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A Pilot Experimental Study on the Thermal Performance of PCM-Enhanced Building Envelopes

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ABSTRACT

Enhancing energy efficiency in the building sector is vital for climate change mitigation. Phase change materials (PCM), known for their high latent heat storage capacity during phase transitions, offer promising potential in regulating indoor temperatures and reducing dependence on HVAC systems. This study presents a preliminary experimental investigation into the thermal performance of wallboards enhanced with PCM under subarctic conditions in Umeå, Sweden. Four types of wallboards were tested: a conventional gypsum board, a commercial PCM board (cPCM), and two lab-fabricated boards with 60% and 82% microencapsulated PCM by mass (mPCM60 and mPCM82). Thermal properties of the PCM were characterized using Differential Scanning Calorimetry (DSC), confirming high latent heat capacity and thermal stability. In a field setup, surface temperatures were monitored to assess thermal buffering capacity. Results show lower temperature fluctuations in the mPCM82 and mPCM60 wallboards, indicating enhanced thermal performance of the envelope compared to the gypsum board. However, the thermal performance of cPCM was even worse than gypsum, which could be attributed to the observed material settlement. These findings suggest the potential of PCM-enhanced wallboards to improve indoor thermal comfort and energy performance, while also emphasizing the importance of material selection and design in practical applications.

Keywords: energy efficiency, phase change materials (PCM), indoor environment, building envelopes

1. INTRODUCTION

Buildings play a crucial role in mitigating climate change by reducing CO_2 emissions, as they account for approximately 40% of total energy consumption and one-thrid of CO_2 emissions globally[1]. Therefore, maintaining a thermally comfortable built environment in an energy-efficient manner is essential to lower energy usage and reduce emissions in the building sector[2–4].

Phase change material (PCM) is a substance that absorbs or releases a large amount of latent heat during a phase transition when the surrounding temperature reaches a specific threshold. Due to this property, PCM is considered an effective solution for enhancing energy efficiency in buildings by regulating indoor temperature and reducing the capacity need for active heating, ventilation, and air conditioning (HVAC) system[5].

Furthermore, PCM can also enhance building resilience, particularly in regions where HVAC systems are not widely deployed or accessible[6]. This is especially critical under extreme weather conditions, where passive thermal regulation plays a vital role in maintaining indoor thermal comfort and survivability.

Researchers are actively exploring PCM to be applied as part of building envelopes to enhance the thermal performance of buildings and therefore significantly reduces energy dependence on HVAC system to maintain thermal environment. Qu et al. used numerical simulations to evaluate the impact of integrating PCM into building envelopes for summer thermal comfort and energy savings[7]. Their performance was found to depend on envelope type, PCM placement, thickness, and material. Proper design led to energy savings ranging from 4.8% to 34.8%, varying with climate. Liu et al. proposed a multi-scale modeling approach based on Physics-Informed Neural Networks (PINNs) to investigate the thermal conductivity characteristics of polyurethane–phase change material (PU-PCM) composite foams [8]. Results showed a 46% reduction in indoor temperature fluctuations and 22% energy savings with the optimized composite. Ahangari et al. developed a two-layer PCM system with different melting points to improve thermal comfort and reduce energy use in dry and semi-arid climates[9]. Simulations showed that comfort compliance time increased to 93% (dry) and 75% (semi-arid), while winter energy use dropped by 17.5% (dry) and 10.4% (semi-arid), respectively. Jamil et al. demonstrated the potential of phase change materials for retrofitting existing residential buildings to improve thermal comfort, using both experimental tests and

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numerical simulations. Their study showed that passive installation of PCM could reduce daytime indoor temperatures by up to 1.1°C and decrease thermal discomfort time by approximately 34%[10]. Hagenau and Jradi used EnergyPlus to conduct dynamic energy modelling to evaluate the performance of PCM-enhanced building envelope in Danish buildings[11]. Results from the sensitivity analysis indicated that more insulated the targeted building is, the more effective the PCM-integrated envelope and the energy savings obtained. In addition, 32-36% of energy savings were achieved under the Danish weather profile.

Although phase change materials have shown great potential in enhancing building energy efficiency, notable knowledge gaps remain. Most existing studies rely heavily on numerical simulations, while empirical validation under real-world conditions[12,13], particularly in diverse climate scenarios, remains limited.

To address this gap and advance the practical understanding of PCM, this study presents a preliminary investigation into thermal performance of integrating PCM into building envelopes. Special attention is given to subarctic climate conditions, which are characterized by long and severe winters, short yet warm summers with extended daylight, and substantial daily temperature fluctuations. These unique climatic features present both challenges and valuable opportunities for assessing the thermal performance of high-efficiency control materials like PCM. This is a priori study focuses on the preparation of PCM-enhanced materials and the design of experiments, aiming to lay the groundwork for a forthcoming full-scale implementation in real buildings.

2. MATERIAL AND METHODS

2.1 Materials preparation

In this study, Four types of wall panels using different materials were used to compare. Each panel was installed as the interior layer (adjacent to the indoor space) of the building envelope. The four wallboards include: a conventional wallboard without any integrated phase change material (PCM), a commercially available PCM-integrated wallboard (cPCM), two lab-fabricated wallboards embedded with microencapsulated PCM (mPCM), referred to as mPCM60 and mPCM82 respectively. The naming convention reflects the PCM content by mass within the boards: PCM60 contains 60% PCM by mass, while PCM82 contains 82%.

Paraffin is selected as the mPCM for the lab-made boards due to its stable chemical properties during phase transitions, low reactivity with other materials, and excellent long-term durability through repeated thermal cycles. Gypsum is incorporated with PCM in producing the lab made PCM wallboards, which is usually considered as a practical way in real world applications[14,15].

Fig. 1 illustrates the micro-structure of the mPCM applied in this study, providing by using the scanning electron microscope (SEM) technique. The process details has been presented in a previous study by the authors[16].

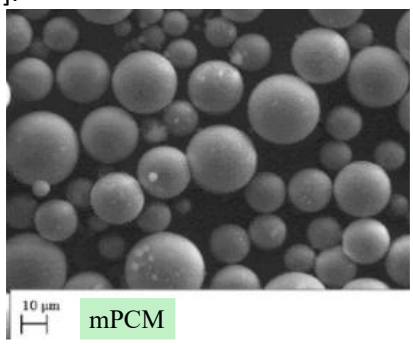

Fig. 1. SEM of mPCM

Fig. 2 presents the Differential Scanning Calorimetry (DCS) results for the pure microencapsulated phase change material, which was conducted in the authors' previous study[16]. The samples were subjected to controlled heating and cooling cycles between -20 °C and 50 °C at a constant rate of 1 °C/min.

Fig. 2(a) shows the temperature-dependent specific heat capacity of the pure mPCM. During both the heating and cooling processes, the specific heat capacity remains stable at approximately 2 kJ/kg·K before and after the phase transition. During the phase change, the specific heat capacity reaches a peak of 48 kJ/kg·K during heating and 43 kJ/kg·K during cooling, indicating significant latent heat release and absorption associated with the solid–liquid phase transition.

Fig. 2 (b) shows the enthalpy change of pure mPCM, calculated based on the specific heat data from Fig. 2 (a). During heating, the total enthalpy change during the phase transition reaches approximately 160 kJ/kg. In the cooling process, two distinct phase transitions are observed in Fig. 2(a). The liquid-to-solid phase transition exhibits an enthalpy change nearly equal to that observed during heating, confirming good reversibility. In contrast, the solid–solid phase transition results in a significantly lower enthalpy change, approximately 70 kJ/kg, indicating a smaller energy contribution from this transition in the pure mPCM.

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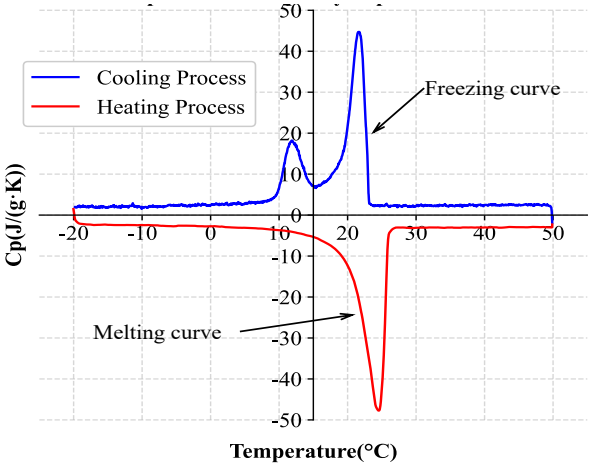
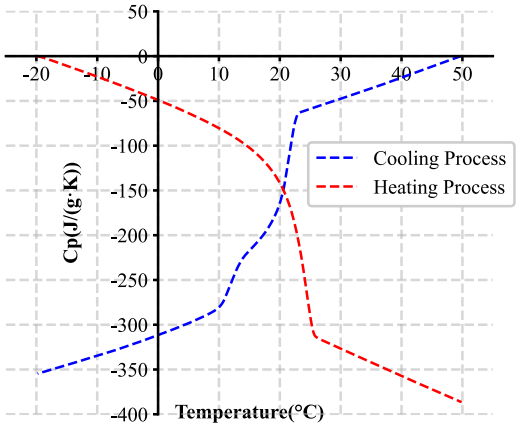


(a) Specific heat capacity of pure mPCM.



(b) Enthalpy change as a function of temperature for both heating and cooling process for pure mPCM.

Fig. 2. DSC results for mPCM.

2.2 *Wallboards fabrication*

Fig. 3 illustrates the fabrication process of both gypsum-based and lab-made PCM wallboards conducted in the laboratory. The microencapsulated PCM content in the composite wallboards was determined by mass fraction. Initially, all wallboards were prepared in an unsolidified state to ensure uniform material distribution. To accelerate the drying and solidification of the fresh boards, a small-scale climate chamber was employed, providing controlled environmental conditions to remove moisture efficiently and ensure consistent curing. Upon completion of the drying process, a total of nine small square wallboards were produced, including three gypsum boards, three mPCM60 boards, and three PCM82 boards. Each wallboard measured 400 mm × 400 mm in length and width, with a thickness of 15 mm.

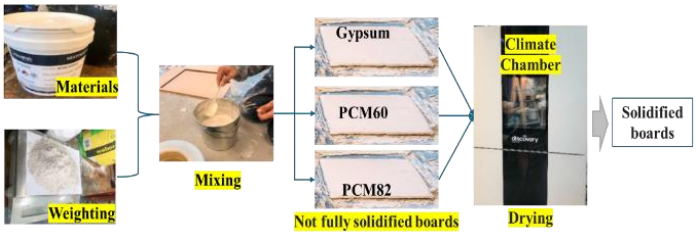


Fig. 3.Procedure of manufacturing wallboards.

Each complete heating and cooling process constituted one cycle, and the measurements were repeated for multiple cycles to assess potential equipment instability and to investigate the memory effect often observed in PCM materials during phase transitions. Furthermore, the consistent performance of the PCM composites across multiple cycles, with no evidence of material leakage, confirms the thermal reliability and structural stability of the fabricated boards.

However, it is important to note that, due to time constraints and the ongoing nature of the project, only the thermal properties of the pure mPCM were measured at this stage.

2.3 *Experiment setup*

The test began on February 7, 2024, and ended on February 21, 2024, and lasted over 280 hours. Fig. 4 shows the layout of the experimental setup. The four wall panels, mentioned in section 2.1, are mounted on the interior wall of a real office building (illustrated in Fig.5) at the Umeå University, Umeå, Sweden. To facilitate thermal equilibrium between the indoor and outdoor environments, thermal insulation was applied to the windows of the test setup. This measure minimized external heat gain or loss, thereby ensuring more accurate assessment of the thermal performance of the wall panels.

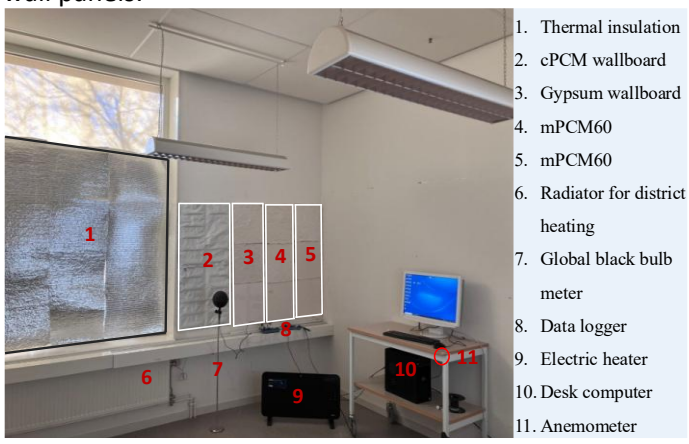


Fig. 4. Layout of experiment setup.

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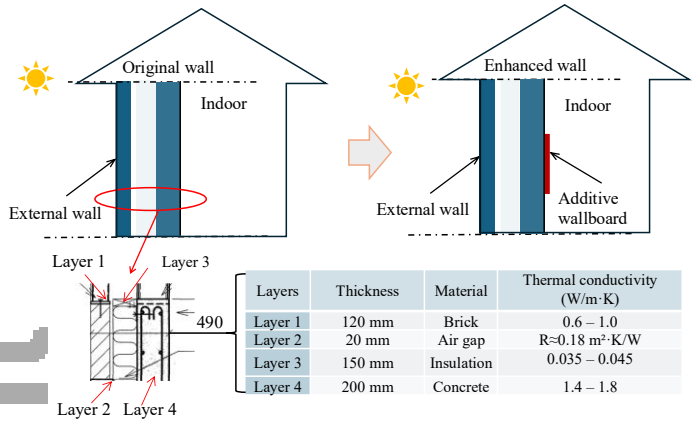
A data logger system was employed to continuously record temperature data captured by thermocouples. These thermocouples were strategically placed to measure the surface temperature of the wallboards throughout the experiment, enabling detailed monitoring of thermal behavior under varying conditions.



Layers	Thickness	Material	Thermal conductivity (W/m·K)
Layer 1	120 mm	Brick	0.6 – 1.0
Layer 2	20 mm	Air gap	R≈0.18 m²·K/W
Layer 3	150 mm	Insulation	0.035 – 0.045
Layer 4	200 mm	Concrete	1.4 – 1.8

Fig. 5. Schematic of the wallboards installation.

The placement of thermocouples used for surface temperature measurements is illustrated in Fig. 6. For the gypsum wallboard, which served as the reference panel without PCM, only one thermocouple was attached to each side. This is due to the relatively uniform surface temperature distribution expected in the absence of phase change behavior. In contrast, for the PCM-integrated wallboards (commercial PCM board, PCM60, and PCM82), three thermocouples were placed on each side of the wallboard. This denser sensor arrangement was intended to capture localized thermal variations resulting from the non-uniform heat absorption and release during phase transitions.

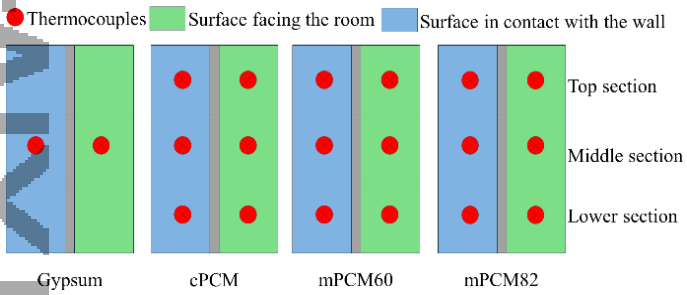


Fig. 6 Schematic of the board walls installation.

During the experiment, the indoor air temperature was measured using Swema anemometers (Swema 03+, Swema AB, Farsta, Sweden), which provide a temperature accuracy of ±0.3 °C. The surface temperatures on both sides of all the material boards were monitored using K-type thermocouples, with a specified accuracy of ±0.5 °C. Prior to use, the thermocouples were calibrated using the ice-water bath method to ensure measurement accuracy. Table 1 summarizes the instruments employed for data collection and thermal measurements.

Additionally, the outdoor weather conditions were taken from a weather station located in Umeå University.

Table 1 Instruments used for the measurement.

	Room Temp. (°C)	Surface Temp. (°C)	
Instrument	Swema 03+	Thermal Couples	
Picture			
Measurement interval	1 s	1 s	

3. RESULTS AND DISCUSSION

Fig. 7 illustrates the outdoor weather conditions during the test period. The ambient temperature ranged from –25 °C to 1 °C, exhibiting clear fluctuations between daytime and nighttime. This variation reflects a typical cold climate pattern.

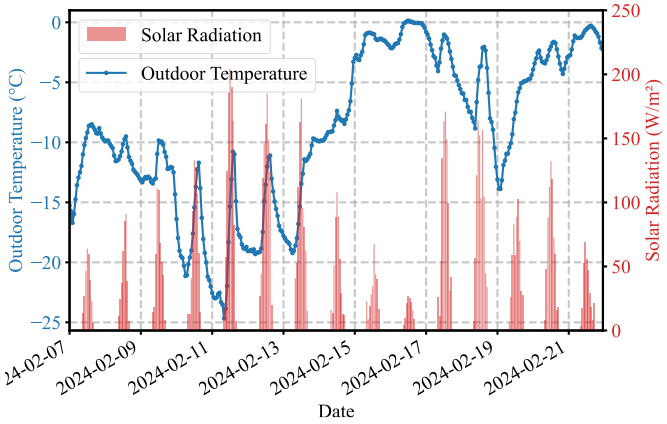


Fig. 7. Outdoor weather condition during test.

Decrement factor (DF) represents the reduction in temperature fluctuation as heat passes through a building envelope element[17,18]. A lower DF indicates better thermal resistance to outdoor temperature variations. It also contributes to assessing the passive thermal resilience of buildings under dynamic climate conditions. It is calculated as the ratio between the amplitude of interior and exterior surface temperature fluctuations and is crucial for assessing thermal comfort parameters such as mean radiant and operative temperatures. The DF of wall i could be calculated as follows

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$$DF_i = \frac{T_{max,in} - T_{min,in}}{T_{max,ex} - T_{min,ex}}$$

where, $T_{max,in}$ is the maximum temperature of the interior wall; $T_{min,in}$ is minimum temperature of the interior wall; $T_{max,ex}$ is the maximum temeperature of the exterior wall; $T_{min,ex}$ is the minimum temperature of the exterior wall.

Fig. 8 shows the calculated DF values of each type of wallboard, with cPCM having the highest value, followed by Gypsum, mPCM60, and mPCM82. Since the four wallboards were attached to the same wall, and due to the harsh cold conditions limiting direct measurements, the recorded outdoor temperature was used as the reference to calculate the DF value.

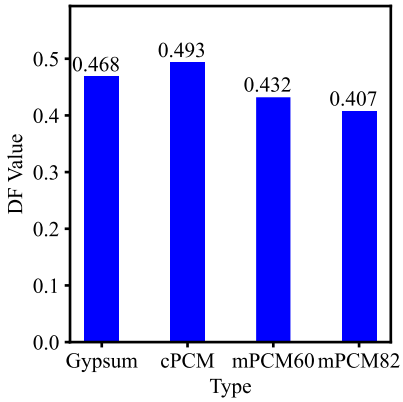

Fig. 8 DF value of four compared wallboards.

Compared to applying gypsum as the additive wallboards, mPCM60 and mPCM82 help reduce DF value by 7.7% and 13%, respectively. This indicates that lab-fabricated PCM wallboards demonstrate the potential to maintain a stable thermal environment. However, DF value increased by 5.3% for the cPCM wallboard. According to the phenomenon we observed, one possible explanation is that, due to the encapsulation process, PCM behaves similarly to a water bag. During the phase transition from solid to liquid, the material may settle toward the bottom under the influence of gravity. This may cause an uneven distribution, and it could compromise the structural integrity of the wallboard and reduce its thermal buffering performance.

As a result, thermocouples may record higher surface temperatures, potentially because the localized thermal insulation becomes even lower than that of the conventional gypsum board in such cases. The recorded surface temperature shown in Fig. 9 could also explain this.

As shown in Fig. 9, the mPCM82 wallboard exhibited the most stable surface temperature profile during both the heating and cooling phases. Its delayed temperature rise, and gradual cooling behavior confirm superior thermal buffering performance. As evidenced by its slowest temperature rise and most gradual cooling curve, this indicates effective latent heat storage and release over a temperature range that aligns well with indoor comfort levels.

In contrast, the cPCM wallboard showed rapid temperature fluctuation, even exceeding that of the gypsum board, suggesting suboptimal PCM distribution or insufficient latent heat capacity in its design.

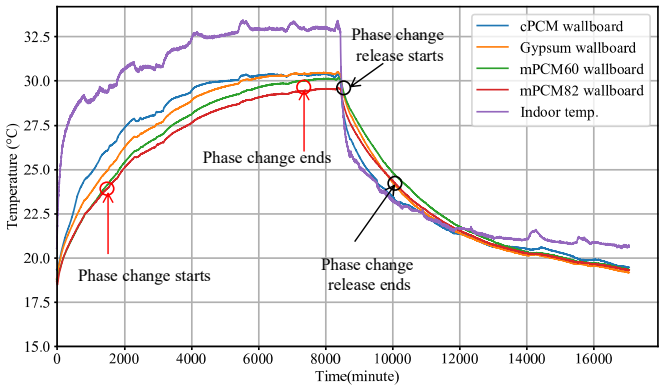

Fig. 9 Indoor and surface temperature during the test.

4. CONCLUSIONS

This study assessed the thermal regulation performance of PCM-integrated wallboards under real-world subarctic climate conditions. Lab-fabricated PCM wallboards, particularly mPCM82, showed better improvements in thermal buffering, as evidenced by lower surface temperature fluctuations and reduced decrement factors. In contrast, in this experiment, the commercial PCM wallboard displayed poorer performance, as what has been observed, possibly due to material settling, suboptimal encapsulation, or mismatched phase transition characteristics. Overall, the results demonstrate that appropriately designed PCM-enhanced materials can contribute to improve the thermal performance of envelopes, which further improves indoor thermal comfort and reduced energy demand. Future studies will focus on optimizing installation configurations, exploring long-term performance, and validating these findings in full-scale buildings.

5. ACKNOWLEDGEMENTS

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6. REFERENCE

[1] P. Nejat, F. Jomehzadeh, M.M. Taheri, M. Gohari, M.Z. Abd. Majid, A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries), Renew. Sustain. Energy Rev. 43 (2015) 843–862.

[2] G. Churkina, G. Churkina, A. Organschi, C. Reyer, A. Ruff, K. Vinke, Z. Liu, B. Reck, T. Graedel, H. Schellnhuber, Buildings as a global carbon sink, Nat. Sustain. 3 (2020) 269–276.

[3] B. Yang, Y. Liu, P. Liu, F. Wang, X. Cheng, Z. Lv, A novel occupant-centric stratum ventilation system using computer vision: Occupant detection, thermal comfort, air quality, and energy savings, Build. Environ. 237 (2023) 110332.

[4] Y. Liu, R. Dang, B. Yang, P. Liu, Energy-efficient control strategy for air conditioning and mechanical ventilation system based on occupant distribution —— A case study on stratum ventilation, J. Build. Eng. 100 (2025) 111709.

[5] F. Souayfane, F. Fardoun, P.-H. Biwole, Phase change materials (PCM) for cooling applications in buildings: A review, Energy Build. 129 (2016) 396–431.

[6] P. Lassandro, S. Di Turi, Energy efficiency and resilience against increasing temperatures in summer: the use of PCM and cool materials in buildings, Int. J. Heat Technol. 35 (2017) S307-15.

[7] Y. Qu, D. Zhou, F. Xue, L. Cui, Multi-factor analysis on thermal comfort and energy saving potential for PCM-integrated buildings in summer, Energy Build. 241 (2021) 110966.

[8] B. Liu, Y. Wang, T. Rabczuk, T. Olofsson, W. Lu, Multi-scale modeling in thermal conductivity of Polyurethane incorporated with Phase Change Materials using Physics-Informed Neural Networks, Renew. Energy 220 (2024) 119565.

[9] M. Ahangari, M. Maerefat, An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions, Sustain. Cities Soc. 44 (2019) 120–129.

[10] H. Jamil, M. Alam, J. Sanjayan, J. Wilson, Investigation of PCM as retrofitting option to enhance occupant thermal comfort in a modern residential building, Energy Build. 133 (2016) 217–229.

[11] M. Hagenau, M. Jradi, Dynamic modeling and performance evaluation of building envelope enhanced with phase change material under Danish conditions, J. Energy Storage 30 (2020) 101536.

[12] Q. Al-Yasiri, M. Szabó, Experimental study of PCM-enhanced building envelope towards energy-saving and decarbonisation in a severe hot climate, Energy Build. 279 (2023) 112680.

[13] M. Song, F. Niu, N. Mao, Y. Hu, S. Deng, Review on building energy performance improvement using phase change materials, Energy Build. 158 (2018) 776–793.

[14] B. Srinivasaraonaik, L. Singh, S. Sinha, I. Tyagi, A. Rawat, Studies on the mechanical properties and thermal behavior of microencapsulated eutectic mixture in gypsum composite board for thermal regulation in the buildings, J. Build. Eng. 31 (2020) 101400.

[15] Y. Yang, Z. Shen, W. Wu, H. Zhang, Y. Ren, Q. Yang, Preparation of a novel diatomite-based PCM gypsum board for temperature-humidity control of buildings, Build. Environ. (2022).

[16] H. Zhou, A.R. Puttige, G. Nair, T. Olofsson, Thermal behaviour of a gypsum board incorporated with phase change materials, J. Build. Eng. 94 (2024) 109928.

[17] Q. Al-Yasiri, M. Szabó, Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot Climate: An experimental study, Appl. Energy 314 (2022) 118957.

[18] C. Suresh, T.K. Hotta, S. Saha, Phase change material incorporation techniques in building envelopes for enhancing the building thermal comfort-a review, Energy Build. (2022).

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