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Capacity of Wood as Flooring Material: Improvement of Thermal Performance of Wood/Phase Change Material Composites

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Abstract. *Wood is a biomaterial with good carbon fixation capacity. Phase change materials (PCMs) can impart thermal storage performances to materials. The goal of this study is to improve thermal performance by impregnating PCM into porous wood. The chemical stability of the composites was analyzed to evaluate whether it was appropriate for PCM to be impregnated into wood. Thermal performance of the composites was evaluated through latent heat analysis and thermal conductivity analysis. As a result of the analysis, the composites showed improved thermal performance compared to pure wood. In addition, in order to evaluate the applicability of the composites for floor heating, the dynamic heat transfer test was conducted using specimens as flooring material. As a result, it was confirmed that room temperature maintained the indoor comfort temperature range for longer time in rooms where composite specimens were applied as floor material. Result suggests that the composites can reduce the time for operating heating energy for floor heating. Thus, composites produced in this study proved to have the potential to be used as floor finishing material for floor radiant heating systems.*

Keywords: *Phase change materials; Thermal storage performance; Floor radiant heating; Biomaterial; Composite;*

1 Introduction

Buildings consume energy and carbon during maintenance and recycling progress (Salaimanimagudam and Jayaprakash 2022). Hence, research on low-carbon building materials is being conducted to reduce carbon consumption. Among low-carbon building materials, wood is a biomaterial that can be easily processed (Cordier et al. 2021), so it is suitable for use as a building material. In addition, wood has a soft wood grain, so it is highly utilized as a floor finishing material. In order to utilize wood as a floor finishing material, discussions should be made on the applicability of the floor heating system (Seo et al. 2011). Thermal storage performance is an essential characteristic for materials used in floor radiant heating because it can reduce the heating load. In this study, thermal storage performance was conferred to porous wood using PCM (Phase Change Material). PCM is a latent heat storage material that stores and releases heat in the form of fusion or solidification types during phase change process (Kim et al. 2021). Since PCM contains latent heat in during the phase change, it is applied to the thermal energy storage (TES) system. TES system reduces the building energy consumption (Jeon et al. 2019).

In this study, composite specimens were produced by impregnating PCM into wood. The thermal performance of the manufactured specimen is evaluated to verify its applicability as a floor finishing material in the floor radiant heating system.

2 Materials and methods

2.1 Materials

Spruce and paulownia were used for support materials of composites. The support material is defined as the material impregnated with PCM (Yoo et al. 2019). Spruce and paulownia wood without processing finishing treatment were used.

Spruce has fine wood grain and clean wood section, therefore applied as indoor finishing material. Paulownia has great function on moisture prevention and also has high dimensional stability, so applied as indoor finishing material. Spruce and paulownia are used as floor finishing materials because of their harmonious wood pattern. However, there is limitation that hard to use as structure material because of wood knots and softwood characteristics.

To exhibit thermal performance by applying PCM to materials, phase change temperature of the PCM should be included in the indoor comfort temperature range. Therefore, in this study, n-Octadecane, corresponds to organic paraffin-based PCM, with a melting point of 28.2 °C, was used as the PCM material.

2.2 Impregnation process of composites

The purpose of the vacuum impregnation method is to properly impregnate the PCM into the wood specimen. Paulownia and spruce were used as support materials, and PCM was stabilized by vacuum impregnation. Three steps were performed for the vacuum impregnation process. First, vacuum heating was executed to extract air and moisture from the pores of wood specimens. Specimens were placed in the vacuum oven for 24 hours under conditions of -0.085 kPa and 110 °C. Vacuum heating process removes air and moisture from the pores, creating a space for PCM to impregnate. Second, specimens were placed in 23 °C state for 20 minutes to immerse PCM into pure woods and apply 15 g weight (0.147 N) to the upper part of the specimens to minimize contact between specimens and air. Third, vacuum impregnation was carried out in a vacuum oven under conditions of -0.085 kPa and 45 °C for 48 hours. To remove PCM from the specimen surface during vacuum impregnation, the sample was wrapped with a textiles consist of microfibers. After the impregnation process, solidified PCM was detached from specimen surfaces.

2.3 Specimen designation

Spruce composite specimens were labeled as SCn, and paulownia composite specimens were labeled as PCn. Pure spruce and paulownia specimens were labeled as SCxn and PCxn, respectively.

Table 1. Specimen designation table.

Size (Length × Width × Height)	Species	Wood/PCM composite	Pure wood
100 mm × 100 mm × 20 mm	Spruce	SC1, SC2	SCx1, SCx2
	Paulownia	PC1, PC2	PCx1, PCx2

2.4 Characterization

FTIR spectroscopy measurements were performed to determine the presence or absence of chemical bond formation between PCM and wood. Analysis was performed under wavenumber range of 4000–600 cm^{-1} using the vacuum FTIR/micrographic spectrometer (Vertex-80V/Hyperion2000, BRUKER, Germany).

Latent heat analysis was performed to measure the latent heat of the PCM impregnated in specimens. Analysis was progessed using the differential scanning calorimeter (DSC, TA instrument, USA), while changing the temperature to 10 °C/min in the range of 0 to 60 °C.

Thermal conductivity was measured using a heat flow meter (HFM 446 NETZSCH). The thermal conductivity was calculated by placing the specimen between a hot plate and a cold plate in thermal equilibrium and applying heat flow. For the accuracy of thermal conductivity values, the average temperature of specimens was set to 20 °C and 40 °C.

A dynamic heat transfer test was progressed by manufacturing the test module and measuring temperature inside rooms. The size of the model is 500 mm × 500 mm × 550 mm (length × width × height) and consists of four rooms with a size of 150 mm × 150 mm × 500 mm. Specimens were disposed at the bottom of each room. Due to the average heating time per day is about 8 hours (Kane et al. 2017), the heating and cooling cycle consisted of 2 hours of heating and 4 hours of cooling, and was measured twice repeatedly. Temperature at 30% height point of the room height was collected and replaced as the indoor temperature. Temperature was measured using temperature sensor and data logger (GL840). Figure 1 illustrates the schematic of the dynamic heat transfer test.

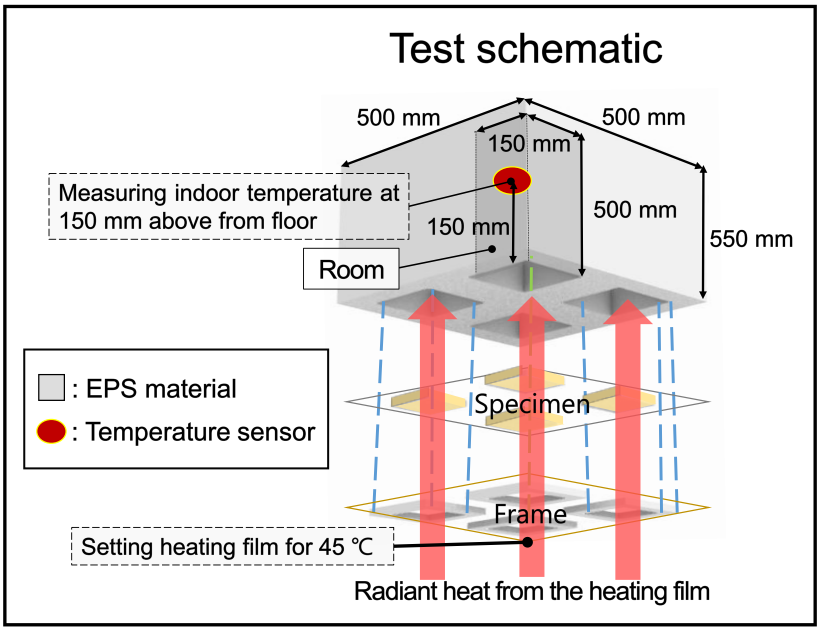

Figure 1. Experimental schematic of the dynamic heat transfer test

3 Results and discussions

3.1 Examination of the chemical stability of the composites

FTIR spectroscopy measurement was performed to determine whether chemical reaction between wood and PCM occurred during PCM impregnation process. Peak values of chemical bonds were detected in the FTIR spectrum. Figure 2 reveals the FTIR spectra of specimens. Chemical bonds of C-H, C-O, C=O, and C-C were identified in the FTIR spectra. The results suggest that the peak of bonds detected in pure wood specimens and the peak of bonds detected in composite specimens are coincide. Through result, it can be seen that wood and PCM do not form chemical bonds, but only physical interactions. Analysis represents that no additional chemical reaction occurred during the PCM impregnation process, and that PCM was stably impregnated. Thus, the composites can be used as a flooring material while maintaining the original characteristics of pure wood.

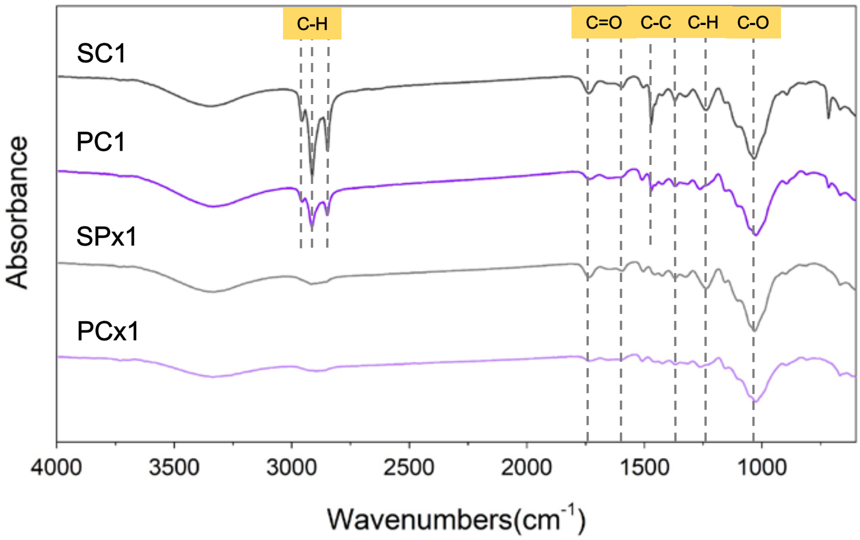

Figure 2. FTIR spectra of species and manifested chemical bonds

3.2 Thermal performance analysis of composites

3.2.1 Latent heat measurement of composites

Figure 3 shows the DSC curve during melt-freezing process of PC1, SC1 specimens and pure n-Octadecane. The peak point on the DSC curve is the phase change temperature of the PCM impregnated inside the specimen. The similarity between the phase change temperature of pure n-Octadecane and the phase change temperature of PCM impregnated in the composites specimens means that the PCM was impregnated normally in the wood specimen. The latent heat of the PC1 specimen was 81.05 and 91.34 J/g, implying that 34.94% of the PCM's thermal performance was expressed. Also, the latent heat of the SC1 sample was 55.97 and 61.01 J/g, indicating that 23.71% of the PCM's thermal performance was expressed. By DSC analysis, the thermal storage performance could be verified by numerically checking the latent heat amount inside the composites.

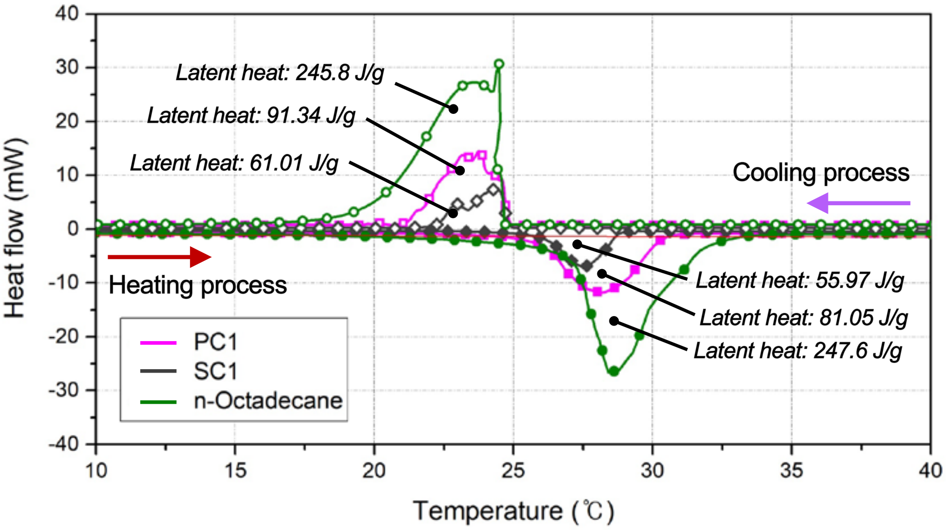

Figure 3. DSC thermographs of specimens and pure n-Octadecane

3.2.2 *Thermal conductivity measurement of composites*

The thermal conductivity analysis was performed twice with the average temperature of both plates set at 20°C and 40°C. Figure 4 presents the thermal conductivity of specimens under two temperature conditions. Porous structures of spruce and paulownia have low thermal conductivity due to the air present in internal pores. The thermal conductivity of the SC2 specimen show a 10.95% improvement compared to the SCx2 specimen, and the thermal conductivity of the PC2 specimen show a 12.86% improvement compared to the PCx2 specimen. PCM inside the composites activates molecular motion with heat convection and stores a large amount of heat. Stored heats indicate high thermal conductivity values. Improved thermal conductivity values demonstrate the thermal storage performance of wood/PCM composites.

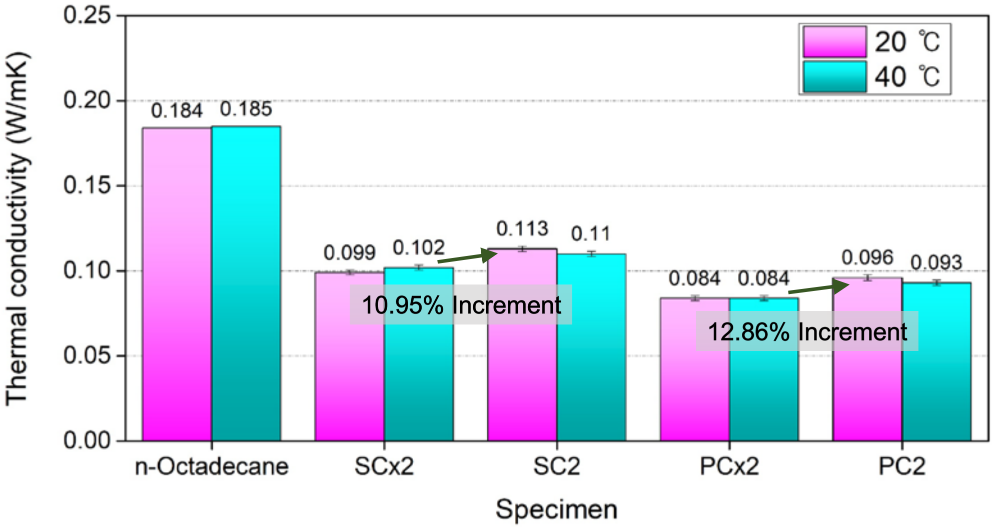

Figure 4. Thermal conductivity illustration of specimens and pure n-Octadecane

3.3 Examination of the applicability of composites in floor radiant heating systems

Dynamic heat transfer tests have been implemented to investigate the potential of reducing the heating load by applying the composite to floor radiant heating. Figures 5 and 6 illustrate the room temperature changes of the dynamic heat transfer test. The room in which the SCx2, SC2, PCx2, PC2 specimen was added to the flooring was labeled as SCx2_inside, SC2_inside, PCx2_inside, and PC2_inside, respectively. During the heating process, the indoor temperature of composites rooms were delayed compared to that of the pure wood rooms, confirming the time-lag effect due to the thermal storage performance of PCM. In addition, during the heating process, the peak temperature was lower in composites rooms than in pure wood rooms. It was confirmed that the indoor temperature slowly changed due to the time-lag effect and peak temperature decrease effect of the composites.

The gentle slope of temperature change implies that composites can maintain the indoor temperature at an indoor comfort temperature range for a long time by utilizing the heat accumulated inside the PCM. In other words, if the composites is used as a flooring material, the indoor temperature can be maintained at an indoor comfort temperature range for a long time with small amount of heating energy consumption. Therefore, the test results suggest the possibility of using composites as a floor finishing material for the floor radiant heating system.

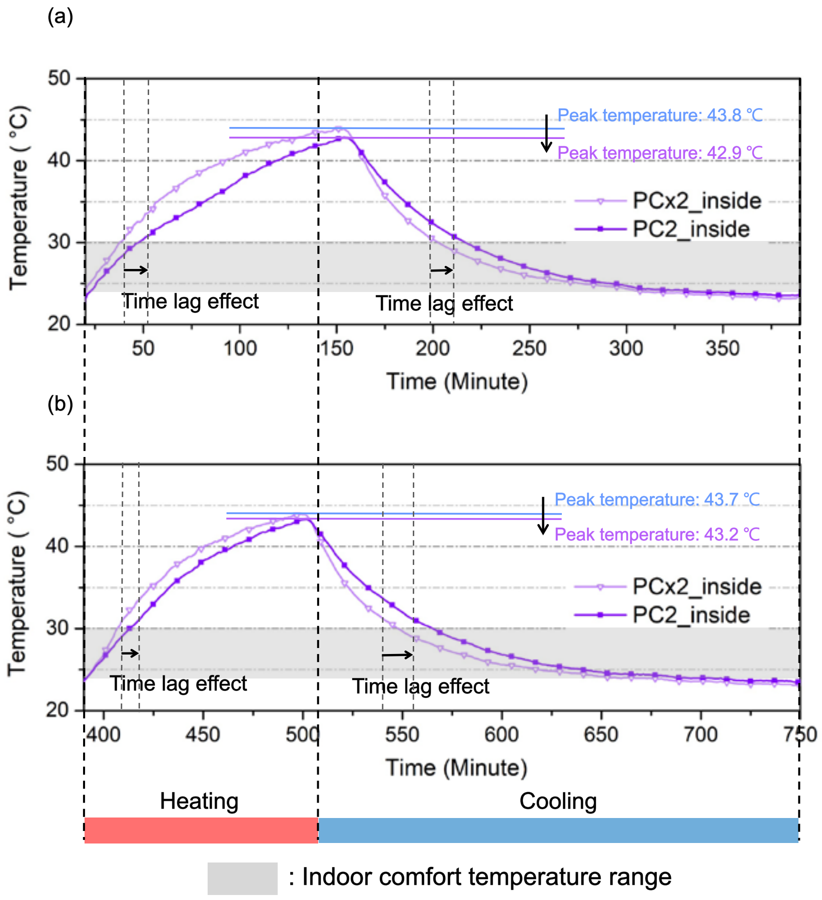

Figure 5. Indoor temperature change results on the (a) first heating & cooling cycle of the PCx2_inside and PC2_inside; (b) second cycle of the PCx2_inside and PC2_inside

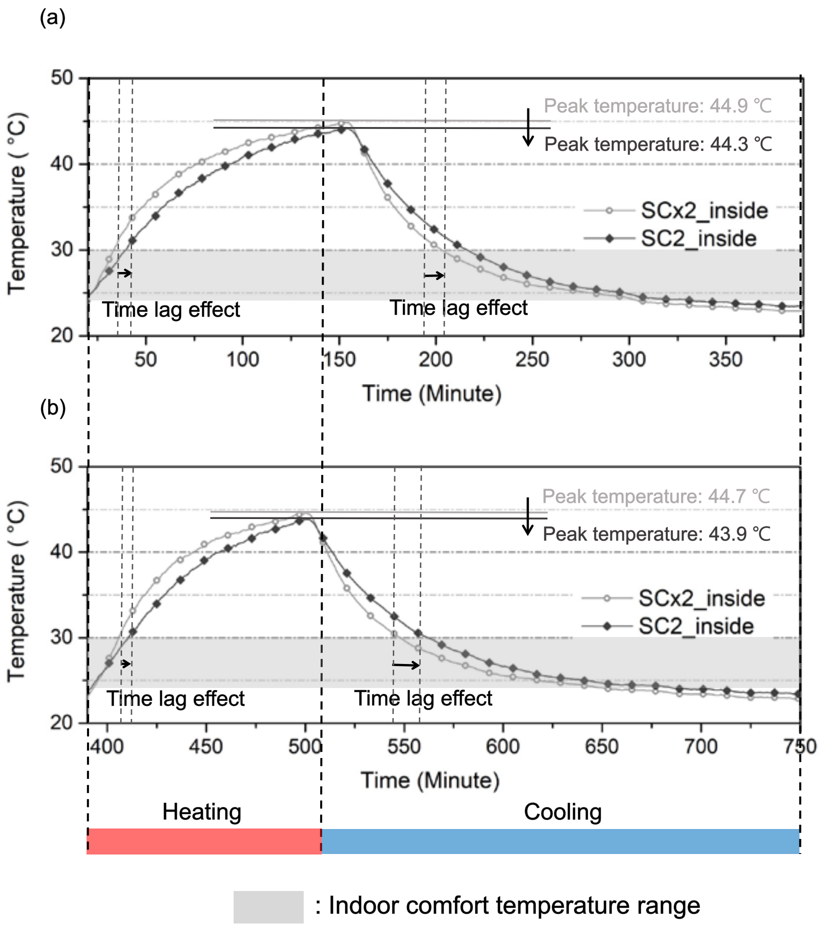

Figure 6. Indoor temperature change results on the (a) first heating & cooling cycles of the SCx2_inside and SC2_inside; (b) second cycle of the SCx2_inside and SC2_inside

4 Conclusions

The chemical bonds present in pure wood and composites were analyzed by FTIR spectroscopy, and it was derived that no additional chemical reaction occurred in wood and PCM during the impregnation process. It has been proven that wood and PCM form only physical bonds. As a result of thermal performance analysis, the composites showed remarkable thermal storage capacity. The paulownia composites showed an average latent heat capacity of 86.20 J/g, and the spruce composites showed an average latent heat capacity of 58.49 J/g, showing 34.94% and 23.71% of the thermal storage performance of pure n-Octadecane. The thermal conductivity of the composites specimens were 11-13% higher than that of pure wood specimens. An increase in the temperature of the PCM inside the composites resulted in higher thermal conductivity values. Through the dynamic heat transfer test, the possibility of reducing heating energy consumption was evaluated by applying the composites to floor radiant heating. It was observed that the slope of the temperature change was gentle in rooms where the composites was used as flooring material. Through the dynamic heat transfer test, it is suggested that indoor temperature can be maintained within the indoor comfort temperature range for a long time to reduce the amount of energy used for heating.

It has been proven that the composites manufactured in this study exhibits thermal storage performance and able to reduce heating load when applied to floor heating. Thus, it has been demonstrated that the composites can be used as a floor finishing material in the floor radiant heating system to operate heating efficiently.

Acknowledgements

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