iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL
FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: VI Month of publication: June 2026

DOI: https://doi.org/10.22214/ijraset.2026.83464

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

Experimental Investigation of Phase Change Material and Thermal Insulation Integrated Building Envelopes for Energy-Efficient Buildings in Hot Climates

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Abstract: The building sector accounts for a substantial share of global energy consumption, particularly due to heating, ventilation, and air-conditioning (HVAC) systems. In hot and tropical climates, excessive cooling demand significantly increases operational energy use and greenhouse gas emissions. This study experimentally investigates the thermal performance of building envelopes integrated with Phase Change Materials (PCMs) and thermal insulation as passive energy-saving strategies. A comparative analysis was conducted among three roof configurations: a conventional roof system, a PCM-integrated roof, and a hybrid PCM-insulation roof system. An organic paraffin-based PCM with a melting temperature range of 26-28 °C was incorporated into the roof assembly along with expanded polystyrene (EPS) insulation. Temperature monitoring was performed under real climatic conditions using calibrated digital sensors and a multi-channel data acquisition system. The results demonstrated that PCM integration reduced indoor peak temperature by 2.9 °C and increased thermal lag from 0.6 h to 2.1 h. The combined PCM-insulation system further reduced indoor peak temperature by 5.0 °C and enhanced thermal lag up to 3.4 h compared with the conventional roof system. The hybrid system also reduced indoor temperature fluctuation and prolonged indoor thermal comfort duration. The findings confirm that integrating PCMs with thermal insulation can significantly improve thermal inertia, reduce cooling demand, and enhance indoor comfort in hot climates. The study highlights the applicability of PCM-insulation systems for sustainable building design and energy-efficient retrofitting of existing and heritage buildings.

Keywords: Phase Change Material, Thermal Insulation, Building Energy Efficiency, Passive Cooling, Thermal Comfort, Building Envelope, Energy Conservation, Sustainable Buildings.

I. INTRODUCTION

Rapid urbanization, population growth, and increasing living standards have substantially increased global energy demand. The building sector alone consumes approximately 40% of global final energy and contributes significantly to greenhouse gas emissions [1,2]. A major share of this energy consumption is associated with heating, ventilation, and air-conditioning (HVAC) systems used to maintain indoor thermal comfort.

In countries with hot and tropical climates, such as India, cooling energy demand has increased considerably due to rising ambient temperatures and increased adoption of mechanical cooling systems. Conventional HVAC-based approaches improve indoor comfort but result in high operational energy consumption and environmental degradation [3]. Consequently, passive thermal regulation strategies have become increasingly important for achieving sustainable building performance.

Thermal insulation reduces heat transfer through building envelopes; however, it cannot effectively regulate transient thermal loads [4]. Phase Change Materials (PCMs), on the other hand, possess high latent heat storage capacity and can absorb and release thermal energy during phase transition [5]. Integrating PCMs with insulation materials offers a promising solution for improving thermal stability and reducing cooling loads in buildings [6]. Previous studies have demonstrated that improving building envelope performance can significantly reduce cooling energy demand [3]. Thermal mass materials such as concrete and masonry can moderate indoor temperature fluctuations; however, their thermal storage capacity is limited [15]. PCMs have emerged as advanced thermal energy storage materials because of their ability to store large amounts of latent heat within a narrow temperature range [5]. Researchers have reported cooling energy reductions of 20-50% through PCM integration in roofs, walls, and ceilings [6,9]. Thermal insulation materials such as expanded polystyrene (EPS), polyurethane foam, and mineral wool effectively reduce steady-state heat transfer [4].

However, insulation alone cannot adequately address dynamic thermal loads caused by solar radiation.

Recent studies suggest that combining PCMs with insulation materials improves thermal inertia and enhances passive thermal regulation [6,9]. However, limited experimental investigations have been conducted under actual tropical climatic conditions, particularly for retrofit applications in existing and heritage buildings. Therefore, the present study experimentally evaluates the combined effect of PCM and thermal insulation on the thermal performance of building roof systems under hot climatic conditions. The study aims to investigate the effectiveness of PCM-insulation integration in reducing indoor temperature variations and improving passive thermal comfort in buildings.

II. METHODOLOGY

A. Experimental Design

An experimental comparative methodology was adopted to evaluate the thermal performance of three roof configurations:

1) Conventional roof system
2) PCM-integrated roof system
3) PCM + insulation integrated roof system

The experiments were conducted under real outdoor climatic conditions representative of hot and tropical environments.

B. Materials Used

1) Phase Change Material (PCM)

An organic paraffin-based PCM was selected due to its chemical stability, non-corrosive nature, and suitable melting temperature range [5].

Table 1. Thermophysical Properties of Organic Paraffin PCM

Property	Value
PCM Type	Organic Paraffin PCM
Melting Temperature	26-28 °C
Latent Heat	180-200 kJ/kg
Thermal Conductivity	0.20-0.25 W/m·K
Density	850-900 kg/m³

2) Insulation Material

Expanded Polystyrene (EPS) insulation was used due to its low thermal conductivity and suitability for hot climates [4].

Table 2. Physical and Thermal Properties of Expanded Polystyrene (EPS) Insulation Material

Property	Value
Material	EPS
Thermal Conductivity	0.035 W/m·K
Thickness	40 mm
Density	20-25 kg/m³

C. *Experimental Setup*

Temperature sensors were installed at multiple locations as shown in figure 1 and temperature data were recorded at 10-minute intervals using a multi-channel digital data logger.

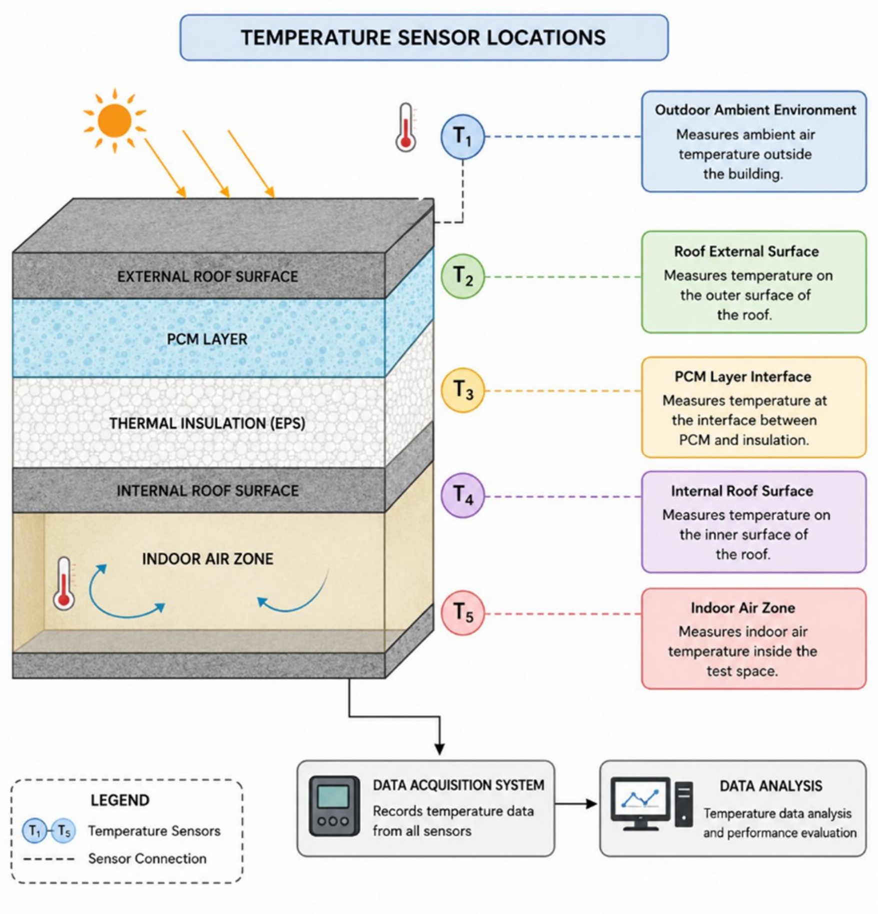

Figure 1. Schematic Representation of Temperature Sensor Locations in PCM-Insulation Hybrid Roof System

D. *Thermal Comfort Assessment*

Thermal comfort was assessed using Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices based on ASHRAE Standard 55 and ISO 7730 [7,8].

III. RESULTS AND DISCUSSION

A. *Thermal Performance of Conventional Roof*

The conventional roof system exhibited high indoor heat gain and limited thermal resistance. The peak indoor temperature reached 36.8 °C when outdoor temperature reached 39.5 °C. The thermal lag was only 0.6 h, indicating rapid heat transfer through the roof.

Table 3. Thermal Performance Parameters of Conventional Roof System

Parameter	Conventional Roof
Peak Indoor Temperature	36.8 °C
Thermal Lag	0.6 h
Indoor Temperature Fluctuation	9.4 °C

B. Performance of PCM-Integrated Roof

The PCM-integrated roof significantly improved indoor thermal performance. The PCM absorbed excess heat during daytime melting and delayed heat transfer into the indoor space.

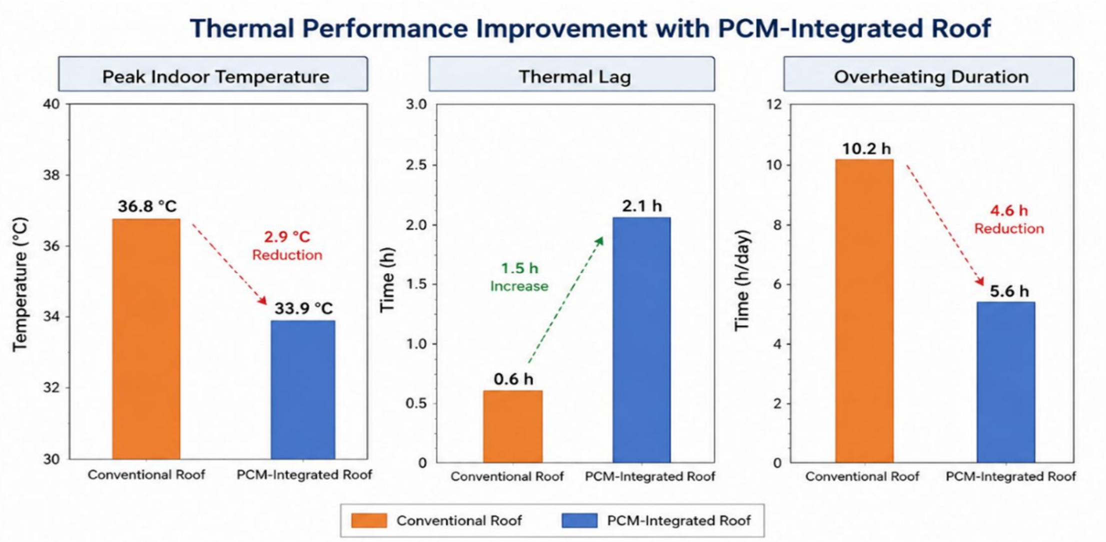

Figure 2. Comparison of thermal performance parameters: Conventional roof vs. PCM integrated Roof

Figure 2 shows the comparative thermal performance analysis demonstrates that the PCM-integrated roof system significantly improved indoor thermal regulation compared to the conventional roof system. The incorporation of PCM reduced the peak indoor temperature from 36.8 °C to 33.9 °C, indicating a temperature reduction of 2.9 °C. This reduction occurred due to the latent heat storage capability of PCM, which absorbed excess solar heat during the daytime melting process.

The PCM roof system also increased the thermal lag from 0.6 h to 2.1 h, showing improved thermal inertia and delayed heat transfer into the indoor environment. Furthermore, the indoor temperature fluctuation decreased from 9.4 °C to 6.2 °C, demonstrating enhanced thermal stability and improved indoor comfort conditions. The results indicate that PCM integration effectively reduces overheating and improves passive cooling performance in building roof systems under hot climatic conditions.

C. Performance of PCM-Insulation Hybrid Roof

The combined PCM-insulation system demonstrated the best thermal performance. The insulation layer reduced steady-state heat transfer, while PCM regulated transient thermal loads.

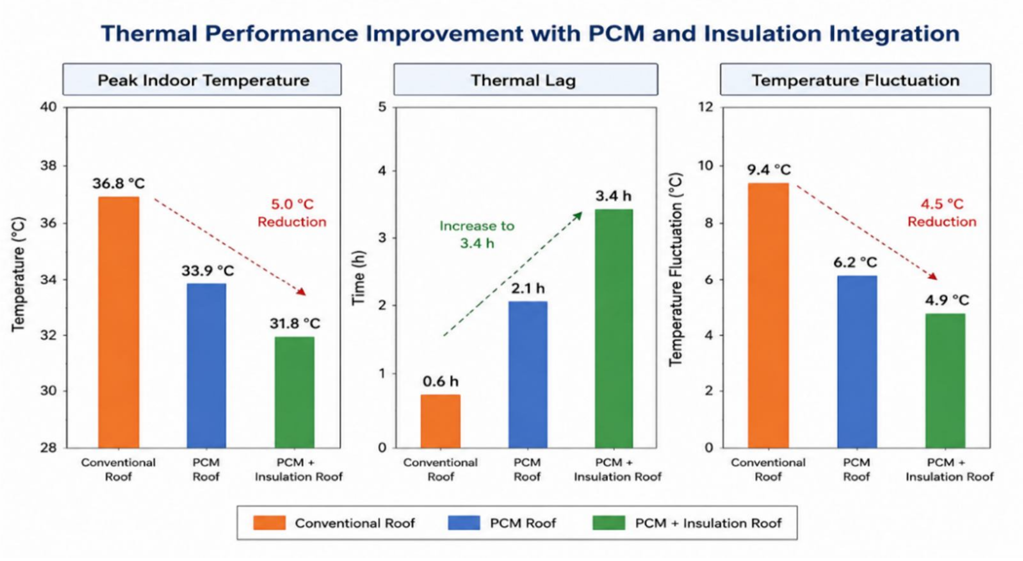

Figure 3 Thermal performance improvement with PCM and insulation integration

Figure 3 compares the thermal performance of three roof configurations, namely Conventional Roof, PCM Roof, and PCM + Insulation Roof, based on peak indoor temperature, thermal lag, and indoor temperature fluctuation. The results indicate that the PCM + Insulation Roof exhibited the best thermal performance among all configurations.

The peak indoor temperature decreased from 36.8 °C for the conventional roof to 33.9 °C for the PCM roof and further to 31.8 °C for the PCM + Insulation roof. This represents an overall reduction of 5.0 °C, indicating effective reduction in indoor heat gain. The thermal lag increased significantly from 0.6 h in the conventional roof to 2.1 h in the PCM roof and further to 3.4 h in the PCM + Insulation roof. The increased thermal lag demonstrates delayed heat transfer through the roof system and improved thermal inertia. Similarly, the indoor temperature fluctuation reduced from 9.4 °C in the conventional roof to 6.2 °C in the PCM roof and further to 4.9 °C in the PCM + Insulation roof. The reduced fluctuation indicates improved indoor thermal stability and enhanced thermal comfort conditions. Overall, the results confirm the synergistic effect of PCM and insulation integration for passive thermal regulation in buildings, leading to reduced cooling requirements and improved energy efficiency under hot climatic conditions.

IV. CONCLUSION

This study experimentally evaluated the thermal performance of PCM-integrated and PCM-insulation hybrid roof systems under hot climatic conditions. The findings demonstrate that PCM integration significantly improves thermal inertia and reduces indoor peak temperature. The combined PCM-insulation system achieved the best overall thermal performance by simultaneously reducing heat transfer and regulating transient thermal loads.

The hybrid system reduced indoor peak temperature by up to 5 °C and increased thermal lag to 3.4 h compared with conventional roof systems. These improvements can substantially reduce cooling energy demand and improve occupant thermal comfort. The study confirms that PCM-insulation systems represent an effective passive cooling strategy for sustainable buildings, particularly in tropical climates and energy-efficient retrofitting applications.

A. Future Scope

Future studies can investigate the long-term thermal performance and durability of PCM-insulation roof systems under different climatic conditions. Further research may also focus on optimizing PCM type, thickness, and placement for enhanced energy efficiency. In addition, numerical simulations and real-scale building applications can be carried out to evaluate the potential of PCM-insulation integration for sustainable and net-zero energy buildings.

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