Heating Energy Saving Potential of a PCM Plastered Wall in Housing for Different Thermal Insulation Performance and Regional Climate Characteristics

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ABSTRACT

The use of phase change materials (PCMs) in buildings with the aim of both improving the indoor environment and saving energy is a research topic of interest. In many of the previous studies, the use of thermal-storage building materials significantly improved the indoor environment and saved energy. In the present study, a new finishing thermal-storage building material was developed without using the conventionally used n-paraffin (e.g., hexadecane and octadecane) derived from petroleum as an interior plastering materials. We will verify the effects of the PCM plastered wall, which is building thermal storage finishing materials.

First, to test their basic thermal performance, thermal-storage building materials (PCM plastered wallboards) were examined via convection heating. A PCM plastered wall comprises plaster, capsulated PCM, and water. The mixing ratio of the PCM is 20 wt.%. The melting point of the material is 23°C, and its thermal storage capacity is approximately 140 kJ/kg.

Second, we calculated the energy-saving effects of the PCM plastered wall for different melting point conditions by performing unsteady thermal calculations using a heat box model. We also evaluated the efficiency of the thermal-storage building materials on buildings with high thermal insulation. The effective thermal storage rate of the PCM plastered wall for different melting points, melting ranges, and latent heats was determined. Finally, we investigated the energy-saving potential of PCM plastered walls in different Asian regions (China, Japan, and Korea) by applying the method mentioned above. The energy-savings with different thermal insulation performance were determined in various places to improve the evaluation and design method of building thermal-storage materials.

KEYWORDS

Phase change material (PCM), Energy savings, Thermal insulation performance, Simulation, Solar energy

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INTRODUCTION

Research on thermal insulation performance and construction methods that provide indoor thermal capacity has been conducted with the view of creating indoor spaces that are more comfortable, and saving energy in our living environments. Active research on phase change materials (henceforth referred to as PCMs) applied to structural frames and buildings, such as PCM boards or PCM panels on both to walls and ceilings, has been conducted around the world. Soeda et al. and Sato et al. considered the energy saving effects of building thermal storage materials contains PCM. However, the energy-saving effects of using PCMs have not been determined for different melting point conditions; to gain a better understanding of these effects it is necessary to study their thermal insulation performance, melting behavior, and regional climate characteristics.

In this study, a novel thermal-storage building finishing material (PCM plastered wall) was developed, and its basic thermal storage performance and energy-saving effects were evaluated. Then its energy-saving effects for different melting points and regional climate characteristics were evaluated by performing unsteady thermal calculations on a heat box model. Development of plant-based thermal-storage building materials, such as the one in this study, reduces the need for fossil fuel, thereby making them more sustainable.

PCM PLASTERED WALL

We developed a new interior finishing material comprising encapsulated PCM, water, and plaster (henceforth referred to as PCM plastered wall). We measured the basic thermal storage performance and specific heat of a PCM plastered wall sample. Photo 1 shows a sample of the PCM plastered wall (PCM mixing ratio is 20%) and Photo 2 shows a thermo-hygrostat. Figure 1 shows the measurement result of specific heat. This PCM is a fatty acid ester-based material derived from a plant (CALGRIP®, JSR Corporation), and its melting point is 23°C, latent heat is 140 kJ/kg, and melting point is in the range of 10 to 28°C.

UNSTEADY HEAT CONDUCTION NUMERICAL CALCULATION

As was done in previous research by Udagawa et al., the sensible heat load was calculated by solving the one-dimensional unsteady heat conduction equation using the forward-difference method. Figure 2 shows a diagram of the wall space parameters. Equation 1 is the thermal equilibrium expression for the indoor air, and Equation 2 is

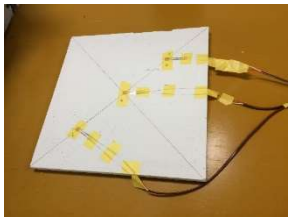

Photo 1. *Sample (PCM plastered wall)*

Photo 2. *Thermo-hygrostat*

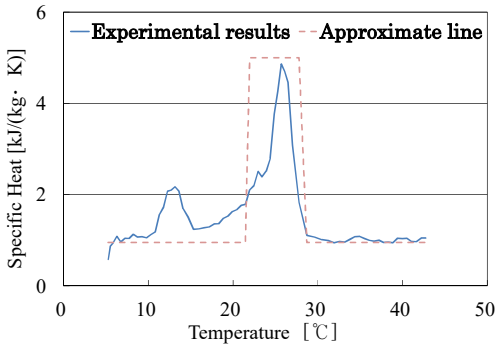

Figure 1. *Specific heat*

$$CAP_{in} \cdot \frac{dT_{in}}{dt} = \sum A_i \cdot \alpha_c \cdot (T_{in} - T_{MRT}) + c_{air} \cdot \rho_{air} \cdot n \cdot V_{in} \cdot (T_{in} - T_{out}) + HS \quad \cdots(1)$$

$$Q_W = A_{wall} \cdot \alpha_i \cdot \left(\frac{\alpha_c T_{in} + \alpha_r T_{MRT} + s_n Q_{gain}/A_{win}}{\alpha_i} - T_{SAT} \right) \quad \cdots(2)$$

$$\frac{T_m^{n+1} - T_m^n}{\Delta t} = \frac{\frac{1}{R_{m+1}}(T_{m+1}^n - T_m^n) - \frac{1}{R_m}(T_m^n - T_{m-1}^n)}{0.5(CAP_m + CAP_{m+1})} \quad \cdots(3)$$

$$S_n = 0.7 \quad A_e/A_i \quad \cdots(4)$$

Nomenclature

T: Temperature [°C], t: Time [s], CAP: Heat capacity [J/K],
R: Thermal resistance [°C /W], Q_W: Heat gain from the outer wall [W],
A: Area [m^2], T_{SAT}: Sol air temperature [°C],
α: Thermal conductivity [W/(m^2 · K)], T_{MRT}: Mean radiant temperature [°C],
s_n: Absorption ratio [-], Q_{gain}: Amount of solar radiation transmission [W/m^2],
c: Specific heat [kJ/(kg · K)], ρ: density [kg/m^3],
n: Ventilation rate [ACH (air changes per hour)], V: Room volume [m^3],
HS: Sensible heating [W/m^2]

Subscripts

n: Time coordinate, m: Space coordinates (Wall contact points number),
in: indoor, c: Convection component, r: Radiation component,
i: Total, air: Air, $wall$: Wall, win: Window, e: each parts

the thermal equilibrium expression for the heat loss from the building's exterior wall in order to indicate both sides air temperature facing outer wall. T_{MRT} was calculated as an area weighted average of the surface temperature in each of the parts (wall, ceiling, floor, and window). A measured value was used for Q_{gain} (amount of solar radiation transmission). Equation 3 shows the basic temperature difference formula for the inside surface of the wall. Equation 4 is an expression for the absorption ratio. Internal heating and ventilation rate are not considered for the experimental module (n = 0).

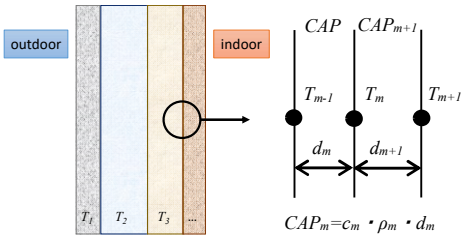

***Figure 2**. Wall space parameters*

***Table 1**. Specification of experimental module*

Name	PB room	PCM room
size [mm]	W2,250×D2,250×H2,400	
Phase Change material	-	Fatty acid ester
Melting / Freezing point[℃]	-	23/22
Latent heat amount [kJ/kg]	-	140
Quantity of PCM [kg]	-	30
Window specification	Triple glass resin window	
Window size [mm]	W1,400×H1,870	
U_A/U_w Value [W/(m^2 · K)]	0.24 / 1.17	

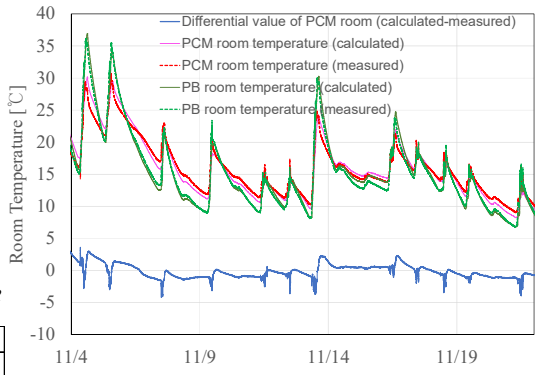

***Figure 3**. Comparison of the measured and calculated values*

Verification of the calculation accuracy

To confirm the accuracy of the numerical calculation, the specific heat of the PCM was approximated by the red curve in Figure 1. The red line was written so as to the latent heat amount 140kJ/kg. Table 1 shows the specifications for the experimental module in Hokkaido. The experimental module consists of two rooms: 1) the PCM room, which is finished with PCM plaster, and 2) the PB room, which is finished with ordinary plasterboards. Figure 3 shows the measured and calculated values of the room temperature in both rooms. It also shows the difference between the measured and calculated values for the PCM room. The temperatures of both the rooms could be predicted fairly accurately.

BOX MODEL

To comprehensively examine the energy-saving effects of the PCM plastered wall under different conditions, we calculated the sensible heating load using a box model that has a simplified housing space (Figure 4). The walls, floor, and ceiling are assumed to have the same thermal insulation performance in each direction. The interior finishing material is gypsum board and the exterior is plywood. Figure 5 shows a section of the wall, with a 9 mm thick PCM finish (mixing ratio: 20 wt.%) on the interior.

In this section, the heat capacity of the furniture, internal heating, and water vapor are ignored. The box model scale is the same as that of the experimental module in the previous section. The ventilation rate is 0.5 ACH.

SENSIBLE HEAT FOR EACH MELTING BEHAVIOR

Figure 6 shows the PCM melting behavior, which was approximated by a rectangle. We considered the energy-saving effects as a function of changes in the latent heat, melting range, and melting point. The melting point temperature is shown in Figure 6. Figure 7 shows the effects of varying the melting range for a fixed latent heat of 140 kJ/kg, melting point of 20°C, and room temperature of 20°C. When the melting range is less than 2°C, the sensible heat load decreases rapidly.

Figure 8 shows the effects of latent heat. The calculation was done with a fixed melting range of 1 K. Increasing the latent heat or decreasing the melting range resulted in a decrease in the sensible heating load. Figure 9 shows the sensible heating load for different melting points and a fixed room temperature of 20°C. The energy-saving effects are the greatest when the melting point value is in the intermediate range of 19–

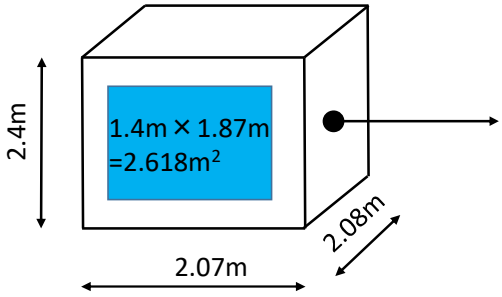

***Figure 4**. Box model*

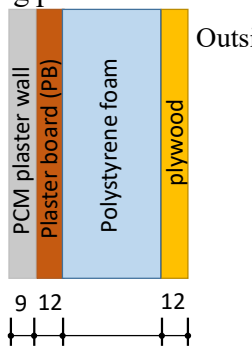

***Figure 5**. Wall section*

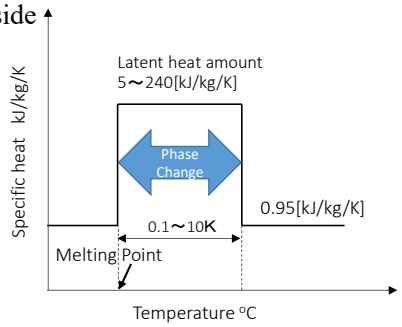

***Figure 6**. Melting behavior*

21°C. Building thermal-storage materials that have high latent heat are known to provide high energy-savings, and by appropriate selection of the melting point or melting width, it is possible to reduce the cost incurred and energy consumed. As a result, using PCM it is necessary to consider its energy-saving performance not only for variation in its latent heat value but also for changes in its melting point and melting range.

ENERGY-SAVING EFFECTS FOR EACH ASIAN AREA

Figures 10–12 show the annual sensible heat load in Beijing (China), Incheon (South Korea), and Tokyo (Japan) for varying insulation strength and a set room temperature of 20°C. We calculated the energy-saving effects of using the PCM plastered wall in all three regions and the reduction ratio for the annual sensible heat load was approximately 40% in all cases. In addition, when the thermal insulation performance is high, the reduction ratio is high; for example in Beijing, the thermal

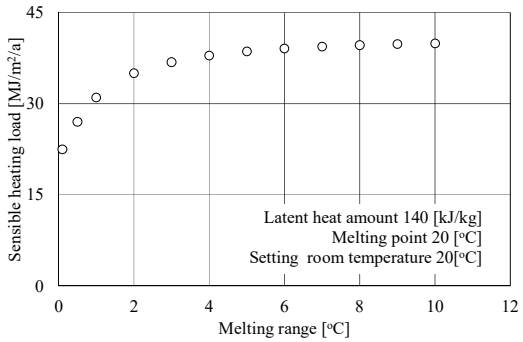

***Figure 7**. Melting range effects*

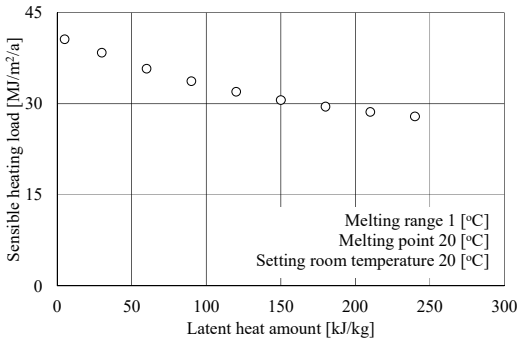

***Figure 8**. Latent heat effects*

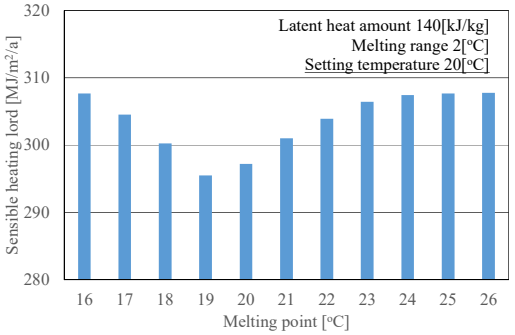

***Figure 9**. Melting point effects*

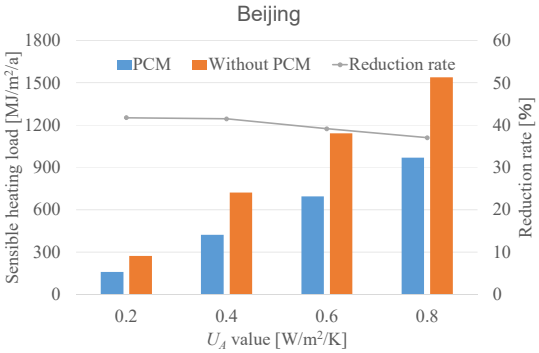

***Figure 10**. Heating load (Beijing)*

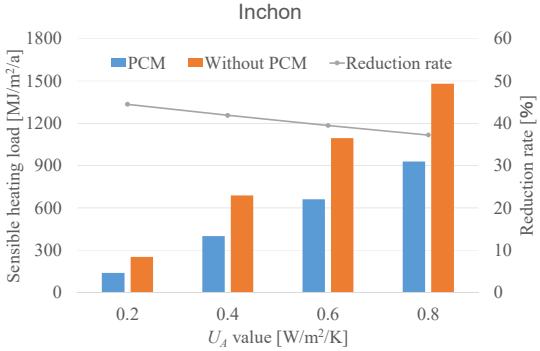

***Figure 11**. Heating load (Incheon)*

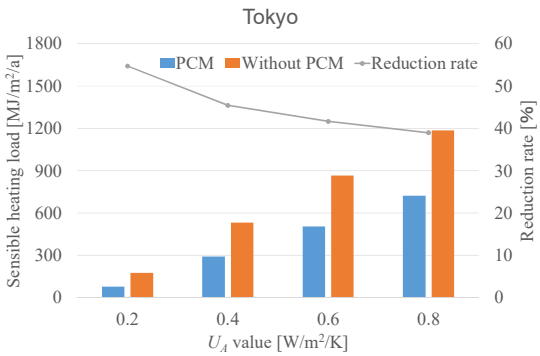

***Figure 12**. Heating load (Tokyo)*

insulation performance and reduction rate shows a linear relationship, and the energy-saving effect was 37–41%. In Incheon and Tokyo, the energy-saving effect was 37–44 % and 39–55 %, respectively. When the heat insulating performance is high, in Tokyo where the outside air temperature is the highest of the three regions, the energy-saving effects were most apparent. This suggests that future work should investigate the relationship between the outside air temperature and energy-saving effects.

CONCLUSION AND IMPLICATIONS

In this study, we developed a PCM plastered wall which is novel wet type building thermal storage finishing materials, and determined the specific heat result from a basic thermal performance test. When the specific heat was approximated by a rectangle and used in an unsteady heat conduction numerical calculation, we were able to accurately predict the thermal properties of an experimental module. We calculated the effect of using a PCM on the air conditioning load for various melting behaviors using a box model. The energy-saving effects are greatest for small melting ranges and large values of the latent heat. We also showed that the energy-saving effects are greatest when the room temperature is near the middle of the melting range (at the peak melting point temperature). The energy saving effects of using a PCM plastered wall was approximately 40% in Beijing, Incheon, and Tokyo. We hope that this work results in the consideration of melting point behavior, latent heat value, and regional characteristics in the evaluation and design of thermal-storage building materials.

ACKNOWLEDGEMENTS

This work was funded by Grant-in-Aid for Japan Society for the Promotion of Science Research Fellow Grant Number JP16J09764 and supported by Hokkaido Polytechnic College, while materials were provided by JSR Corporation. We would like to express our heartfelt gratitude to those listed above.

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