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Mock-up test on the application of phase change materials in underfloor radiant heating system in apartments

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ABSTRACT

Apartment housing in South Korea mainly uses underfloor radiant heating systems. However, the performance of these systems has not improved significantly in recent years. The heat storage capacity of the floor influences the heating energy required and impacts the comfort level of occupants. Thermal energy storage materials, such as phase change materials (PCMs), can be employed to increase the heat storage capacity. This study aims to investigate the appropriate installation position and phase change temperature of PCMs applied to an underfloor radiant heating system. Two mock-up tests were conducted. First, the PCM was installed on the top, side, and bottom of the heating pipe, and the floor surface temperature was compared with that of a conventional floor structure in each case. Second, PCMs with phase change temperatures of 34 and 43 ℃ were installed in different rooms, and the floor surface temperatures were compared. The results indicated that PCMs should ideally be installed at the bottom of the heating pipe, and a phase change temperature of 34 ℃ is appropriate for use in Korean underfloor radiant heating systems.

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KEYWORDS
Apartment housing; underfloor radiant heating system; phase change material; mock-up test

1. Introduction

In Korea, apartment housing accounts for approximately 53.2% of all residential buildings (Ministry of Land, Infrastructure and Transport 2020), which primarily use underfloor radiant heating systems. This system consists of a base, insulating, filling, piping (heating pipe), and top finishing layers, in accordance with the "regulations for facilities in buildings" (see Figure 1). Specifically, the base layer is a concrete slab that constitutes the lowest or inter-story floor. The insulating layer is installed on top of it to prevent heat loss through the base layer. Next, the filling layer is installed to adjust the height of the structure or to improve the soundproofing and insulation performance. In general, the height is leveled using cement mortar, concrete, and autoclaved lightweight concrete. On top of this layer, the piping layer is installed with the appropriate positioning of heating pipes, followed by the pouring of cement mortar. Finally, flooring materials are installed. In this approach, the filling and piping layers serve as thermal energy storage layers to maintain the temperature of the floor over an extended period of time. In the system, a hot-water heater based on a boiler transmits heat to the concrete floor structure via piping. The heat storage capacity of the floor influences the required heating energy, directly impacting the occupants' comfort. However, it is not feasible to substantially increase the thickness of the floor structure to improve the heat storage capacity owing to cost constraints. Therefore, to improve the heat storage capacity of underfloor heating systems at the same thickness, it is necessary to investigate the development of alternative materials and structures to concrete and cement mortar.

Thermal energy storage materials, such as phase change materials (PCMs), can be used to increase the heat storage capacity. PCMs can store energy and maintain a specified temperature (Fleischer 2015; Sarı 2004). PCMs can store 5 to 14 times more heat per unit volume than water, bricks, or rocks (Sharma et al. 2009). Several studies have been conducted on the architectural application of this material. It can be applied to a structure by mixing microencapsulated PCM with gypsum to create plaster wallboards (Lachheb et al. 2017) or by directly using PCM mixed with mortar (Cunha, Aguiar, and Tadeu 2016). PCM can also be inserted into the holes in bricks (Vicente and Silva 2014) for thermal applications. Additionally, it is possible to add PCM layers to walls (Panayiotou, Kalogirou, and Tassou 2016) and roofs (Pasupathy et al. 2008) or attach PCM tiles (Chung and Park 2016) to roofs. Particularly, the use of PCM in a building structure is effective in controlling time lag and peak temperature. It has also been reported that ventilation efficiency and energy performance are improved when PCM is used in heat exchangers (Promoppatum et al. 2017) or thermal storage systems (Gholamibozanjani and Farid 2020) in ventilation systems. Recently,

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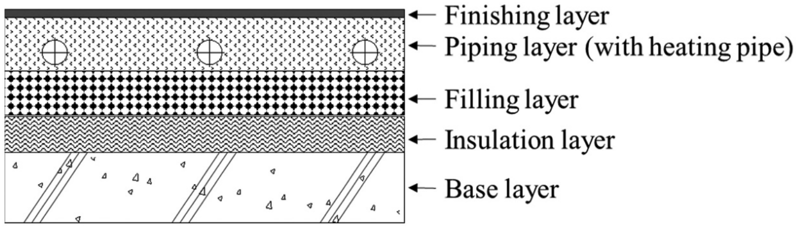


Figure 1. Configuration of a underfloor radiant heating system in Korea.

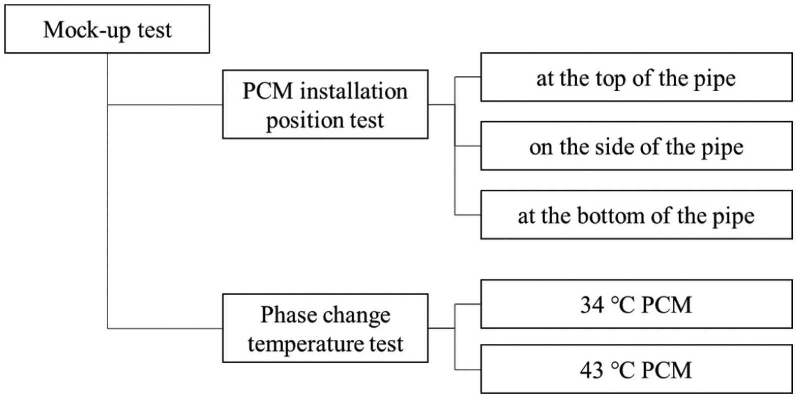


Figure 2. Framework of mock-up test.

machine learning technology is used to improve performance by combining with PCM-based building cooling and ventilation systems(Zhou et al. 2020a; Zhou et al. 2020b; Zhou and Liu 2023)

Particularly, the application of PCM in underfloor radiant heating is known to improve the duration of heating and comfort compared to conventional structures. Zhou et al. (Zhou and He 2015) reported that the application of PCM can double the heat dissipation time compared to sand and maintain the indoor temperature within a comfortable range. Lin et al. (Lin et al. 2005) proposed a dry construction method in which flooring materials mixed with electric panels and PCM were installed. They reported that daytime energy costs are reduced because heat storage is performed at night when electricity rates are low. Xia et al. (Xia and Zhang 2016) and Park and Kim (Park and Kim 2019) confirmed that a higher floor temperature can be maintained in PCM floors than in existing floor structures.

However, most of the studies on PCM floor heating so far have mainly considered the heat capacity of PCM. There is no study considering the installation location and phase change temperature of PCM. In a similar study, there is a study on convection and temperature changes inside the packing according to the location where heat is applied to the PCM (Peng et al. 2019; Zhang et al. 2021). But research on heat transfer characteristics when materials with different characteristics are combined, such as floor radiation heating structures, is insufficient. In addition, the PCM phase change temperature of the heating system used in the existing studies is in the range of 27 to 45 °C (Zhou and He 2015; Mazo et al. 2012; Cheng et al. 2015; Lu, Xu, and Tang 2020; Larwa, Cesari, and Bottarelli 2021). This temperature range had a very large interval. Since the phase change temperature may vary depending on the temperature of the supplied hot water and the conditions for setting the indoor temperature, it is necessary to suggest an appropriate phase change temperature according to the general climate of Korea, indoor temperature, hot water supply temperature, etc.

Therefore, in this study, comparative tests were conducted focusing on the PCM installation position and phase change temperature in an underfloor radiant heating system to achieve optimal heating performance. Ideally, the findings will lead to increased PCM application in apartment underfloor radiant heating systems, resulting in optimal heating and energy savings.

2. Materials and methods

2.1. Mock-up test overview

In this study, two mock-up tests were conducted to determine the appropriate PCM installation position and phase change temperature.(see Figure 2) First, PCM was installed on the top, side, and bottom of the piping in a conventional Korean underfloor radiant heating system to investigate the effect of the installation position. Here, two identical mock-up rooms (1) were built indoors. The conventional and PCM underfloor radiant heating systems were separately installed in the two rooms to compare the temperature change over time and delay time between the rooms.

Second, the appropriate PCM phase change temperature for use in the underfloor radiant heating system was determined. Here, two identical mock-up rooms (2) were constructed outdoors. PCMs with phase change temperatures of 34 ℃ and 43 ℃ were installed separately in the two rooms, and the temperature changes associated with the PCMs were measured.

2.2. PCM underfloor radiant heating system structure

The typical underfloor radiant heating systems used in apartment housing in Korea are outlined in the "structural standards on inter-floor impact sound insulation for noise prevention (Ministry of Land, Infrastructure and Transport 2018)". The floor structure consists of cushioning material (insulating layer), autoclaved lightweight concrete (filling layer), and finishing mortar (piping layer). The type preferred by construction companies is shown in Figure 3. Here, the finishing mortar of the piping layer dissipates and stores the heat obtained from the heating pipe.

Increasing the thickness of the finishing mortar layer can increase the heat storage capacity at the cost of the indoor floor height (see Figure 3). Therefore, utilizing PCMs with higher heat storage capacity, compared to conventional mortar in the floor structure, could effectively improve this parameter without increasing the thickness.

In the PCM floor structure, the heat storage and transfer characteristics are different because the finishing mortar and PCM are applied together. Therefore, the temperature delay time and construction may vary depending on the installation position of the heating pipe and PCM. In the underfloor heating system, PCM was installed on the (a) top, (b) side, and (c) bottom of the heating pipe (see Figure 4), and the temperature change characteristics for each position were compared.

2.3. Mock-up room configuration

2.3.1. Mock-up room (1): comparative test according to the PCM installation position

Two identical mock-up rooms, each having a floor area of 3.50 m^2 and volume of 8.4 m^3, were constructed (see Figure 5). A conventional underfloor radiant heating system was installed in Room 1 and the PCM system in Room 2. PCM was installed on the top, side, and bottom of the heating pipe, and a comparative test was performed with the standard floor structure of Room 1.

2.3.2. Mock-up room (2): comparative test according to the PCM phase change temperature

Two mock-up rooms, each having a volume of 13.2 m^3 and a floor area of 5.5 m^2, were constructed using 100-mm prefabricated panels and installed outdoors (see Figure 5). These two rooms were in the center of the four consecutive mock-up rooms, and an insulation of 20 mm was added to the side walls to prevent heat loss. Additionally, 250 T extruded insulation boards were installed in the walls between the rooms to minimize thermal bridging. The same 28-m heating pipe was installed in the two rooms, and blackout curtains were installed at each window to block out direct sunlight.

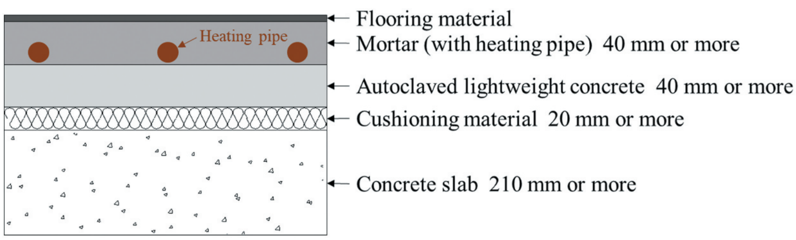


Figure 3. Standard floor structure in Korea.

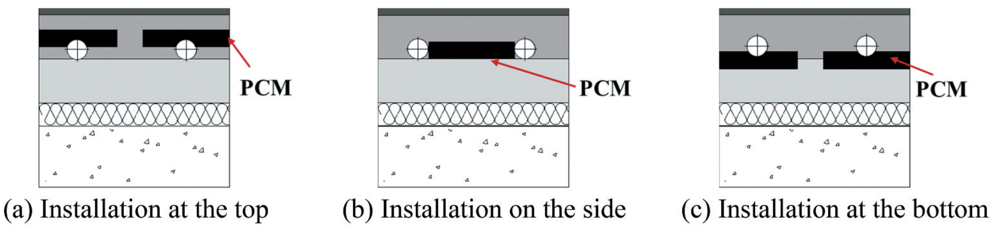


Figure 4. PCM installation position of the pipe: (a) top, (b) side, and (c) bottom.

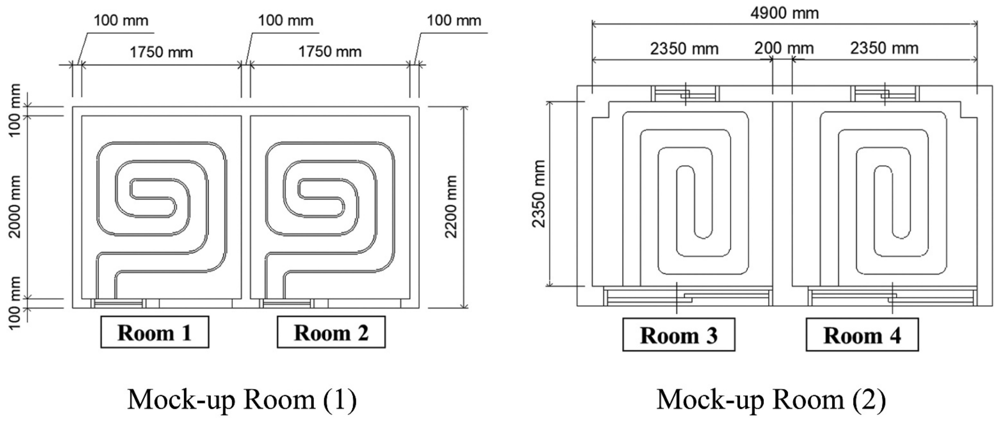


Figure 5. Dimensions and layout of mock-up rooms.

Table 1. Properties of applied PCMs.

PCM Type	43 °C PCM*	34 °C PCM**	Packing
Chemical name	n-docosane	n-eicosane	
Molecular Weight	310 g/mol	282 g/mol	
Typical Latent Heat Capacity	63.9 Wh/kg	57.8 Wh/kg	
Specific Heat Capacity	0.6 Wh/kg	0.6 Wh/kg	
Heat Conductivity	0.2 W/m·K	0.2 W/m·K	
Volume Expansion	12.5%	12.0%	
Phase Change Temperature	40 to 43 °C	31 to 34 °C	

*Company Sasol, PARAFOL 22–95
**Company Sasol, PARAFOL 20Z.

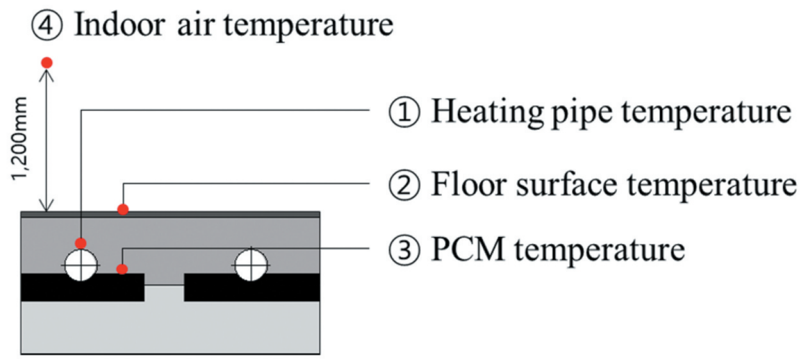


Figure 6. Locations of sensors.

The current standard floor structure applied to Mock-up room (1) was also applied to Mock-up room (2); however, the autoclaved lightweight concrete was removed such that the heat energy received from the pipe could be completely transferred to the PCM and upper mortar; the PCM was positioned at the bottom of the pipe.

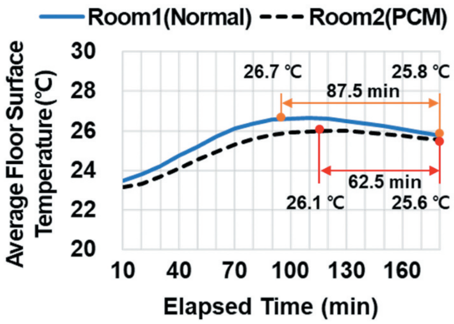
2.4. PCM types and properties

In the first comparative test, n-docosane PCM with a phase change temperature (melting point) of 40–43 °C (hereafter, 43 °C PCM) was applied. A PCM with a phase change temperature in the range of 32–45 °C was selected based on the results of a study by Beak and Park (Baek and Park 2017). It allows for a comfortable indoor heating temperature of 22 °C and a floor surface temperature of 28–30 °C, based on domestic recommendations. The 43 °C PCM has a latent heat capacity of 63.9 Wh/kg (see Table 1). A total of 20 kg of this material was used by preparing 0.2 kg units using an aluminum packing material.

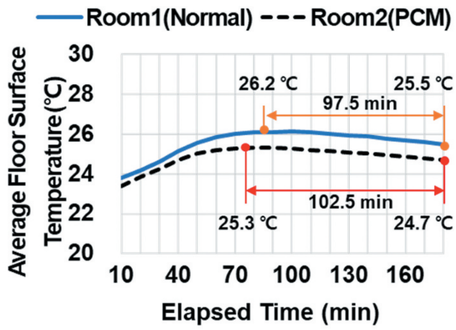
In the second comparative test, the 43 °C PCM and n-eicosane PCM with a latent heat capacity of 57.8 Wh/kg and a phase change temperature of 31–34 °C (hereafter, 34 °C PCM) were applied (see Table 1). The 34 °C PCM was installed in Room 3 and the 43 °C PCM in Room 4 using the same PCM amount (20 kg).

Table 2. Measuring instrument.

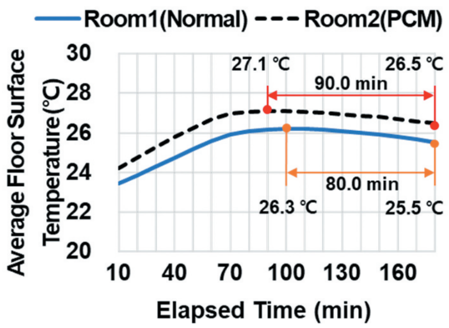
Category	Measurement sensor	Data collection
Product name	T-type thermocouple	midi LOGGER GL820
Measurement range	−250 to 350 °C	-
Error range	±0.5 °C, ±0.4%	±3%



(a) Case 1: Installation at the top



(b) Case 2: Installation on the side



(c) Case 3: Installation at the bottom

Figure 7. Changes in the average floor surface temperature of the heating cycle for each case.

2.5. Measurement conditions and boiler operation schedule

Temperature sensors were installed at the center of each room and at the center points of four equally divided areas to measure the changes in the floor surface, heating pipe, and PCM temperatures (see Figure 6). The indoor temperature was measured at 1.2 m above floor level at the center of each room. T-type thermocouples were used as temperature sensors (see Table 2). Data were measured every minute, and 10 min average values were used for analysis.

In the first comparative test, the boiler operation was set to intermittent heating based on the time required to supply hot water at the same temperature for a fixed time interval. A 1-h operation with a 2-h stop was repeatedly performed. The hot water supply temperature of the boiler was set to 75 °C, which is the highest temperature of the boiler.

Here, the floor surface temperature was compared between Rooms 1 and 2. Depending on the PCM installation location, the comparative cases were divided into the top (Case 1), side (Case 2), and bottom (Case 3). The measurement time was approximately 12 h for each case, in which four heating cycles could be repeated.

Unlike the first test, the boiler was set to operate continuously to maintain the same indoor temperature range (18–20 °C) in the second comparative test. Thus, the boiler was turned on at an indoor temperature of 18 °C and turned off at 20 °C. Here, the PCM temperature change was compared between Rooms 3 (34 °C) and 4 (43 °C). The hot water supply temperature of the boiler was set to 60 °C, which is generally used in Korea's underfloor heating systems. During the measurement process, the outdoor temperature ranged between 3 and 9 °C with an average of 6.3 °C.

3. Results and discussion

3.1. Test results of the PCM installation position

Overall, the surface temperature of the floor was found to be higher when the PCM was installed at the bottom rather than the top or side. On average, the time required to reach the peak temperature during heating was 10 minutes shorter than that required by the conventional room.

Table 3. Floor surface temperatures and temperature delay times according to the PCM installation position compared to the standard floor structure.

Category	Case 1		Case 2		Case 3	
	Room 1 (Normal)	Room 2 (PCM)	Room 1 (Normal)	Room 2 (PCM)	Room 1 (Normal)	Room 2 (PCM)
Temperature delay time (min/℃)	94.6	125.0	150.0	170.8	103.2	138.5
Difference (min/℃)	30.4		20.8		35.3	

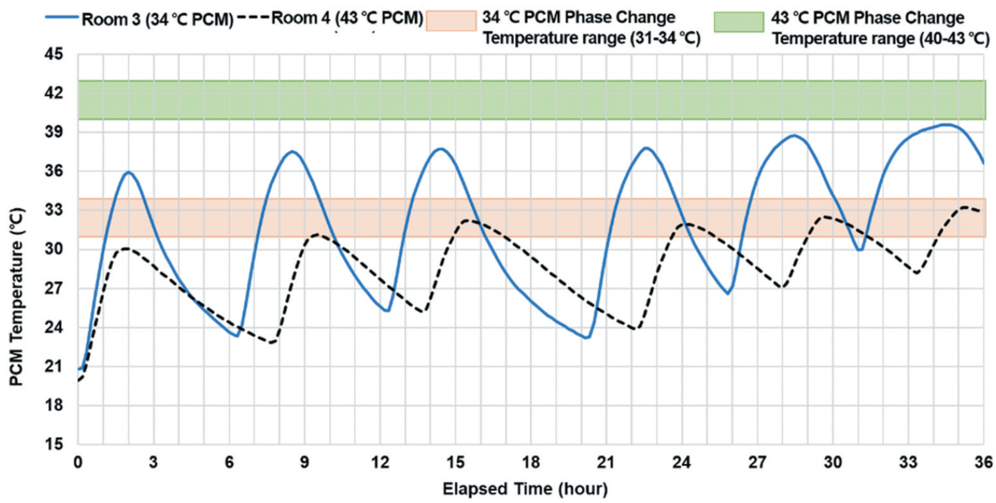


Figure 8. Test results for the PCM phase change temperature (34 ℃ and 43 ℃).

Figure 7 shows the changes in the average surface temperature of the floor for the heating cycle and the time required for the peak temperature to fall to the lowest temperature when heating was discontinued in each case. First, looking at the average floor surface temperature change, compared to the conventional rooms, the room with PCM installed at the top and side of the heating pipe had a relatively lower floor temperature, while the room with PCM installed at the bottom of the heating pipe had a higher floor height. This is related to the fact that the time taken to rise to the peak temperature during heating operation appears 10 minutes faster on average than in normal rooms when installed at the bottom rather than the top and side. In other words, when installed in the lower part, the temperature of the floor surface rises faster than in other cases, so it is considered that the average temperature during the total experiment time is higher than the temperature of the existing room.

Next, the heat storage was evaluated by comparing the temperature delay time (T) required for the temperature difference between the conventional and PCM underfloor heating systems to decrease by 1 ℃. Thus, the value obtained when the time (H) required for the peak temperature (T_1) to fall to the lowest temperature after heating was discontinued (T_2) was divided by the temperature difference (T_2-T_1) for comparison.

Table 3 shows the calculated values for the temperature delay time for each case. In all experimental cases, the PCM room appeared to be longer than the conventional room. The temperature delay time was longer by the order of 35.3 min/℃ at the bottom, 30.4 min/℃ at the top, and 20.8 min/℃ on the side. Therefore, by comparing the temperature delay times, it was determined that installing PCM at the bottom resulted in the best heat storage performance.

3.2. Test results of the PCM phase change temperature

Based on the experiments, the average temperature of each room is shown in Figure 8. For the 34 ℃ PCM, the maximum temperature was 38.7 ℃ and the time required for the phase change range from 31℃ to 34 ℃ was 1250 min. For the 43 ℃ PCM, however, the maximum temperature was 32.5 ℃. As a result, the phase change temperature range from 40 ℃ to 43 ℃ was not achieved. This was probably because the heat from the heating pipe could not diffuse throughout the packing owing to its high heat storage capacity and the low reaction rate of the 43 ℃ PCM compared to that of the 34 ℃ PCM. Also, for this reason, it is considered that the temperature fluctuation width was smaller at 43 ℃ PCM than at 35 ℃ PCM. This implies that the 34 ℃ PCM stored heat more effectively than the 43 ℃ PCM, thereby affecting the increase in the surface temperature of the floor.

4. Conclusions

This study investigated the appropriate installation position and phase change temperature of PCMs for application in underfloor radiant heating systems using two primary tests.

First, a PCM was installed on the top, side, and bottom of the heating pipe, and its installation position was examined by comparing the floor surface temperature with that of a conventional floor structure. The test results revealed that installing PCM at the bottom of the heating pipe required the shortest time interval for the temperature of the floor surface to reach its maximum. In addition, it was found that the temperature was maintained higher than that of the conventional room, and the temperature delay time was maintained longer.

Second, in the phase change temperature test, the 34 ℃ and 43 ℃ PCM were utilized. For the former, the heat was evenly transmitted throughout the packing. But, for the latter, the phase change temperature range was not achieved. This was probably because, apart from the region that receives heat directly from the heating pipe, a specific time interval was required for heat to be transmitted to the outer part of the PCM. The results of the two tests revealed that the PCM must be installed at the bottom of the heating pipe, and that using 34 ℃ PCM is more efficient than using 43 ℃ PCM in the underfloor radiant heating system.

There were several limitations to this investigation. For example, only two PCMs were compared under short-term heating conditions. In addition, Koreans consider a floor surface temperature in the range of 27 to 33 ℃ to be comfortable (Song 2008), which is slightly higher than the temperature range recommended by ASHRAE (19 ℃ to 29 ℃) (ASHRAE and ANSI/ASHRAE/IES 2013) and that used in the tests. Thus, further research on comfort is required. Additionally, although the demand for heating is higher compared to that for cooling owing to the typical cold and long winter, there is a growing demand for cooling in Korea. However, we did not consider the influence of the PCM floor structure during the summer. In future research, additional tests on the effect of the floor structure on the indoor temperature change and energy consumption for long-term winter outdoor environmental conditions and changes in the summertime indoor environment should be considered.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Author contributions

S.E. Kim: Conceptualization, Methodology, Data curation, Writing – Original Draft. Y.W. Song: Methodology, Formal analysis, Validation. J.C. Park: Supervision, Project administration, Writing – Reviewing and Editing.

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