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Simulation Analysis of Thermal Insulation Performance of PCM for Mitigating Urban Heat Island Effect

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Abstract **-** This study aimed to analyze the Thermal Insulation Performance of the PCM Cool Roof System, which is being developed for mitigating the Urban Heat Island Effect. We compared the performance of general insulation material versus that of PCM, both applied on a standard roof model. General insulation material contained 50mm Expanded Poly Styrene, 135mm Expanded Poly Styrene, and 135mm cellulose. We found that PCM had less cooling energy consumption compared to general insulation, whereas general insulation had less heating energy consumption. The annual total energy consumption was found to be lower when using PCM. Therefore, we conclude that the PCM Cool Roof System has insulating capacity comparable to that of general insulation. And its thermal insulation performance is similar or better compared with general insulation, although thermal conductivity of PCM in solid status is generally 0.24 W/mK which almost eight times higher than general insulation.

Keywords**:** Phase Change Materials(PCM), Energy Plus Simulation, Insulation Performance, Cooling & Heating Energy Consumption

1. Introduction

1.1. Background and Purpose of Study

Urban heat island effect refers to high temperatures in the downtown areas where structures with relatively high heat storage performance are concentrated. In South Korea, the urban heat island effect is emerging as a serious environmental problem due to the urban development around large cities such as Seoul, the capital area, and metropolitan cities through compressed economic growth and the subsequent concentration of population.

Consequently, our research team conducted the "Experiment on the Performance of PCM and Cool Roof System for Mitigating Urban Heat Island" as a precedent study, and verified the mitigating effect of urban heat island effect by applying a phase change material (PCM) to an existing building.

However, the thermal insulation performance of PCM applied as the roof finishing material of existing buildings has not been verified yet. Thermal insulation is very important to reduce the energy consumption of a building. The thermal insulation effect of PCM is essential from the aspect of buildings because it is a system that is additionally applied to the building finishing materials.

In this study, therefore, the applicability of PCM to building finishing materials was derived through energy simulation analysis to examine the thermal insulation performance of PCM.

1.2. Scope and Method of Study

The scope of this study is to analyze the thermal insulation performance of PCM through an analysis of simulation results for office and residence standard models. The target of the energy simulation standard model was set as an existing building considering that the PCM Cool Roof System is targeted at existing buildings. The flow of this study is as follows, and the flowchart is shown in Fig. 1.

First, previous studies and theories were considered to examine the thermal insulation performance of PCM as a building finishing material and to conduct energy simulation analysis. Second, the indoor energy consumptions were comparatively examined between the case where PCM was additionally applied to the roof of an existing building and the case where a general thermal insulation material was additionally applied to the roof using the energy simulation application EnergyPlus ver. 8.1 which was developed by the U.S. Department of Energy. Third, the applicability of PCM was determined based on the derived thermal insulation performance result of PCM.

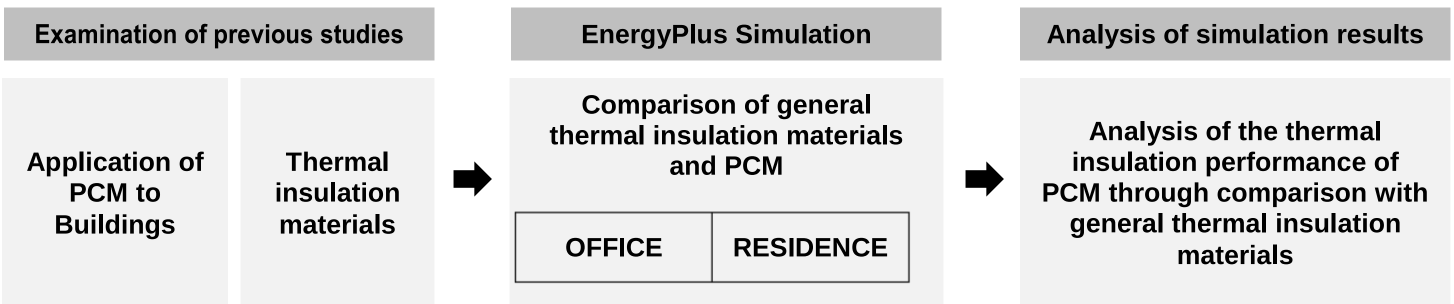

Fig. 1: Study Flowchart.

2. Discussion of Previous Studies

2.1. Application of PCM to Buildings

An examination of previous studies on the thermal performance of PCM applied to buildings revealed that PCM was effective in mitigating urban heat island effect and improving indoor comfort.

Bang (2016) conducted a scaled model test that measured the surface reflectance when PCM was inserted in a building roof structure, the surface temperature reduction effect by PCM type, and the thermal performance of PCM on structures. The experiment results showed that the application of PCM under the identical reflectance, ambience condition, and solar radiation decreased the surface temperature by approximately 10℃.

According to Kim et al. (2011), applying PCM that causes phase change in a comfortable temperature range as felt by occupants can produce great effects in terms of energy, reduce environmental load, and guarantee the comfort of occupants.

Jiawei Lei et al. (2016) used Energy Plus ver.8.1 to study the reduction of cooling load, and conducted numerical analysis according to the ambient condition of the building, phase change, temperature, location, and the thickness of PCM.

Many studies have been conducted of the excellence of PCM and its contribution to the improvement of the comfort of occupants, but no studies have discussed the thermal insulation of PCM, and this is the reason that this study was conducted.

2.2. Thermal Insulation Performance of Buildings

Kim (1996) studied on the change of thermal performance according to the thermal insulation method applied to the outer walls of buildings. The heat conductivity varies by the use or no use of thermal insulation material, the thickness of the thermal insulation material, and the characteristics of the finishing material. Furthermore, the resistance of heat conductivity of walls is identical and the annual cooling and heating loads are almost identical if they are made of the same material and have the same thickness. In other words, theoretically, the energy saving effect does not vary by the interior and exterior insulation. Thus, the simulation model prepared in this study does not consider the difference in thermal performance by the location of thermal simulation materials.

3. Outline of the Simulation to Compare Indoor Energy Consumption between PCM and General Thermal Insulation Materials

3.1. Outline of Simulation

The analysis model for evaluating the thermal insulation performance was created using Design Builder, an integrated construction simulation tool developed by Design Builder Software Ltd. in the UK, and the energy performance was evaluated by using the energy simulation program EnergyPlus ver. 8-5 developed by the U.S. Department of Energy. To analyze the thermal performance when applied to existing buildings, the Regulation for the Standards of Building Facilities, etc., 1992 was used. Thus, the heat conductivity of the wall and floor was set at 0.5 ㎉/㎡ h℃, and that of the roof was set at 0.35 ㎉/㎡ h℃. In addition, PCM and general thermal insulation materials were applied to the roof and the changes in cooling and heating energy consumption were compared between the two types of materials.

For climate date, the average year data (1981-2010) of Seoul for 30 years by the Korea Meteorological Administration was used.

3.2 Simulation Variables

The PCM applied to the analysis model was the n-docosane-based RT44 PCM of RUBITHERM® with the phase change temperature (melting point) of 44℃. For the control group, three types and thicknesses of thermal insulation materials in general use were selected. The first is 50 mm expanded polystyrene (EPS) which had been most frequently used in 88 buildings with 10 or higher stories built in 1980s and 1990s in South Korea, and has a thermal conductivity of 0.04 W/mk (Kim, 1996). The second one is 135mm EPS which is mainly used for roof insulation of multi-dwelling houses and has the same thermal characteristics as those of the first one (Park, 2013). The third one is cellulose 135mm which has a high density, is relatively environment-friendly. And has a thermal conductivity of 0.04 W/mk. The thickness was set at 135mm, which is identical to that of the second and third ones. The simulation was conducted by applying these three general thermal insulation materials to a roof with a heat conductivity of 0.35 ㎉/㎡ h℃ and RT 44 PCM in thicknesses corresponding to those of the general thermal insulation materials.

Table 1: Types and thicknesses of general thermal insulation materials versus PCM.

	General thermal insulation materials	PCM
1	50mm Styrofoam (bead method, EPS)	50mm RT44 PCM
2	135mm Styrofoam (bead method, EPS)	135mm RT44 PCM
3	135mm cellulose	135mm RT 44 PCM

The analysis model is defined with the two cases of office and residential with different factors influencing energy load such as occupancy schedule, cooling and heating air condition systems, and size. The analysis model settings of each case are listed in Table 2.

The specifications of the analysis model referred to previous studies and ASHRAE 62.1, and the heat conductivity was based on the Regulation for the Standards of Building Facilities, etc., which was revised in 1992, to provide similar conditions as those of existing buildings. As the office HVAC system is a fan coil unit (4-pipe) which can provide cooling, heating, and mechanical ventilation, cooling and heating energy consumptions are generated in four seasons. On the other hand, the residential HVAC system consists of floor heating boilers and the cooling method of air conditioning in most apartment and detached houses in South Korea, thus generating cooling and heating energy consumptions separately in summer and winter.

Table 2: Analysis Model and Settings by Case.

Setting Factors \ Case	Office	Residence
Size	Area: 288㎡ Story height: 4m	Area: 85㎡ Story height: 2.6m
Heat transmittance (U-value)	Walls and floors: 0.5㎉/㎡h℃ Roof: 0.35㎉/㎡h℃	
Window area ratio	30%	
HVAC System	Fan Coil Unit(4-Pipe) with District Heating+Cooling	Heated floor, Boiler HW, Nat Vent
Occupation schedule	ASHRAE 62.1 - Office Buildings - Office-Open Plan	ASHRAE 62.1 - Residential - Dwelling unit (with kitchen)

4. Comparison Results of Indoor Energy Consumption between PCM and General Thermal Insulation Materials

4.1. 50mm EPS (Expanded Poly Styrene) vs. 50mm RT44 PCM

1) Office

The application results of the 50 mm EPS which had been most frequently used in 88 buildings with 10 or higher stories built in 1980s and 1990s in South Korea and 50 mm RT44 PCM with the same thickness to a roof with a heat conductivity of 0.35㎉/㎡ h°C are as follows. When the EPS was applied, the annual cooling energy consumption was 26757.26kWh, the annual heating energy consumption was 13443.58kWh, and the total was 40200.84kWh. When the PCM was applied, the annual cooling energy consumption was 26744.01kWh, and the annual heating energy consumption was 26744.01kWh, and the total was 38503.51kWh. When the PCM was applied, the cooling energy consumption was lower by 13.25kWh and the heating energy consumption of was lower by 1684.08kWh; thus, the total energy consumption was lower by 1697.33kWh.

2) Residence

When 50mm EPS was applied to the residence, the annual cooling energy consumption was 7021.36lkWh, the annual heating energy consumption was 1593.82kWh, and the total consumption was 8615.18kWh. When the PCM was applied, the annual cooling energy consumption was 6463.96kWh, the annual heating energy consumption was 1971.39kWh, and the total consumption was 8435.35kWh. In other words, the cooling energy was saved by 557.4kWh when the PCM was applied, and the heating energy was saved by 377.57kWh when the EPS was applied. As a result, the use of PCM saved 179.83kWh in total annual cooling and heating energy consumptions.

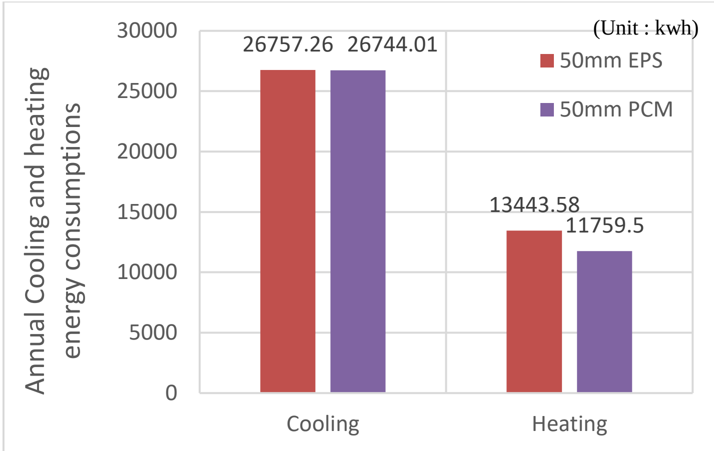

Fig. 2: Cooling and heating energy consumptions with 50mm EPS and 50mm PCM in Office.

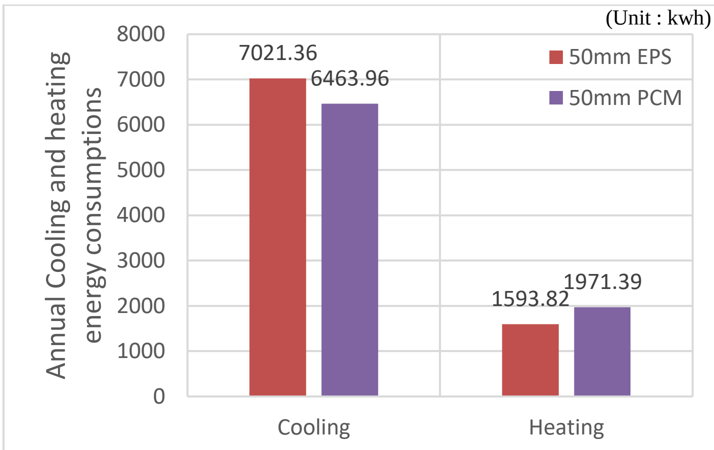

Fig. 3: Cooling and heating energy consumptions with 50mm EPS and 50mm PCM in Residence.

4.2. 135mm EPS (Styrofoam) vs. 135mm RT44 PCM

1) Office

The application of thermal insulation materials is being strengthened recently with the gradually intensifying building energy saving standards. According to a survey of small design offices in 2013, the most frequently used thermal insulation material for roof is 135mm EPS (Park. et al. 2013). The comparison results between the application of 135 mm EPS and PCT are as follows.

When EPS was applied, the annual cooling energy consumption was 29127.95kWh and the annual heating energy consumption was 11873.53kWh. When PCM was applied, the annual cooling energy consumption was 26696.53kWh and the annual heating energy consumption was 12825.57kWh. Thus, from the aspect of cooling energy consumption, PCM is advantageous by 2431.42kWh, and from the aspect of heating energy consumption, EPS is advantageous by 952.03kWh. The total annual cooling and heating energy consumption is 41001.49kWh for EPS and 39522.1kWh for PCM. Thus, PCM is advantageous by 1479.39kWh over EPS.

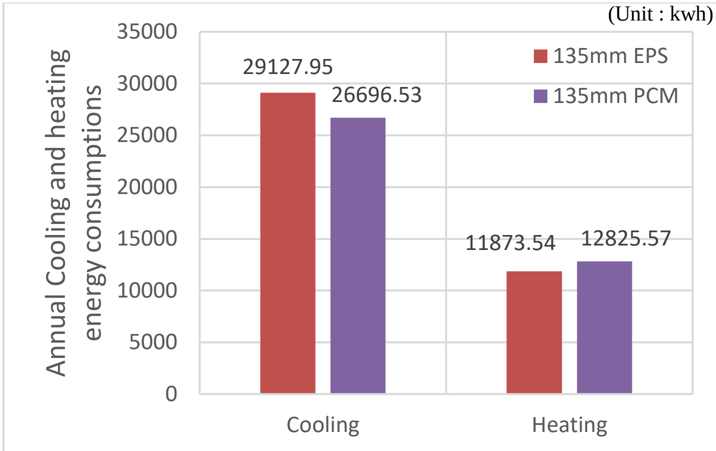

Fig. 4: Cooling and heating energy consumptions with 135mm EPS and 135mm PCM in Office.

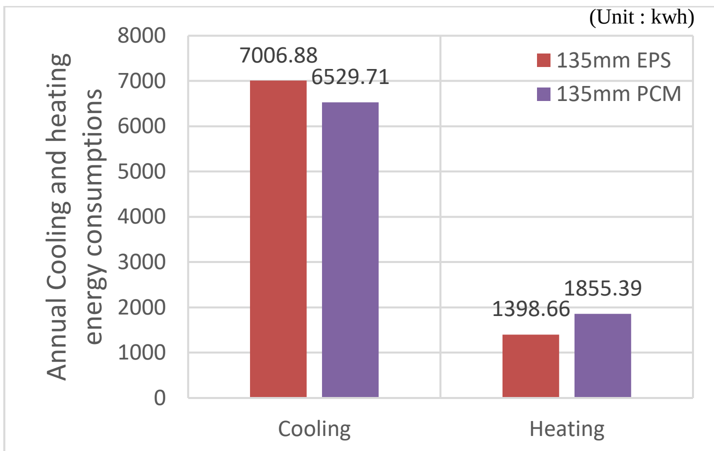

Fig. 5: Cooling and heating energy consumptions with 135mm EPS and 135mm PCM in Residence.

2) Residence

The application results of residence were similar to those of office. The cooling energy consumptions of the EPS and PCM application cases were 7006.88kWh and 6529.71kWh, respectively. Thus, the PCM application saved the energy of 477.17kWh. On the other hand, the heating energy consumptions of the EPS and PCM application cases were 1398.66kWh and 1855.39kWh, respectively. Thus, the EPS application saved the energy of 456.73kWh. Thus, the difference in total annual cooling and heating energy consumption was 20.44kWh and the PCM was slightly advantageous.

4.3. 135mm Cellulose vs. 135mm RT44 PCM

1) Office

Cellulose is a thermal insulation material produced by recycling paper such as newspaper and is classified as an environment-friendly insulation material because it has three times greater density than that of fiberglass and does not generate toxic gas when it is burned. The thermal insulation performance was compared and analyzed between cellulose and PCM with the same thickness as described in section 4.2.

Cellulose consumed less cooling and heating energy by 581.02kWh and 143.99kWh, respectively compared to EPS with the same thickness. However, the PCM with the same thickness consumed 26696.53kWh in cooling energy and 12825.57kWh in heating energy, with a total cooling and heating energy consumption of 39522.1kWh. Thus, PCM saved the energy of 754.38kWh compared to cellulose. As with the case in the previous section, cellulose is advantageous from the aspect of cooling energy consumption and PCM is advantageous from the aspect of heating energy consumption.

2) Residence

When the applications of cellulose and PCM to residence were compared, the total annual cooling and heating energy consumptions of cellulose and PCM were 8384.36kWh and 8385.1kWh, respectively. Thus, the cellulose application consumed less energy, but the difference was only 0.74kWh. Thus, they were almost identical. The cooling energy consumption was 6529.71kWh for PCM and 6955.91kWh for cellulose. Thus, PCM was advantageous by 426.2kWh. However, the heating energy consumption of cellulose was lower by 426.94kWh compared to PCM. Thus, cellulose was slightly advantageous from the aspect of total annual cooling and heating energy consumption.

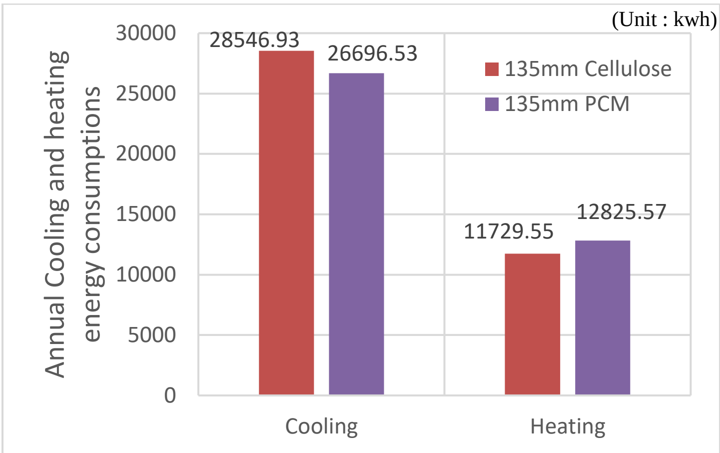

Fig. 6: Cooling and heating energy consumptions with 135mm EPS and 135mm PCM in Office.

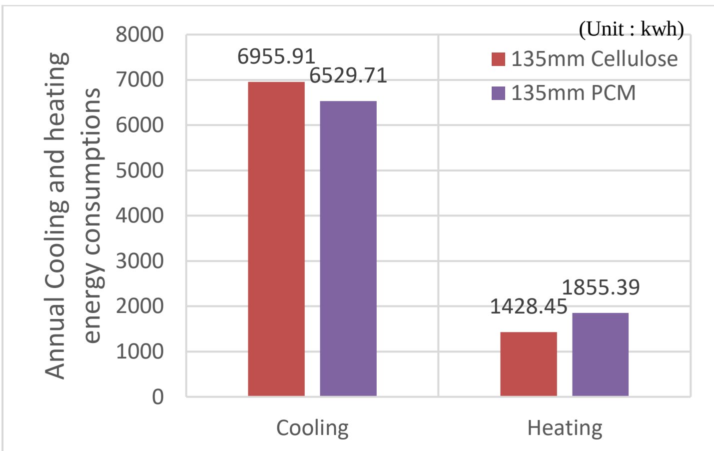

Fig. 7: Cooling and heating energy consumptions with 135mm EPS and 135mm PCM in Residence.

4.4. Comparison of EPS, Cellulose and PCM

The annual cooling and heating energy consumptions were compared among EPS, cellulose, and PCM with the same thickness. PCM was lower in the cooling energy consumption for both office and residence, but the general thermal insulation materials showed lower heating energy consumptions than that of PCM. The differences in total annual cooling and heating energy consumptions were small, less than 21 kWh, and the consumption of PCM was smaller.

1) Office

The PCM showed the lowest cooling energy consumption of 26696.53kWh, but the highest heating energy consumption of 12825.57kWh. The total energy consumption of PCM was 39522.1kWh, which was also the lowest. The difference of PCM with EPS and cellulose were 1479.39kWh, 754.38kWh, and 1255.49kWh.

2) Residence

As with the office, PCM showed a lower cooling energy consumption and the general thermal insulation materials showed a lower heating energy consumption. The total energy consumption of PCM was 8385.1kWh, which was higher by 20.44kWh than that of EPS, and it was lower by 0.74kWh than that of cellulose.

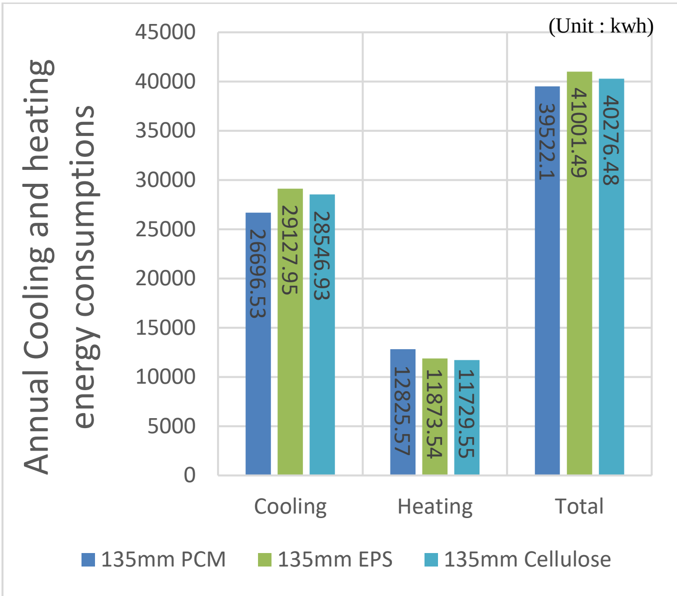

Fig. 8: Comparison of EPS, Cellulose, and PCM (Office).

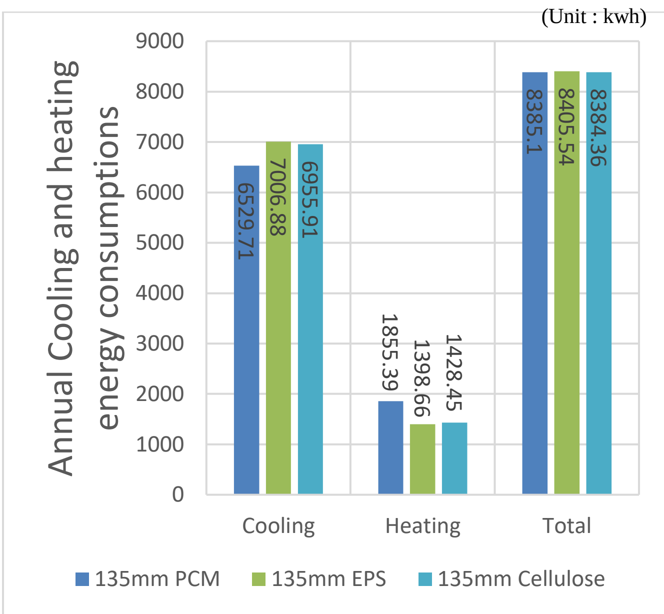

Fig. 9: Comparison of EPS, Cellulose, and PCM (Residence).

5. Conclusion

In this study, simulation analysis was conducted to analyze the thermal insulation performances of PCM applied to the PCM Cool Roof System for mitigating urban heat island effects. The main findings of this study are as follows:

(1) For the 135mm thickness of PCM, the RT 44 PCM was advantageous from the aspect of cooling energy consumption and disadvantageous from the aspect of heating energy consumption.

(2) The reason for these results seem to be due to the fact that the thermal conductivity of RT44 PCM in sold state is approximately 0.24 W/mK, which is higher than that of general thermal insulation materials by around 8-fold and that the composition of solid and liquid varies by the solar radiation and the thickness of PCM.

(3) The total annual cooling and heating energy consumption of PCM was similar to or smaller than those of general thermal insulation materials. Thus, PCM is advantageous for energy saving.

(4) Therefore, the thermal insulation performance of PCM that is applied to the PCM Cool Roof System for mitigating urban heat island effects was comparable to that of general thermal insulation materials and the applicability of PCM as building finishing material was verified.

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