Enhanced Thermal Energy Storage of \( n \)-Octadecane-Impregnated Mesoporous Silica as a Novel Shape-Stabilized Phase Change Material

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ABSTRACT: A series of \( n \)-octadecane/mesoporous silica (C\(_{18}/\)MS) shape-stabilized phase change materials (SSPCMs) with varying C\(_{18}\) content were prepared, and the effects of adsorbed C\(_{18}\) distributed within porous MS on the thermal properties were analyzed. As characterized, C\(_{18}\) was first infiltrated into the mesoporous space, resulting in a SSPCM with a maximum of \( \sim 52 \) wt % C\(_{18}\). Additional adsorption of C\(_{18}\) occurred on the external surface of MS. Consequently, the optimum 70 wt % C\(_{18}\) SSPCM had no C\(_{18}\) leakage and exhibited a heat storage capacity of 135.6 J/g and crystallinity of 83.5%, which were much larger than those of 52 wt % C\(_{18}\) SSPCM (60.2 J/g and 68.2%, respectively). The prepared C\(_{18}/\)MS SSPCMs showed excellent thermal stability and thermal reliability up to 1000 accelerated thermal cycle tests. Moreover, the C\(_{18}/\)MS SSPCM incorporated in gypsum effectively reduced the temperature changes compared with the original gypsum, suggesting the promising application of the prepared C\(_{18}/\)MS SSPCM for energy-saving building applications.

1. INTRODUCTION

Using shape-stabilized phase change materials (SSPCMs) comprised of phase change materials (PCMs) impregnated in porous matrices for thermal energy storage (TES) in buildings can smooth the temperature fluctuation and reduce energy consumption.\(^{1,2}\) PCMs are active thermal energy storage materials that can store large amounts of latent heat during melting/solidification within a small phase change temperature range. In turn, the leakage of liquid PCMs during melting is prevented by the capillary and surface tension forces of the porous matrixes.\(^{3}\) Practically, SSPCMs are usually incorporated with construction materials such as gypsum, mortar, cement, and brick.\(^{4,5}\) According to the thermal comfort (20 < \( T < 26 \) °C) of human beings, PCMs with a phase change temperature of 18−30 °C are most suitable.\(^{5}\) During the daytime, PCMs absorb heat and melt due to temperature rise; at night, as the temperature decreases, they release the stored heat and solidify. Several organic PCMs (paraffins,\(^{6,7}\) biobased PCMs,\(^{8}\) fatty alcohols\(^{9}\)) and inorganic PCMs (CaCl\(_2\)·6H\(_2\)O,\(^{10}\) Na\(_2\)SO\(_4\)·10H\(_2\)O\(^{11}\)) have been investigated for building applications. Inorganic PCMs usually show advantages of low cost, flame retardance, and relatively high latent heat storage capacity. However, severe supercooling, phase segregation, and strong corrosivity still restrict their applications.\(^{2,13}\) To overcome these limitations, organic PCMs have gained increasing attention for preparing SSPCMs.\(^{14}\) Of the organic PCMs, \( n \)-octadecane is considered a potential candidate for its high heat storage capacity and high chemical and thermal stability after a long-term utilization period.\(^{15,16}\)

Porous supports allow us to stabilize PCMs in nanopores and continue to maintain the PCMs after multiple melting/solidification cycles. Pore size is an important parameter, which greatly affects the PCM storage amount and thermal properties of SSPCMs. Very small pores, i.e., micropores, can only adsorb a small amount of PCM due to the low pore volume, leading to poor latent heat storage capacity. In contrast, large pores, i.e., macropores, can result in high PCM adsorption but cause leakage due to insufficient capillary and surface tension forces. Practically, mesoporous structures are often used for high PCM stability and enhanced PCM adsorption. Commonly employed porous supports include silica,\(^{17,18}\) carbon-based materials,\(^{13,19}\) organic porous polymers,\(^{12,20,21}\) and metal foams.\(^{22}\) Of them, porous silica has been considered the most promising candidate for large-scale building applications due to its low cost, high availability, high thermal resistance,

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and high surface adsorption. For example, Min et al.\textsuperscript{23} used mesoporous silica (MS) as a porous matrix for adsorption of poly(ethylene glycol) (PEG) PCM, which resulted in a PEG/MS SSPCM up to 80 wt % PEG. Chen et al.\textsuperscript{24} prepared an MS to support myristic acid (MA), and up to 65 wt % MA could be stabilized in the MA/MS SSPCM. The high PCM contents in the SSPCMs greatly benefited the thermal performance since the latent heat storage capacity was directly proportional to the PCM amount. It can be calculated that the MS supports from the as-mentioned studies provide limited mesoporous space for infiltrating PCMs so that the volume of mesopores occupied is only about 40 wt % PEG by Min et al.\textsuperscript{23} or 50 wt % MA by Chen et al.\textsuperscript{24} Thanks to the large surface area of microsized silica particles, PCMs can be continued to be adsorbed onto the external surface of MS particles with enough physical forces to maintain the stability of the resultant SSPCMs. Thus, PCM contents were practically much larger than their maximum amounts calculated from mesoporous adsorption capability of siliceous materials, i.e., 80 wt % PEG for PEG/MS SSPCM and 65 wt % MA for MA/MS SSPCM. In other words, the external surface of MS played the role of adsorption sites for PCMs. However, the behaviors of PCMs residing on the external surface and their role in affecting thermal properties have not been fully clarified in the literature.

Table 1. Porosities and Thermal Properties of the MS, C\textsubscript{18} and C\textsubscript{18}/MS SSPCMs

| Porosity | Melting | Solidification |
|----------|---------|----------------|
|          | $V^a$ (cm$^3$/g) | $d$ (nm) | $S$ (m$^2$/g) | $T_{M,pore}$ (°C) | $T_{M,surf}$ (°C) | $\Delta H_{M,pore}$ (J/g) | $\Delta H_{M,surf}$ (J/g) | $\Delta H_{M,tot}$ (J/g) | $T_{S,pore}$ (°C) | $T_{S,surf}$ (°C) | $\Delta H_{S,pore}$ (J/g) | $\Delta H_{S,surf}$ (J/g) | $\Delta H_{S,tot}$ (J/g) |
| MS       | 1.45    | 16.6 | 291 | 22.3 | 60.2 | 0 | 60.2 | 21.5 | 59.5 | 0 | 59.5 |
| 40 wt %  | 0.53    | 22.4 | 97  | 22.1 | 81.7 | 0 | 81.7 | 22.9 | 82.1 | 0 | 82.1 |
| 52 wt %  | 0.22    | 44   | 22.3 | 29.3 | 64.7 | 40.4 | 105.1 | 24.1 | 79.8 | 24.5 | 104.3 |
| 60 wt %  | 0.087   | 34   | 22.4 | 29.1 | 56.7 | 78.9 | 135.6 | 23.9 | 67.2 | 134.4 |
| 70 wt %  | 0.086   | 21   | 24.2 | 29.1 | 56.7 | 78.9 | 135.6 | 23.9 | 67.2 | 134.4 |
| 80 wt %  | 0.04    | 9    | 24.7 | 29.3 | 38.9 | 125.3 | 164.2 | 23.0 | 25.5 | 139.4 | 164.9 |
| C\textsubscript{18} | 0.04    | 9    | 24.7 | 29.3 | 38.9 | 125.3 | 164.2 | 23.0 | 25.5 | 139.4 | 164.9 |

$^a$The pore volume was calculated at $P/P_0$ of 0.95.
In addition, it is worth mentioning that different PCM materials can exhibit unique physicochemical interactions with the porous host. Hence, C18 exhibits different performances compared with PEG and MA if it was loaded in porous silica. However, to the best of our knowledge, the insight into C18 distribution in mesoporous silica and its thermal properties has never been reported.

In this study, the chemistry insights into the C18 distribution between the mesopores and the external surface of mesoporous silica (MS) and the thermal properties of the C18/MS SSPCM were deeply investigated. A series of C18/MS SSPCMs with increasing C18 contents (40, 52, 60, 70, and 80 wt %) were prepared and characterized using N2 adsorption−desorption isotherms, Fourier transform infrared (FT-IR) spectroscopy, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and X-ray diffraction (XRD). The obtained materials were examined for potential application in the field of buildings by incorporating SSPCM with gypsum.

2. RESULTS AND DISCUSSION

2.1. Characterization. Figure 1a,b shows the N2 adsorption−desorption isotherms and pore size distribution (PSD) of MS compared with C18/MS SSPCMs, respectively, and the detailed porosities are exhibited in Table 1. In Figure 1a, MS presented a type IV isotherm with a capillary condensation step that occurred at a P/P0 (N2 relative pressure) of approximately 0.7−0.9 and a H1 hysteresis loop as classified by IUPAC, indicating a mesoporous structure. The pore size distribution (PSD) of MS (Figure 1b) showed that the mesopores were distributed in a broad range of 5−35 nm with a peak at 16.6 nm. The specific surface area and pore volume obtained were 291 m2/g and 1.42 cm3/g, respectively. Assuming that the amount of C18 fully occupies the pore volume of MS, we obtain $V_p \cdot \rho \cdot W_{MS}$ and thus, the total mass of SSPCM is $W_{MS} + V_p \cdot \rho \cdot W_{MS}$. The maximum content ($\phi_{MAX}$) of C18 loaded in mesopores could be calculated using eq 1.

$$\phi_{MAX} = \frac{V_p \cdot \rho \cdot W_{MS} \cdot 100}{W_{MS} + V_p \cdot \rho \cdot W_{MS}}$$

where $V_p$ is the specific pore volume of MS, $\rho$ is the density of liquid octadecane (0.77 g/cm3), and $W_{MS}$ is the mass of MS. $\phi_{MAX}$ was computed to be approximately 52 wt % for the mesopores. This means that all mesopores in MS are fully loaded as the adsorbed C18 reached the $\phi_{MAX}$ value. For the
prepared 40 wt % SSPCM (%C_{18} < \phi_{\text{MAX}}), the N\textsubscript{2} sorption isotherm (Figure 1a) exhibited a significant reduction in N\textsubscript{2} adsorption. Additionally, the PSD (Figure 1b) showed a strong decrease of mesopores below \textasciitilde 17 nm, and the peak was shifted to 22.4 nm, larger than that of pristine MS. These indicated that the PCM initially filled the smaller mesopores and then larger ones during the impregnation process, thus resulting in the shift of the PSD peak. At 52 wt % C_{18}, the SSPCM showed almost no N\textsubscript{2} uptake with the disappearance of the PSD peak, indicating that the mesopores were fully filled with the PCM. Therefore, as the C_{18} contents surpassed \phi_{\text{MAX}}, i.e., 60, 70, and 80 wt %, the PCM was adsorbed onto the external surface, filling interparticle voids. These additional contents accounted for about 17, 37, and 58 wt % C_{18} residing on external surfaces, for the 60, 70, and 80 wt % SSPCMs, respectively (see Figure 2b).

Figure 2 presents the SEM images of the prepared C_{18}/MS SSPCMs compared with pristine MS and C_{18}. The two SSPCMs exhibited combined characteristics of pure MS and C_{18} with no new peaks observed. For example, the peaks at 462, 802, and 1095 cm\textsuperscript{-1} could be assigned to bending vibration, symmetric stretching vibration, and asymmetric stretching vibration of the siloxane group (Si–O–Si) inherited from MS, respectively. The peak at 1627 cm\textsuperscript{-1} was characterized for the bending mode of adsorbed water, while the overlapped stretching vibration of adsorbed water and surface silanol groups (–Si–OH) was observed at 3245 cm\textsuperscript{-1}.\textsuperscript{26} Meanwhile, the inherent properties of C_{18} were presented for the bending vibration peaks at 1377 and 1465 cm\textsuperscript{-1} and the stretching vibration peaks at 2854, 2915, and 2962 cm\textsuperscript{-1} assigned to the –C–H group. In addition, the peak at 725 cm\textsuperscript{-1} was attributed to the –CH_{2}– in-plane rocking vibration. These results demonstrated that C_{18} and MS were intact after the impregnation process and physically compounded without chemical reactions. Additionally, thermogravimetric analysis of the prepared SSPCMs showed C_{18} fractions of 41.5, 51.4, 60.6, 69.2, and 79.1 wt %, corresponding to the initially added C_{18} contents of 40, 52, 60, 70, and 80 wt % C_{18}/MS SSPCMs, respectively (see Figure 6a).

Figure 3. Illustration of the infiltration process of C_{18} into MS at % C_{18} exceeding the \phi_{\text{MAX}} value.

Figure 3 illustrates the infiltration process of C_{18} into MS at % C_{18} exceeding the \phi_{\text{MAX}} value. during melting and solidification, which was similar to pure C_{18} although their endothermic peaks shifted to lower temperatures by approximately 7 °C compared to pure C_{18}. This could be attributed to the strain in C_{18} molecules as they are narrowly confined in the mesopores.\textsuperscript{25} However, an additional phase change peak appeared in both melting and solidification for the SSPCMs with 60, 70, and 80 wt % C_{18}. This suggests a different phase change behavior for those of C_{18} residing on the external surface of the MS. As the PCMs residing on the external surface have larger space, these molecules suffered less from the strain. This resulted in higher phase change temperatures than for those residing in the mesopores, hence approaching the temperature of pure C_{18}.

The latent heat storage capacity or phase change enthalpy including the melting/solidification enthalpy of C_{18} residing in mesopores (\Delta H_{\text{M,pore}}/\Delta H_{\text{S,pore}}), on the external surface (\Delta H_{\text{M,surf}}/\Delta H_{\text{S,surf}}), and total melting/solidification enthalpy (\Delta H_{\text{M,tot}}/\Delta H_{\text{S,tot}}) are shown in Table 1. The total melting and solidification enthalpy increased with increasing C_{18} content, ranging from 60.2 and 59.5 J/g for the 40 wt % SSPCM to 165.6 and 163.2 J/g for the 80 wt % SSPCM, respectively. This was because the enthalpy of the SSPCMs was solely generated from C_{18} and became larger with increasing C_{18} content. The lower enthalpy of the SSPCMs compared to that of pure C_{18} (230.6 and 231.4 J/g for melting and solidification enthalpy, respectively) indicates the formation of a nonfreezable layer at the interfacial regions between PCM and pore walls during the infiltration of C_{18}, which cannot be crystallized even at a temperature below the solidification point of the PCM. This phenomenon is known to suppress the crystallinity of the SSPCM and thus did not play a role in thermal change.

Meanwhile, such a nonfreezable layer can be minimized at a high C_{18} content, leading to increasing enthalpy. To clarify the effects of the nonfreezable layer on the crystallinity of loaded C_{18}, the crystallization fraction (F_{C} (%) was calculated using eq 2,\textsuperscript{18} and the results are illustrated in Figure 5a.

\[ F_{C} = \frac{(\Delta H_{\text{M,tot}} + \Delta H_{\text{S,tot}}) \times 100}{(\Delta H_{\text{M,PCM}} + \Delta H_{\text{S,PCM}}) \times x} \]  

where \Delta H_{\text{M,tot}} and \Delta H_{\text{S,tot}} are the total melting and solidification enthalpy of the SSPCM, respectively, \Delta H_{\text{M,PCM}} and \Delta H_{\text{S,PCM}} are the melting and solidification enthalpy of pure C_{18}, respectively, and x is the relative fraction of PCM in the SSPCM.

As shown in Figure 5a, the F_{C} values increased from 64.7 to 91.4% on increasing the C_{18} content from 40 to 80 wt %, respectively. This was consistent with the steady growth of the XRD peak intensity with the growing C_{18} content (Figure 5b). The less than 100% crystallization fraction suggested that the crystallinity of the loaded C_{18} was suppressed by the nonfreezable layer. In the MS porous network, the mesopores

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generated a much larger surface area than the external surface. The large surface area could lead to a higher fraction of the nonfreezable layer, thus lowering the crystallinity. The $F_C$ values increased with the increased $C_{18}$-content SSPCMs because $C_{18}$ was increasingly adsorbed onto the external surface. It is noted that $\Delta F_C = 3.4\%$ with the $C_{18}$ content increasing from 40 to 52 wt % suddenly soared to $\Delta F_C = 7.3\%$ on increasing the $C_{18}$ content to 60 wt %, then steadily increased at $\Delta F_C = 7.9$ and 5.5% with the $C_{18}$ content reaching 70 and 80 wt %, respectively. The strong increase of the $F_C$ value from the 52 wt % SSPCM to 60 wt % SSPCM marked the change in PCM distribution from filling mesopores to the external surface. It was emphasized that the employment of the external surface as a storage cavity greatly enhanced the crystallinity of the SSPCMs compared to that of mesopores, thus benefiting the heat storage capacity. For example, the crystallization fraction increased by 15.3% from the 52 wt % SSPCM (68.2% crystallinity) to the 70 wt % SSPCM (83.5% crystallinity), corresponding to an increase by 66% from 81.7 to 135.6 J/g for the heat storage capacity, respectively. These results suggest

Figure 4. (a) Melting DSC curves and (b) solidification DSC curves of $C_{18}$ and the prepared SSPCMs.

Figure 5. (a) Crystallization fraction and (b) XRD patterns of pure $C_{18}$ and the prepared SSPCMs (40, 52, 60, 70, and 80 wt % $C_{18}$).

Figure 6. (a) Thermogravimetric analysis (TGA) curves and (b) derivative thermogravimetry (DTG) curves of $C_{18}$ and the prepared SSPCMs (40, 52, 60, 70, and 80 wt % $C_{18}$).
that the external surface adsorption of PCM plays an important role in enhancing the thermal properties of the C18/MS SSPCM.

2.3. Thermal Stability and Leakage Resistance. The thermal stability of the prepared SSPCMs compared to that of pure C18 was investigated using TGA, and the results are presented in Figure 6a. All of the samples showed a one-step weight loss because of the thermal decomposition of C18. Pure C18 presented a weight loss of nearly 100% in a temperature range of 100–207 °C. Meanwhile, all of the prepared SSPCMs exhibited a weight loss in a higher temperature range of about 150–225 °C. For precise comparison, the thermal stability was evaluated by the characteristic temperature at a maximum decomposition rate (\(T_{\text{MAX}}\)) in the DTG curve (Figure 6b). As can be seen, pure C18 showed a \(T_{\text{MAX}}\) at 203.5 °C while the prepared SSPCMs presented a higher \(T_{\text{MAX}}\) value of about 230 °C, indicating that the thermal stability of the SSPCMs can be considerably improved by the introduction of the MS matrix. This result suggested that the interactions (capillary and surface tension forces) and interfacial interactions between C18 and functional groups on the MS surface can effectively delay the thermal degradation of the loaded C18. Moreover, the prepared SSPCMs decomposed at a temperature considerably exceeding the working melting point of C18 (\(~30^\circ\text{C}\)). Therefore, the C18/MS SSPCMs possessed excellent thermal stability during repeated melting/solidification operations.

Figure 7 shows the digital photos of pure C18 and the prepared SSPCMs after 60 min at 60 °C.

2.4. Thermal Reliability. The 70 wt % C18 SSPCM, which had the largest C18 content with no C18 leakage and exhibited a large latent heat storage capacity, was selected for the thermal tests. The cycle durability or thermal reliability of the material was tested over 1000 accelerated thermal cycles, and the melting/solidification DSC curves and melting/solidification latent heat storage capacity during the test are exhibited in Figure 8. The DSC curves were almost unchanged during the 1000 thermal cycles, and the phase change temperatures
SSPCMs recently reported. Overall, the prepared SSPCM is comparable and even better than most reported materials in terms of heat storage capacity. Meanwhile, the prepared SSPCM had slightly lower thermal enthalpy than C_{18}/G18 SSPCM and C_{18}/fumed silica SSPCM; however, it has the advantages of simple preparation and cost-effectiveness, promising the potential of large-scale applications.

### 2.5. Thermal Performance Evaluation of C_{18}/MS SSPCM in Building Materials. Figure 9 shows the temperature rise compared to the original gypsum and gypsum incorporated with 70 wt % C_{18}/MS SSPCM at two mass ratios of SSPCM 10 and 20 wt %. It is undoubtedly seen that the gypsum incorporated with SSPCMs delayed the temperature rise compared to the pristine one, indicating that the composites could effectively store a larger heat due to the additional latent heat absorption of the SSPCM. Based on the tangential method, the temperature profile of the SSPCM-incorporated gypsiums can be divided into three steps as follows. The first step of <22 °C and the last step of >30 °C exhibited a temperature increase before and after the melting of the SSPCM driven by the adsorption of sensible heat. The middle step (22–30 °C) showed the temperature increase during the melting of the SSPCM driven by both sensible and latent heat. Thus, a lower slope in temperature rise was observed in the middle step than in the other steps. The result was consistent with the literature where an SSPCM generally possesses much larger latent heat than sensible heat.\(^{10,36}\) Contrarily, the pristine gypsum showed a quick temperature increase due to lack of latent heat storage, nearly reaching a peak at 41.6 °C after 500 s. For comparison, at the same time (500 s), the temperatures for 10 and 20 wt % SSCPM-incorporated gypsiums were 38.5 and 28.2 °C, respectively. These results demonstrated that the C_{18}/MS SSPCM-incorporated gypsum could reduce temperature fluctuation, suitable for energy-saving building applications.

### 3. CONCLUSIONS

In this work, the C_{18}/MS SSPCMs were simply prepared and thoroughly characterized using a range of instrumental analyses. The major results were pointed out as follows.

- C_{18} PCM was impregnated into MS by initially filling the mesopores and then the external surface. Such addition of external surface adsorption resulted in an optimal SSPCM of up to 70 wt % C_{18} content with excellent thermal stability and leakage prevention, where the crystallinity extent increased by ∼15%.
- The 70 wt % C_{18}/MS SSPCM exhibited high heat storage capacity (135.6 J/g) and crystallinity (83.5%) and excellent thermal reliability of up to 1000 repeated melting/solidification cycles. It allowed for reducing the temperature fluctuation of SSPCM–gypsum as building materials. With good thermal performance and cost-effectiveness, the C_{18}/MS SSPCMs are a promising candidate for large-scale industrial preparation in energy-saving buildings.

### 4. MATERIALS AND METHODS

#### 4.1. Materials.

- Mesoporous silica gel with a mean particle size of 4 μm was purchased from S-Chemtech (South Korea). n-Octadecane 99% was bought from Alfa Aesar (USA), and n-hexane (99%) was purchased from Samchun (South Korea). Gypsum powder was bought at a local shop.
- The C_{18}/MS SSPCMs were prepared with varying C_{18} contents between 40 and 80 wt % (40, 52, 60, 70, and 80 wt %) employing an evaporative impregnation method\(^{20,37}\) as illustrated in Figure 10. A known amount of C_{18} was dissolved in n-hexane, and then an appropriate amount of MS was added to the solution. The mixture was stirred with a magnetic bar for 2 h at ambient temperature. Afterward, the mixture was heated to 70 °C until the solvent was dried out. Finally, the as-obtained material was placed in an oven at 70 °C for 24 h to totally remove the solvent, obtaining C_{18}/MS SSPCMs.

#### 4.3. Characterization Methods.

The morphology was examined using field emission scanning electron microscopy (FE-SEM) with a FE-SEM S4800 instrument (Hitachi, Japan). The porosities were evaluated with nitrogen adsorption–desorption isotherms, using a BELSORP–Max instrument (MicrotacBel, Japan) at the temperature of liquid nitrogen (−196 °C). The surface area was calculated based on the Brunauer–Emmett–Teller (BET) method. The pore size distribution was estimated by the nonlocal density functional...
theory (NLDFT). The mesopore volume was calculated at a P/P₀ of 0.95. The chemical compositions were examined with Fourier transform infrared spectroscopy using a Nicolet 6700 FT-IR instrument (Thermo Scientific, USA) in a wavenumber range of 400−4000 cm⁻¹.

The thermal characteristics were studied with differential scanning calorimetry, using a DSC 4000 instrument (Perkin Elmer, USA). The measurements were conducted in the temperature range of 0−45 °C at a ramp rate of 10 °C/min and with 20 mL/min N₂ purge gas. The phase change temperature of the materials was regarded as the onset temperature in DSC curves. DSC measurement was conducted every two cycles, and the second one was used for discussion and calculation. The crystallization properties were examined with powder X-ray diffraction, using a Rigaku Miniflex instrument (Japan) with Cu-Kα radiation. The measurements were conducted at a current of 15 mA, voltage of 40 kV, and a scanning rate of 5°/min in a 2θ range of 5−50°.

The leakage resistance test was performed as follows. Approximately, 5 g of the prepared materials was compressed into a round block with dimensions of 30 mm × 10 nm using a homemade mold and compressor. The round block was placed on filter paper and kept in an oven for 60 min at 60 °C. Subsequently, the round block was taken off the filter paper and observed for possible leakage. The thermal stability was examined by thermogravimetric analysis, using a TGA 4000 instrument (Perkin Elmer, USA). The measurements were conducted at a temperature range of 30−500 °C, at a ramp rate of 10 °C/min, and with 20 mL/min N₂ purge gas.

The thermal performance evaluation of the prepared C₁₈/MS SSPCM in building materials was tested with an apparatus illustrated in Figure 11. A prepared C₁₈/MS SSPCM with 70 wt % C₁₈ was thoroughly mixed with gypsum at two contents of 10 and 20 wt % SSPCM to form SSPCM-incorporated gypsums. The selected material (~15 g) was compressed in a cylindrical storage unit (30 mm × 150 mm). A thermocouple (T-type) and a data acquisition unit (MV200, Yokogawa Electric Corporation, Japan) were used to record the temperature change during the tests. The storage unit was first placed in a low-temperature oil bath (2 °C) until the temperature was stabilized. Then, the storage unit was rapidly moved to a high-temperature oil bath (50 °C), and the temperature change during heat storage (melting) was monitored. When the unit reached a stable temperature at nearly 50 °C, it was rapidly moved to the low-temperature oil bath and the temperature change during heat release (solidification) was recorded.

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Notes
The authors declare no competing financial interest.

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