Dynamic heat transfer analysis on hwangtoh with PCM/eco-material for improving thermal inertia

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Abstract. The use of a latent-heat storage composite system for which phase-change materials (PCMs) are used is an effective way of storing thermal energy, and it has the advantages of a high energy-storage density and the isothermal nature of the storage process. Therefore, latent heat storage is considered to be the most effective way to use PCM to charge or discharge thermal energy as latent heat during the phase change period. However, the application of PCMs is difficult in a variety of fields due to their phase instability in the liquid state, and PCMs therefore need shape stabilization. To solve this problem, some investigators have studied the possibility of using a container that can prevent the leaking of liquid from PCMs by using a shape-stabilized PCM (SSPCM), a microencapsulated PCM (MPCM), or incorporated PCM techniques. The SSPCM was prepared by eco-material which are perlite and vermiculite. The selected PCM was n-octadecane, belongs to organic PCM. The thermal properties of the PCM, such as their melting and freezing temperatures and latent heat capacities, were measured using differential scanning calorimetry. The melting and freezing temperatures were measured by drawing a line at the point of maximum slope of the leading edge of the peak, and extrapolating to the base line. The latent heat capacities of the PCM were determined by numerical integration of the area under the peaks that represent the solid–solid and solid–liquid phase transitions. The thermal conductivities of the PCM and hwangtoh composite panels were measured by TCi thermal conductivity analyzer. The TCi developed by C-Therm Technologies Ltd. is a device for conveniently measuring the thermal conductivity of a small sample, by using the Modified Transient Plane Source (MTPS) method.

1. Introduction

One of the ways to reduce building energy is to actively release or store the thermal energy through phase change materials (PCMs) to use heat energy efficiently. PCMs have the major drawback of leaking during the solid-liquid phase transition. Therefore, PCMs must be applied to buildings through phase stabilization. Expanded vermiculite (EV) and expanded perlite (EP) are porous nanoclay materials possessing excellent properties as containers for PCMs.

In this study, the building materials were manufactured in the form of panels with shape-stabilized PCM (SSPCM), and their thermal performance was evaluated. For vacuum impregnation to achieve shape stabilization using porous materials, two nanoclay materials—EV [1, 2] and EP [3, 4]—were used as PCM containers. The PCM used was n-octadecane, which belongs to the organic paraffin series. The prepared SSPCM was mixed with a Korean red clay (RC), Hwangtoh, to form a panel. RC is a traditional eco-friendly and healthy building material in Korea [5] and is a type of kaolin clay. It has recently been studied as a substitute for cement, and has excellent strength and durability through activation. The developed RC-SSPCM panels were analyzed for thermal stability and thermal properties through thermogravimetric analysis (TGA), TCi thermal conductivity analysis, and enthalpy analysis. The climate cycling test was performed for analyzing the peak temperature, thermal inertia.
2. Experimental
2.1. Materials and preparation

n-Octadecane (C<sub>18</sub>H<sub>38</sub>) is an organic paraffin PCM and has high latent heat and thermal stability. n-Octadecane undergoes no supercooling [6], and its latent heat performance is maintained at 90% even after 100 cycles of thermal cycling [7]. Its phase change range is from 24 °C to 34 °C, making it suitable for building applications. EV can be obtained by heating and stripping at temperatures above 900 °C, with excellent specific surface area and low density and porosity [8]. EP is generally very porous and therefore suitable for impregnating PCM due to strong capillary forces and surface tension [9]. The thermo-physical properties of EP, EV, and RC are shown in Table 1.

| Properties                  | EP     | EV     | RC     |
|----------------------------|--------|--------|--------|
| Thermal conductivity λ (W/mK) | 0.051  | 0.058–0.064 | 0.243  |
| Specific heat capacity (Solid) C<sub>p</sub> (kJ/kgK) | 0.84   | 0.84–1.08  | 1.38   |
| Density ρ (kg/m<sup>3</sup>)    | 35–65.6| 50–120  | 1860   |

The SSPCMs were developed by using the vacuum impregnation method. The EP and EV was dried in a vacuum oven before the impregnation process with pressure of -740 mmHg. It was put inside a filtering flask, which was connected to a water trumpet apparatus, to evacuate air from the porous structure of the EP and EV. Then, a valve between the flask and a container with 200g of liquid PCM was opened, to allow the PCM to flow into the flask and cover the nanoparticles of EP and EV. The vacuum process was continued for 90 minutes, and then air was allowed to enter the flask again, to force the liquid organic PCM to penetrate the porous structure of the xGnP. After the penetration process, excess PCM remained in the flask, and was removed through a filtering process. The EV-SSPCM and EP-SSPCM in a colloidal state were filtered through 1μm filter paper until a granular sample appeared, which was dried in a vacuum drier at 80°C for 48 hours. EP-SSPCM and EV-SSPCM were analyzed for chemical compatibility using Fourier-transform infrared (FTIR) spectroscopy in a previous study [10]. The RC-SSPCMs were developed at 100 mm × 100 mm × 20 mm (width × length × height) according to the mixing ratios shown in Table 2.

| RC-SSPCMs             | Water (g) | RC (g) | EP-SSPCM (g) | EV-SSPCM (g) |
|-----------------------|-----------|--------|--------------|--------------|
| RC only (Ref.)        | 23.0      | 100.0  | 0.0          | 0.0          |
| RC/EP-SSPCM 2.5 wt/% (P2.5) | 23.0  | 100.0  | 2.5          | 0.0          |
| RC/EP-SSPCM 5.0 wt/% (P5)   | 23.0   | 100.0  | 5.0          | 0.0          |
| RC/EP-SSPCM 7.5 wt/% (P7.5) | 23.0  | 100.0  | 7.5          | 0.0          |
| RC/EP-SSPCM 10 wt/% (P10) | 23.0   | 100.0  | 10.0         | 0.0          |
| RC/EV-SSPCM 2.5 wt/% (V2.5) | 23.0  | 100.0  | 0.0          | 2.5          |
| RC/EV-SSPCM 5.0 wt/% (V5) | 23.0   | 100.0  | 0.0          | 5.0          |
| RC/EV-SSPCM 7.5 wt/% (V7.5) | 23.0  | 100.0  | 0.0          | 7.5          |
| RC/EV-SSPCM 10 wt/% (V10) | 23.0   | 100.0  | 0.0          | 10.0         |
2.2. Characterization techniques

Thermal properties such as the thermal conductivity and latent heat of n-octadecane and SSPCMs were analyzed by TCi thermal conductivity analysis and DSC. A TCi thermal analyzer uses a modified transient plane source method and is measured at room temperature. The DSC measurements were performed over a 5 °C/min endothermic and exothermic process in temperature ranges of 0–80 °C. The enthalpy value of SSPCMs was calculated from the latent heat capacity using a Cp calculation program, which converts the heat flow to specific heat.

The thermal stability of SSPCMs was analyzed by TGA (TA Instruments, TGA Q500). The TGA measurements were performed at a heating rate of 10 °C/min, over the temperature range from room temperature to 600 °C. TGA analysis was performed to verify the thermal stability of PCM in a typical temperature range in buildings.

The climate cycling test was conducted to analyze the daily thermal behavior of the prepared RC-SSPCMs. The climate cycling tests were performed by placing RC-SSPCMs in a constant temperature and humidity chamber, over 72 hours. The RC-SSPCMs were insulated with 30 mm of extruded polystyrene (XPS). Each insulation box was made in dimensions of 160 mm × 160 mm × 50 mm and temperature data were collected by attaching a type K thermocouple to the top and bottom surfaces. The temperature data were recorded for 72 h at an interval of 30 s using a data logger (Graphtec GL-840).

3. Results and discussion

The thermal conductivities of n-octadecane, EP-SSPCM, and EV-SSPCM were analyzed using a TCi thermal conductivity analyzer, to be 0.265, 0.231, and 0.157 W/m∙K at 25 °C, respectively. EV has characteristics of low thermal conductivity because of its porosity. Thus, the thermal conductivity of EV-SSPCM impregnated with n-octadecane was also determined to be low.

The thermal stability of SSPCMs were analyzed through TGA. SSPCMs undergo no weight change below 100 °C. The temperature behavior in a typical building is not exhibited above 100 °C; hence, it is thermally stable. n-Octadecane was pyrolyzed in the interval between 100 °C and 200 °C. This is the amount of n-octadecane impregnated in the SSPCM and can be judged by the impregnation amount.

In the climate cycling results of RC/EP-SSPCMs and RC/EV-SSPCMs, the thermal behavior changes due to latent heat between 26 °C and 28 °C constitute the phase change range of PCM. A more detailed analysis used the second cycle from 24 h to 48 h. The thermal behavior of RC/EP-SSPCM from 24 h to 48 h is shown in Figure 1.
Figure 1. Thermal behavior of RC/EP-SSPCM panels by climate cycling test. (a) Top, and (b) bottom.

Figure 2. Thermal behavior of RC/EV-SSPCM panels by climate cycling test. (a) Top, and (b) bottom.

Figure 1 (a) shows the surface of the top, where there is a surface-exposed climate condition, and Figure 1 (b) shows the surface of the bottom, where there is insulation. The time lag effect and peak temperature reduction occurred due to the phase change of PCM. The time lag effect of the upper surface occurred for P10 up to 1.30 h. The time-lag effects of each specimen at the bottom surface were determined to be at 0.15 h, 0.21 h, 0.69 h, and 1.33 h for P2.5, P5, P7.5, and P10, respectively. The thermal behavior of RC/EV-SSPCM from 24 h to 48 h is shown in Figure 2. Figure 2 (a) shows the surface of the top, where there is a surface-exposed climate condition, and Figure 2 (b) shows the surface of the bottom, where there is insulation. Unlike the RC/EP-SSPCM above, the time-lag effect of RC/EV-SSPCM is insignificant. This is due to the low thermal conductivity and the amount of n-octadecane of the EV. For charging or discharging the heat of the PCM actively, the thermal conductivity should be high; however, the low heat conductivity of the EV interferes with the heat accumulation and heat
dissipation. As a result of the climate cycling test, the RC/EP-SSPCMs panel showed a larger time-lag effect and peak temperature reduction.

4. Conclusion

The prepared SSPCMs were impregnated with 80.5% of EP-SSPCM and 59.0% of EV-SSPCM. The EV and EP with n-octadecane were impregnated by physical bonding without chemical reaction. The thermal properties of the prepared SSPCMs were analyzed by TGA, TCI. EP-SSPCM and EV-SSPCM had a suitable temperature range and excellent latent heat capacity for building applications. The thermal performance of the RC-SSPCM energy storage panels was evaluated through climate cycling tests. The time lag effect was up to 1.33 h and the peak temperature decreased by up to 1.6 °C at the phase change range of RC-SSPCM. Applying energy storage building materials that can efficiently use thermal energy to a building can reduce the peak load of building energy use and reduce the heating and cooling load by efficient use of thermal energy and, furthermore, increase the thermal comfort.

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