Performance of Roofs Integrated with Phase Change Materials for Reduction the Cooling Load and Overheating Severity in Hybrid Ventilated Classroom, Taiwan

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1. INTRODUCTION

PCM (phase change materials) is an innovative technology and an effective method for improving the thermal mass of buildings owing to it possesses the property of large thermal capacity within a limited temperature range, which is similar to an isothermal energy tank. However, most of the previous studies focused on the combination of PCM and walls that the utilization potential of rooftop is lack of concern though there is a significant amount of heat gains from rooftop. Several previous studies used experimental or numerical simulation methods to investigate the energy-saving potential of installing PCMs in roofs and analyzed the relationship between energy conservation, climatic conditions, and the features of PCM such as thickness, positions and PCT [1]~[3]. The utilization of PCM is now gradually used for better building heat insulation. In addition, for building located in different climate zones during different seasons, it is important to select appropriate PCMs possessing suitable phase-change parameters to meet the energy-efficiency requirements of a building. Specifically, a PCM with ideal performance in the cooling season may yield poor or unfavorable results in the natural-ventilation season. There are few previous studies attempted to analyze the efficacy of PCMs in reducing the cooling load during the air-conditioning (AC) season and the thermal discomfort during the natural-ventilation (NV) season simultaneously. Consequently, this study aims at investigating the effectiveness of roofs with PCMs under the thermal management conditions in terms of reducing the cooling load demand during the AC season and ensuring thermal comfort of classrooms during the NV season. It is expected to suggest the appropriate properties of PCM for school buildings, including thickness and PCT. In addition, the optimal pattern of PCM which is proper to be utilized through the entire year is proposed to fulfill the indoor comfort and energy-saving potential.

2. METHODOLOGY

The top-floor classrooms of a typical high-school building located in northern Taiwan (Taipei) is set as a model; EnergyPlus and the Typical Meteorological Year 3 (TMY3) data are used for conducting the simulations. The setting conditions of the classroom model are listed in Table 1. Regarding the defination of AC and NV season, the air-conditioning is available for use during the hot-humid period from May to October (AC season); as for the NV season, it is defined as from November to April. Besides, the PCM considered in this paper is BioPCM™, which is generally used by other studies, and is set to be installed at the inner side of the existing roof. In order to investigate the climate and seasonal adaptability of PCM, six types of phase change temperature (PCT) are considered, including 23 °C (22 – 25 °C), 25 °C (24 – 27 °C), 27 °C (26 – 29 °C), 29 °C (28 – 31 °C), 31 °C (30 – 33°C), and 33 °C(32 – 35 °C). Furthermore, four different thickness types of PCM are set, including 10, 20, 30, and 40 mm.

This study firstly compared the cooling load and overheating risk of rooftop classroom and non-rooftop classroom to discuss the importance of rooftop heat insulation. Afterwards, the optimal PCM properties for Taipei is suggested based on the simulation results of PCM with different features. Regarding the assessment of overheating risk, there are two measures for thermal discomfort to simultaneously consider the frequency and level of discomfort severity [4], including number of overheating hours (I1) and number of weighted overheating hours (I3). The weighted measure indicates the level of thermal dissatisfaction among subjects, and takes discomfort to be proportional to the non-

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linear ratio of the discomfort curve (PD_{hot}) [5]. The measures are defined by Eq (1)- Eq (3). Eventually, the energy-saving potential of PCM is defined as the percentage of energy saving amount based on the cooling load (Eq (4)).

$$T_{max} = 0.62 \times T_{om} + 14.5 \quad (1)$$

$$I_i = \int wf_i(\tau) \cdot d\tau \qquad if\ T_{op}(\tau) \geq T_{max} \quad (2)$$

$$PD_{hot}(\tau) = \frac{e^{(0.6802\Delta T - 3.7690)}}{[1 + e^{(0.6802\Delta T - 3.7690)}]} \qquad \Delta t = T_{op}(\tau) - T_{max} \quad (3)$$

$$Energy - saving\ potential\ of\ PCM = \frac{Cooling\ load\ without\ PCM\ roof - \text{Cooling}\ load\ wth\ PCM\ roof}{Cooling\ load\ without\ PCM\ roof} \times 100\% \quad (4)$$

Where T_{max} is the maximum temperature of thermal comfort; T_{op} is the operating temperature; T_{om} is the daily average of the outdoor air temperature for the past 30 days; for the first measure, wfi(τ) = 1.0; for the second measure, wf(τ) = PDhot(τ) / 0.2.

Table 1 Setting condition of school building model

Classroom	Length * width * height	9.0 m * 8.1 m * 3.6 m
	Orientation	Face toward the south
	Lighting density	12 W/m^2
	Room capacity	30 people (including teachers and students)
	Occupancy period	8:00-17:00
	Window-wall ratio	North: 29%; South: 37%
Material of facade and roof structure	Window glass	6 mm thick clear glass
	Exterior wall	Reinforced concrete (RC) U value: 2.3 W/m^{2}K
	Roof	RC roof with 25 mm polystyrene (PS) insulation board (U value: 1.0 W/m^{2}K)

3. RESULTS AND DISCUSSION

3.1 Cooling load and thermal environment with no PCM roof

The simulation results of monthly cooling loads (CL), the number of overheating hours (I1) and number of weighted overheating hours (I3), which represent the thermal discomfort level of the classrooms without a PCM in roof structure in Taipei are shown in Figure1. It is known that the annual cooling load is 59.0 GJ and the thermal discomfort levels of I1 and I3 are respectively 234 hours and 519 hours. For the improving projects of roof structure, the ideal outcome is to reduce the cooling load and thermal discomfort in the top-floor classrooms to be the same level as in non-top-floor classrooms at the same time. Therefore, the simulation results of the non-top-floor classrooms which have the same identical configuration with top-floor classrooms are also shown in Figure1 for comparing the difference. Specifically, the contribution of heat transferred from the roof to the cooling loads and thermal discomfort levels of classrooms without PCM in roof structure is shown in Table 2. According to the results mentioned above, the importance and urgency of improving the thermal performance of the roof structure are confirmed.

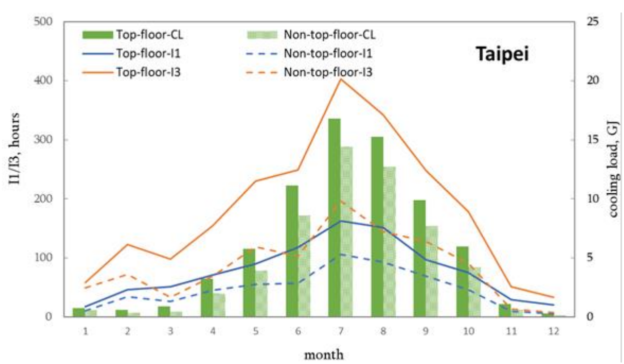

Figure 1 Comparison of cooling load, overheating hours, and weighted overheating hours between top-floor and non-top floor classroom

Table 2 The contribution of heat transferred from the roof to cooling loads and thermal discomfort levels without PCM in roof structure

	May to October (AC season)		November to April (NV season)			
	Cooling load (GJ)	Ratio (%)	I1 (hours)	Ratio (%)	I3 (hours)	Ratio (%)
Taipei	13.2	20.4%	104.0	44.4%	274.1	52.8%

3.2 Influence of PCM on the energy consumption of air-conditioning season

In this paper, 30 cases of different properties of PCM are set to analyze the parameters which make influences on the thermal performance. Figure 4 shows the energy-saving effects achieved by coupling different PCTs and thicknesses of PCM during the AC season from May to

October. Both PCT and thickness of PCM significantly influenced the reduction percentage of cooling load during the AC season. Within the scope of study cases, the energy-saving potential of a PCM layer on the cooling load is 1.2 %–7.8 %. Under the circumstance of same PCM layer thickness during the air-conditioning season, the analysis results of the six selected PCTs show that the energy-saving effect initially increases with the increasing PCT; however, after reaching the peak of energy-saving effect, the energy-saving effect decreases as the PCT increases. For achieving the maximum energy-saving effect, the optimal PCTs for AC season under different thicknesses of PCM are confirmed. As shown in Figure 2, when the thickness of the PCM layer in Taipei is 50 mm, the energy-saving effect of PCT = 29°C or the optimal PCT = 27°C is almost the same that the differences between these two cases is negligible. Therefore, the optimal PCT of a PCM roof in the AC season can be regarded as 29 °C. Overall, under the circumstance of a thicker PCM layer, the full capacity of PCM has not yet been utilized; therefore, the relationship between energy-saving effect and the thickness of PCM is not in linear relation.

3.3 Influence of PCM on thermal comfort in the ventilation season

The roof structure with PCM creates a more comfortable environment during the ventilation season from November to April, which can reduce the number of overheating hours and weighted overheating hours under the situation of classroom operating temperatures exceeding 80 % of the acceptable upper limitation. Figure 3 shows the relationship between number of overheating hours (I1, represented by dashed line), weighted overheating hours (I3, represented by solid line), PCT, and different thickness of PCM. The reduction percentage in the number of overheating hours is 3.7 % – 45.5 % in Taipei which are equivalent to 9 – 110 hours, and are less than the case of not using PCM. As shown in Figure 3, among all the analyzed cases, the decrements in I3 are higher than those in I1.

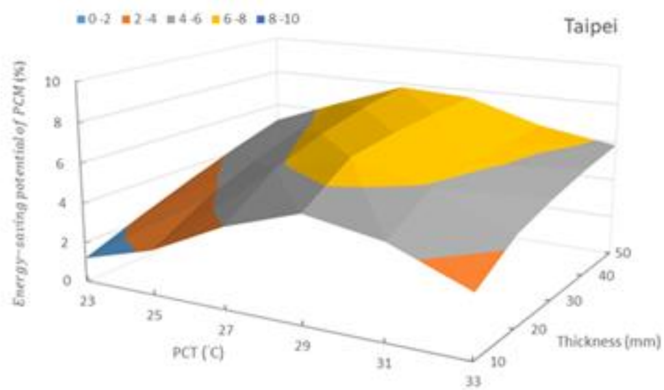

Figure 2 Energy-saving effects of different PCM roofs during the AC season from May to October

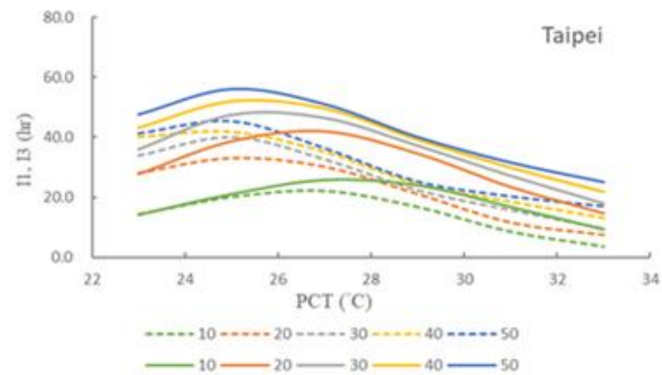

Figure 3 Effects on thermal comfort of different thickness of PCM roofs during the NV season from November to April

CONCLUSION

Owing to the undergoing policy of broadly installing the air-conditioning in school buildings in Taiwan, it is essential to draw up the energy-saving strategies that not only reduce the energy consumption but create superior indoor comfort. This paper discussd the cooling load in AC season and thermal discomfort in NV season under the circumstance of installing PCM in rooftop structure of school building. Specifically, thirty cases of different setting parameters of PCM including thickness and PCT are set to simulate their energy-saving effect and thermal discomfort; eventually, the recommended optimal utilization patterns of PCM for better indoor comfort and energy-saving potential are proposed. Regarding the relationship between different PCT and energy-saving effect in AC season, when the thickness of PCM is fixed, it is worth noting that the energy-saving effect increases as the PCT increase. However, when reaching the peak, the energy-saving effect decreases as the PCT increases. Consequently, for achieving the maximum energy-saving potential, the optimal PCT for all different thickness of PCM is clarified as 29 °C. Furthermore, the most economic thickness of PCM for improving the energy-saving effect and thermal comfort is clarified as 20mm in Taipei. Through the recommendations proposed in this study, it is expected to efficiently utilize the PCM in school buildings to reduce the additional energy consumption and eventually realize the goal of energy conservation.

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