investigations involving sugar alcohols as PCMs have been performed by theoretical simulation, only a few studies involving the use of sugar alcohols for preparation of PCM composites have been reported to date. With these values, the latent heat for KKf/Man and KKf/Ery are larger than that of paraffin/CMPs, paraffin/xGnP, and PP/MA \(^9\) composites, owing to the intrinsic larger latent heat of Man and Ery.

Moreover, it was observed from the DSC curves that the freezing temperatures of Man and Ery in composites (KKf/Man and KKf/Ery) increase compared with those of pure Man and Ery. That is, the supercooling of these two kinds of sugar alcohol PCMs is greatly decreased by incorporation of Man.

### Table 3. Thermal Properties of the Pure Alcohols and PCM Composites

| sample       | PCM percent (%) | \(T_{\text{onset}}\) heating/°C | latent heat \(\text{onset}\) (J g\(^{-1}\)) | PCM percent (%) | \(T_{\text{onset}}\) cooling/°C | latent heat \(\text{onset}\) (J g\(^{-1}\)) |
|--------------|----------------|-------------------------------|--------------------------------|----------------|-------------------------------|--------------------------------|
| Man          | 100            | 171.06                        | 321.86                         | 117.38         | 240.96                        | 248.75                         |
| KKf/Man      | 92.54          | 173.74                        | 297.84                         | 129.42         | 248.69                        | 248.75                         |
| KKf/Man (500 cycles) | 77.29          | 171.93                        | 248.75                         | 118.85         | 212.82                        | 248.75                         |
| Ery          | 100.00         | 125.84                        | 341.53                         | 36.72          | 226.82                        | 248.75                         |
| KKf/Ery      | 94.41          | 126.07                        | 322.46                         | 46.53          | 221.67                        | 248.75                         |
| KKf/Ery (500 cycles) | 87.42          | 123.67                        | 298.54                         | 39.45          | 183.95                        | 248.75                         |

**Figure 6.** XRD of KKf, pure Man, and KKf/Man.

**Figure 7.** DSC curves of different pure sugar alcohols and PCM composites.
and Ery into the kapok fiber. The melting and freezing temperatures (Table 3) were measured to be 171.06 and 117.38 °C, respectively, for Man; 173.74 and 129.42 °C, respectively, for KKf/Man; and 171.93 and 118.85 °C, respectively, for KKf/Man after 500 heating and cooling cycles, which is a decrease of 9.36 and 0.6 °C of supercooling for these two samples, respectively. For Ery and KKf/Ery, and KKf/Ery after 500 heating and cooling cycles, the supercooling decreased 9.58 and 4.9 °C, respectively. The phenomenon is attributed to the rapid crystallization rate of the Man and Ery in composites originating from the restricted molecular motion area and increased regional undercooling caused by the enhanced viscosity.40 It is well known that the sugar alcohols have large latent heat compared with other organic PCMs (e.g., paraffin wax); unfortunately, however, usually their large supercooling degree makes them unsuitable for practical applications. In this case, interestingly, the decrease in the supercooling of PCM composites based on Man and Ery is greatly advantageous for their practical applications, in addition to their large latent heat. The phenomenon for latent heat of the cooling process is much smaller than that of heating process is common for PCMs composites. In the heating stage, the PCMs tend to disorder from their ordered structure because of an endothermic process. In this case, according to the published literature, Ery is identified with at least two crystalline forms, a metastable polymorph and a stable crystalline. The stable crystalline form is only obtained upon heating the frozen solid or leaving it for a long time at room temperature. Hence, in the cooling stage, it has a relative lower latent heat than that in the heating stage. To our knowledge, such an observation has rarely been reported for sugar alcohol-based FSPCMs so far.

The thermal stability for PCMs is one of main factors for its applications.41 In this study, we evaluate the thermal stability of the resulting PCM composites by thermogravimetric analysis (TGA). From Figure 9, it can be seen that the KKf was stable and decomposed slightly at 31.78 °C. Although the initial decomposition temperature and complete decomposition temperature of the composite were almost the same as those of pure Man, the composite was reduced by 93.42% over the course of the entire process, about 5.2% increase compared to pure Man, indicating that Man was dispersed into the pores of KKf.

The thermal conductivity of pure sugar alcohols and the as-synthesized PCM composites was investigated by using a thermal conductivity tester, and the results are shown in Table 4. The thermal conductivity of pure Man is 0.265 W m⁻¹ K⁻¹, whereas the KKf/Man exhibits a much more high thermal conductivity of up to 0.353 W m⁻¹ K⁻¹, which is about 133% higher than that of the control. Similarly, KKf/Ery also shows an enhanced thermal conductivity of 0.401 W m⁻¹ K⁻¹, equal to 131% of that of pure Ery (0.305 W m⁻¹ K⁻¹). Clearly, a significant improvement of thermal conductivity was achieved when pure sugar alcohols were loaded into KKf, owing to the inherently high thermal conductivity of KKf and its interconnected carbon skeleton. Therefore, during the heat transfer process, thanks to the presence of interconnected three-dimensional honeycomb-like carbon, heat conduction was rapid and effective along the carbon skeleton, resulting in the significant increase of thermal conductivity of composites. In this regard, the KKf used here can not only serve as supporting materials but also could significantly improve their thermal conductivity without adding any additive.

### CONCLUSIONS

In summary, we have demonstrated an approach for the creation of novel FSPCM composites with exceptional latent heat by employment of two kinds of sugar alcohols as organic PCMs and carbonized kapok fiber as porous supporting materials. Compared with other FSPCM composites based on porous supporting materials such as carbon nanotubes, porous

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**Figure 8.** Latent heat of some medium-temperature PCMs.

**Figure 9.** TGA curves of KKf, pure Man, and KKf/Man between room temperature and 800 °C.

**Table 4.** Thermal Conductivity Properties of the PCMs and PCM Composites

| sample       | thermal diffusivity (mm² s⁻¹) | specific heat (J g⁻¹ K⁻¹) | density (g cm⁻³) | thermal conductivity (W m⁻¹ K⁻¹) |
|--------------|-------------------------------|---------------------------|------------------|----------------------------------|
| pure Man     | 0.241                         | 1.284                     | 1.099            | 0.265                            |
| KKf/Man      | 0.388                         | 1.57                      | 0.91             | 0.353                            |
| pure Ery     | 0.227                         | 1.237                     | 1.088            | 0.305                            |
| KKf/Ery      | 0.354                         | 1.416                     | 1.134            | 0.401                            |
polymers, and so on, the carbonized kapok fiber, as a kind of natural plant fiber with abundant availability, has great advantages such as its high BET surface area (up to 3396 m² g⁻¹) and unique cylindrical structure with hollow pores in the tubular wall, which could provide a larger accessible surface and faster transport channel for loading of sugar alcohols. Furthermore, compared with the reported PCM composites for low and medium temperatures, usually having latent heat ranges from 150 to 258 J g⁻¹, our PCM composites display exceptionally high latent heat ranging from 297 to 350 J g⁻¹ because of the inherent large latent heat of sugar alcohols, in addition to their enhanced thermal conductivity, large loading value, excellent thermal stability, and dramatically reduced supercooling. Based on these merits, the resulting PCM composites may have great potential as a promising heat-storage medium for solar energy or other thermal energy saving applications.

**EXPERIMENTAL SECTION**

**Materials.** Kapok fiber (Kf) was purchased from Shanghai Panda Co. Ltd., China. Ery and Man were received from Shanghai Macklin Biochemical Technology Co., Ltd., China. All chemicals were used as received without further purification.

**Preparation of Kapok Fiber as the Supporter Material.** An appropriate amount of Kf was put into 2 wt % NaOH solution and kept for 48 h to remove the wax and impurities on the fiber surface. The as-treated fiber was repeatedly washed with distilled water until the pH reached neutrality and then dried in an oven at 105 °C for 70 min. After that, the precarbonized kapok fiber (CKf) was mixed with KOH and then heated to 800 °C under a nitrogen atmosphere; this temperature was maintained for 2 h. The sample was thoroughly washed with 1 M HCl to remove the residual KOH. Finally, the resulting fiber was washed with hot distilled water several times until the filtrate reached neutral and was dried at 105 °C overnight. The as-prepared sample was marked as KKf.

**Preparation of Form-Stable KKf/PCM Composite Materials.** The KKf/PCMs were prepared through the melting-impregnation method by using Ery and Man as PCMs and KKf as the supporting materials. The resulting samples were named as KKf/Ery and KKf/Man, respectively. Taking KKf/Man as an example, Man was placed in a glass tube source, and 2 wt % of KBr was put into 2 wt % NaOH solution and kept for 48 h to remove the wax and impurities on the fiber surface. The as-treated fiber was repeatedly washed with distilled water until the pH reached neutrality and then dried in an oven at 105 °C. The treated kapok fiber was first placed into a porcelain boat and carbonized at 650 °C for 70 min. After that, the precarbonized kapok fiber (CKf) was mixed with KOH and then heated to 800 °C under a nitrogen atmosphere; this temperature was maintained for 2 h. The sample was thoroughly washed with 1 M HCl to remove the residual KOH. Finally, the resulting fiber was washed with hot distilled water several times until the filtrate reached neutral and was dried at 105 °C overnight. The as-prepared sample was marked as KKf.

**Material Characterization.** The micromorphology of the supporting materials and PCM composites was observed by using cold field emission SEM (JSMM-6701F, JEOL, Ltd.) and TEM (JEM-1200EX, FEI, Co.). XRD measurements were performed on a Rigaku D/Max-2400 diffractometer with a Cu tube source, and 2θ scans were obtained from 10 to 80 °C.
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