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Research Article

Proposal of a PCM Underfloor Heating System Using a Web Construction Method

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Apartment buildings in Korea have adopted underfloor heating systems using web construction methods based on concrete and hot water systems. However, since such systems consume significant amounts of energy for heating owing to their low thermal storage performance, it is necessary to develop a new system that can minimize energy consumption by improving concrete thermal storage performance. This study proposes a phase-change material (PCM) underfloor heating system to reduce energy consumption in apartment buildings. An optimal design for a PCM underfloor heating system is proposed, and thermal storage performance of the proposed system is evaluated experimentally. The temperature range of the PCM for underfloor heating is also calculated considering the proposed design and comfortable heating conditions for domestic apartment buildings. Results indicate that a PCM underfloor heating system can be constructed in the following order: (1) a 210 mm concrete slab, (2) a 20 mm cushioning material, (3) 40 mm of mortar including a 10 mm PCM thermal storage container, and (4) 40 mm of finishing mortar including wire mesh and hot water pipes. The temperature range of the PCM used for underfloor heating in domestic apartment buildings is 32–45°C. Experimental tests reveal that thermal storage performance of underfloor heating systems that apply 35, 37, 41, and 44°C as representative PCM temperatures is superior to existing systems.

1. Introduction

As underfloor heating systems (UFHSs) use radiation from a floor surface for indoor heating, they can maintain indoor air temperature more comfortably than other types of heating systems [1–4].

In Korea, UFHSs have been widely used in residential buildings. Specifically, most apartment buildings, which account for approximately 65% of total residential buildings in Korea, adopt this type of heating system [5–10].

Unlike other countries that mainly use the dry construction method, most UFHSs applied to apartment buildings in Korea are constructed using the wet construction method.

System construction is completed by installing materials over a concrete slab in the following order: cushioning material, autoclaved lightweight concrete (ALC), wire mesh, hot water pipes, and finishing mortar. In addition, hot water, which is supplied by individual boilers or from the Korea District Heating Corporation (KDHC), is used as the heat energy source [11]. Among these materials, ALC and finishing mortar are essential in determining heating energy consumption because they store or discharge the heat energy supplied by the hot water [12–17].

However, the poor thermal storage performance of ALC and finishing mortar necessitates a large supply of hot water and increases energy consumption. Moreover, when the hot water supply is interrupted, the underfloor surface temperature drops drastically. These are the disadvantages of UFHSs [18–20].

Therefore, a new UFHS with superior thermal storage performance should be designed to reduce heating energy consumption of apartment buildings in Korea.

Recently, a UFHS using a phase-change material (PCM) has been introduced as an alternative. This type of UFHS does not require an additional supply of heat energy but uses stored latent heat to maintain a constant temperature [21–41].

In the USA, China, Japan, and some European countries, such UFHSs using PCMs have already been actively studied and are being applied in both residential and nonresidential buildings [42–45].

However, most systems adopted in these countries use the dry construction method and electricity as a heat source [25, 43]. For this reason, these systems are not suitable for Korean apartment buildings, which adopt the wet construction method and hot water as a heat source.

Consequently, it is necessary to design another type of PCM-based UFHS that can be applied to apartment buildings in Korea to reduce energy consumption. This study proposes a new PCM underfloor heating system (PUFHS) that uses the wet construction method and hot water.

For this, in Section 2, we analyze the current standard for underfloor heating of domestic apartment buildings and propose the optimal design of a PCM underfloor heating system that can improve the thermal storage performance of existing systems. Temperature ranges of PCMs that satisfy both indoor temperatures and floor surface temperature conditions for heating are also proposed. In Section 3, the experimental method and conditions for evaluating thermal storage performance for the proposed PCM underfloor heating system are explained, and Section 4 presents the analysis of the results obtained from the experimental tests.

2. Design of a PCM Underfloor Heating System

2.1. Standard for Underfloor Structure in Apartment Buildings. In Korea, the standard trend for underfloor structure of apartment buildings does not focus on energy consumption but on noise between floors, which has recently emerged as a social problem [46, 47]. However, every apartment building should conform to the "standard of structure for insulating floor impact sound between floors for noise prevention" by the Ministry of Land, Infrastructure and Transport (MOLIT).

The key points of this standard are as follows [11]:

① A heavy-weight floor impact sound of an underfloor structure shall be 50 dB or below.

② A lightweight floor impact sound of an underfloor structure shall be 58 dB or below.

③ Otherwise, one of the standard underfloor structures suggested by MOLIT shall be adopted.

The underfloor structure of apartment buildings should conform to articles ① and ② of the abovementioned standard. Otherwise, as shown in Figure 1, one of the standard underfloor structures presented in article ③ should be adopted.

In Korea, most apartment buildings choose the first model of the standard underfloor structures in article ③ provided by MOLIT, as it is easy to construct and maintain and incurs low construction costs [49].

Almost all apartment buildings adopt the first standard underfloor structure in Figure 1; however, as mentioned in the introduction, this structure includes ALC and finishing mortar, which have very poor thermal storage performance [18–20]. Therefore, in order to solve the problem of large energy consumption caused by underfloor heating, the thermal storage performance of ALC and finishing mortar must be improved. One of the most effective alternatives is to incorporate a PCM, which is a latent heat storage material, into the floor. The details of this solution are described in the following sections.

2.2. Concept of a PCM Underfloor Heating System. Figure 2 shows the design of the PUFHS proposed in this study to be applied in apartment buildings in Korea. Because of the MOLIT standard for floor thickness and noise between floors, the concrete slab and cushioning material shall be the same as before, whereas the ALC is replaced by mortar and PCM in order to enhance thermal storage performance.

In this structure, 15 mm of mortar, 10 mm of PCM, and 15 mm of mortar are sequentially installed over a concrete slab and cushioning material. Afterward, a wire mesh and 40 mm of finishing mortar including hot water pipes are installed over the cured mortar.

In this type of construction, the PCM can improve the thermal storage performance of both ALC and finishing mortar, and all stages of this process shall be the same as before except for the PCM installation, which also results in good constructability.

Although the MOLIT standard for light- and heavy-weight floor impact sound requires testing and verification, no additional building material is necessary if the standard is satisfied. For this reason, the PUFHS proposed in this study is applicable to both existing and new apartment buildings as an alternative heating system in order to save energy.

2.3. Selection of PCMs for Underfloor Heating. The first step in constructing a PUFHS is to select a PCM that can satisfy the conditions of indoor temperature and underfloor surface temperature for apartment buildings in Korea.

Based on the initial conditions of indoor heating temperature (T_{in}), underfloor surface temperature (T_{sur}), and PCM temperature, the surface temperature of each underfloor layer can be calculated using (1), for which the mathematical model is shown in Figure 3 [50].

$$\begin{aligned}
\dot{Q} &= \frac{T_{\text{pcm}} - T_{\text{in}}}{R_{\text{total}}} \\
R_{\text{total}} &= \sum R_{\text{cond}} + R_{\text{sur}} \\
R_{\text{cond}} &= \frac{l}{k \cdot \mathrm{A}} \\
R_{\text{sur}} &= \frac{1}{\alpha \cdot \mathrm{A}} \\
T_{\text{mor}} &= T_{\text{pcm}} - \left(\dot{Q} \cdot R_{\text{cond,mor}}\right) \\
T_{\text{sur}} &= T_{\text{mor}} - \left(\dot{Q} \cdot R_{\text{cond,woo}}\right),
\end{aligned} \tag{1}$$

where A (m^2), k (W/m·°C), and l (m) represent the surface area, thermal conductivity, and thickness, respectively. $\dot{Q}$ (W)

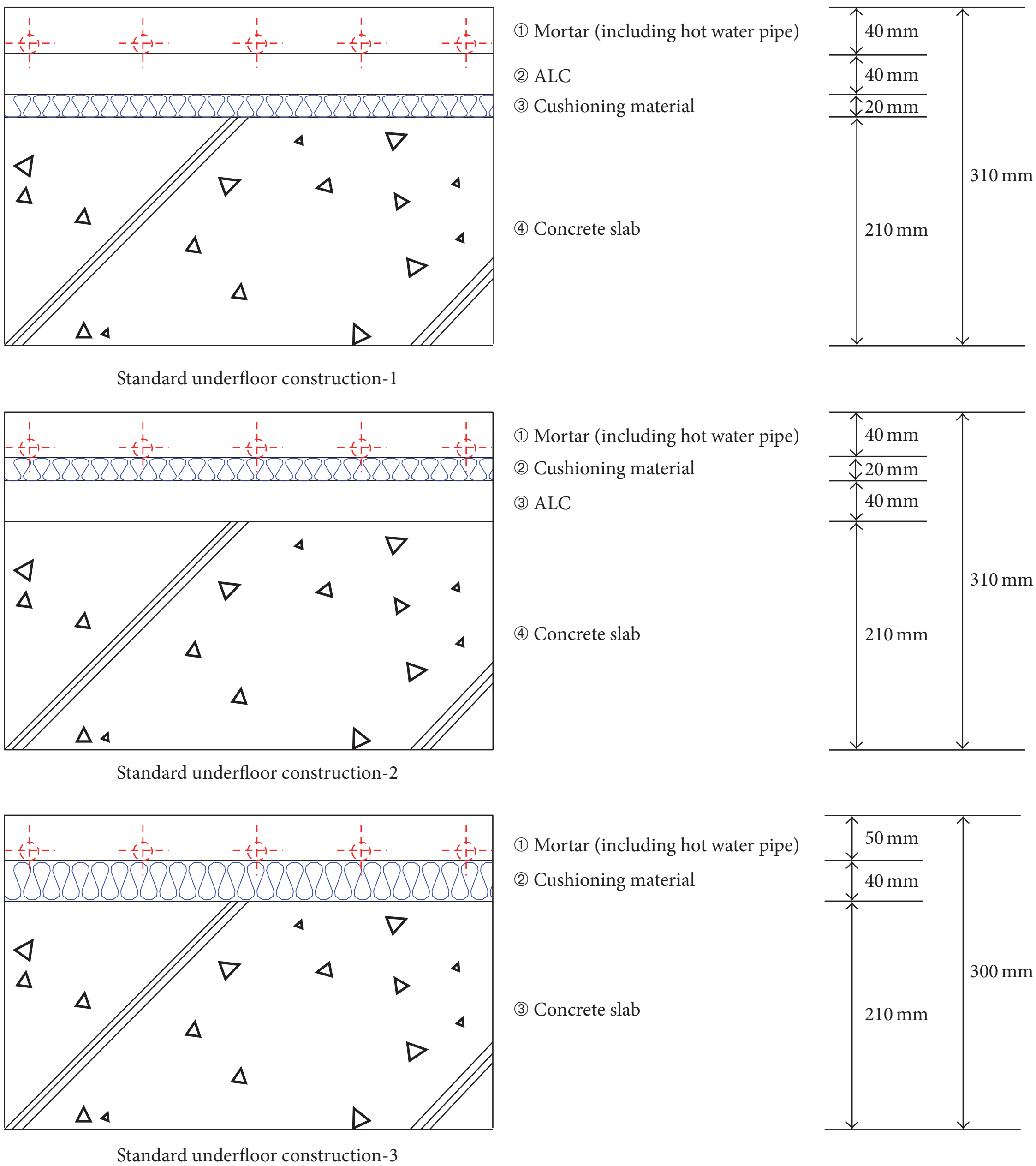

Figure 1: Standard underfloor structures proposed by MOLIT.

is the amount of heat transferred from the PCM to the heated space.

In addition, R_{total} (°C/W), R_{cond} (°C/W), and R_{sur} (°C/W) are the total heat transfer resistance, thermal conductivity resistance of the phase-change material, and underfloor surface heat transfer resistance, respectively. T_{pcm} (°C), T_{in} (°C), T_{mor} (°C), and T_{sur} (°C) refer to the temperatures of the PCM, heat space, mortar, and underfloor surface, respectively. In addition, α (W/m^2 · °C) is the total heat transfer coefficient of the underfloor surface.

As for initial conditions, the indoor heating temperature T_{in} and the underfloor surface temperature T_{sur} range from 22 to 26°C and from 28 to 30°C, respectively, as proposed by recent studies conducted in Korea [51, 52].

Table 1 provides the temperatures for each layer calculated by applying these conditions.

When the indoor temperature T_{in} was 22°C, the temperature of the PCM satisfying the proposed underfloor surface temperature of 28–30°C was calculated to be in the range of 38–45°C. When T_{in} was 26°C, the result of the calculation ranged from 32 to 39°C.

As a result, the applicable temperature of the PCM that satisfies the conditions of indoor temperature and underfloor surface temperatures ranged from 32 to 45°C.

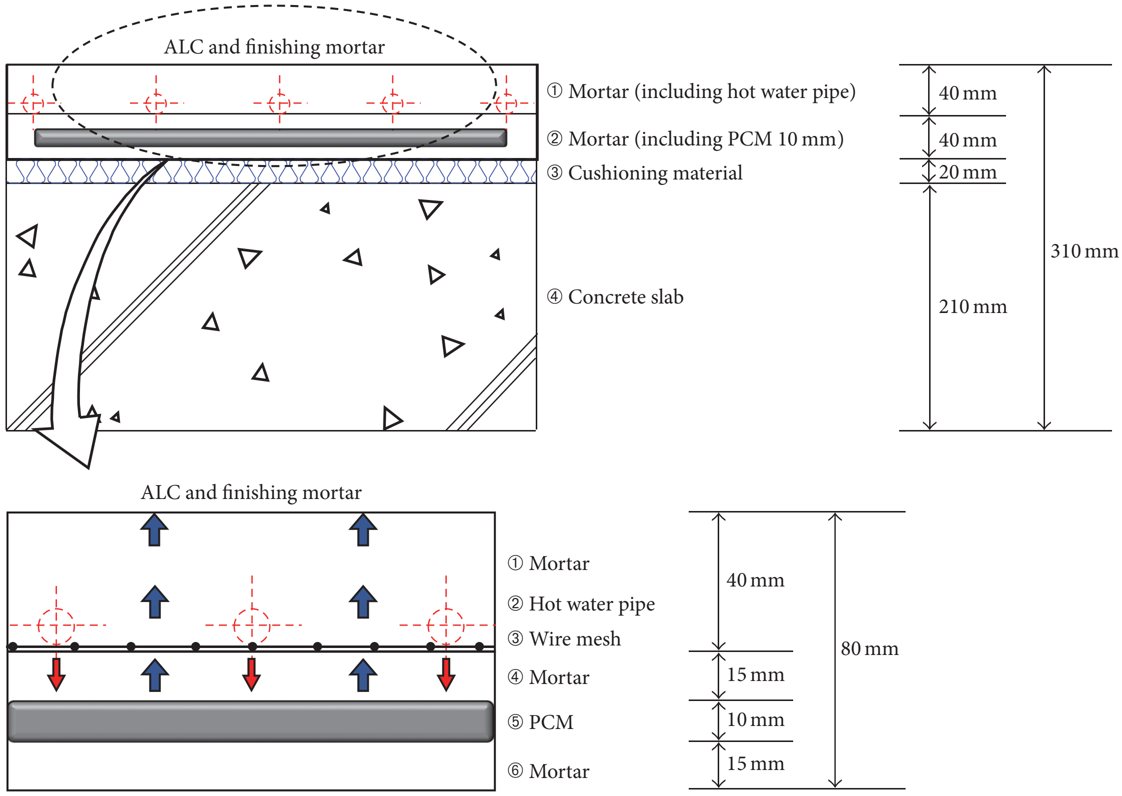

FIGURE 2: Design and characteristics of PCM underfloor heating system.

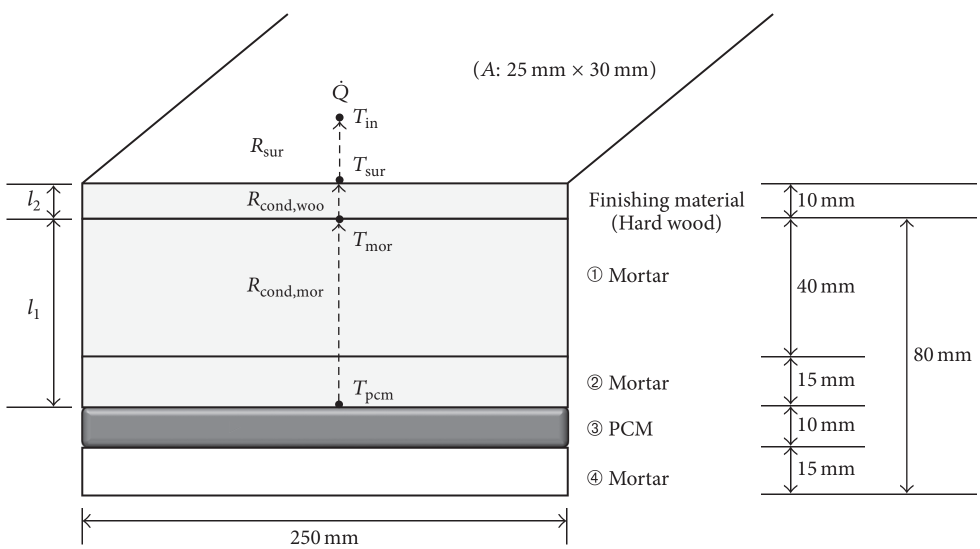

FIGURE 3: Mathematical model for producing optimal PCM for PCM underfloor heating system.

However, as PCMs are not produced in Korea and only some types of imported PCM are available, the types of PCM that satisfy the results above are extremely limited.

Therefore, considering the market conditions in Korea, the types of PCM applicable to underfloor heating have relevant temperatures of 35, 37, 41, and 44°C, and the thermal storage performance of a PUFHS using these four types of PCMs was evaluated by the experiments presented in the next section [48].

3. Experimental Method

3.1. Phase-Change Material. Based on results determined by the mathematical model above, PCMs with relevant temperatures of 35, 37, 41, and 44°C can be used for the PUFHS, and the details of each PCM are shown in Table 2 [48].

3.2. PCM Thermal Storage Container. In order to integrate the selected PCM into the mortar, a container that can stably

Table 1: Calculations of indoor underfloor surface and PCM temperatures.

T_{pcm} (°C)	T_{in} (°C)	T_{mor} (°C)	T_{sur} (°C)
38.0	22.0	32.5	28.1
39.0	22.0	33.2	28.5
40.0	22.0	33.8	28.8
41.0	22.0	34.5	29.2
42.0	22.0	35.2	29.6
43.0	22.0	35.8	30.0
44.0	22.0	36.5	30.4
45.0	22.0	37.1	30.7
32.0	26.0	29.9	28.3
33.0	26.0	30.6	28.7
34.0	26.0	31.3	29.0
35.0	26.0	31.9	29.4
36.0	26.0	32.6	29.8
37.0	26.0	33.2	30.2
38.0	26.0	33.9	30.6
39.0	26.0	34.6	30.9

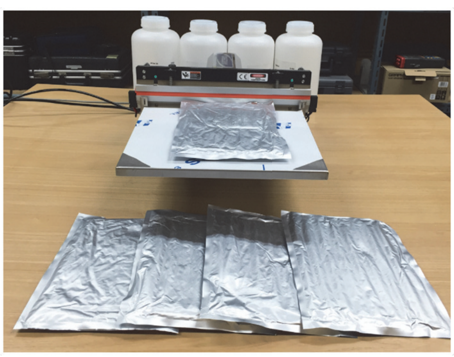

Figure 4: PTSCs embedded with PCM 35, 37, 41, and 44°C.

perform thermal storage and discharge through a phase change is required.

For this purpose, a PCM thermal storage container (PTSC) was fabricated by incorporating the PCM into an aluminum container with high thermal conductivity as well as good corrosion resistance and durability within the mortar.

After 1 kg of the solidified 10 mm thick PCM was incorporated into an aluminum container 200 mm in width, 300 mm in depth, and 0.1 mm in thickness, air was removed from the aluminum container by a vacuum device, and the container was sealed by a hot wire at a temperature above 200°C [53].

Figure 4 shows the completed PTSCs embedded with PCMs with relevant temperatures of 35, 37, 41, and 44°C.

3.3. Experimental Module of the PCM Underfloor Heating System. As shown in Figure 5, a small underfloor module was fabricated to evaluate the thermal storage performance of a PUFHS that uses PTSC.

For the purpose of comparison, the existing UFHS module (number 1 in Figure 5) was made with a thickness of 80 mm, which included 40 mm of ALC and 40 mm of finishing mortar. On the other hand, the module of the PUFHS proposed in this study (numbers 2–5 in Figure 5) was made with a total thickness of 80 mm, which included (sequentially) 15 mm of mortar, 10 mm of PTSC, 15 mm of mortar, and 40 mm of finishing mortar.

Each module was fabricated using a wooden form (300 mm width × 400 mm depth × 200 mm height), and sufficiently solidified PCM and mortar were used for experimental evaluation.

3.4. Boundary Conditions. As the main focus of this study was to develop a PUFHS with a new underfloor design incorporating a suitable PCM, the process of incorporating a boiler and hot water pipes into the underfloor system was excluded from this study.

Consequently, an alternative heat energy supply system was needed; thus, we used a small constant-temperature chamber (750 mm width × 250 mm depth × 650 mm height).

As this chamber can control the supplied quantity of heat over a range of 0–70°C, a sufficient quantity of heat can be supplied from the chamber to the underfloor system, similar to that when hot water is used as the heat energy source [54].

In addition, a monitoring system was used to collect temperature data during a set time period and to check the temperature change in real time [55]. The detailed configuration of the system is shown in Figure 6.

To compare thermal storage performance between the existing UFHS and the proposed PUFHS, temperature sensors were installed on the surfaces of the existing underfloor module and PUFHS module in order to monitor the variations of surface temperature with time.

In particular, both the existing and PUFHS modules were continuously heated at 46°C, which exceeds the melting points of all PCMs, so that the PCM could store as much latent heat as possible.

After the underfloor modules were sufficiently heated, the heat energy supply from the constant-temperature chamber was stopped, and the decrease of surface temperature between the two modules was compared.

The results of the experiments conducted under these conditions are presented in the next section.

4. Results and Analysis

Figures 7–10 show the comparative results of temporal variation of surface temperatures between the existing underfloor module and the PUFHS module embedded with PCMs with relevant temperatures of 35, 37, 41, and 44°C, respectively, when the heat supply from the constant-temperature chamber was stopped.

Figure 7 shows the analysis of surface temperatures of the existing module and the PUFHS module embedded with a 35°C PCM. After the heat energy supply from the constant-temperature chamber was stopped, the surface temperatures of both modules decreased very similarly for a period of time; however, after approximately six hours, when the latent heat

Table 2: Thermal characteristics of PCM in each temperature range [48].

Product name	Chemical description	Melting point (°C)	Heat storage capacity kJ/kg (Wh/kg)
Celsius PCM 35	Organic PCM	35	208 (57.6)
Celsius PCM 37	Organic PCM	37	200 (55.4)
Celsius PCM 41	Organic PCM	41	200 (55.4)
Celsius PCM 44	Organic PCM	44	230 (63.7)

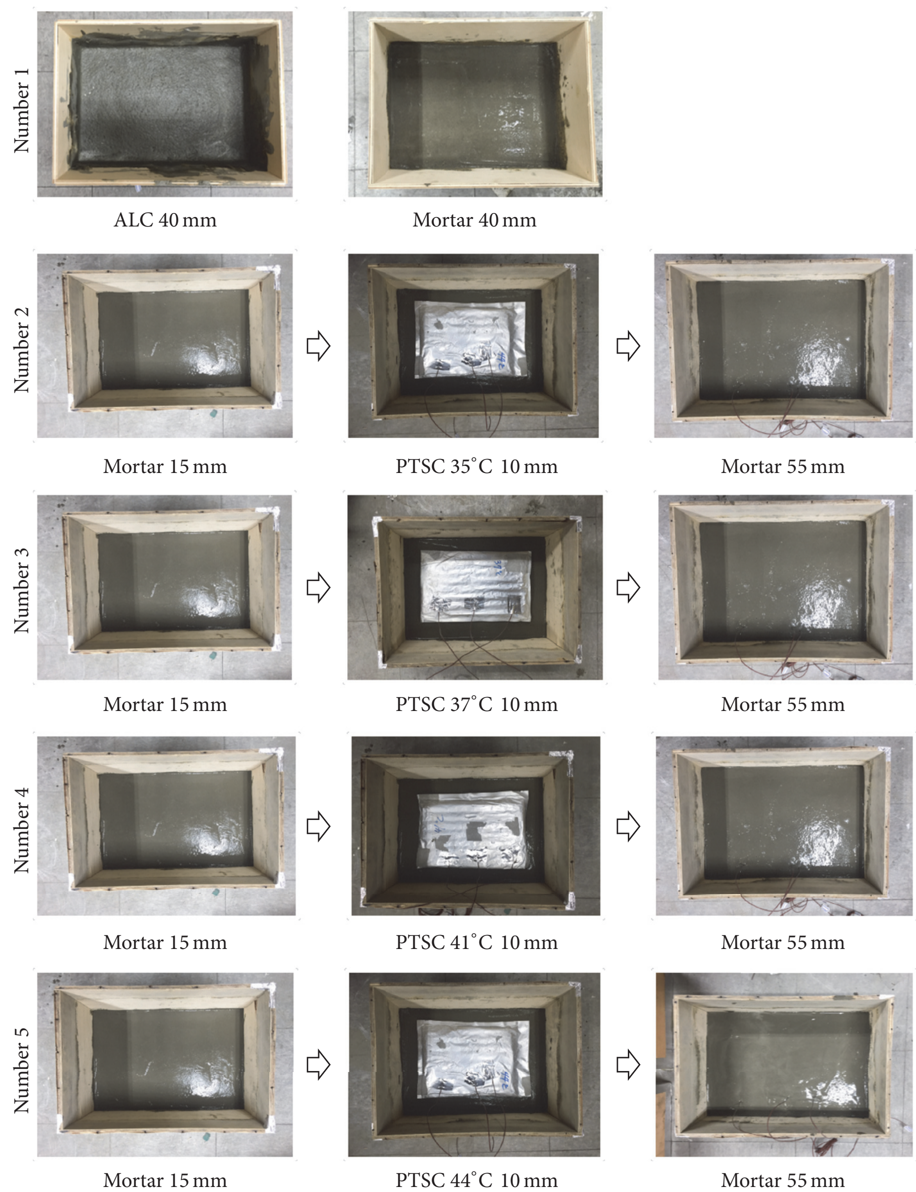

Figure 5: Fabrication process of experimental modules for existing and PCM underfloor heating system.

of the PCM began to be discharged, the surface temperature of the PUFHS was maintained at approximately 35°C or decreased gradually. In particular, the surface temperature of the PUFHS did not decrease drastically, even after the latent heat of the PCM was exhausted. This was because the sensible heat stored in the PCM was discharged. The overall difference of surface temperatures between the existing module and the PUFHS module was calculated to be in the range of approximately 0.7–2.9°C.

Figure 8 shows the analysis result of the surface temperatures of the existing module and the PUFHS module embedded with the 37°C PCM. Approximately four hours

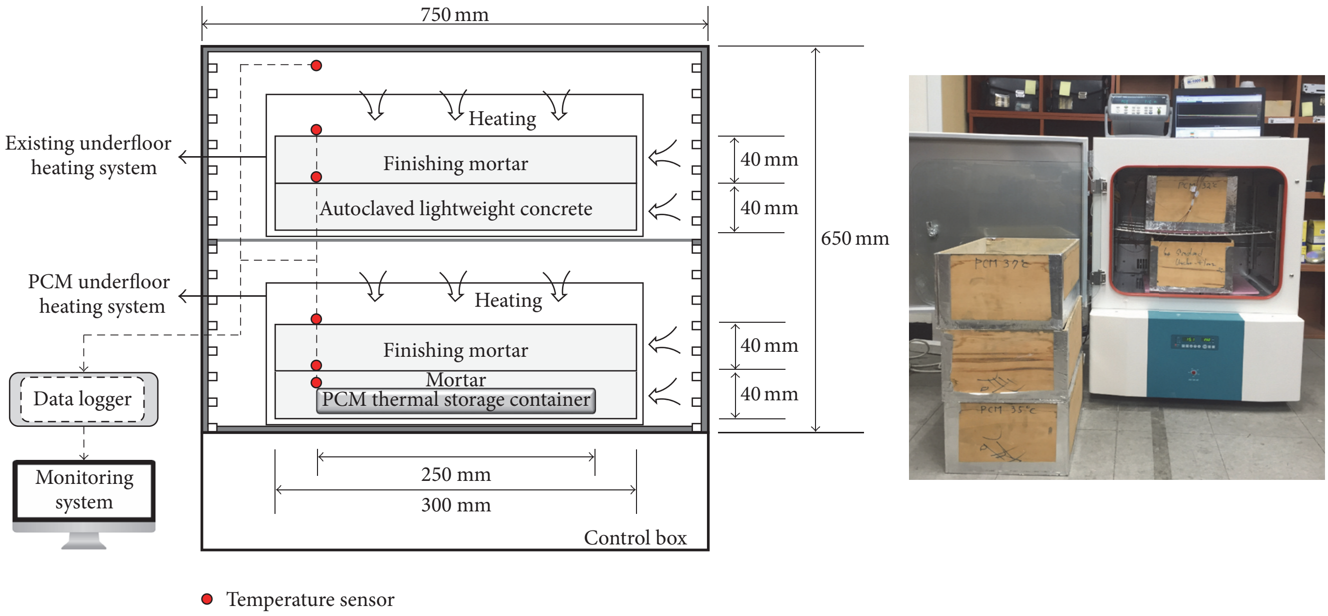

Figure 6: Construction of constant-temperature chamber and monitoring system.

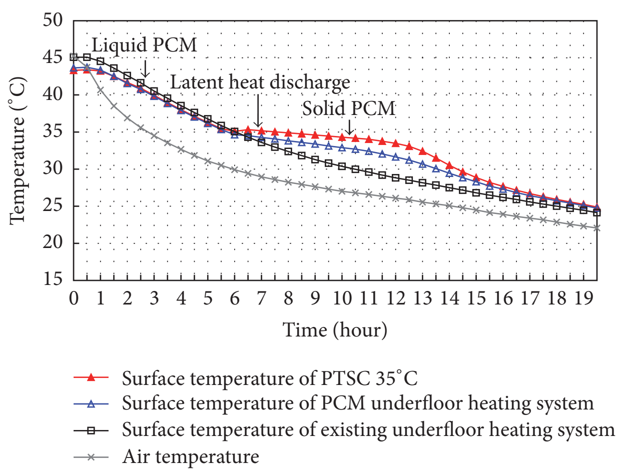

Figure 7: Surface temperatures of existing underfloor heating system and PUFHS with PTSC 35°C.

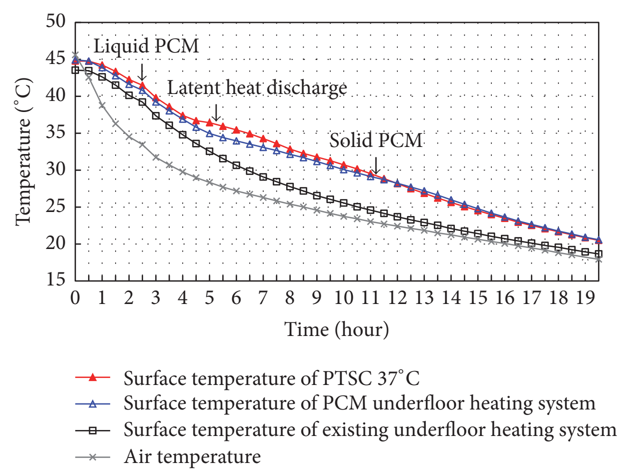

Figure 8: Surface temperatures of existing underfloor heating system and PUFHS with PTSC 37°C.

after the heat energy supply was stopped, the latent heat discharge from the PCM started, resulting in approximately 1.3 to 4.4°C of surface temperature difference between the existing module and the PUFHS module. Although the same types of organic PCMs were used, the 37°C PCM discharged sensible heat after a short period of latent heat discharge. This was because the 37°C PCM had less latent heat storage capacity than the 35°C PCM. In this case, a large amount of PCM would be required in order to maintain a constant surface temperature for a long period. Consequently, if this were applied to a real building, the initial investment cost would exceed those of other cases.

Figure 9 shows the analysis of surface temperatures of the existing module and the PUFHS module embedded with the 41°C PCM. Approximately four hours after the heat energy supply was stopped, the latent heat discharge from the PCM started, resulting in approximately 1.7°C to 5.2°C of surface temperature difference between the existing module and the PUFHS module. This case produced the largest difference of surface temperature between the two modules in the latent heat section of the PCM. Furthermore, the duration of constant temperature caused by the latent heat was also the longest in this case.

Finally, Figure 10 shows the analysis of surface temperatures of the existing module and the PUFHS module embedded with the 44°C PCM. The difference of surface temperatures between the existing and PUFHS modules was approximately in the range of 0.7–4.1°C. Approximately three hours after the heat energy supply was stopped, the latent heat was discharged. However, approximately one hour after

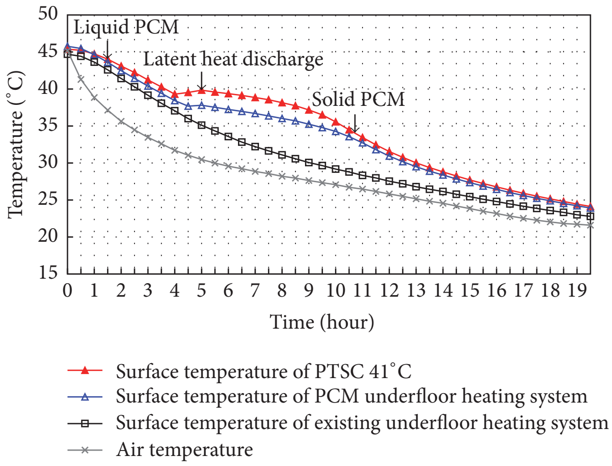

Figure 9: Surface temperatures of existing underfloor heating system and PUFHS with PTSC 41°C.

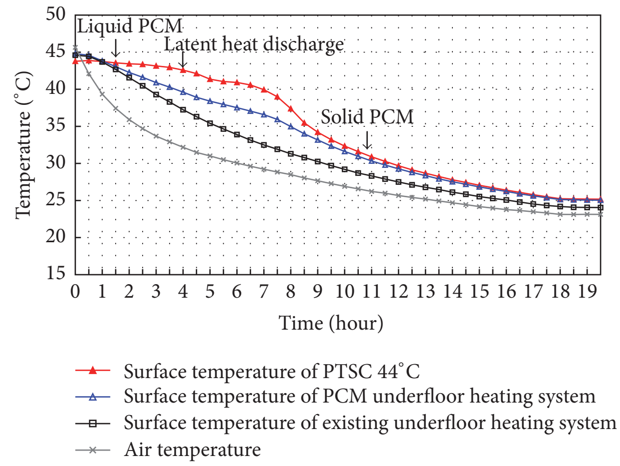

Figure 10: Surface temperatures of existing underfloor heating system and PUFHS with PTSC 44°C.

the discharge, the surface temperature decreased drastically. We assume that this is because the 44°C PCM has a very low latent and sensible heat storage capacity; thus, it had the lowest performance for PUFHS among the candidate PCMs.

From the results of our experiment, we conclude that the 41°C PCM is the most effective PCM that can be applied in a PUFHS for apartment buildings in Korea, as it has a large latent and sensible heat storage capacity and shows the largest difference of surface temperature compared with the existing module.

5. Conclusion

This study proposed a PUFHS for apartment buildings and evaluated its performance through experiments, of which the results are as follows:

(1) The structure of a PUFHS using the wet construction method and hot water to reduce heating energy in apartment housing is as follows:

① Concrete slab (210 mm)

② Cushioning material (20 mm)

③ Mortar (15 mm)

④ PTSC (10 mm)

⑤ Mortar (15 mm)

⑥ Wire mesh

⑦ Hot water pipes

⑧ Finishing mortar (40 mm)

(2) For apartment buildings in Korea, the temperature conditions of indoor heating and the underfloor surface range from 28 to 30°C and from 32 to 45°C, respectively. The temperature of the PCM satisfying these conditions is in the range of 32–45°C.

(3) To integrate the underfloor structure and the PCM, an aluminum container with good thermal conductivity, corrosion resistance, and durability can be used as a PCM thermal storage container (PTSC).

(4) The types of PCM applicable to apartment buildings in Korea are PCMs with relevant temperatures of 35, 37, 41, and 44°C, among which the 41°C PCM is the most suitable because it has the largest latent and sensible heat storage capacity and shows the largest difference of surface temperature compared with the existing underfloor module.

(5) The proposed PUFHS, which utilizes the wet construction method and hot water, can be adopted as a next-generation system to reduce heating energy consumption and greenhouse gas emissions in apartment buildings, which constitute approximately 65% of residential buildings in Korea.

Competing Interests

There are no competing interests to declare.

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