

Energo-Economic Evaluation of Macroencapsulated PCM and NePCM Integrated Concrete Roof for Passive Building Design

Doctoral Thesis

by

Peerzada Jaffar Abass

(2017CEZ0005)



DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROPAR

July, 2024

Energo-Economic Evaluation of Macroencapsulated PCM and NePCM Integrated Concrete Roof for Passive Building Design

A Thesis Submitted
In Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy

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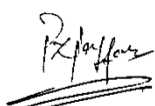
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Declaration of Originality

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Acknowledgments

I take great delight in expressing my heartfelt appreciation and profound gratitude to all those individuals who have provided unwavering support and valuable contributions, instrumental in completing this research endeavor. In particular, I must extend my recognition and gratitude to the almighty God for bestowing me such a wonderful platform to conduct my Ph.D. research.

I sincerely appreciate my Ph.D. supervisor, Dr. Muthulingam Subramanian, for his consistent guidance, encouragement, and unwavering support throughout my research journey. His benevolence and insightful discussions have been instrumental in shaping my research progress thus far, and I look forward to continued collaboration and guidance in the future. I would also like to express my sincere gratitude to the esteemed members of my Doctoral Committee (DC), namely, Dr. Sagar Rohidas Chavan, Dr. Mitesh Surana, Prof. Ravibabu Mulaveesala, and Prof. Rajendra Srivastava for their invaluable suggestions and counsel during the various stages of research evaluation. Their expertise and input have been pivotal in refining and advancing my research endeavors.

Additionally, I extend my heartfelt thanks to Prof. Emeritus Deepak Kashyap for his initial guidance and unwavering moral support during the initial phases of my PhD, even amidst his busy academic and professional commitments. His involvement and encouragement have been greatly appreciated and have had a positive impact on my research journey.

I sincerely thank the weather station team, specifically Dr. Ratan Sarmah, RajKumar Meena, and Surinder Kumar, for their invaluable assistance in obtaining the weather data. I extend my deepest gratitude to the Catalysis and Materials Chemistry Lab staff and the central workshop at IIT Ropar for their invaluable support in the preparation of NEPCM and molds essential for conducting thermal conductivity experiments.

Furthermore, I express my deep gratitude to Dushyant Gumra of the Advanced Materials Research Centre, IIT Mandi, for helping with DSC equipment and their invaluable support and provision of essential facilities throughout my Ph.D. journey. Their expertise has been instrumental in shaping my research endeavors. I extend my sincere thanks to Dr. Devranjan Samanta and Mr. Anuj Babar of the thermal lab, Department Research Facility, Department of Mechanical Engineering, IIT Ropar, for their practical knowledge and valuable guidance and help with the thermal analyzer. I thank Dr. Nahid Rasool of Functional Nanoporous Materials for Catalytic Applications Laboratory, Department of Chemistry, IIT Ropar for helping with FT-IR equipment. I want to extend my sincere thanks to Dr. Dhiraj K. Mahajan and Mr Rupinder Singh Mundra of the Department of Research

Facility, Department of Mechanical Engineering, IIT Ropar, for helping with the Universal Testing Machine.

I am grateful for the unwavering encouragement and cooperation from my research colleagues, including Dr. Abdin Bedada and Dr. Sidharat Chauhan, whose support has been crucial to the progress of my research work.

Finally, I wish to extend my heartfelt appreciation to my parents for their unwavering and consistent support throughout my academic pursuits. Their enduring presence in my life motivates me, fostering a positive mindset during challenging periods and instilling a drive to constantly strive for new achievements and aspirations.

Additionally, I would like to express my deepest gratitude to Dr. Nancy Ghangas for her unwavering support, encouragement, and understanding throughout this journey. Her patience and constant belief in me have been invaluable. I also express my gratitude to all individuals who provided support during my research work, although their names have not been explicitly mentioned in this acknowledgment. Their assistance has played a crucial role in successfully executing this research endeavor.

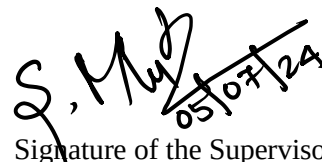


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Certificate

This is to certify that the thesis entitled **Energo-Economic Evaluation of Macroencapsulated PCM and NePCM Integrated Concrete Roof for Passive Building Design**, submitted by **Peerzada Jaffar Abass (2017CEZ0005)** for the award of the degree of **Doctor of Philosophy** of Indian Institute of Technology Ropar, is a record of bonafide research work carried out under my guidance and supervision. To the best of my knowledge and belief, the work presented in this thesis is original and has not been submitted, either in part or full, for the award of any other degree, diploma, fellowship, associateship or similar title of any university or institution.

In my opinion, the thesis has reached the standard fulfilling the requirements of the regulations relating to the Degree.



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Lay Summary

Thermal energy storage (TES) encompasses the technology of storing thermal energy by heating or cooling a storage medium, allowing for subsequent use in various heating and cooling applications. TES systems are commonly deployed in both building and industrial contexts. Initially, thermal storage was not employed for backup purposes but to stabilize systems thermally, eventually finding its niche in solar-assisted thermal systems. TES systems can be categorized into three main types: sensible heat storage, latent heat storage, and thermochemical systems. Sensible heat systems store energy in materials as the temperature rises, releasing it when temperature decreases, while latent heat systems utilize stored energy during phase change. Phase change materials (PCMs) are known for their capacity to store and release thermal energy as latent heat, providing thermal stability and reducing peak cooling and heating loads in buildings. A wide array of PCMs is available, melting and solidifying across various temperatures and applied in diverse applications, including reducing building energy consumption and enhancing the performance of solar-based systems. This thesis focuses on PCM selection, metal void former development, PCM macroencapsulation, and their integration into roof slabs to efficiently manage thermal conditions for building space heating and cooling. The TES performance of a biaxial voided roof slab integrated with PCM is experimentally analyzed under ambient conditions and compared with standard reinforced concrete slabs, aiming to optimize solar energy utilization and reduce building cooling loads. Assessment includes thermal performance metrics and financial viability indicators, establishing a foundation for the effective deployment of PCMs in TES systems and contributing to the sustainable development of society. The findings aim to contribute valuable insights into sustainable building design and energy-efficient construction practices, potentially leading to greener and more environmentally friendly buildings.

Abstract

Global energy consumption, specifically in buildings, has increased significantly over the past three decades, largely due to economic and population growth. Improving the energy efficiency of buildings is critical to reducing global energy consumption, mitigating the effects of global warming, promoting environmental sustainability, and strengthening energy security. In this context, phase change materials (PCMs) are highly effective in storing thermal energy as latent heat. PCMs are widely used in various industries and buildings because of their ability to store latent heat during solid-liquid phase transition at higher temperatures and release it during liquid-solid phase transition at lower temperatures. However, the inherent low thermal conductivity of PCMs, particularly organic PCMs, limits their ability to respond quickly to thermal fluctuations during charge and discharge cycles. Incorporating nanoparticles, metal foam, and fins into PCMs, called nano-enhanced phase change material (NePCM), has improved their thermal conductivity. Roofs, being exposed to direct sunlight, experience significant thermal energy transfer into a building's interior. Employing PCMs has been identified as a promising solution for reducing heat transfer from roofs to interiors. This has significant practical implications for maintaining thermal comfort and optimizing energy savings. However, experimental studies on the thermal evaluation of PCM-integrated roofs, specifically those constructed with reinforced cement concrete (RCC), are very limited. In this study, a comprehensive experimental-based energo-economic assessment of RCC biaxial voided roof macroencapsulated with PCM and NePCM is performed. Further, thermal storage performance measures such as temperature profiles, heat flux, thermal loads, temperature time lag, and temperature decrement factor are evaluated. Financial feasibility indicators, such as electricity cost savings, payback period, and CO₂ emissions savings for various fuels, such as lignite, coal, diesel, natural gas, and naphtha, are also calculated. Temperature fluctuations influence the working of PCM in the surrounding environment. Hence, selecting a suitable PCM is critical to ensure the daily charging and discharging of PCMs. This study evaluates a novel selection of the best PCM implemented in a building envelope, utilizing Multi-Criteria Decision-Making (MCDM) techniques while considering local climatic conditions. The AHP weighs, and TOPSIS and VIKOR decision-making methods choose the most preferred material. By integrating MCDM techniques with climate-specific considerations, the OM35/37 is identified to offer the best overall performance and suitability for the specific environmental context of the building location. Following PCM selection, thermophysical characterization using various techniques is performed. Due to the lack of established characterization standards, thermal characterization of PCMs and PCMs enhanced by carbon-based nanoparticles, including multi-walled carbon nanotubes (MWCNT) and graphene nanoplatelets (GNP) are carried out. In addition to augmenting thermal conductivity, nanoparticle incorporation altered the phase change process,

resulting in a narrower temperature range and reducing supercooling while preserving high latent heat capacity. The PCM-integrated roof reduced interior temperature by up to 7.2 °C during sunny hours, heat transfer to the interior by up to 60.6%, and thermal load by up to 54%. In addition, considering heating and cooling, it offers an average daily saving of 0.06 USD/kWh/m² with a payback period of about 5.7 years. Further, it gives CO₂ emissions savings of up to 13.7, 12.3, and 4.3 kgCO₂/kWh for lignite-, coal-, and natural gas-fired power plants. In addition, its mean time lag is 4.2 hr., with a decrement factor of 0.75 compared to 3.9 hr. and 0.85 for the normal RCC unit. Similar trends were observed with the OM37 integrated roof.

Furthermore, 2% and 4% GNP–NePCMs integrated roof reduced indoor temperatures by an average of 8.0, 9.3, and 9.7 °C during sunny hours, saving 89%, 42%, and 48% more electricity for space cooling than for heating, and have simple payback periods of 5.7, 5.8, and 7.3 years. The average heat flux in OM35, 2%, and 4% GNP–NePCMs is 63%, 79%, and 82% lower than the conventional slab. Further, 2% and 4% GNP–NePCMs save 67% and 65% more CO₂ emissions and 40% and 46% less mean time lag than OM35. From the study, it can be concluded that the proposed PCM-integrated roof is promising and commercially viable.

Keywords: Biaxial voided roof, Phase change materials; NePCM; Macroencapsulation; Electricity cost savings; CO₂ emissions savings; Time lag; Decrement factor.

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Notations and Abbreviations

Acronyms

Symbols	Description
AHP	Analytical Hierarchy Process
APS	Announced Pledges Scenario
BEE	Bureau of Energy Efficiency
BICPV	Building Integrated Concentrated Photovoltaic
BIPV	Building Integrated Photovoltaic
BVS	Biaxially Voided Slab
CAGR	Compound Annual Growth Rate
CPV	Concentrator Photo Voltaic
DPBP	Discounted Payback Period
DSC	Differential Scanning Calorimetry
ECS	Electricity Cost Savings
FE-SEM	Scanning Electron Microscope
FT-IR	Fourier Infrared Spectroscopy
HDPE	High-Density Polyethylene
HVAC	Heating Ventilation, Air Conditioning
IEA	International Energy Agency
LHS	Latent Heat Storage
LHTES	Latent Heat Thermal Energy Storage
LWA	Lightweight Aggregates
MCDM	Multi-Criteria Decision Making
MPCM	Microencapsulated Phase Change Material
NEPCM	Nano Enhanced Phase Change Material
PCM	Phase Change Material
PCT	Phase Change Temperature
PVC	Polyvinyl Chloride
SEM	Scanning Electronic Microscopy
SHS	Sensible Heat Storage Systems
SPBP	Simple Payback Period
SSPCM	Shape Stabilized Phase Change Material
STEPS	Stated Policies Scenario
TCS	Thermochemical Reactions

TES	Thermal Energy Storage
TGA	Thermal Gravimetric Analyzer
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPS	Transient Plane Source Method
TRC	Textile-Reinforced Concrete
TSM	Thermal Storage Medium
VIKOR	Visekriterijumska Optimizacija I Kompromisno Resenje
XRD	X-Ray Diffraction

List of symbols

Symbols	Description
C_s	CO ₂ emissions savings, Kg CO ₂
D_p	Discounted payback period, years
E	Energy storage density, kg/m ³
EF_{CO_2}	CO ₂ emission factor
E_s	Electricity savings, kWh
f_{BVS}	Decrement factor of biaxial voided roof slab unit
f_{CRS}	Decrement factor of normal RCC roof slab unit
H	Latent heat, kJ/kg
H_L	Thermal load, Wh/m ²
ΔH_f	Change in freezing enthalpy, kJ/kg
$H_{f,CRS}$	Variation of heat flux for normal RCC slab unit, W/m ²
$H_{f,BVS}$	Variation of heat flux for Biaxial voided roof slab unit, W/m ²
ΔH_m	Change in melting enthalpy, kJ/kg
$\Delta H_f^{\max}$	Peak heat flux reduction, W/m ²
$\Delta H_m^{\text{NePCM}}$	Melting enthalpy of NePCM, J/g
ΔH_m^{PCM}	Melting enthalpy of PCM, J/g
K	Thermal conductivity, W/mK
K_{eff}	Effective thermal conductivity, W/mK
l_f	Liquid fraction

m	Mass, kg
S_p	simple payback period, years
T	Temperature, °C
T_{AMB}	Ambient temperature, °C
$T_{is,BVS}$	Interior surface temperature of the PCM integrated BVS unit, °C
$T_{is,CRS}$	Interior temperature of the conventional RCC unit, °C
T_l	Liquidus temperature, °C
T_m	Peak melting temperature, °C
T_p	Phase change temperature, °C
T_s	Solidus temperature, °C
T_{es}	Temperature at the exterior surface of the specimen, °C
T_{is}	Temperature at the interior surface of the specimen, °C
T_{sc}	Supercooling degree, °C
t	Time, s
U_p	Unit price of electricity, Rupees

Greek symbols

Symbol	Description
Al	Aluminium
α	Enthalpy efficiency
ε	Emissivity of surface
η	Relative enthalpy efficiency
ϕ_{BVS}	Time lag in biaxial voided roof slab unit, hrs
ϕ_{CRS}	Time lag in normal RCC roof slab unit, hrs
ϕ_w	Weight fraction of nanoparticles
ρ	Density, kg/m ³

1.1 Background

Development of global economy is significantly driven by energy, which has been evolving over millennia due to industrialization and rapid urbanization. There is an urgent need to explore renewable energy sources to ensure a sustainable future, considering challenges such as soaring fuel costs, environmental degradation caused by greenhouse gas emissions, and an escalating energy demand. Among renewable energy sources, solar energy stands out as an abundant and enduring option to replace fossil fuels. The global energy consumption is rapidly increasing, leading to environmental deterioration and the depletion of fossil fuel reserves. The primary energy market is projected to expand by 48% from 2012 to 2040 (*EIA projects 48% increase in world energy consumption by 2040 - U.S. Energy Information Administration (EIA)*, n.d.).

Buildings play a significant role in global energy consumption, accounting for 40% of total energy (*2021 Global Status Report for Buildings and Construction | Globalabc*, n.d.-a) and contributing to 30% of carbon emissions (*2022 Global Status Report for Buildings and Construction | UNEP - UN Environment Programme*, n.d.; *Embodied Carbon - World Green Building Council*, n.d.). The energy demand for buildings has risen by approximately 4% compared to 2020, reaching 135 exajoules (EJ), representing the most substantial increase in the past decade. Correspondingly, carbon dioxide (CO₂) emissions resulting from building operations have reached a record high of around ten gigatons of CO₂ (GtCO₂), reflecting a 5% increase compared to 2020 and a 2% increase compared to the previous peak in 2019 (*2021 Global Status Report for Buildings and Construction | Globalabc*, n.d.-a). Due to its substantial share in the world's total energy consumption, the building industry attracts significant attention from energy policymakers and experts. If the current trajectory persists, it is projected that by 2050, heating and air-conditioning activities will collectively contribute to over half of the total energy consumption in buildings, with heating accounting for 12% and air-conditioning for 37% (Al-Yasiri & Szabó, 2021c). Consequently, reducing peak cooling and heating loads offer the most promising opportunities for reducing energy consumption in the building sector.

Hence, optimizing building performance is paramount in curbing primary energy consumption, mitigating greenhouse gas emissions, promoting sustainable development, and enhancing energy market security. Over 40% of CO₂ is generated through fossil fuel utilization and electricity

generation from thermal power plants (*Carbon Dioxide Emissions From Electricity - World Nuclear Association*, n.d.-a; *Net Zero by 2050 – Analysis - IEA*, n.d.). This CO₂ will account for more than half of the GHG emissions responsible for global warming and climate variability. The global mean surface temperature is projected to increase about 1- 3.5 °C by the year 2100 caused by sea level rising by about 15-95 cm (Koraim et al., 2011). The resultant climate change is a consequence of escalating global temperatures. Researchers anticipate that with rising ambient temperatures, the efficiency of air conditioners will decline, leading to an up to 47.1% surge in electricity consumption for cooling systems by 2050 (*The Future of Cooling – Analysis - IEA*, n.d.). Irrespective of geographical latitude, several emerging nations, including India, are exposed to warm-to-hot weather conditions, and favorable climatic conditions are projected to significantly contribute to global population growth by 2050 (*India - Countries & Regions - IEA*, n.d.). Surface temperatures in these nations are progressively rising due to regular energy production from fossil fuels and thermal power plants and erratic weather phenomena like heat waves (Tripathi et al., 2016). The IEA highlights that the escalating sales of air conditioners in countries like India have led to a rapid increase in residential energy consumption.

Over the past two decades, substantial endeavors have been dedicated to developing and implementing various low-energy systems. A novel and innovative approach to reducing the heating and cooling loads in buildings involves incorporating PCMs for TES systems within buildings (Lawag & Ali, 2022). Integrating passive PCM applications into building envelopes is pivotal in designing net zero energy buildings. Consequently, numerous studies have been conducted to investigate the performance of PCMs in this context. Due to their high thermal storage density, PCMs enhance building components' overall energy storage capacity and reduce internal temperature fluctuations. However, selecting the appropriate PCM, considering each PCM possesses a unique phase change temperature or range, is crucial to designing building elements effectively.

1.2 Why Phase Change Materials?

PCMs can store or release substantial energy while maintaining stable or marginally altered temperatures, [Fig. 1.1](#). PCMs are frequently integrated into building components to reduce the need for air conditioning and heating, mitigate thermal peak loads, regulate temperatures within building elements, or enhance the overall resilience of the system (Akeiber et al., 2016; Yi Gao & Meng, 2023; L. Liu et al., 2022). PCMs are commonly categorized based on material type into three classes: organic, inorganic, and eutectic (Ramakrishnan et al., 2017). Organic PCMs originate from hydrocarbon-based paraffin wax, while inorganic PCMs are derived from metals, alloys, and hydrated salts. Scholars have extensively explored methods to enhance PCM performance and

adaptability. Integrating PCMs into building envelopes significantly augments the heat capacity of the structure (Z.-A. Liu et al., 2023; L. Ma et al., 2023). The amalgamation of PCMs with diverse building elements, including walls, roofs, floors, and ceilings, has demonstrated promising potential in substantially diminishing energy consumption associated with space cooling and heating. Incorporating PCMs into the building envelope can be achieved through various approaches such as impregnation, immersion, direct incorporation, encapsulation, and shape stabilization (Z. Liu et al., 2018; N. Shukla et al., 2012; Tyagi et al., 2011; D. Zhou et al., 2012). PCM encapsulation can be achieved at nano, micro, and macro scales. The sizes range from 1–1000 nm, 1–1000 μm , and ≥ 1 mm, respectively (Arshad et al., 2019). Among these approaches, microencapsulation and macroencapsulation have garnered considerable attention from researchers as innovative ways to integrate PCMs into building materials. Encapsulating the PCM offers several advantages, including preventing leakage, avoiding direct interaction between the PCM and the matrix material, enhancing strength, and increasing the heat transfer area. The macroencapsulation technique offers advantages such as high strength, increased energy density due to a higher PCM-to-coating ratio, and the ability to be easily produced in various shapes and sizes as needed. It provides a practical approach to incorporating PCMs into shell materials of different geometries, such as spheres, rectangles, and tubes (Zayed et al., 2020c). Additionally, it allows for integrating a higher amount of PCM, resulting in an improved encapsulation ratio (Parameshwaran et al., 2012). PCM can be applied to various building components, including external walls (Lee et al., 2015a; D. Zhou et al., 2014; G. Zhou et al., 2010), roofs (Hu & Yu, 2019, 2020), floors (S. Lu et al., 2020a; Roman et al., 2016), glazing units (D. Li et al., 2018), (Memon et al., 2015) and bricks (Saxena et al., 2020a; Xu Wang et al., 2016b). Among these, researchers have emphasized incorporating PCM into external walls due to their extensive exposed surface area.

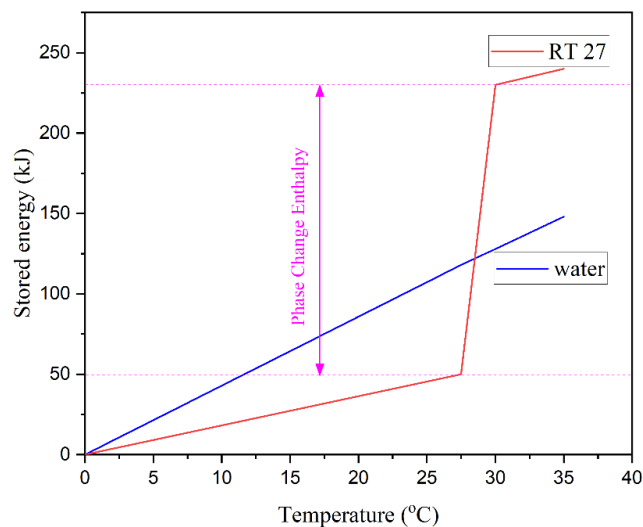


Fig. 1.1 Energy storage comparison between PCM and building materials (Sajawal et al., 2019).

1.3 Does NePCMs outperform PCMs?

PCMs demonstrate a substantial energy storage capacity that manifests during their phase transition. Despite PCM advantages, these materials exhibit various limitations, such as low thermal conductivity, sub-cooling, leakage, phase segregation, corrosiveness, and thermal instability (Milián et al., 2017). Organic PCMs are extensively utilized in building envelopes for their benefits, including non-corrosiveness, congruent melting, self-nucleation, latent heat capacity, chemical inertness, and thermal stability (Zeng et al., 2012). Hydrocarbon-based PCMs typically exhibit thermal conductivity values ranging from 0.1 to 0.4 W/m K (Khodadadi et al., 2013a). Notably, modifying the thermal conductivity of PCMs may influence their energy storage or release capabilities, making improved thermal conductivity desirable in numerous applications. Adding nanoparticles, metal foam, and fins to PCMs has enhanced their thermal conductivity (Ashraf et al., 2017; T X Li et al., 2017; N. H. Mohamed et al., 2017b). However, incorporating metal foams and fins into PCMs increases weight and design complexity compared to nanoparticles (Leong et al., 2019). In this research, nano-enhanced phase change material (NePCM) denotes PCMs infused with nanoparticles. Various nanomaterials, such as copper, copper oxide, aluminum, alumina, titanium, silver, silica, carbon nanotubes, and graphite nanofibers, have been utilized in the development of NePCMs (Al-Shannaq et al., 2016; Ashraf et al., 2017; Kalaiselvam et al., 2012; Khodadadi et al., 2013a; Leong et al., 2019; N. H. Mohamed et al., 2017b; Sayyar et al., 2014; Tunçbilek et al., 2022).

1.4 Motivation

The pursuit of improved comfort and living standards has increased energy consumption in buildings, increasing construction costs. The precise design of energy storage systems is vital for functionality and efficiency while enhancing energy conservation is key to building sustainability and reducing reliance on non-renewable sources. Reducing energy consumption and bolstering energy conservation are pivotal in advancing buildings' sustainability and energy efficiency. However, an imprecise understanding of TES often leads to design inaccuracies. The integration of renewable energy sources aids in diminishing the reliance on conventional energy sources for building operations. Despite the straightforward use of PCMs, optimizing their latent heat for optimal energy performance remains challenging. Evaluating buildings integrated with PCMs and NePCMs aims to enhance energy efficiency and thermal comfort by reducing heating and cooling demands, thus saving energy and lowering carbon emissions. Additionally, PCMs and NePCMs can stabilize indoor temperatures and improve occupants' comfort by minimizing temperature fluctuations. Furthermore, the development of NePCMs offers an opportunity to enhance the thermal properties of base PCMs, maximizing their effectiveness in buildings.

While there has been significant investigation into integrating PCMs into diverse building elements, relatively less emphasis has been placed on incorporating PCMs into roofs. Given that roofs are subjected to direct solar radiation; they play a substantial role in facilitating thermal energy transmission to the interior of buildings. Under clear sky conditions, the surface of a roof can absorb solar energy at a rate of 1 kW/m^2 , with absorption levels ranging from 20% to 95%. Integrating PCMs into roofs offers a viable solution to mitigate heat transfer from roofs to interior spaces, thereby enhancing thermal comfort and energy efficiency (Alqallaf & Alawadhi, 2013; Guichard et al., 2014; D. Li et al., 2015; Pasupathy & Velraj, 2008a; Shanmuganathan et al., 2021; Xamán et al., 2020; J. Yu et al., 2020).

1.5 Need for Further Research

Though the previously discussed sub-topics make it easy to go with the flow, the specific area to be worked on is discussed in this paragraph. According to the IEA, world energy consumption is expected to increase 29% from 2015 to 2040. TES can potentially diminish energy consumption and reliance on fossil fuels by eroding the mismatch between energy supply and demand. TES with PCMs in this context offers a distinctive aptitude to diminish the demand for fossil fuels and conquer GHG emissions. Using PCM, the construction segment is expected to grow by 85%, while China, India, and the US cover 57%. Such materials are incorporated into building envelopes, viz. floors, ceilings, wallboards, roofs, shuttering, etc., for TES to restrain temperature fluctuations and achieve lower energy consumption. Less emphasis has been placed on incorporating PCMs into roofs. The market of PCM is expected to experience a noteworthy compound annual growth rate (CAGR) of 17.4% from 2020 to 2026 (*Phase Change Materials Market Size & Share | Statistics - 2026*, n.d.). Moreover, promoting the concept of green buildings by increasing leadership in energy and environmental design popularity has pushed construction activities globally to flourish with PCM incorporation.

Growing heat waves and rising temperatures have led builders and architects to adopt cool-roof techniques using PCM. Furthermore, selecting the proper PCM for a given application still needs to be experienced more. A crucial facet to consider is how durable a material is after going through loops of charging and discharging. Design macroencapsulations integrated with PCMs to satisfy the mismatch between charging and discharging of the available heat/cold. A custom-designed solution is needed for each application bearing source and sink.

1.6 Problem Definition

Over the past two decades, considerable research efforts have been devoted to exploring the applicability of PCMs as TES media. Among organic PCMs, paraffin wax has gained significant

popularity as a latent heat storage material. However, organic PCMs exhibit a notable drawback of low thermal conductivity, typically around 0.167 W/mK or less, leading to prolonged energy transfer rates during melting and freezing processes. This limitation hinders the efficient storage of thermal energy within organic PCMs. To address this challenge, researchers have proposed various techniques, including using multiple PCMs, fins, shells, and metal matrices with PCMs, aiming to enhance heat transfer performance. Despite such efforts, the theoretical understanding and empirical data regarding the practical applicability of these approaches beyond laboratory conditions remain limited.

Moreover, the complexity associated with these heat transfer enhancement methods contributes to the overall expenditure of TES systems. Additionally, there is a notable absence of comprehensive numerical analysis and knowledge to assess the potential energy savings in building envelopes during PCM melting or crystallization processes. Of particular importance is the understanding of the role of the solid-liquid interface boundary in shaping the behavior of PCM materials. Therefore, conducting experimental studies on PCM-based TES systems becomes imperative to obtain crucial performance metrics, such as charging time, PCM temperature, storage efficiency, and surface temperature. These experimental insights are vital in developing and optimizing effective TES systems that maximize energy utilization and thermal comfort in various applications.

The thesis is based on the assumption that TES can significantly contribute to enhancing the efficiency of buildings. To evaluate the research statement, the following inferences are drawn:

1.6.1 Aims

- i. To what extent can TES contribute to the sustainability of buildings, and what are the potential environmental and economic benefits?
- ii. How do heat exchangers impact thermal energy's charging and discharging rates in TES systems, and what are the crucial design considerations and performance metrics associated with their implementation?
- iii. What are the techno-economic benefits of promoting energy efficiency in buildings, and how can TES systems be effectively integrated into building energy management strategies to optimize energy supply and demand matching?
- iv. What are the various materials, technologies, and methodologies that can be adopted to reduce the dependency on fossil fuels in buildings, and what are the associated technical and economic challenges and opportunities?
- v. How can the integration and optimization of PCMs in heating ventilation and air-conditioning (HVAC) systems effectively reduce the demand for cooling and heating loads during summer and winter? what are the key factors influencing their performance and cost-effectiveness?

1.7 Objectives

The study focuses on developing a new biaxial voided RCC roof slab (BVS) integrated with PCM/NePCM. To effectively control indoor thermal comfort, reduce energy consumption, and provide cost savings to the occupants. In this slab, PCM/NePCM macroencapsulated metal void formers with a high encapsulation ratio are integrated into the concrete matrix during the casting process. The thermal energy storage performance of the roof slab is evaluated under ambient conditions and compared with a normal RCC roof slab.

In this context, the thesis focusses on analyzing an innovative TES system, to exploit its full potential in enhancing energy efficiency of a roof. To achieve this, the following objectives were formulated:

1. To employ multi-criteria decision-making analysis to systematically evaluate and select the most appropriate PCM for integration into the roof under a hot climate, considering various thermophysical characteristics.
2. To conduct comprehensive thermophysical characterization of PCM using various techniques.
3. To perform an energo-economic evaluation of PCM-integrated concrete roof under ambient conditions.
4. To conduct comprehensive thermophysical characterization of NePCM using various techniques.
5. To perform an energo-economic evaluation of NePCM-integrated concrete roof under ambient conditions.

1.8 Scope

The primary scope for this research stems from the pressing need to enhance the energy efficiency and economic viability of buildings while minimizing their environmental footprint. By evaluating the thermal performance, financial feasibility, and environmental impact of PCM and NePCM integrated roofs, this study aims to provide valuable insights into their potential as sustainable solutions for passive building design. Challenges in PCM implementation include selecting materials tailored to building requirements, necessitating structural modifications, and precision fabrication. Despite rational energy utilization and integration of TES systems leading to sustainable building construction, economic evaluation for heating and cooling applications is yet to be studied. The compatibility of PCM and optimal location/thickness is yet to be explored. Integration processes are resource-intensive, raising cost concerns. Research explores nanoparticle

effects on PCM properties and phase transitions. Moreover, thermal performance evaluation studies of NePCMs integrated building envelopes are limited.

1.9 Thesis Outline

The thesis is divided into two main parts, [Fig. 1.2](#): part A delves into the experimental investigation of a concrete roof slab integrated with PCMs. In contrast, part B explores the performance of NePCMs integrated concrete roof. Part A comprises Chapters 2 to 5, which focus on the selection, characterization, and thermal performance of PCMs. Meanwhile, Part B encompasses Chapters 2, 6, and 7, which discuss the thermal performance evaluation of PCMs and NePCMs within the concrete roof slab.

Chapter 2 serves as a comprehensive survey of PCMs/NePCMs and their utilization in building envelopes, encompassing analysis of integration techniques and suitable locations within building structures. Chapter 3 centers on the meticulous selection of appropriate PCMs for the considered temperature profiles, while Chapter 4 is devoted to the thorough characterization of PCMs using different techniques. An energo-economic evaluation of PCM-integrated concrete roofs under ambient conditions is evaluated in Chapter 5.

Chapter 6 highlights the limitations of PCMs overcome by adding nanoparticles. Adding nanoparticles improves the thermal conductivity of PCM, thus improving thermal stability by reducing sub-cooling. The performance of NePCM-integrated concrete roofs under ambient climatic conditions is evaluated in Chapter 7.

Finally, a summary of conclusions and future recommendations is presented in chapter 8.

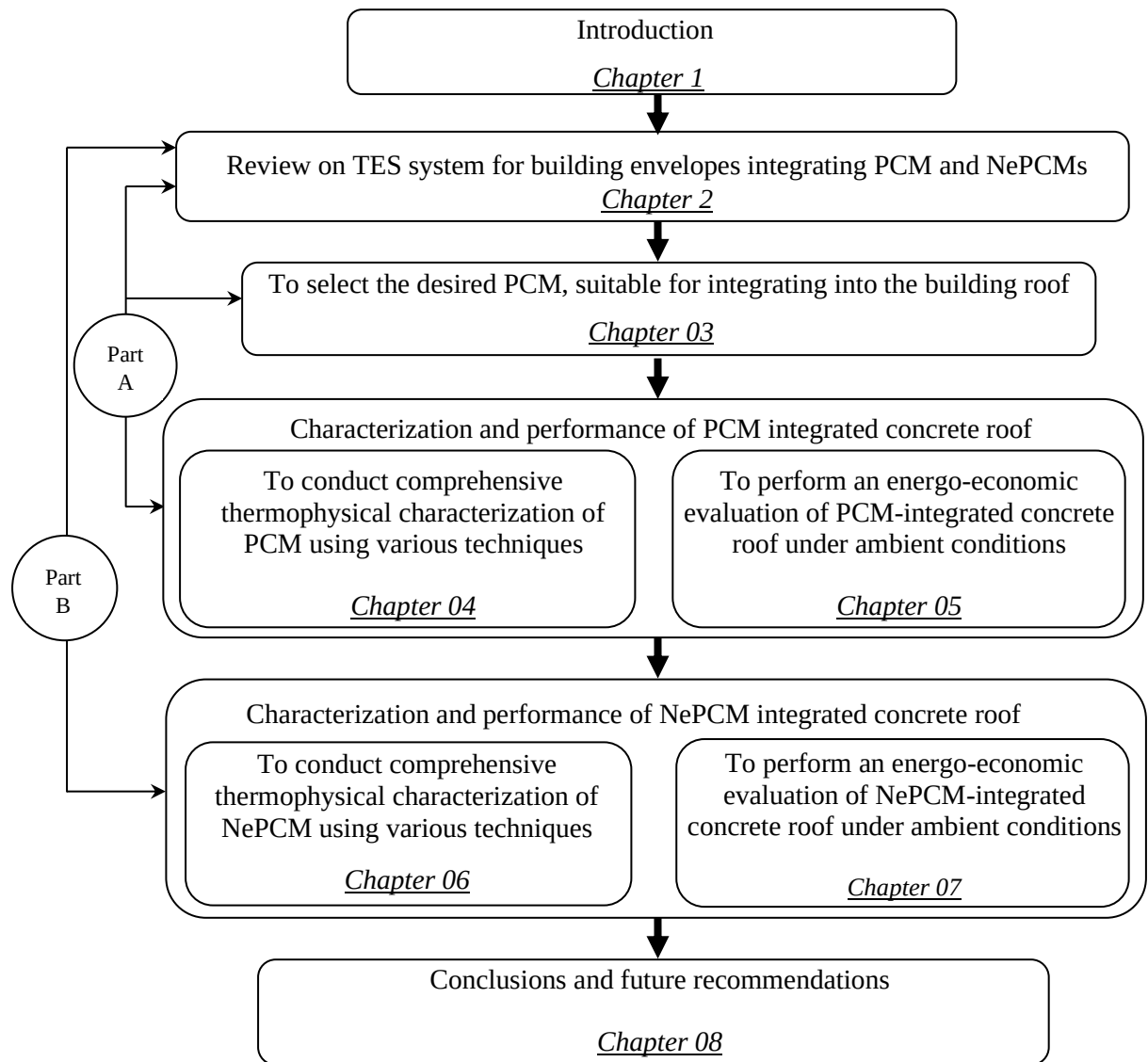


Fig. 1.2 Flowchart describing the outline of thesis.

2.1 Energy Outlook

Between 2020 and 2030, a forecasted annual growth rate of 1.3% is anticipated in the overall energy supply, resulting in the attainment of 670 EJ under the stated policies scenario (STEPS) framework. However, with the announced pledges scenario (APS) implementation, the yearly growth rate is expected to reduce to 1.0%, leading to a total supply of 650 EJ by 2030 (as per IEA's 2021 data). The combined contributions of the building and construction sectors comprise approximately 40% of global energy consumption while also accounting for about one-third of total energy-related emissions worldwide (in both direct and indirect forms) (*2021 Global Status Report for Buildings and Construction* | Globalabc, n.d.-b). This encompasses 8% of emissions from building operations and an additional 18% originating from the electricity and heat generation used within buildings. Notably, the building industry has observed a marked surge in energy consumption over the last decade, particularly in terms of heating and air conditioning demands. In 2022, the buildings sector witnessed a 1% increase in energy consumption compared to the preceding year (*Buildings - Energy System* - IEA, n.d.). Several factors, including enhanced energy access in emerging economies, growing cooling requirements in tropical regions, increased ownership and utilization of energy-intensive appliances, and global expansion of building structures, contribute to this trend. Alarming, a substantial proportion of nations, around 2/3rd, lack mandatory building energy regulations, which leads to the incorporation of billions of square meters of non-mandatory performance standards in the building sector annually (*Building envelopes - Fuels & Technologies* - IEA, n.d.). In regions heavily reliant on traditional biomass, building energy usage can constitute up to 80% of total energy consumption. Notably, in warm and humid climates with elevated humidity levels, factors like comfort preferences, economic status, and improved electricity access significantly drive this gradual escalation. The trajectory of energy consumption in buildings indicates that air conditioning is the most rapidly growing sector among energy-consuming building applications. Space cooling energy demand has doubled since 2000, primarily due to rising temperatures and related factors. Unless notable efficiency enhancements are achieved, the need for space cooling energy is projected to surge significantly, potentially exceeding a two-fold increase between the present and 2040 due to heightened human mobility and the adoption of air conditioning units, (*Cooling - Fuels & Technologies* - IEA, n.d.).

India's burgeoning energy demands hold substantial implications for the global energy landscape. Due to robust economic progress and improving living standards, India presently holds the position

of the third-largest energy consumer worldwide. Despite experiencing a growth in energy consumption since the year 2000, a significant portion, approximately 80%, of the worldwide energy demand is still met by solid biomass, coal, and oil sources. Interestingly, India's per capita energy consumption and associated emissions are comparatively lower than the global average, primarily influenced by variables such as steel and cement production and vehicle ownership rates. The forthcoming energy needs in India will heavily hinge on critical sectors, including construction, buildings, automotive industries, and household appliances. Projections suggest that a notable proportion of India's emissions under the STEPS scenario will originate from power plants, factories, buildings, and vehicles that are slated to be constructed within the upcoming two decades. (*India Energy Outlook 2021 – Analysis - IEA*, n.d.). Since 2000, the total energy supply has surged from 417.88 Mtoe (growth of 49.12%) to 937.94 Mtoe (a surge of 234.7%). In contrast, energy consumption has witnessed a dramatic increase from 407.24 TWh (a growth of 73.81%) to 1349 TWh (a surge of 475.81%), resulting in a remarkable 394.84% escalation in CO₂ emissions as depicted in Fig. 2.1.

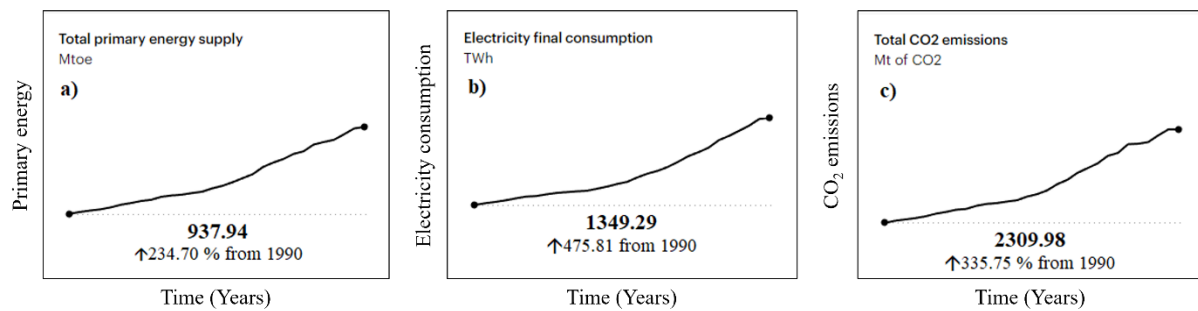


Fig. 2.1 The key statistics of overall India energy outlook (*India - Countries & Regions - IEA*, n.d.).

If this trend persists, space cooling and heating will constitute over 50% of the total energy consumption in buildings by the year 2050. Consequently, these aspects offer the most significant potential for reducing energy in building applications. To curtail the electricity demand for heating and air conditioning, buildings need to adopt energy-efficient techniques and advanced technologies. TES systems present a promising solution for minimizing the energy requirements for heating and cooling by redistributing peak demands to off-peak periods and effectively managing indoor temperatures.

2.2 Introduction to Thermal Energy Storage

In light of the escalating global population, the reliance on renewable energy sources to fulfill energy demands has intensified. Given the rising greenhouse gas emissions and the mounting economic costs tied to fossil fuels, the adoption of renewable sources and energy-efficient practices

has gained paramount significance. Notably, the building sector accounts for a substantial fraction of the worldwide energy consumption and continues to grow annually. Within the ambit of building energy consumption, HVAC systems contribute to 60% of the aggregate energy usage (Akeiber et al., 2016). To address the challenges posed by building energy consumption, innovative solutions have surfaced, encompassing the deployment of diverse energy storage systems such as mechanical, electromagnetic, chemical, and thermal energy storage. TES technology has garnered significant attention due to its high energy storage density. TES involves the accumulation of excess heat and its subsequent release as per demand, thereby bridging the gap between energy supply and demand. These systems store energy in a thermal state, which is achieved through the heating or cooling of the storage medium. TES systems have widespread applications across various sectors, including buildings and industries.

Integrating TES into energy storage media yields several advantages, including heightened overall efficiency, enhanced reliability, cost-effectiveness, and reduced environmental pollution levels. Nevertheless, these storage media are not without limitations, mainly stemming from their suboptimal thermophysical properties (Berardi & Gallardo, 2019). The success of energy consumption management, appliance efficiency, and the optimization of solar utilization heavily hinges on the energy storage density exhibited by the selected storage media. The technology of TES enables the storage and utilization of energy over diurnal or seasonal cycles, facilitating the storage of excess heat during summer for subsequent use in winter and vice versa for cooling applications during warmer periods. In this context, PCMs have emerged as prospective contenders for solar applications and warrant further in-depth exploration. The advantages provided by TES systems are like:

- i. Application in active and passive systems.
- ii. Peak load shifting techniques.
- iii. Sensible use of thermal energy.
- iv. Increase overall efficiency and dependability.
- v. Lower investment and operating costs.
- vi. Lower CO₂ emissions and pollution.

2.2.1 Thermal Energy Storage Methods

The TES systems possess distinct characteristics concerning energy media, encompassing capacity, efficiency, storage period, power, cost, and charging and discharging time. Within the temperature range of -40°C to $+400^{\circ}\text{C}$, three primary TES systems are available: sensible heat storage systems (SHS), latent heat storage (LHS) systems, and thermochemical reactions (TCS), as depicted in [Fig. 2.2](#). [Table 2.1](#) provides a comprehensive depiction of the typical parameters associated with these storage systems. The choice of TES depends on the specific application requirements.

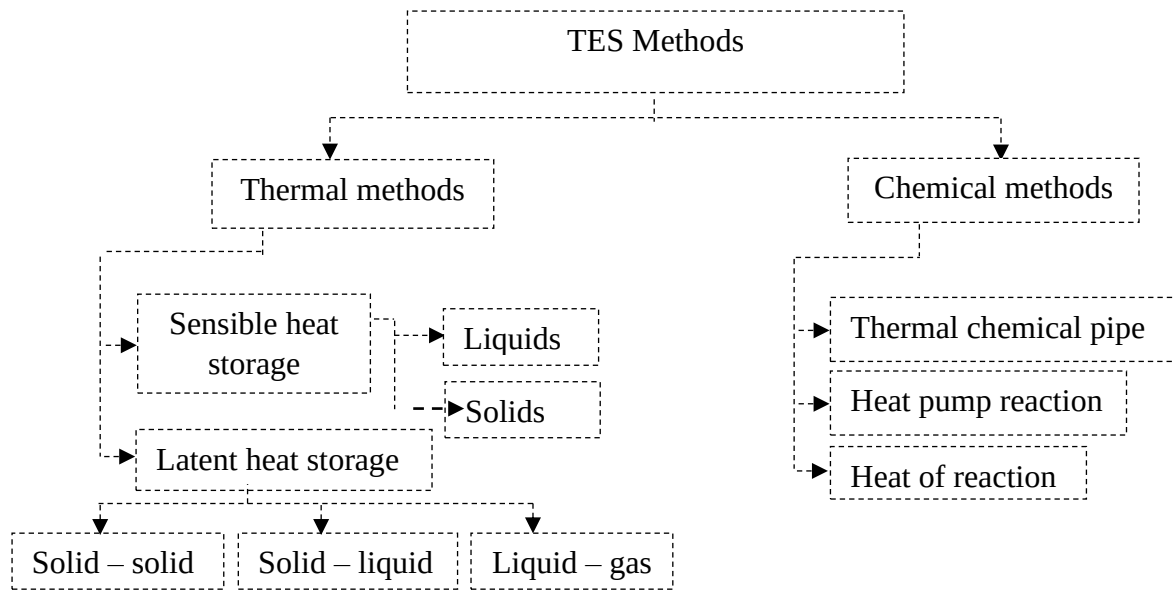


Fig. 2.2 Classification of thermal energy storage systems.

Table 2.1 Typical parameters of thermal energy storage systems.

S.No.	TES systems	Capacity (kWh ^{t-1})	Energy Efficiency (%)	Power (MW)	Storage period	Cost (\$/kWh)
1.	Sensible	20-50	50-90	0.001-10.0	D/M *	0.1-10
2.	Latent heat	50-150	75-90	0.001-1.0	H/M	10-50
3.	Thermo-chemical	120-250	75-100	0.01-1.0	H/D	8-100

* D is for days, M for months, and H for hours.

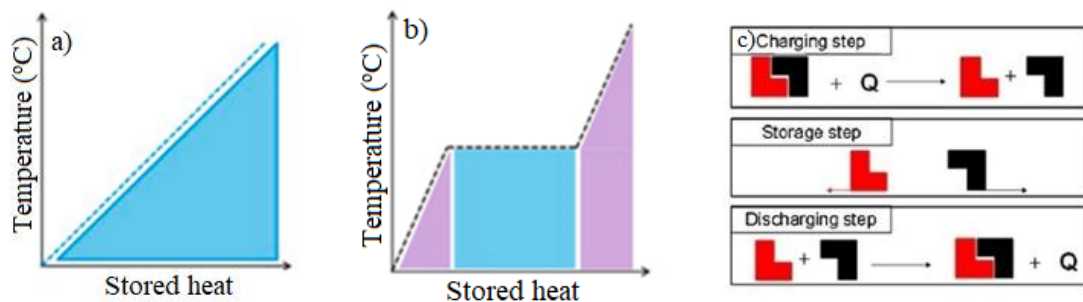


Fig. 2.3 The categories of TES systems: (a) sensible; (b) latent heat; (c) thermo-chemical reactions.

2.2.1.1 Sensible Heat Storage System

Sensible heat thermal energy storage, as depicted in Fig. 2.3a, refers to the conventional approach of storing energy by utilizing heat transfer to increase or decrease the temperature of the storage medium. SHS devices leverage the medium's heat capacity and temperature change, enabling the cyclic storage and recovery of heat. However, this method demands considerable storage material

(A.Sharma et al., 2009). The amount of heat stored is governed by the storage material's heat capacity, temperature variations, and mass of the storage material. The selection of SHS materials for energy storage depends on the intended application and the temperature range. The process of storing energy involves gradually raising the body's temperature from its initial temperature (T_i) to a final temperature (T_f) while maintaining its mass (m) and specific heat capacity ($c(T)$) constant. The following equation (Eq. 2.1) converts the amount of heat stored (Prasad et al., 2019).

$$Q = \int_{T_i}^{T_f} m \times c(T) \times dT \quad (2.1)$$

When the specific heat is assumed to remain steady over the temperature range, the relationship is rewritten as follows (Eq. 2.2):

$$Q = m \times c(T) \times (T_f - T_i) \quad (2.2)$$

The temperature differential determines the quantity of energy stored. As a result, there are two scenarios:

- If $T_f > T_i$: Heat storage.
- If $T_f < T_i$: Cold storage.

A solid or liquid substance is utilized as a storage medium for sensible heat storage. Metals and non-metals are commonly used in solid storage mediums. The dependability of this storage method is hampered by non-metals poor specific heat capacity and thermal conductivity. For high-temperature SHS, Metals are appropriate; however, the metal-based TES system is costly, making this a significant barrier to commercialization (Tatsidjodoung et al., 2013). Metals and graphene are ideal for rapid melting and freezing because of high thermal diffusivity. In contrast, non-metals low thermal diffusivities suit them for slow melting and freezing cycles.

Table 2.2 Thermophysical properties of some storage mediums employed as sensible heat storage (Ayyappan et al., 2016).

Storage material	Melting point (°C)	Specific heat capacity (C_p), kJ/kgK	Density (ρ), kg/m ³	Thermal conductivity (k), W/mK	Thermal diffusivity $\alpha = k/\rho c \times 10^6$ (m ² /s)
Sand	1500	0.8	1555	0.15–0.25	1.172
Rock	1800	0.84	2480	2–7	1.450
Concrete	1000	0.75	2240	1.7	0.356–0.514
Granite	1215	0.82	2640	1.7–4.0	0.799–1.840
Brick	1800	0.84	1698	1.04	0.484
Aluminum	660	0.896	2707	204	84.10
Cast iron	1150	0.837	7900	29.3	4.431

Molten salts, water, and thermal oils are examples of liquid storage media, although the poor thermal characteristics limit the range of applications for this class of TES. [Table 2.2](#) shows the characteristics of certain materials employed as sensible heat storage materials (Ayyappan et al., 2016). Water is the most incredible medium for heat storage in solar heating systems since it is readily accessible, affordable, and has a high specific heat capacity and density. On the other hand, Molten salts have more acceptable thermophysical characteristics and are used in various high-temperature TES applications.

2.2.1.2 Latent heat storage systems

Latent heat refers to the amount of energy required to induce a material to transition from one state to another while absorbing or releasing a substantial quantity of heat (Ref. [Fig. 2.3b](#)). The LHS system functions at a constant temperature, corresponding to the phase transition temperature. The feature of minimal volume and temperature change makes energy storage through latent heat form highly intriguing (Ahmed et al., 2020). LHS provides a higher energy storage density without experiencing temperature variations compared to SHS. PCMs are utilized in LHTES to effectively absorb and release heat energy during the phase transition process. The following equation ([Eq. 2.3](#)) describes the heat storage capacity of LHS when utilizing PCMs:

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \quad (2.3)$$

2.2.1.3 Thermochemical energy storage system

TCS is a reversible process that enables energy storage and release (Pardo et al., 2014). This method offers a higher storage density, reducing mass and storage requirements. TCES systems utilize solid-gas, liquid-gas, and gas-phase systems to achieve efficient energy storage. The storage process in TCES relies on a disintegration reaction that allows for chemically reversible reactions, enabling subsequent retrieval of the stored energy during the thermal cycle of charging, storing, and discharging (André et al., 2016) as illustrated in [Fig. 2.3c](#). Various metal carbonates, oxides, and hydroxides have been identified as potential candidates for TCES based on their chemical energy and working temperature, offering promising future possibilities for thermal energy storage research.

2.2.2 Assessment between SHS, LHS, and TCE systems

The assessment between SHS, LHS, and TCE systems is illustrated in [Table 2.3](#).

Table 2.3 Assessment between SHS, LHS, and TCE systems (Abedin, 2011; Gil et al., 2010).

Properties	SHS	LHS	TCE
Retention capacity	Low	High	Low
Storage density	Low	Low	High
Life span	Longest	Less	Least
Flexible working temperature range	Less	High	Least

2.2.3 Application of TES systems in buildings

Three primary categories of TES systems incorporate PCMs in buildings: passive, active, and free cooling systems. Passive systems involve the integration of PCMs into the building envelope, increasing thermal mass, and operating without an external source. Extensive research by (Al-Yasiri & Szabó, 2021b; Lee et al., 2018; Rathore & Shukla, 2019; Stritih et al., 2018; Vanaga et al., 2018) indicates that employing PCMs in passive applications enhances interior thermal comfort and reduces building energy consumption. The thermophysical characteristics of the PCM, incorporation technique, and regional environmental conditions are crucial factors influencing energy savings and temperature decrease in passive cooling applications. The limitation of passive cooling lies in the incomplete solidification of PCM after cooling nights. Researchers have focused on free cooling and active application approaches over the past two decades to address this issue. One of the earliest free-cooling TES systems was introduced around 2000 by Turnpenny et al. (2000), which demonstrated a heat transfer rate of 40 W. Free-cooling TES systems' effectiveness is highly dependent on the regional daily temperature range, typically between 12 and 15 °C. In contrast, active TES systems employ pumps and fans to transfer thermal energy from PCMs to air or water and are commonly integrated with traditional HVAC systems (Weinläder et al., 2014).

The thermal conductivity of the thermal storage medium (TSM) significantly influences TES performance. Various methods, such as fins Hosseinzadeh et al. (2020), metal foams Guo et al. (2021), and the incorporation of nanofillers (Danes hazarian et al., 2021; Yazdanifard et al., 2021) into the PCMs have been employed to enhance the thermal efficiency of PCMs. Different TSMs can be chosen to meet the specific energy demands of different buildings, as their heating and cooling loads vary (S. Shukla et al., 2021).

2.3 Phase Change Materials: The Concept

The escalating energy demand and the limited availability of fossil fuels have driven researchers to seek renewable power solutions. The adoption of TES systems has become crucial to address the intermittent nature of renewable energy sources. TES effectively bridges the gap between energy

supply and demand while enhancing the overall efficiency and reliability of power grids. LHTES systems, in particular, exhibit the capability to store and release significant amounts of energy during charging and discharging cycles (Aljehani et al., 2020). PCMs are the TES media that enable the storage and discharge of latent heat during their phase transition at nearly constant temperatures. The LHTES system using PCMs has proven to be the most viable option among the three energy storage technologies due to its capacity to efficiently store and release energy within a specific temperature range during phase change processes (Soliman et al., 2022). By incorporating various energy-saving and sustainable energy applications, the LHTES system enhances energy efficiency significantly (Selvnes et al., 2021). PCMs have found diverse applications in buildings, cooling systems, textiles, electronics, military sectors, solar energy systems, and other areas, thanks to their distinctive characteristics. TES systems have found significant applications in space heating to improve energy efficiency in buildings, and PCMs have gained considerable attention as a viable solution for energy saving, effectively bridging the gap between energy supply and demand (Luo et al., 2022). PCMs can be classified based on phase change models into four groups: solid-liquid, solid-solid, gas-liquid, and gas-solid. However, only solid-liquid phase change PCMs can be practically implemented in building applications due to technical challenges associated with other categories, such as significant volume changes, the need for a considerable amount of material to store a given energy, and variable temperatures during energy storage. Solid-liquid PCMs can absorb and release heat energy through endothermic and exothermic processes during their charging and discharging phases, as depicted in Fig. 2.4. This phase change is characterized by high enthalpy with minimal volume change (Changhui Liu & Tan, 2021), making it a suitable option for efficient TES with ease of handling.

Through the incorporation of PCMs, efficient energy management is achieved in various applications. PCMs exhibit significant potential in regulating the ambient temperature within a specific temperature range near their melting point. When integrated into buildings, PCMs play a vital role in stabilizing the indoor environment by reducing peak temperatures and temperature fluctuations. As shown in Fig. 2.5, buildings equipped with PCM experience lower temperature swings and shorter time delays, resulting in improved comfort compared to buildings without PCM. As a result, PCMs have been extensively employed in buildings to maintain interior temperature despite changing external weather and temperature conditions. This approach is more environmentally friendly, as it reduces the need for excessive electrical energy for heating or cooling the building using radiators during freezing winters or conditioning systems during hot summers (Osterman et al., 2012; D. Zhou et al., 2012).

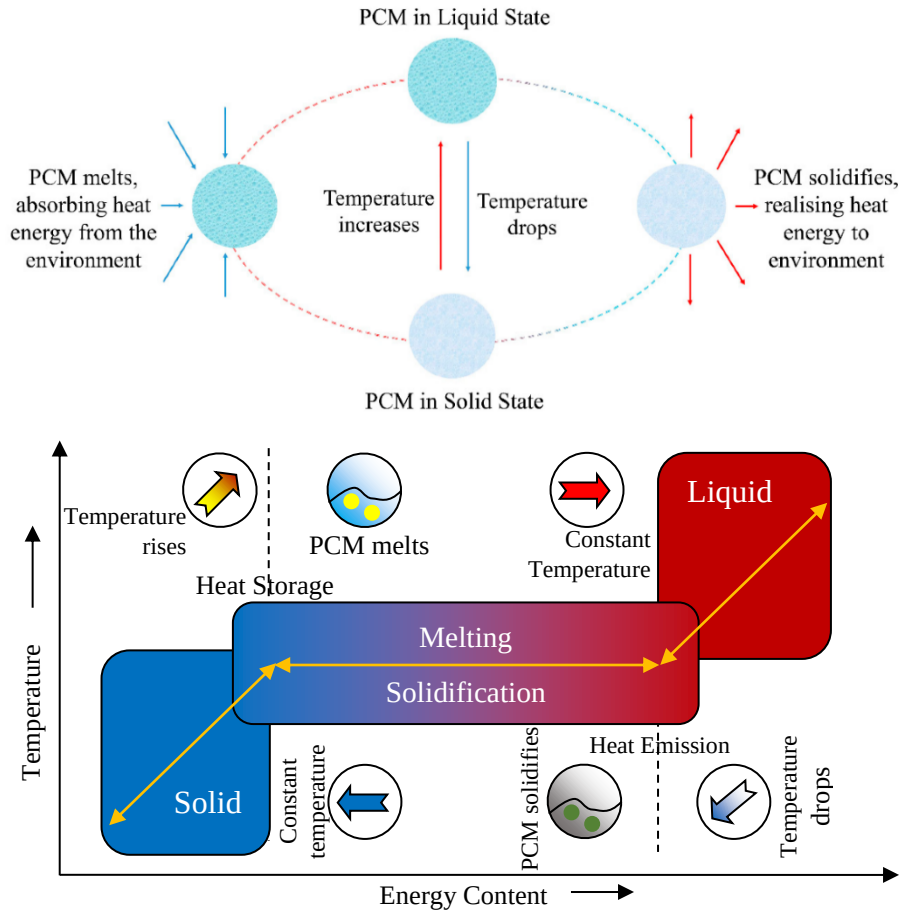


Fig. 2.4 Phase transition process in PCMs (Frigione et al., 2019).

Outside of green building thermal management, PCM applications have expanded to various high technology sectors over the last decade, including electronics, healthcare, waste heat recovery, food preservation, solar energy, building ceilings, and more. This widespread adoption of PCMs in diverse fields has captured the attention of researchers globally (Akeiber et al., 2016; İsmail KIRAN, ÖzgeÖZŞEN, TürkanTİKNA, Fatih DEMİRCİ, 2017; Junaid et al., 2021; Leungtonkum et al., 2022; Lloyd et al., 2015; Mousavi et al., 2021; Omara, 2021; Prieto & Cabeza, 2019; Ren et al., 2020; Sahoo et al., 2016; X. Sun et al., 2022; Venkateswarlu & Ramakrishna, 2022). Fig. 2.6 provides an overview of the LHTES system's diverse applications. The phase transition of PCMs occurs when the ambient temperature surpasses the melting point, leading to the storage of latent heat through the breaking of chemical bonds.

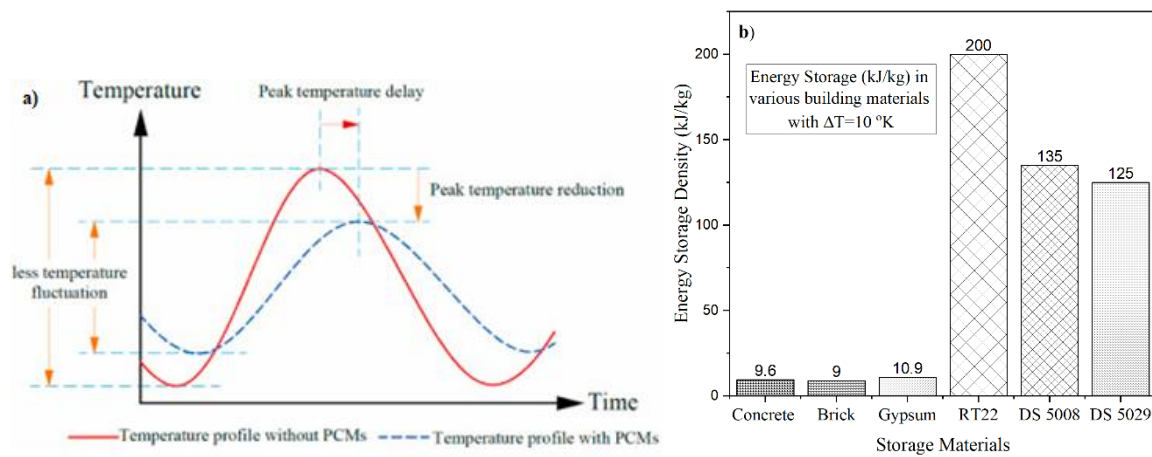


Fig. 2.5 PCM inclusion into building envelopes: a) Effect of PCM integration on buildings' indoor environment; b) relative comparison between building materials and commercial PCMs (Akeiber et al., 2016).

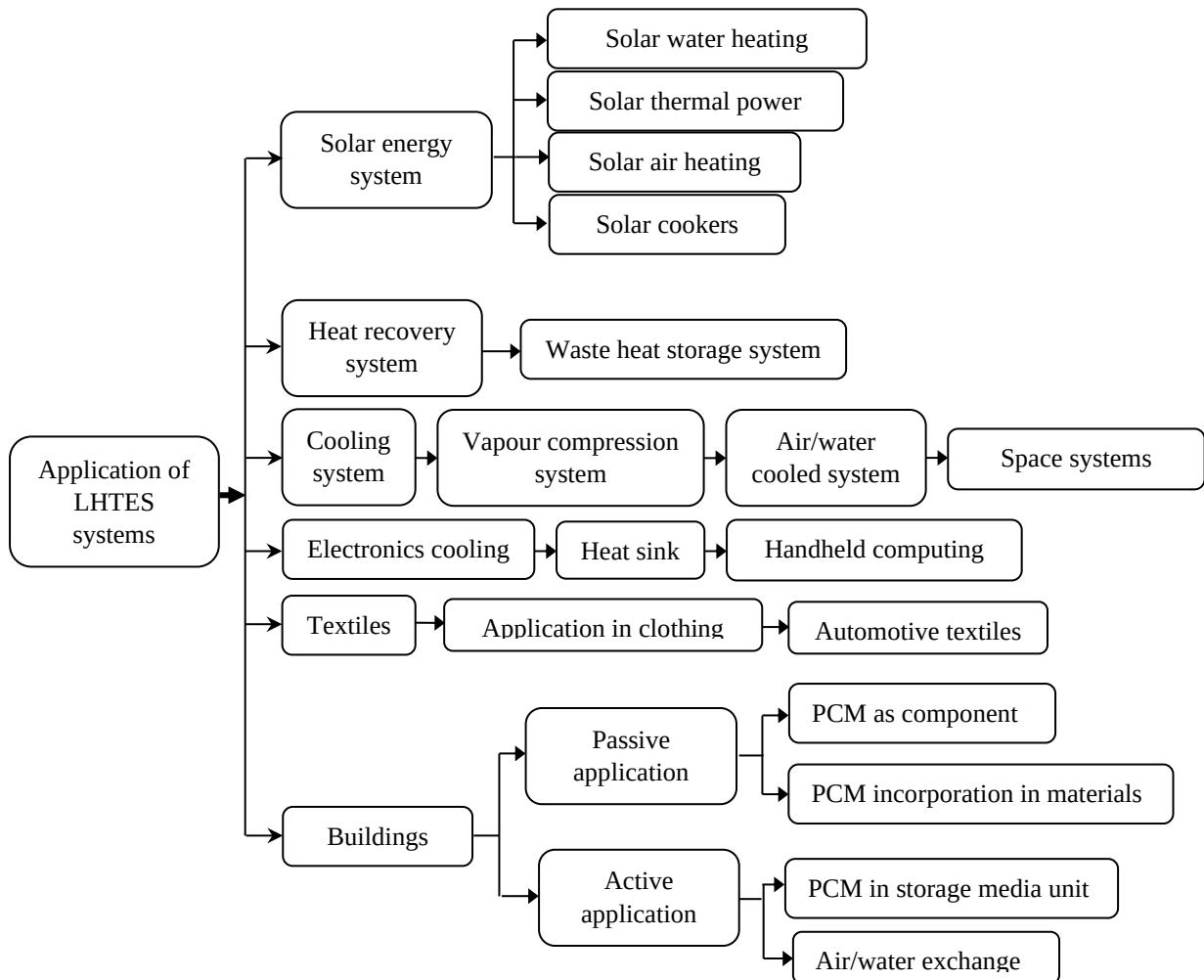


Fig. 2.6 Application of PCMs in various fields.

Conversely, when the temperature drops below the solidification temperature, the PCM returns to its solid state and releases the stored energy. During the charging phase, an endothermic reaction takes place, while the discharging phase involves an exothermic reaction. By selecting PCMs with melting points corresponding to the desired indoor comfort temperature, cooling/heating loads can be reduced, off-peak hours can be utilized for absorbing excess heat, and comfortable indoor thermal conditions can be maintained. The advantage of PCMs lies in their ability to store a substantial amount of energy within a thin layer of material. For instance, the PCM wall can be as much as 20 times thinner compared to a concrete wall.

2.3.1 Phase Change Material Classification

A range of PCMs in the market, each with a different operating temperature and enthalpy range, is illustrated in Fig. 2.7. Generally, solid-liquid PCMs are classified into Organic, Inorganic, and Eutectic PCMs based on their chemical composition. Each category of PCM has distinct thermo-physical characteristics. The PCM classification is presented in Fig. 2.8 and discussed in the succeeding sections.

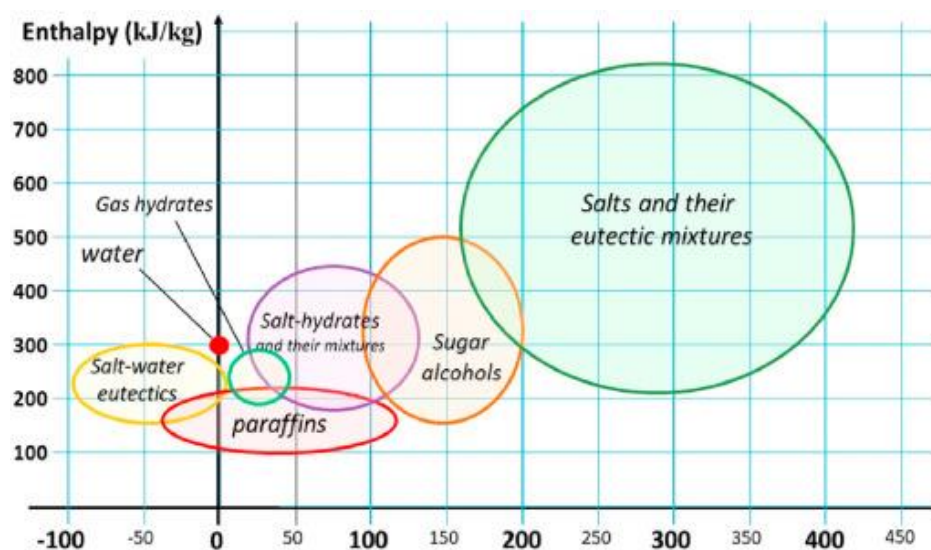


Fig. 2.7 Temperature and enthalpy range of all classes of PCMs (Al-Yasiri & Szabó, 2021).

2.3.1.1 Organic PCMs

Organic PCMs are commonly preferred for TES due to their favorable characteristics, such as suitable phase change temperatures, consistent physicochemical properties, high latent heat capacity, and availability. Among the organic PCMs, pure n-alkanes, Fatty acids, and esters are frequently employed for latent heat storage. However, despite their advantages, pure organic PCMs have certain limitations that hinder their widespread use, including low thermal conductivity (0.2W/mK), potential leakage, and significant volume variation during phase change, making them

less practical. Nevertheless, organic PCMs are widely adopted in TES systems due to their favorable attributes, including congruent melting, absence of supercooling, and non-corrosive nature (Z. Li & Gariboldi, 2021; Magendran et al., 2019; Moinuddin et al., 2021). They are stable, non-toxic, possess high latent heat (180 kJ/kg), and have a wide range of suitable operating temperatures (15 – 45 °C), making them compatible with various building materials (Souayfane et al., 2016). Organic PCMs can be categorized into two subcategories: paraffins and non-paraffins. Among these, the solid-liquid PCM paraffin is the most commonly used in buildings presently. It has gained widespread implementation due to its broad phase transition temperature range, high TES density, minimal volume changes during the phase transition process, and cost-effectiveness.

2.3.1.1.1 Paraffins

Paraffins are saturated hydrocarbons comprised of straight/branched—chain *n*-alkanes with the chemical formula of C_nH_{2n+2} . The transition temperature and latent heat increase with the length of the hydrocarbon chain. They are available in a wide range of temperatures -12C° to 71 C° with a storage density of 128 kJ/Kg to 400 kJ/Kg. Each member varies from preceding and succeeding by the methylene ($-CH_3$) group. Paraffins are commonly used for lack of supercooling, reliability, being non-corrosive, less expensive, and low vapor pressure. Moreover, paraffins are stable and are inert below 500C°. Apart from the desirable properties, paraffins show undesirable properties, too. They are relatively flammable with flammability index (*q*), between 15–50, high volume change, incompatible with plastics, and low thermal conductivity of 0.21–0.24 W/mK.

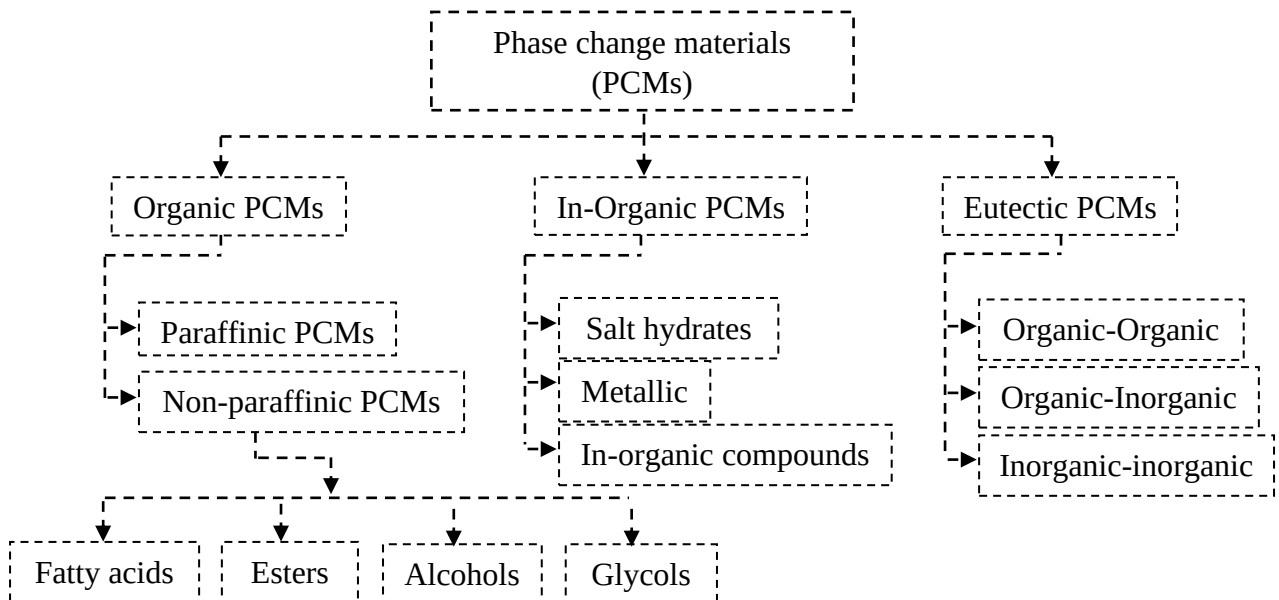


Fig. 2.8 Categorization of phase change materials (Wahid et al., 2017).

Table 2.4 Thermophysical characteristics of paraffins (Su et al., 2015).

S No.	Paraffins	Melting temperature (C°)	Enthalpy (kJkg ⁻¹)	Thermal Conductivity (Wm ⁻¹ k ⁻¹)	Molecular formula
1.	<i>n</i> -Dodecane	-12	216	0.21	C ₁₂ H ₂₆
2.	<i>n</i> -Tetradecane	4.5-5.6	231	n.a.	C ₁₄ H ₃₀
3.	<i>n</i> -Hexadecane	18.2	238	0.21	C ₁₆ H ₃₄
4.	<i>n</i> -Octadecane	28.2	245	0.35	C ₁₈ H ₃₈
5.	<i>n</i> -Eicosane	37	247	n.a.	C ₂₀ H ₄₂
6.	<i>n</i> -Docosane	44	249	n.a.	C ₂₂ H ₄₆
7.	<i>n</i> -Tetracosane	51	255	n.a.	C ₂₄ H ₅₀
8.	<i>n</i> -Hexacosane	56	257	n.a.	C ₂₆ H ₅₄
9.	<i>n</i> -Octasane	61	255	n.a.	C ₂₈ H ₅₈
10.	<i>n</i> -Triacontane	65	252	n.a.	C ₃₀ H ₆₂
11.	<i>n</i> -Dotritriacontane	70	170	n.a.	C ₃₂ H ₆₆
12.	<i>n</i> -Tetratriacontane	75.9	269	n.a.	C ₃₄ H ₇₀

There are two categories of paraffin: (i) saturated hydrocarbons that pursue the general formula of linear alkanes; (ii) a mixture of alkanes with other compounds of the type $CH_3(CH_2)_nCH_3$ (Kahwaji et al., 2018). The thermal and physical characteristics of some paraffins, along with the molecular formula, is illustrated in [Table 2.4](#).

2.3.1.1.2 Non-paraffins

Non-paraffins represent a diverse group of PCMs with a wide range of properties, unlike paraffins, where each material within this category exhibits unique characteristics. Due to the variability in properties, non-paraffin is favored for TES applications, as they offer a broader scope of options to suit specific needs. Non-paraffins encompass various substances, including fatty acids, alcohols, glycols, and esters. Fatty acids, among the non-paraffin PCMs, possess distinctive thermal properties that make them particularly suitable for building applications (An et al., 2019; Shahzor et al., 2019). However, it is important to note that fatty acids are flammable, which restricts their use to applications involving higher temperatures and environments with oxidizing content to ensure safety and mitigate potential hazards. $CH_3(CH_2)_{2n}.COOH$ formula describes an entire family of fatty acids.

According to thermal stability tests, non-paraffins have high chemical and thermal stability (Boussaba et al., 2021; Fabiani et al., 2020). In comparison with paraffin, non-paraffin materials are costly and corrosive. The cost of fatty acids is almost 2–2.5 times greater than paraffin. The non-paraffin materials with their thermophysical characteristics are listed in [Table 2.5](#).

Table 2.5 Thermophysical characteristics of non-paraffins (Dhamodharan & Bakthavatsalam, 2020; A. Sharma et al., 2009; Su et al., 2015; Suresh Kumar et al., 2017; Wi et al., 2015).

S No.	Non-Paraffins	Melting point (°C)	Thermal Conductivity (W/m ⁻¹ k ⁻¹)	Latent heat (kJkg ⁻¹)	Density (kgm ⁻³)
1.	Formic acid	7.8	n.a.	247	1226.7
2.	Palm oil	4	0.289	33	n.a.
3.	Caprylic acid	16.3	0.14	148	901
4.	Acetic acid	16.7	n.a.	187 - 273	1050
5.	Glycerin	17.9	n.a.	198.7	1260
6.	Coconut oil	23.3	0.174(s)/0.165(l)	103	n.a.
7.	D-lactic acid	26	n.a.	184	1249
8.	Capric acid	32	0.15	152.7	878
9.	Trimyristin	33-57	n.a.	201-213	862
10.	Lauric acid	42 - 44	1.6	178	862(l)/1007(s)
11.	Cyanamide	44	n.a.	209	1080
12.	Methyl eicosanate	45	n.a.	230	851
13.	Camphene	50	n.a.	238	842
14.	Myristic acid	52.2 - 58	n.a.	182.6 - 199	862.2
15.	Chloroacetic acid	56	n.a.	130	1580
16.	Palmitic acid	57.8 – 61.8	0.16	185.4	850(l)/989(s)
17.	Bee wax	61.8	n.a.	177	950
18.	Alpha naphthol	96	n.a.	163	1095
19.	Quinone	115	n.a.	171	1318
20.	Salicylic acid	159	n.a.	199	1443
21.	O-Mannitol	166	n.a.	294	1489

2.3.1.2 Inorganic Phase Change Materials

Inorganic PCMs belong to a category of PCMs exhibit high tolerance for a wide temperature range. Although their latent heat per unit mass is comparable to organic PCMs, inorganic PCMs often possess higher latent heat per unit volume due to their higher density (Aridi & Yehya, 2022). Unlike organic PCMs, inorganic ones do not experience supercooling and possess characteristics such as high thermal conductivity and a broad range of phase transition temperatures, making them favorable for specific applications. Their significant latent heat capacity generally characterizes Inorganic PCMs. However, they face challenges related to phase segregation, thermal instability, and corrosion (Tan et al., 2020). Inorganic materials include salt hydrates, inorganic compounds, and metallic (Junaid et al., 2021; Y. Lin et al., 2018; S. A. Mohamed et al., 2017). In buildings, salt hydrates are the primary inorganic materials to be incorporated. They have been explored widely for TES applications.

2.3.1.2.1 Salt hydrates

Salt hydrates are among the extensively studied PCMs and can be regarded as a combination of inorganic salts and water. These PCMs exhibit phase transition temperatures within the range of 8

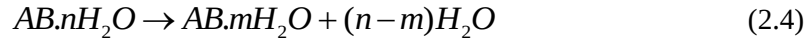
to 120°C, making them suitable for a wide array of applications. The market offers a significant number of commercially available salt hydrates with specific phase transition temperatures and desirable enthalpy values, [Table 2.6](#).

Table 2.6 Characteristics of salt hydrates with their chemical formula (Su et al., 2015).

S No.	Salt hydrates	Melting temperature (°C)	Latent heat (kJkg ⁻¹)	Thermal Conductivity (W/mk)	Chemical formula
1.	Lithium chlorate trihydrate	8	235	n.a.	LiClO ₃ .3H ₂ O
2.	Potassium fluoride tetrahydrate	18	330	n.a.	KF.4 H ₂ O
3.	Iron bromide hexahydrate	21	105	n.a.	FeBr ₃ .6 H ₂ O
4.	Lithium metaborate hexahydrate	25.7	289	n.a.	LiBO ₂ .8 H ₂ O
5.	Calcium chloride hexahydrate	29-30	170-192	1.008	CaCl ₂ .6 H ₂ O
6.	Sodium carbonate decahydrate	32	267	0.51	Na ₂ CO ₃ .10 6 H ₂ O
7.	Calcium bromide hexahydrate	34	115-138	n.a.	CaBr ₂ .6 H ₂ O
8.	Iron chloride hexahydrate	37	223	n.a.	FeCl ₃ .6 H ₂ O
9.	Potassium fluoride dihydrate	42	162-266	n.a.	KF.2 H ₂ O
10.	Calcium iodide hexahydrate	42	162	n.a.	CaI ₂ .6 H ₂ O
11.	Sodium sulphite pentahydrate	48	168	n.a.	Na ₂ SiO ₃ .5 H ₂ O
12.	Calcium nitrate trihydrate	51	104	n.a.	Ca(NO ₃) ₂ .3 H ₂ O
13.	Iron chloride dihydrate	56	90	n.a.	FeCl ₃ .2 H ₂ O
14.	Sodium acetate trihydrate	58	270-290	n.a.	NaCOONa.3 H ₂ O
15.	Ferrous sulphate heptahydrate	64	200	n.a.	FeSO ₄ .7 H ₂ O
16.	Barium hydroxide octahydrate	78	265-280	0.65 - 1.25	Ba(OH) ₂ .8 H ₂ O
17.	Ammonium alum	95	269	n.a.	(NH ₄)Al(SO ₄) ₂ .6 H ₂ O
18.	Magnesium nitrate hexahydrate	89.9	167	0.49 – 0.61	Mg(NO ₃) ₂ .6H ₂ O
19.	Calcium bromide tetrahydrate	110	n.a.	n.a.	CaBr ₂ .4H ₂ O
20.	Magnesium chloride hexahydrate	117	167	0.57 – 0.70	MgCl ₂ .6H ₂ O
21.	Lithium ethanoate dihydrate	70	150-251	n.a.	LiCH ₃ COO.2H ₂ O

Salt hydrates are composed of inorganic salts represented as (*AB*) combined with one or more H₂O molecules, resulting in a crystalline solid form known as (*AB. xH₂O*). The phase transition of salt hydrates is primarily characterized by the dehydration of the salt, leading to the breakdown of the salt hydrate into either the salt hydrate along with a few moles of water ([Eq. 2.4](#)) or directly into

the anhydrous form (Eq. 2.5). The breakup of salt hydrate is illustrated through the reactions given below:



Where n and m are the metal salt (AB)'s crystallization fluids existing both before and after dehydration, respectively.

Salt hydrates exhibit a process of dissolution in water or lower hydrate when they melt, resulting in anhydrous salt and water formation. The melting behavior of salt hydrates can be classified into three categories: congruent, incongruent, and semi-congruent melting. Congruent melting occurs when all of the salt completely dissolves at the melting temperature, whereas incongruent melting involves only partial salt dissolution. A balance between the solid and liquid phases characterizes semi-congruent melting. In practice, most salt hydrates exhibit incongruent melting. To address this issue, various techniques can be employed, including encapsulation, mechanical stirring, the use of excess water, and the addition of thickening agents. During the crystallization process, not all of the released water is incorporated back into the solid phase, leading to the descent of the lower hydrate due to its higher density. Salt hydrates possess favorable properties for thermal storage applications, such as high thermal conductivity (0.5W/mK), high storage density, and low volume change (Agarwala & Prabhu, 2022). Additionally, salt hydrates are cost-effective, non-corrosive, and compatible with plastics. However, supercooling is a notable drawback of salt hydrates, primarily caused by poor nucleation. To address this limitation, the use of nucleating agents and applying the rolling cylinder heat storage system developed by General Electric Co. New York have been proposed as potential solutions.

2.3.1.2.2 *In-organic compounds*

Inorganic compounds are a category of PCMs with relatively low latent heat capacity. The utilization of inorganic PCMs can have adverse impacts on human health and the environment. Only a limited number of PCMs mentioned in Table 2.7 are practiced in building applications.

2.3.1.2.3 *Metallics*

The metallics category comprises metals and their alloys having low melting points. Metallics can be employed as storage materials. They exhibit little volume variations during phase shift, substantial latent heat, and significant thermal conductivity (15W/mK). However, they are more expensive, roughly 2 or 2.5 times that of paraffin (W. Q. Li et al., 2014; A. Sharma et al., 2009).

Improvement in heat transfer can be seen after integrating metallics as PCMs. A list of metallics with thermophysical properties is given in [Table 2.8](#).

Table 2.7 List of inorganic compounds with thermophysical properties (Su et al., 2015).

S No.	In-organic compounds	Melting temperature (°C)	Latent heat (kJkg ⁻¹)	Thermal Conductivity (Wm ⁻¹ k ⁻¹)	Chemical formula
1.	Water	0	333	0.598	H ₂ O
2.	Deuterium oxide	3.7	318	0.595	D ₂ O
3.	Sulphuric acid	10.4	100	0.26	H ₂ SO ₄
4.	Phosphoric acid	26	147	0.434	H ₃ PO ₄
5.	Tin bromide	30	28	0.085	SnBr ₄
6.	Titanium bromide	38.2	23	n.a.	TiBr ₄
7.	Sodium nitrate	307	199	0.51	NaNO ₃
8.	Antimony trichloride	73.4	25	n.a.	SbCl ₃
9.	Arsenic bromide	30	38	n.a.	AsBr ₃

Table 2.8 Thermophysical properties of metallics (Su et al., 2015).

S. No.	Metallics	Thermal conductivity (Wm ⁻¹ K ⁻¹)	Latent heat of fusion (kJkg ⁻¹)	Melting point (°C)
	Mercury	8.34	11.4	-38.87
	Gallium	29.4	80.3	30
	Potassium	54	59.59	63.2
	Bismuth	8.1	53.3	271.4
	Bismuth indium	n.a.	25	72
	Sodium	n.a.	n.a.	97.8
	Bismuth tin	19	44.8	138
	Lithium	41.3	433.78	186
	Tin	15.08	60.5	232
	Bismuth lead-tin	24	34.7	96
	Cerollow	n.a.	90.9	58
	Cerrobend	n.a.	32.6	70
	Rubidium	29.3	25.74	38.85

2.3.1.3 Eutectic PCMs

Eutectic PCMs are formed by combining two or more PCMs with distinct melting temperatures. The resultant mixture forms a blend crystal during crystallization, composed of different components. These eutectic PCM compositions can involve various combinations, such as organic–organic, inorganic–inorganic, or organic–inorganic. The melting point of eutectic PCMs can be adjusted based on the specific components used in the blend. Eutectic PCMs typically have lower melting temperatures compared to the individual phase transition components present in the mixture. For example, combining Tetradecane and Hexadecane at 91.67% and 8.33%, respectively, results in a melting point of 1.7°C. Similarly, when Capric Acid and Myristic Acid are combined

at 73.5% and 26.5%, respectively, the mixture melts at 21.4°C with a latent heat of 152 kJ/kg. One notable advantage of eutectic PCMs is their absence of segregation and supercooling, as all components undergo a phase change simultaneously. Eutectic PCMs also exhibit high thermal conductivity. However, it is essential to note that their latent heat and specific heat are comparatively lower than those of paraffin and salt hydrates. A list of eutectic PCMs with respective weight combinations is given in [Table 2.9](#).

2.3.2 Analysis of phase change materials

As discussed in the previous section, organic PCMs offer several advantages, including self-nucleation, congruent melting, no supercooling, high latent heat of fusion, and chemical stability. They also do not undergo phase separation and can be used with plastic containers. However, organic PCMs have certain limitations, such as low thermal conductivity and a relatively higher flammability risk.

Table 2.9 List of eutectic PCMs along with wt.(%) (A. Sharma et al., 2009; Su et al., 2015).

S. No.	Eutectic PCMs	Composition (%)	Melting point (°C)	Latent heat of fusion (kJ/kg)
1.	Tetradecane + hexadecane	91.67 + 8.33	1.7	156.2
2.	Sodium sulphate + sodium chloride + potassium chloride + water	31 + 13 + 16 + 40	4	234
3.	$C_5H_5C_6H_5 + (C_6H_5)_2O$	26.5 + 73.5	12	97.9
4.	Calcium chloride hexahydrate + calcium bromide hexahydrate	45 + 55	14.7	140
5.	Capric + Lauric acid	82 + 18	19.1-20.4	147
6.	Capric + Myristic acid	73.5 + 26.5	21.4	152
7.	Calcium chloride hexahydrate + magnesium chloride hexahydrate	50 + 50	25	95
8.	Capric + Stearic acid	86.6 + 13.4	26.8	160
9.	Lauric + Palmitic acid	69 + 31	35.2	166.3
10.	Magnesium nitrate hexahydrate + magnesium bromide hexahydrate	59 + 41	66	168
11.	Aluminum chloride + sodium chloride + potassium chloride	66 + 20 + 14	17	209
12.	Lithium nitrate + ammonium nitrate + ammonium chloride	27 + 68 + 5	81.6	108
13.	Sodium nitrite + sodium nitrate + potassium nitrate	40 + 7 + 53	142	n.a.
14.	Triethylolethane + urea	62.5 + 37.5	29.8	218
15.	Naphthalene + benzoic acid	67.1 + 32.9	67	123.4
16.	Triethylolethane + water + urea	38.5 + 31.5 + 30	13.4	160

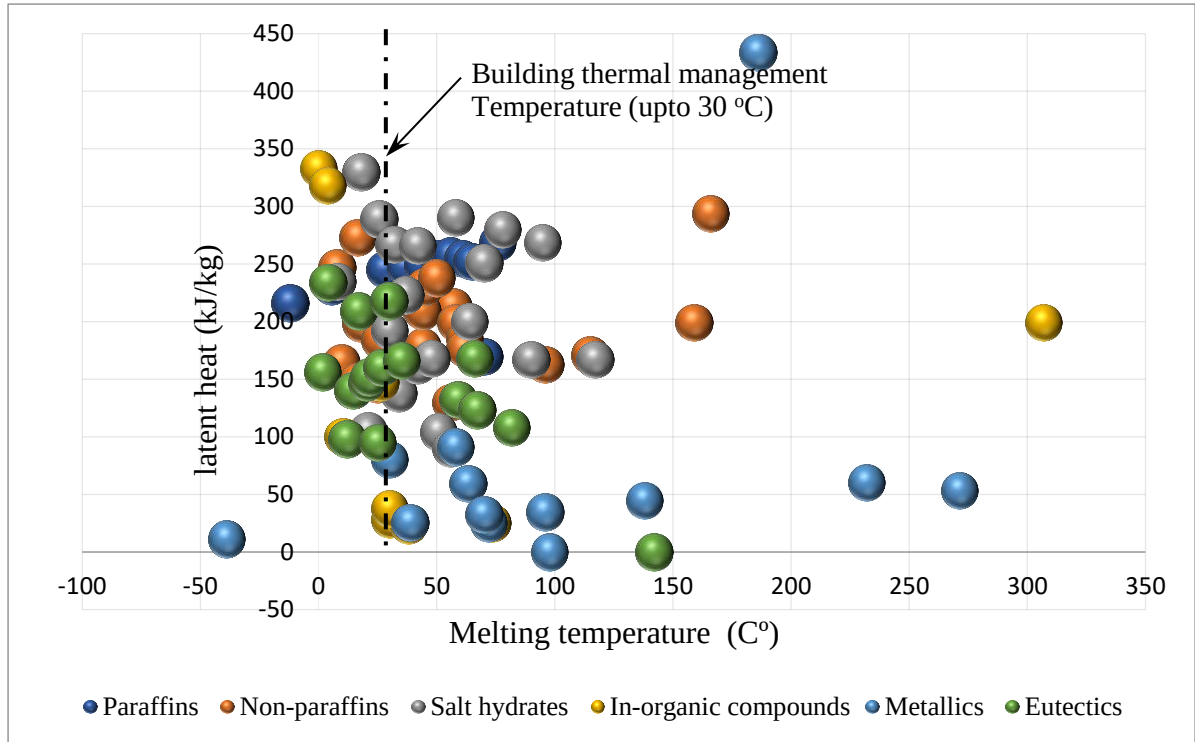


Fig. 2.9 Distribution of latent heat and melting temperature of various PCMs.

On the other hand, inorganic PCMs possess a high energy storage density, are non-flammable, and exhibit excellent thermal conductivity. However, they may experience segregation and supercooling during phase transitions. Further, Fig. 2.9, illustrates that salt hydrates, paraffins, non-paraffins, and eutectics exhibit high energy storage densities, while metallic PCMs have high melting temperatures. Additionally, Fig. 2.10 compares the thermal conductivities of various PCMs along with their corresponding melting temperatures. Metallic and inorganic compounds exhibit higher thermal conductivities of around 10 W/mK compared to organic and specific inorganic PCMs, which have lower thermal conductivities.

2.3.3 Characteristics of PCMs

The common characteristics of PCMs are given in Table 2.10.

2.3.4 Selection criteria of PCMs

The selection of PCMs for TES systems involves careful consideration of various physicothermal and kinetic properties, affordability, accessibility, product liability, flexibility, and dependability. The thermophysical characteristics of PCMs play a pivotal role in determining their suitability for TES systems, with a particular focus on meeting the specific operating requirements for demand-side control. Reliability and cycle stability are critical in evaluating the alternatives' performance, aiming to identify promising PCMs for practical applications. The successful implementation of

PCM technology in the market requires attention to individual user perception and ease of use, competing with conventional techniques. Overcoming challenges lies at the base of the decision-making process, where cost-effectiveness and meeting specific limits become crucial factors.

Table 2.10 Typical characteristics of PCMs.

PCM	Advantages	Dis-advantages
Organic	▪ Their latent heat is high. ▪ Are chemically and mechanically stable ▪ Available in a wide range of temperatures ▪ They show no supercooling ▪ Recyclable ▪ They are compatible with various containers ▪ Non-reactive	▪ During the phase transition, organic PCM shows high volume change. ▪ They possess a low thermal conductivity ▪ Plastic container incompatibility ▪ They are unstable at high temperatures ▪ Highly flammable ▪ Expensive. ▪ They show low enthalpy
Inorganic	• High energy-storing density • Have a high thermal conductivity (double for organics) • Incombustible • Plastic container compatibility • Easily obtainable • Inexpensive	• Inorganic PCMs show supercooling • Metallic container incompatibility • Appreciable volume change • Phase segregation occurs
Eutectic	▪ High density for the given volume ▪ Excellent thermal conductivity ▪ Adjustable melting point ▪ No supercooling ▪ No segregation	▪ Expensive ▪ Sparse literature on thermophysical properties ▪ The specific heat capacity is minimal. ▪ Minimal latent heat of fusion.

Additionally, product safety considerations and compliance with environmental sustainability and regulatory requirements are essential for ensuring the overall viability and acceptance of PCM-based TES systems. A comprehensive evaluation of these factors guides the selection of optimal PCMs to enhance energy efficiency and drive advancements in the field of thermal energy storage. (Nazir et al., 2019). Fig. 2.11 shows a generic selection process for PCMs.

The PCMs utilized as LHTES systems need to meet the requirements indicated in Fig. 2.12. The materials hosting the PCMs should possess the following characteristics (Kenisarin & Mahkamov, 2016):

- i. Large contact surface for high heat transfer.
- ii. Reducibility is easy.
- iii. PCM retention over the surface.

- iv. The depth of the heat exchanger is small.
- v. Quality control.

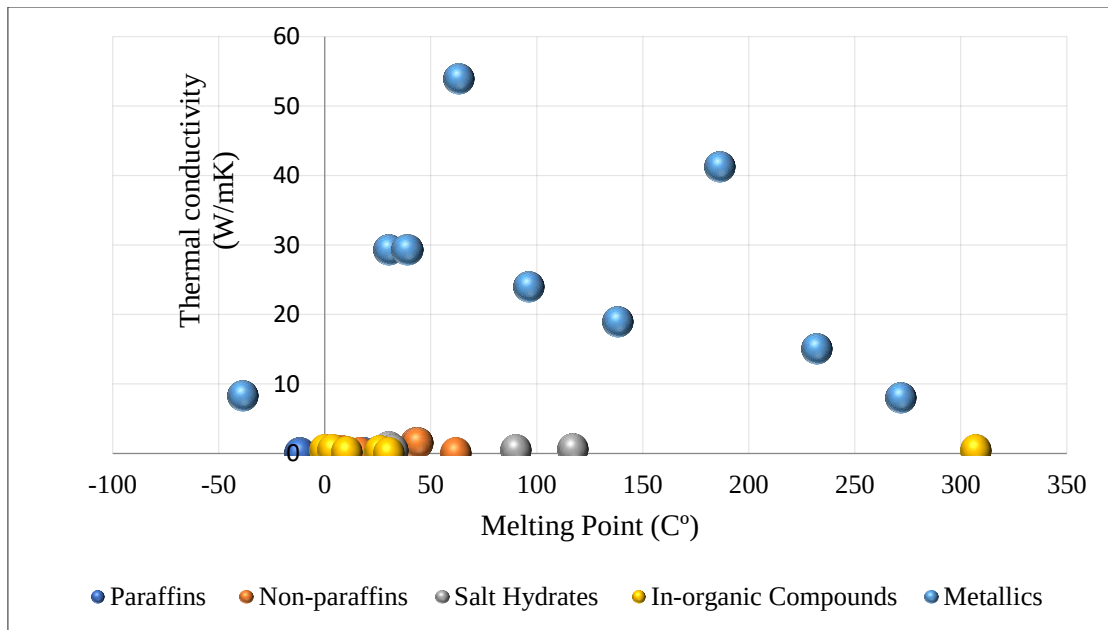


Fig. 2.10 Thermal conductivity distribution of various PCMs

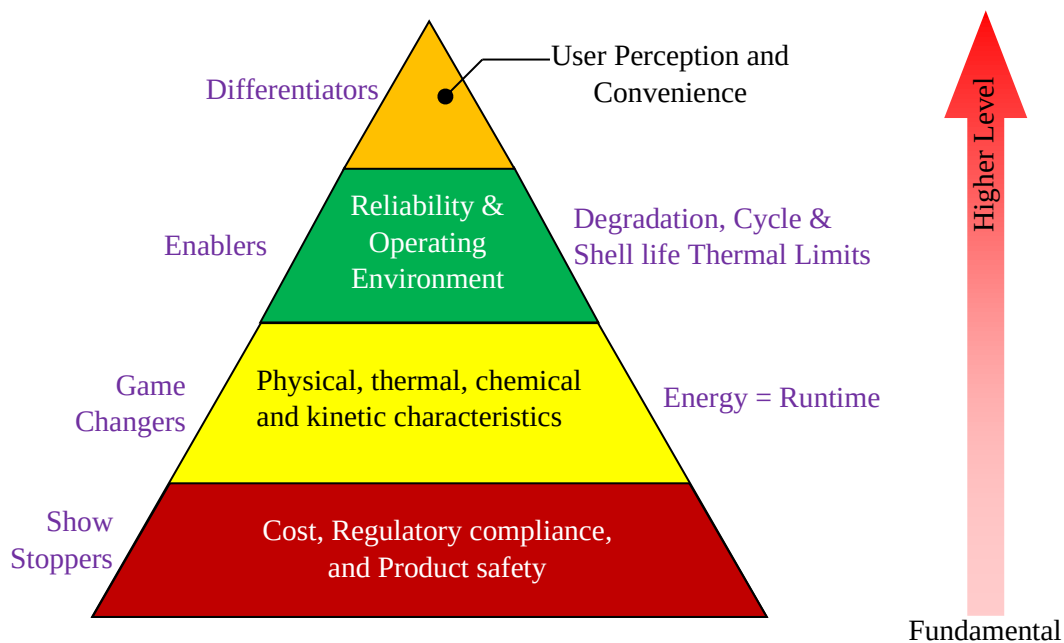


Fig. 2.11 Generic selection criteria of PCMs for thermal energy storage systems.

2.3.5 Problems in PCM Application

Even if the PCM to be used is carefully chosen, it may not always be able to satisfy all of the criteria. Phase segregation, supercooling, and fire resistance are the most common constraints encountered while using PCMs.

2.3.5.1 Phase segregation

Phase separation is a critical concern that can lead to the failure of PCMs. Ideally, during phase transition, a PCM should maintain its homogeneous composition, consistently exhibiting the same enthalpy and temperature change throughout its entire lifecycle. It is crucial to ensure that eutectic mixtures undergo a phase transition at the same temperature; otherwise, one of the components may remain in the solid state while the other transitions to the liquid state, resulting in phase separation. This causes the original composition of the material to vanish, leading to the loss of its initial phase transition characteristics. Avoiding phase separation is essential to ensure the effective and reliable performance of PCMs in thermal energy storage applications.

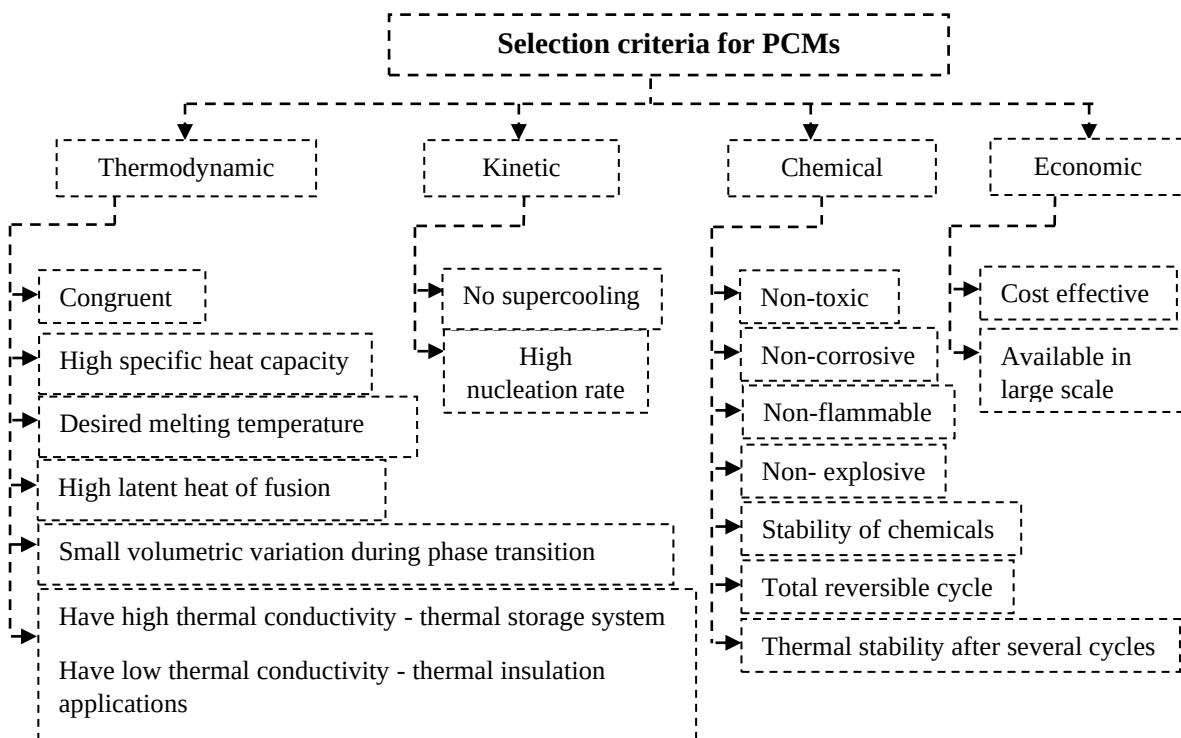


Fig. 2.12 Selection criteria of materials for LHSS.

2.3.5.2 Supercooling

Supercooling is a phenomenon in which a PCM remains liquid even when it is below its designated transition temperature. The PCM behaves as expected during the heating phase but fails to release the stored energy during cooling. This implies that the ambient temperature must sufficiently drop below the transition temperature for the material to complete its entire working cycle. Supercooling occurs due to the slow rate of nucleation or nuclei development in the PCM. For inorganic PCMs, supercooling poses a significant drawback, leading to prolonged solidification times and reduced performance. However, organic PCMs based on paraffins generally do not experience supercooling. One approach to address this issue is adding a nucleating agent, which helps promote the formation

of nuclei and prevents supercooling in the PCM (Cabeza et al., 2011). The degree of sub-cooling can be defined as $T_{sc} = T_m - T_s$ where T_m and T_s are the melting and solidification temperatures, respectively. The two primary issues that supercooling might create are: i) the freezing temperature might not fall within the system temperature range that is controlling, and (ii) an increase in energy consumption.

Solidification in buildings occurs primarily at night and only briefly. The inability of the PCM to release the thermal energy stored in it if supercooling takes place rather than solidification. As a result, the primary purpose of the PCM's existence is not met in the daytime, which causes performance issues. Using a verified TRNSYS model Schranzhofer & Puschig, (2006), contrasted a brick wall layer with a PCM wall layer to illustrate this issue. The calculations show that PCM plaster results in lower temperature peaks because latent heat is a critical factor in moving and reducing the peak load.

2.3.5.3 Different behavior during cooling

Below discussed are five standard water cooling curves. The five phases in the PCM cooling process are (Guzman & Braga, 2005):

1. During 1st phase, water freezes even when no supercooling is involved. The sensible heat of water is dissipated as it cools until it reaches solidification temperature (T_s), at which the latent heat is discharged and phase transition occurs. Once all of the latent heat has been released, the solid water begins to cool by discharging sensible heat. Dendritic ice is missing and crystalline ice is created due to no supercooling.
2. Due to the latent heat being liberated from the dendritic ice and being absorbed by the supercooled liquid, the temperature goes up until it reaches T_s . Once nucleation temperature (T_n) is attained, dendritic ice develops.
3. Phase 3rd illustrates the situation where water has a low energy level and freezes when T_s is reached.
4. A case identical to the one in 3rd phase is shown in phase 4th. The latent heat of the crystalline part is discharged entirely at a reduced temperature than T_s , but there is not enough latent heat to bring the temperature to T_s due to the low energy.
5. No phase transition occurs in phase 5th, and the water remains super cooled. Water continues to be present in step (b) in this scenario for an arbitrary amount of time. This could be caused by coolant temperatures near T_s and above T_n .

2.3.5.4 Corrosion

The consideration of corrosion is of paramount importance when designing the TES container that uses PCMs as the storage medium. This issue has been extensively researched and acknowledged in the scientific community for high-temperature applications, but it also poses a concern for cold storage applications. Commonly used metals incorporating PCMs include Aluminum, copper, and stainless steel. Researchers have explored alternative non-metallic materials to mitigate corrosion effects, but significant progress in preventing corrosion of the PCMs mentioned above on metals is yet to be achieved. A comprehensive study by (Oró et al., 2013) examined the corrosion effects of nine different PCM types on four metals and four different polymers. Among these materials, stainless steel was identified as the most suitable metal for serving as the storage container for the salt solution, displaying favorable performance in terms of corrosion resistance.

2.3.5.5 Fire resistance

To safeguard buildings against fire dangers, there has been an increase in interest in fire resistance in recent years. Concerns concerning the fire resistance of items when these materials are applied are raised by the flammability threats presented by organic phase change materials. The insertion of a stabilizing element with fire retardant qualities, such as $Mg(OH_2)$ and SiO_2 , is one remedy that has been researched (Song et al., 2010).

2.4 Techniques of PCM Incorporation

To optimize energy consumption, careful consideration must be given to the processing and integrating PCMs into building materials. Various methods have been developed for incorporating PCMs into construction materials.

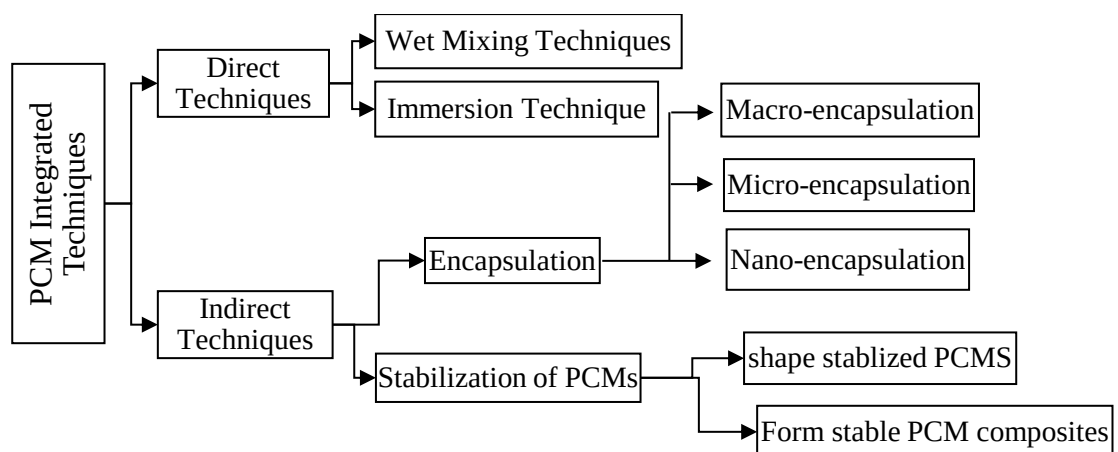


Fig. 2.13 Flow chart representing distinct techniques of PCM incorporation.

These methods include direct integration, immersion, encapsulation, and stabilization, each offering distinct advantages in introducing PCMs into the building materials. The section also emphasizes the promising techniques that effectively prevent PCM leakage. These incorporation techniques can be broadly classified into two categories: direct and indirect techniques, as depicted in [Fig. 2.13](#), which pertain to the integration of PCMs into the building envelope.

Nevertheless, among the various methods available, indirect techniques have received widespread attention in the research literature. Of the indirect techniques, encapsulation stands out as the most commonly employed approach for incorporating PCMs. Microencapsulation constitutes approximately 70% of the studies conducted using the encapsulation method, while macroencapsulation accounts for around 30%. In contrast, direct techniques have seen fewer well-established applications, but they continue to be of great interest due to their promising potential.

2.4.1 Direct Techniques of PCM Incorporation

The direct incorporation technique is the simplest and most cost-effective way of integrating PCMs into construction materials. In this approach, PCMs are directly introduced into the concrete using either wet mixing or immersion methods.

2.4.1.1 Wet mixing technique

In the wet mixing technique, liquid PCMs are directly added to the construction material, such as cement mortar, concrete, gypsum, or mortar (Cunha et al., 2016; Lee et al., 2018). However, this method leads to leakage issues since there is no barrier between the PCM and the construction material. The leakage makes the construction materials incompatible and poses a fire risk due to the explosive nature of PCMs. As a result, this technique is no longer considered practical.

2.4.1.2 Immersion technique

The immersion technique involves submerging the construction material (e.g., concrete, gypsum, or bricks) into a hot liquid PCM container. Liquid PCM is immersed into building materials to facilitate capillary absorption. This technique is commonly employed to integrate PCM into lightweight and porous aggregates. Through capillary action, the PCM is absorbed by the porous substance of the construction material. After being taken out of the PCM container, the material is allowed to cool, and the PCM resides in the gaps of the absorbent material. This process has been shown to improve the energy efficiency of buildings when PCM is supported on porous aggregates (D. Zhang et al., 2004). However, this technique also faces leakage, corrosion, and material incompatibility challenges. Despite these challenges, both direct incorporation techniques have

been explored in early studies of PCM-integrated concrete. The bottlenecks found in this technique are leakage, corrosion, and material incompatibility.

In the immersion process, In recent years, numerous researchers have proposed various porous aggregates that have been impregnated with PCM using direct and vacuum impregnation techniques, along with different coating and supporting materials (Suttaphakdee et al., 2016; B. Xu et al., 2015). The porous nature of lightweight aggregates makes it feasible to incorporate PCM into concrete. However, these materials must possess specific properties, including surface area, porosity, and void size, to effectively host the PCM. Four distinct types of lightweight aggregates have been studied by (Aguayo et al., 2017) in this context. It was feasible to conclude that these materials' porosity and pore diameter can impact their ability to absorb PCM.

2.4.2 Indirect Techniques of PCM Incorporation

PCMs are incorporated into the construction materials in indirect techniques either by PCM encapsulation or PCM-integrated lightweight aggregates (LWA).

2.4.2.1 Encapsulation

Due to issues related to PCM leakage during melting, environmental reactivity, and volume change during phase transition, direct use of PCMs in many applications is not feasible. To address these concerns and enhance the compatibility of PCM with the surroundings, encapsulation is a suitable technique (Z. Liu et al., 2018). Encapsulation involves covering the PCM (liquid or solid) with a protective shell. Barrett K Green initially introduced the concept of encapsulation in the 1940s-50s (Hawladar et al., 2003). Encapsulation primarily aims to isolate the solid/liquid PCM from the surroundings, ensuring compatibility, improving heat transfer, and enhancing PCM stability. In encapsulation, the PCM is the core, and the protective shell is the encapsulant. The shell is not completely filled, leaving some space for volume change during the phase transition process. The effectiveness of encapsulated PCM is directly influenced by the thickness of the coated shell. Thinner shells provide lower strength, while thicker shells result in less PCM content. There are two processes for encapsulating PCM: physical and chemical processes. Physical processes yield larger microcapsules with rough surfaces, while chemical processes result in more uniform shells. Various manufacturing methods for PCM shells are depicted in [Fig. 2.14](#). However, the performance of PCM-mortar composites degraded when encapsulated PCMs were used (Djamai et al., 2019). Due to their caustic nature towards metals and water solubility, encapsulating salt hydrates presents challenges. Conversely, organic PCMs are only partially water-soluble and do not corrode metals. Therefore, for encapsulation procedures, organic PCMs are preferred over salt hydrates.

The efficiency of the encapsulation can be evaluated by the given equation. Higher encapsulation efficiency is preferred for increased strength and leakage issues. Quantifying PCM encapsulation depends on encapsulation efficiency.

$$E = \frac{(\Delta H)_{m,encapPCM} + (\Delta H)_{s,encapPCM}}{(\Delta H)_{m,PCM} + (\Delta H)_{s,PCM}} \times 100 \quad (2.8)$$

The effective performance of the core can be evaluated by the encapsulation ratio. The encapsulation ratio (η) is given by:

$$\eta = \frac{(\Delta H)_{m,encapPCM}}{(\Delta H)_{m,PCM}} \times 100 \quad (2.9)$$

Where, $(\Delta H)_{m,encapPCM}$ is phase change enthalpy for encapsulated PCM during melting, $(\Delta H)_{m,PCM}$ defines the phase change enthalpy of PCM.

To fabricate the capsule for building applications, one has to follow the given design criteria (Milián et al., 2017):

- i. The thickness of the walls (flexible or stiff design)
- ii. Pressure levels inside and outside
- iii. Capsule material compatibility with PCM and heat carrier fluid
- iv. For the expansion of the PCM during melting, there is a void volume.
- v. Capsule long-term stability

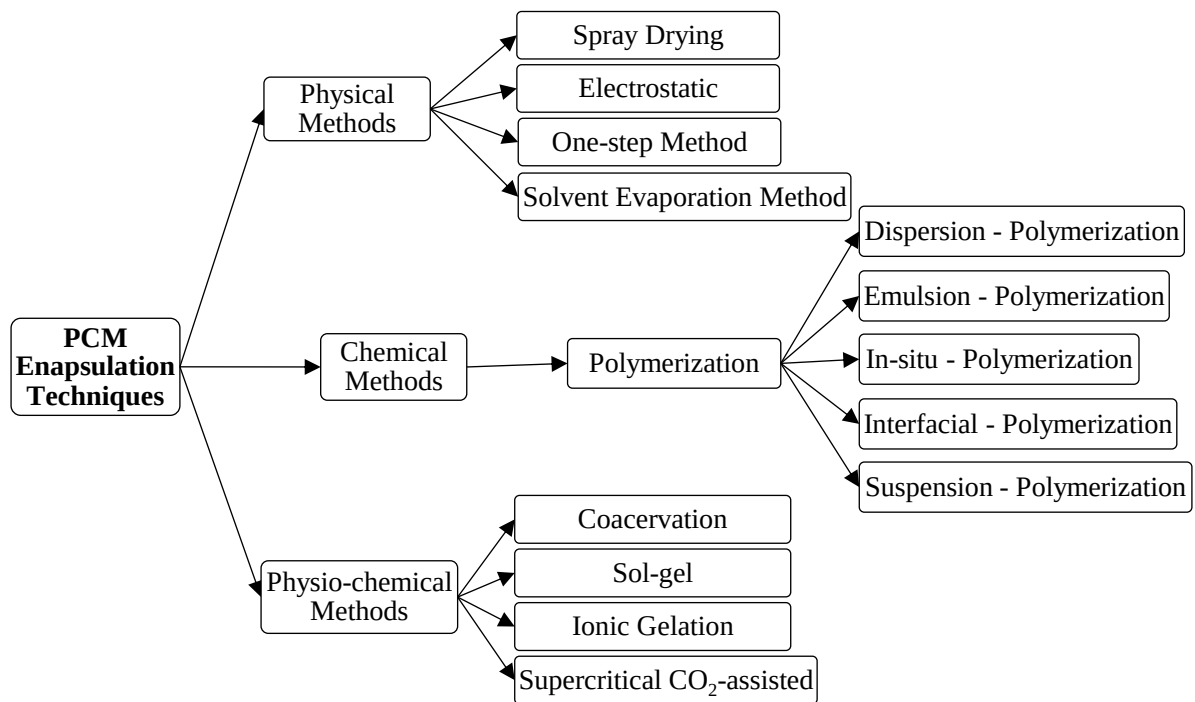


Fig. 2.14 Flowchart depicting various manufacturing methods of PCM encapsulation.

Encapsulation on the basis of size can be categorized into (Jacob & Bruno, 2015; Rodríguez-Cumplido et al., 2019):

- i. Macro encapsulation, with $\phi > 1\text{mm}$
- ii. Microencapsulation, with $0 < \phi < 1000\mu\text{m}$
- iii. Nano-encapsulation, with $0 < \phi < 1000\text{nm}$

2.4.2.1.1 Macroencapsulation

Macroencapsulation is the prevailing method for encapsulating PCMs in TES systems. This process involves enclosing a considerable amount of PCM within a single container with a size exceeding 1mm, as depicted in Fig. 2.15. The key advantages of macroencapsulation include its straightforwardness in terms of transportation and storage, the potential for customization to suit specific applications, improved material compatibility, and reduced external volume changes (Memon, 2014). The choice of encapsulation material depends on the intended application and can be categorized into two groups: metals and non-metals. Commonly used metals for encapsulation are Copper (Cu), Aluminum (Al), and stainless steel, which are preferred when heat transfer is a crucial criterion (X. Shi et al., 2014). These metallic containers must possess high thermal conductivity to enhance thermal performance. On the other hand, non-metal materials such as high-density polyethylene (HDPE), glass, polyvinyl chloride (PVC), and plastic are used for encapsulation due to their cost-effectiveness. However, the compatibility of both plastic and metallic containers with the PCM is thoroughly assessed.

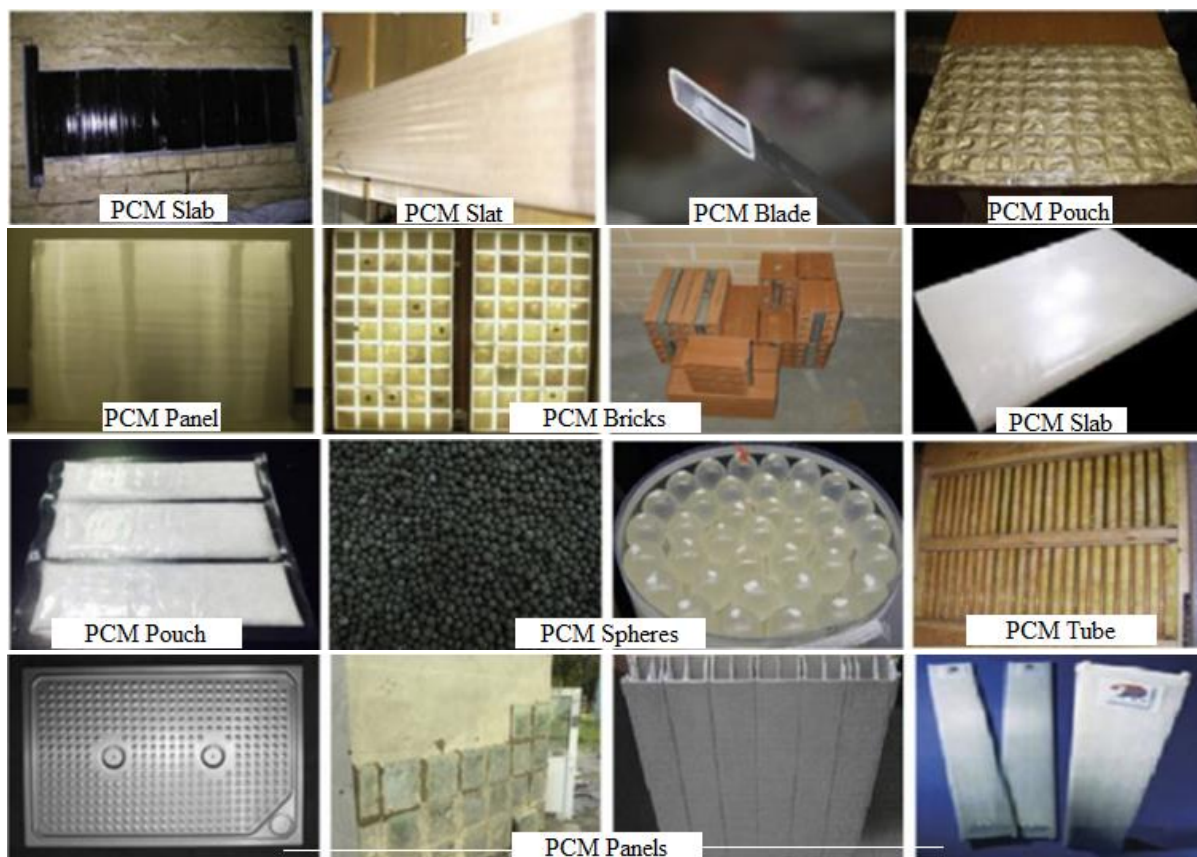


Fig. 2.15 Various Macroencapsulated forms implemented into building envelopes
(Al-Yasiri & Szabó, 2021a; Z. Liu et al., 2018)

In the context of macroencapsulation, the performance of PCM encapsulation is significantly influenced by various variables, including the positioning of macrocapsules, the type of PCM, the building envelope, and the thermal characteristics of the encapsulation material (Marani & Nehdi, 2019). Proper consideration of these factors is crucial in achieving optimal performance and efficacy of the PCM macroencapsulation in TES systems.

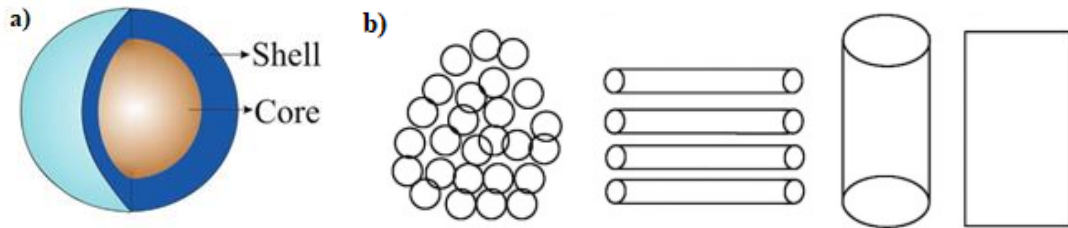


Fig. 2.16 Representation of PCM encapsulation and Shapes of containers used for macroencapsulation (Salunkhe & Shembekar, 2012).

Table 2.11 Commercial manufacturers of macro encapsulated PCM with their used containers
(Rathore & Shukla, 2019).

Trademark	Container Type	Region	Official Website
Microtek Laboratories, Inc.	Polymers	USA	Www.Microteklabs.Com
Rubitherm Technologies GmbH	Panels, Pouches, and Bags	Germany	Www.Rubitherm.Eu/En//Index.Html
Pure Temp LLC	Plastic Blocks, Polymers, Flexible Films, and Tubes	USA	Www.Puretemp.Com
MikroCaps	Polymers	Slovenia	Www.Mikrocaps.Com
Teappcm	Stainless Steel Balls, HDPE and Al Panels	USA	Www.Teappcm.Com
PCM Energy P. Ltd	Panels, Balls, Aluminum Pipes,	India	Www.Pcmenergy.Com
Shanghai Tempered Entropy New Energy Co.	Polymers	China	Www.Pcmgel.Com

Macroencapsulation demonstrates a substantial reduction in leakage issues over multiple thermal cycles, indicating the integrity of the capsules containing PCM (Mohseni et al., 2019). Various geometries of macroencapsulation, including spherical, cylindrical, tubular, rectangular, or panel shapes, are illustrated in Fig. 2.16. Macroencapsulated PCMs exhibit behavior similar to large aggregates, allowing direct incorporation into concrete mixes. Additionally, higher PCM concentrations can be achieved within the capsules at a low production cost. Due to their

compatibility with concrete, macroencapsulated PCMs are widely applied in hollow concrete slabs (Pomianowski et al., 2012).

Unlike microencapsulation, macro encapsulation does not require pre-defined exercises. Numerous commercial manufacturers have successfully produced and marketed various forms of PCM encapsulated products. Table 2.11 provides a list of renowned commercial manufacturers along with their macro encapsulated containers. The properties of PCM are significantly influenced by the material, shape, and size of the capsules. Capsules designed to maximize surface area per unit volume often feature cylindrical pipes, fins, and flat plates. However, using large containers can lead to a non-homogeneous phase transition. While macro encapsulation offers thermal stability and corrosion resistance, its main limitation lies in low thermal conductivity. PCM macro encapsulation is achieved using the containment method while considering the provision for volume expansion.

2.4.2.1.2 Microencapsulation

Enclosing micron-size PCM particles (solid/liquid) in a thin microcapsule ($1 < \phi < 1000\mu\text{m}$) made up of natural or synthetic polymers comprises microencapsulation. Unlike macroencapsulation, microencapsulation is more complex due to the smaller size of the capsules involved. The microencapsulated PCM particles resemble tiny particles, with PCM serving as the core or nucleus and the shell acting as an outer protective layer, as depicted in Fig. 2.17. The shell is created using either physical or chemical methods, and its material significantly influences the performance of the microencapsulated phase change material (MPCM). A robust shell ensures high mechanical strength and efficiency of the MPCM. The shell should fulfill the criteria given below:

- i. It should be leak proof
- ii. It must bear high thermal conductivity
- iii. It should withstand during high temperatures
- iv. It should perpetuate thermophysical properties
- v. It should be compatible with external environment.

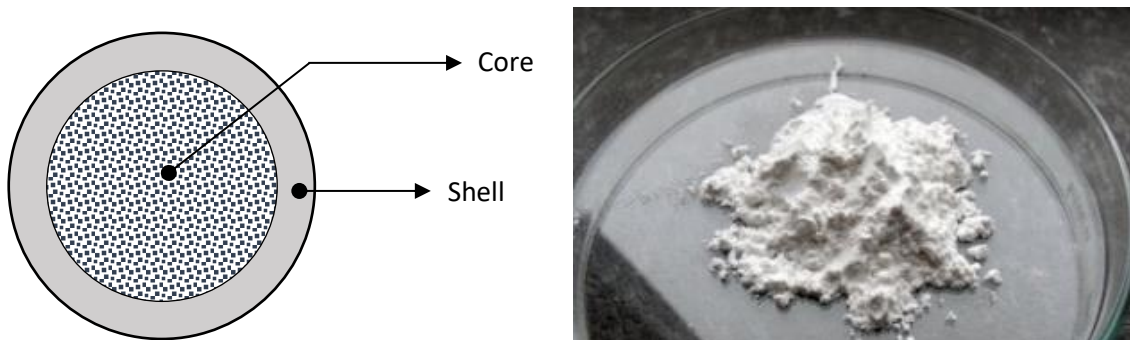


Fig. 2.17 Representation of MPCM (Cárdenas-Ramírez et al., 2020; Mohaine et al., 2016).

The primary advantage of microencapsulation over macroencapsulation is the prevention of PCM leakage during phase change and the improvement of heat transfer, which mitigates compatibility issues with the external environment (T. Wang et al., 2016). Microencapsulation is suitable for PCMs with melting temperatures between 10 and 80°C. Microcapsules are produced in various geometries, including spherical, tubular, cylindrical, and irregular shapes. The specific configurations of the microcapsules are mainly influenced by the shell deposition process and the filler material, as shown in Fig. 2.18.

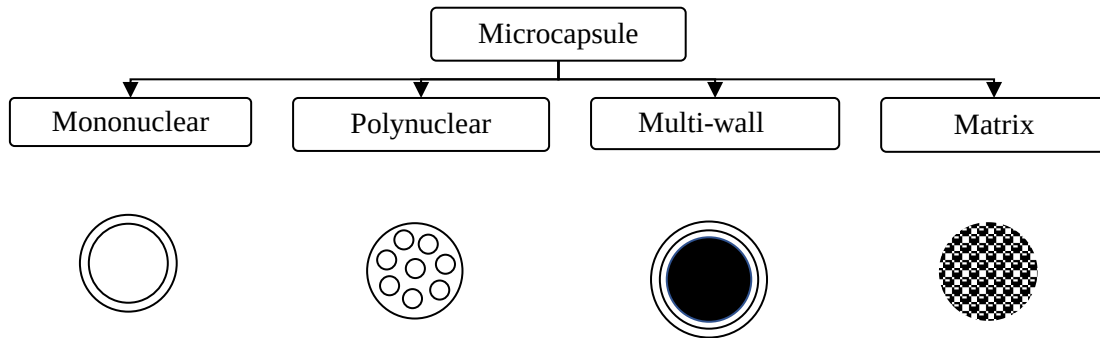


Fig. 2.18 Different geometries of microcapsules for encapsulation.

Furthermore, the utilization of MPCM results in a notably high heat transfer rate due to the significant surface area-to-volume ratio. This heightened heat transfer rate translates into rapid charging and discharging of MPCM. In the context of buildings, MPCM finds extensive applications when integrated into the building envelopes to assess energy performance. However, the incorporation of microencapsulated PCM into concrete has been observed to reduce the mechanical properties of the concrete material. There are two main methods for integrating microencapsulated PCMs into concrete: (i) additive method and (ii) replacement method. In the additive method, microencapsulated PCM serves as an additive mixed with the concrete, while the replacement method involves replacing a portion of the construction material with microencapsulated PCM. The replacement method is preferred when maintaining the strength of the concrete is the primary concern. Unlike macroencapsulation, where there is a temperature differential between the core and shell, microencapsulated PCM exhibits enhanced supercooling, leading to incomplete solidification during phase change.

In terms of cost, the total expense of PCM microencapsulation, as reported by the National Renewable Energy Laboratory in the USA, is 5/2 of PCM macroencapsulation. However, the final cost varies depending on the type of PCM used for encapsulation. Among the various available PCMs, encapsulating Paraffinic PCMs is the most economical option. A comparison of the two encapsulation techniques is presented in Table 2.12.

Table 2.12 Comparison of two highly implemented encapsulating techniques (Chandel & Agarwal, 2017; Lee et al., 2015b).

Encapsulation techniques	Advantages	Disadvantages
Microencapsulation	▪ During a phase change, the volume change is well controlled. ▪ Easily incorporated into the traditional construction materials ▪ Thermodynamic stability is substantially improved. ▪ Improving the conductivity of heat transmission between the PCM and the surrounding material. ▪ Serve as a barrier to inhibit PCM leakage. ▪ Chemical stability is enhanced.	▪ Impact on the material's strength ▪ supercooling effects. ▪ Disrupted natural convection can have an impact on the solidification process. ▪ Expensive procedure
Macroencapsulation	• Better material compatibility with the core and surrounding materials • The consequences of external volume changes are diminished. • During the manufacturing process, PCM is easily managed. • No effect on material composition when subjected to the external environment. • Can be utilized directly as heat exchangers.	• Inadequate heat transfer properties. • Solidification occurs at the edges.

2.4.2.1.3 Nanoencapsulation

Nanoencapsulated Phase Change Materials (NPCMs) are PCMs that have been encapsulated at the nano-scale using advanced technologies. These NPCMs have garnered significant attention in the field of thermal energy storage systems. Research in the literature has revealed that structurally, NPCMs exhibit greater stability compared to micro or macroencapsulated PCMs. Note that most of the research conducted on nanoencapsulated PCMs remains limited to laboratory settings, and further exploration is necessary to advance these technologies to a commercial level (Salunkhe & Shembekar, 2012).

PCMs encapsulated by nano-scale are worthy for thermal energy storage systems. Nanoparticles retain the phase change enthalpy even after several thermal cycles (Navarrete et al., 2019). NPCM can be amalgamated by ultrasonic assistant mini-emulsion in-situ polymerization with thermal properties equivalent to thermal properties of the core (Y. Fang et al., 2008). The thermal stability

nature of NPCMs makes them suitable for TES applications and heat transfer applications (G. Fang et al., 2009). The SEM and TEM micrographs of NPCMs are shown in Fig. 2.19.

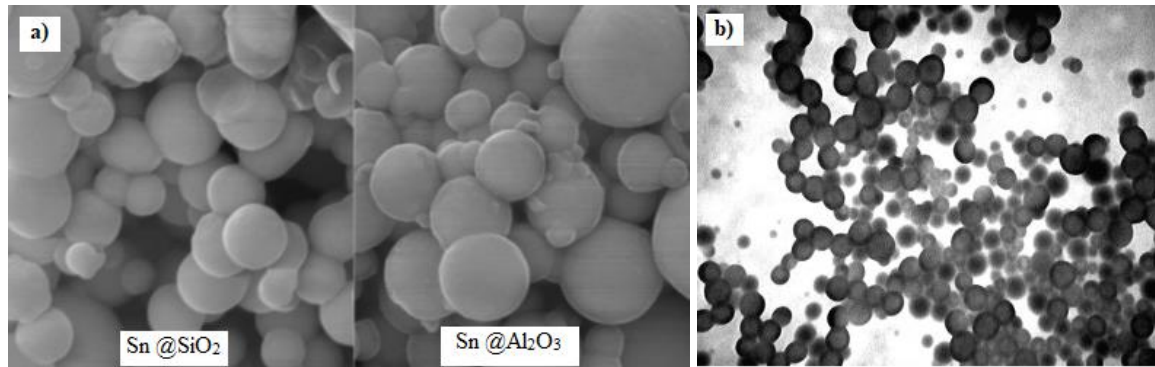


Fig. 2.19 Photos of NPCM: (a) SEM and (b) TEM micrographs of Nano encapsulated PCM (G. Fang et al., 2009; Rathore & Shukla, 2019).

2.4.2.2 Stabilization of PCMs

2.4.2.2.1 Shape-stabilized PCM

In recent years, there has been a growing interest in Shape-Stabilized Phase Change Materials (SSPCMs) due to their unique properties, such as high specific heat capacity and the ability to retain their shape during phase change (Mohaisen et al., 2022; Xiaonan Wang et al., 2022). SSPCMs are composite materials with dispersed PCM particles embedded within a supporting material. The process involves heating the mixture to elevated temperatures, allowing the PCM to disperse within the supporting material, and cooling the mixture until it solidifies. In SSPCMs, paraffinic PCMs typically make up around 80% of the total mass, which contributes to their high thermal conductivity and excellent performance even after undergoing multiple thermal cycles. In building applications, SSPCMs are commonly integrated into floors, ceilings, and wallboards. A graphical representation of SSPCMs and their morphological behavior can be observed in Fig. 2.20.



Fig. 2.20 Pictures of SSPCM plate: (a) Plate appearance; (b) SSPCM plate; (c) SEM picture of SSPCM (K. Lin et al., 2005; Y. P. Zhang et al., 2006).

SSPCM has been proved energy efficient in building applications (K. Lin et al., 2005; Marani & Nehdi, 2019; Xu Wang et al., 2016a; X. Xu et al., 2005). Both numerically and experimentally, SSPCMs have reported being more reactive in terms of utilizing latent heat. Thus, making the SSPCMs the potential candidates for solar buildings.

2.4.2.2.2 Form stable PCM composites

Form-stable PCM composites are advanced materials that effectively retain a maximum amount of PCM without experiencing leakage issues commonly associated with solid-liquid PCMs. This integration method involves incorporating multiple PCMs into a supporting material, resulting in a stable form. There are three main approaches for synthesizing form-stable PCMs: i) amalgamation of PCM with high or low-density polyethylene, ii) PCM dispersion into a carbon matrix, and iii) microencapsulation. However, the synthesis of form-stable PCMs is a complex and costly process that involves techniques such as polymerization and vacuum impregnation, leading to a prolonged production cycle. Form-stable PCMs are further classified into two categories: solid-solid PCMs, which consist of crystal molecules and polymers, and solid-liquid PCMs, which include compound PCMs. These form-stable PCMs are particularly well-suited for low-temperature heat storage applications. (Y. Li et al., 2020). It has been shown that FSPCMs could be the potential candidates for increasing buildings' energy efficiency (Ahmet Sari & Biçer, 2012).

2.5 Review of LHTES with PCMs in building applications

In the domain of applying PCMs in buildings, two primary systems are distinguished: Passive and active systems. Passive systems rely solely on the ambient temperature and weather variations to release energy through PCM solidification and absorb it during PCM melting, without utilizing any mechanical power. However, their effectiveness is contingent upon significant nighttime temperature drops below the PCMs' phase transition temperature for complete solidification to occur (Souayfane et al., 2016). In cooling applications, if nighttime temperatures do not meet this criterion, passive systems may become ineffective and require supplementary cooling mechanisms to regenerate the PCM units overnight. In contrast, active systems employ fans or pumps to actively enhance heat transfer into and out of the PCM, offering better control over the regeneration process and the option to supplement passive cooling with active cooling. While active systems address the limitations of passive PCM systems, they consume additional energy. To assess a building's energy efficiency, the energy consumption data provides insights into how efficiently energy is either lost or gained through the building envelope. Typically, buildings lose around 25% of energy through walls, 30% through windows, 22% through the roof, and 30% through other sources (Yan Liu et al., 2017). PCMs are indeed applied in building materials and building envelopes to enhance

thermal comfort, reduce energy consumption, reduce reliance on conventional HVAC systems, and create more sustainable and energy-efficient buildings. As the technology and research in PCM integration continue to advance, these applications are expected to play a significant role in promoting greener and more environmentally friendly building practices. Application of PCM in buildings into materials and envelopes are classified as:

1. PCM Enhanced Building Materials

- i. PCM integrated Cementitious Concrete
- ii. PCM integrated Bricks
- iii. PCM enhanced mortar

2. Application of PCM in building envelopes

- i. Application of PCM in Floors
- ii. PCM Enhanced Wallboards
- iii. PCM-integrated glazing units
- iv. Application of PCM in Roofs/Ceilings

2.5.1 PCM Enhanced Building Materials

2.5.1.1 PCM Integrated Cementitious Concrete

Using PCMs at varied positions within concrete blocks significantly augments thermal performance to different extents, contingent upon its application. Moreover, the interplay between PCM and cementitious materials remains a noteworthy concern. Nevertheless, various non-contact integration techniques of PCM with concrete garner considerable attention among researchers in sustainable construction (Mohseni et al., 2019). Eddhahak-Ouni et al. (2014) conducted a study using quantitative and homogenization methods to investigate the effects of incorporating organic microencapsulated PCMs into Portland cement concrete. The PCMs underwent detailed characterization using various techniques. Subsequently, several PCM-concrete blends were created with varying PCM loadings. Artificial ageing was applied to the PCM-concrete blends before analyzing their thermal properties. The research revealed that including PCMs improved the heat storage capacity of the PCM-integrated concrete. However, as the PCM loading increased, the compressive strength of the concrete started to decline. The thermal conductivity of the concrete was not significantly affected by the PCM inclusion, owing to the low thermal conductivity and PCM loadings in the concrete. The study concluded that the thermal behavior of the modified concrete would stabilize over time, as the aged PCM-incorporated concrete exhibited thermal responses comparable to unaged PCM-incorporated concrete.

The homogenization models used by the authors to evaluate the equivalent thermal conductivity of PCM-integrated concrete are presented in the following equations:

1 Voigt and Reuss scheme

$$\lambda_e^{\text{Reuss}} = f_v \cdot \lambda_{PCM} + (1 - f_v) \cdot \lambda_m \quad (2.10)$$

$$\lambda_e^{\text{Voigt}} = \frac{\lambda_m \lambda_{PCM}}{f_v \lambda_m + (1 - f_v) \lambda_{PCM}} \quad (2.11)$$

2 Dilute scheme

$$\lambda_e^{\text{Esh}} = \lambda_m + f_v (\lambda_{PCM} - \lambda_m) \cdot [I + (\lambda_{PCM} - \lambda_m) \cdot P_{PCM}]^{-1} \quad (2.12)$$

Where P_{PCM} is the hill tensor and varies with PCM's shape ratio and matrix's thermal conductivity.

3 Mori–Tanaka (MT) approach

$$\lambda_e^{MT} = \lambda_m + f_v (\lambda_{PCM} - \lambda_m) \cdot A_{PCM}^{MT} \quad (2.13)$$

In a subsequent study, Figueiredo et al. (2016) assessed the influence of PCM microencapsulation on the thermomechanical properties of concrete. The experimental tests compared concrete specimens with PCM enhancement to reference specimens without PCM. The results indicated a considerable loss in resistance, with a 66% reduction in compression strength and a 52% reduction in bending strength for the PCM-enhanced concrete. It was observed that the addition of PCM somewhat improved the thermal behavior of the concrete. However, the substantial strength losses suggested that better control over the mixing procedure and water-to-cement (w/c) ratio was necessary to minimize these effects. To further enhance the heat storage capabilities of PCM-incorporated concrete, address PCM leakage issues, and reduce heat storage costs, Shen et al. (2021) proposed the use of PCM-CLSC (Calcium Limestone Silica Cement) aggregate and PCM-concrete thermal storage blocks with varying PCM loadings (0, 2, 4, and 6 wt.%), as depicted in Fig. 2.21. Both the aggregate and storage blocks underwent comprehensive tests to evaluate their thermal, mechanical, and absorption characteristics. The experimental outcomes revealed that the developed aggregate exhibited high compatibility and absorption capacity. The average heat capacity increased by 12.54%, 31.60%, and 41.23% for PCM loadings of 2, 4, and 6 wt.%, respectively. However, as the PCM loadings increased, the blocks' compressive strength and thermal conductivity diminished. Nonetheless, improvements in the heat flux rate and reduction in thermal resistance were achievable while enhancing the overall heat storage and discharge capacity, as shown in Fig. 2.23. These findings highlight the potential of PCM-CLSC aggregate and PCM-concrete thermal storage blocks in enhancing energy efficiency and thermal performance in building applications.

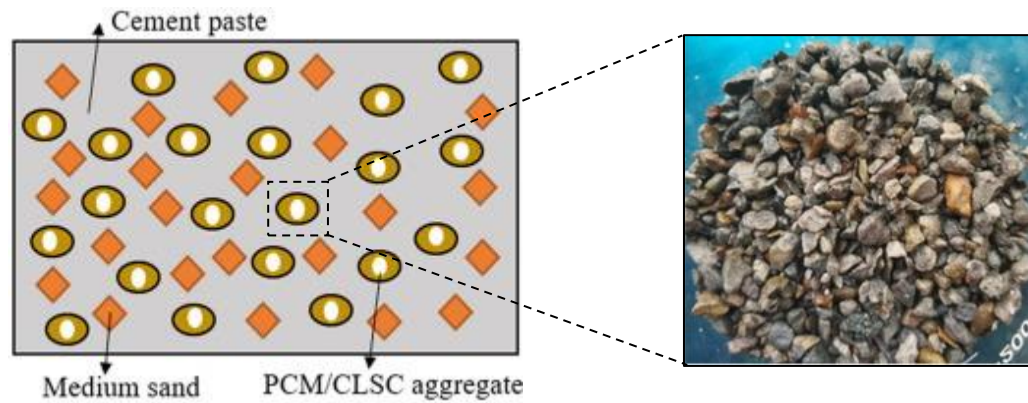


Fig. 2.21 Schematic diagram of PCM-CTSB (Shen et al., 2021).

In a study conducted by Farnam et al. (2017) PCMs were integrated into concrete pavements to serve as a heat source for melting snow and ice. The research involved large concrete slabs (Ref. Fig. 2.23) with PCMs, and their thermal properties were assessed using low-temperature differential scanning calorimetry. Two different methods were employed to incorporate PCM into the concrete: one

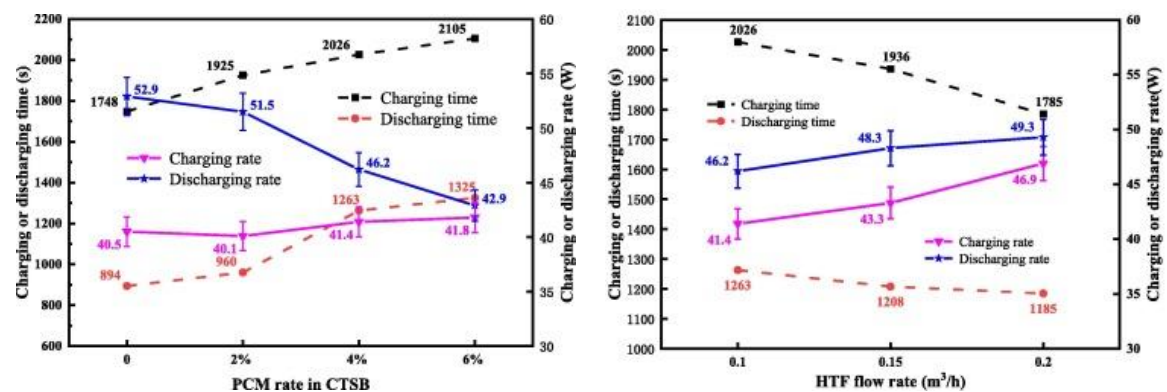


Fig. 2.22 Behavior of charging and discharging cycles with PCM loadings, and heat transfer fluid flow rate (Shen et al., 2021).

involved mixing PCM with LWA and then adding it to the concrete, while the other method used embedded metal pipes inserted into the concrete slabs during casting. When subjected to an ambient temperature above the PCM's freezing point before snowfall, the integrated pipe approach demonstrated a relatively rapid heat release during PCM phase change, while the LWA approach showed a more gradual release. Both approaches showcased the potential to effectively melt ice and snow on the top surface of the concrete slabs.

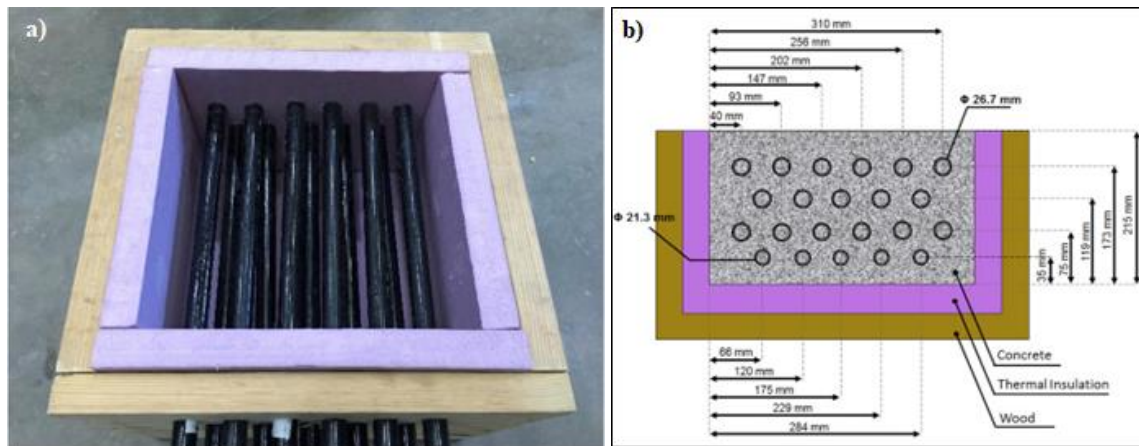


Fig. 2.23 PCM incorporated concrete slabs: a) wooden mold with embedded metallic pipes; b) crosssectional (Farnam et al., 2017).

Following this, Refaa et al. (2018) developed and validated a numerical model to estimate asphalt pavement temperatures under actual weather conditions, considering the influence of PCM. Additionally, a parametric study was conducted to modify the thermal behavior of asphalt concrete pavement. By reducing the temperature within the asphalt concrete (AC) throughout the day, PCM minimizes the likelihood of malfunctions such as rutting in AC roads associated with high temperatures. The integration of PCM and the customization of thermophysical characteristics in the asphalt mixture can result in a tailored thermal response for AC pavements, which may be especially crucial in addressing urban heat island issues.

Furthermore, incorporating PCMs in AC pavements increases the complex shear modulus of bitumen. In a study conducted by Djamai et al. (2021), a multiphysics analysis was carried out to evaluate the effectiveness of a composite material consisting of PCMs and textile-reinforced concrete (TRC). The potential of this composite lies in combining TRC's lightweight property with PCM's ability for heat storage. The research focused on investigating how PCMs impact the thermal and mechanical properties of TRCs. Despite some deterioration in the mechanical characteristics, the composite slabs retained their multicracking behavior and ductile response. The mechanical properties of both the PCM-mortar matrix and the composite slab are significantly influenced by temperature changes and the state of the PCM, which can induce volume changes during phase transition. The composite slab with a PCM loading of 10 wt. % and a thickness of 4.5 cm exhibited enhanced thermal performance compared to the standard TRC slab, resulting in a maximum temperature drop of 4 °C and achieving an energy savings of 37%.

2.5.1.2 PCM Integrated Bricks

The incorporation of PCMs into various building materials has been extensively researched. In one such study, conducted by Alawadhi, (2008) the thermal behavior of a brick with cylindrical

perforations containing PCM was analyzed using the finite element method to solve a 2D energy equation. Several variables, including the amount, type, and location of PCM, were investigated to assess their impact. The numerical results revealed that the introduction of PCM into the brick significantly reduced heat gain, with the best thermal performance achieved when PCM was placed at the brick's centerline.

In high-rise structures, lightweight materials are often employed to reduce building weight. However, this also results in decreased thermal inertia, leading to greater variations in air-conditioning load and lower thermal comfort conditions. To address this issue, PCM is incorporated into voided bricks to enhance the thermal behavior of building envelopes. Yanna Gao et al. (2020) carried out a full-scale experiment to validate the numerical model, which depicts the heat transfer during melting-solidifying. The PCM that was filled enhanced the hollow bricks' thermal performance. The delay time can go from 3.83h to 8.83h–9.83h if the PCM is filled. Whilst it's occurring, the incorporated PCM can lower the maximum heat transfer from 45.26–19.19 W/m². The dynamic heat transfers through 2D brick wall simulating melting – freezing process can be described as:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\frac{\lambda_s}{\rho_s C_{p,s}} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\lambda_s}{\rho_s C_{p,s}} \frac{\partial T}{\partial y} \right) \quad (2.14)$$

An enthalpy model clarifying the melting-solidifying heat transmission across the PCM layer can be defined as:

$$\frac{\partial(\rho_{PCM} H)}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_{PCM} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_{PCM} \frac{\partial T}{\partial y} \right) \quad (2.15)$$

$$H = \begin{cases} \int_{T_0}^{T_1} C_{p,PCM} dT (T < T_s) \\ \int_{T_0}^{T_s} C_{p,PCM} dT + \frac{T - T_s}{T_L - T_s} L (T_s \leq T \leq T_L) \\ \int_{T_0}^{T_s} C_{p,PCM} dT + L + \int_{T_L}^T C_{p,PCM} dT (T_L < T) \end{cases} \quad (2.16)$$

Through the analysis of PCM positioning within a double wall of hollow bricks, Hamidi et al. (2021) investigated the energy efficiency of a PCM-integrated hollow brick wall. The study involved a mathematical analysis of four different PCM locations within hollow bricks in a region with a warm climate (Ref. Fig. 2.24). The results demonstrated the potential benefits of partially filling bricks with PCM compared to completely filling them. Specifically, the PCM placement in

the 3rd and 4th positions showed the capability to save up to 97% of the energy required to maintain comfortable indoor conditions at a set temperature of 26°C. As a result, it is recommended that PCMs be included in position 4 instead of entirely filling the bricks in new construction projects to enhance comfort and reduce energy demands. The heat transfer in PCMs is governed by the following equation:

$$\rho_{PCM} C_{p,PCM} \frac{\partial T_{PCM}}{\partial t} = k_{PCM} \left(\frac{\partial^2 T_{PCM}}{\partial x^2} + \frac{\partial^2 T_{PCM}}{\partial y^2} \right) \quad (2.17)$$

$$\rho_{PCM} = \theta \rho_s + (1 - \theta) \rho_l \quad (2.18)$$

$$C_{p,PCM} = \frac{1}{\rho} \left(\theta \rho_s C_{p,s} + (1 - \theta) \rho_l C_{p,l} \right) + L_f \frac{\partial \alpha_m}{\partial T} \quad (2.19)$$

$$k_{PCM} = \theta k_s + (1 - \theta) k_l \quad (2.20)$$

Where, θ is the solid part of PCM.

Mahdaoui et al. (2021) introduced hollow bricks integrated with PCM to investigate the thermal efficiency of PCMs in bricks under the weather conditions of Morocco. The study emphasized the importance of considering the latent heat and melting temperature as critical characteristics when selecting a suitable PCM for integration. Furthermore, the thermal performance of brick walls experienced substantial improvement as the quantity of PCM integrated into the bricks increased. However, for economic and structural strength reasons, the optimal quantity of PCM must be carefully optimized. The study employed an energy equation to simulate both the charging and discharging processes, represented by the following Eqns. (2.21 and 2.22). f and L_f are liquid fraction and latent heat of PCM.

$$\frac{\partial}{\partial t}(\rho h) = \nabla(\lambda \nabla T) + S \quad (2.21)$$

$$h = h_{ref} + \int_{T_{ref}}^T C_p T + f \cdot L_f \quad (2.22)$$



Fig. 2.24 Graphical representation of PCM locations in a hollow bricks (Hamidi et al., 2021).

Insulating materials, viz. cotton, fiberglass, and foam, are installed in building structures in hot climates. The building envelopes play a remarkable role in energy consumption, including optimizing window areas. The specific heat and thermal conductivity of insulation materials affect heat transfer at a steady state. The inclusion of PCMs into building facades has overcome these hurdles by retarding the heat flow by mopping up the heat. PCM-integrated building envelopes don't change overall heat conduction. The incorporation of PCM into bricks in Mediterranean countries was pointed out by Castell et al. (2013), in which macroencapsulated PCMs were incorporated into cubicles of conventional bricks and alveolar bricks. The experimental results conveyed diminishing peak temperatures with daily temperature fluctuations smoothened out, leading to a 15% reduction in energy consumption and saving almost 1-1.5 kg/year/m², thus demonstrating the potential of PCMs in building envelopes. The thermal performance of a brick with PCM has been evaluated experimentally, thus limiting dynamic heat transfer through thermal conduction. Characterizing the brick geometry remained a principal challenge in analyzing the dynamic heat transfer, which later was subjugated by a tool Sierpinski carpet based on the three traits viz. pore sizes are dissimilar, discrete distribution of pores, and solid matrix can withhold loads. C. Zhang et al. (2011) introduced Sierpinski carpet in his theoretical model to analyze the thermal analysis of PCM integrated brick walls with varying temperatures based on characterizing structure through thermal conduction ushered by melting and solidification processes. The model uses the enthalpy porosity technique and is validated through experimental results. Results pointed out enhancement in the thermal storage of PCM brick walls. Inside the brick wall, the discrete space distribution disturbs the temperature distribution; meanwhile, the amplitude of temperature fluctuation inside the solid brick wall diminishes with an increase in PCM quantity while enhancing temperature hysteresis. The performance of evaluating energy savings in PCM integrated concrete brick highly depends on the measurement of thermo-physical properties. Lack of effective ways to accurately measure thermo-physical properties lead the Cheng et al. (2013) to introduced a novel method to figure out dynamic specific heat and thermal conductivity of PCM incorporated concrete-brick. The technique relies on the inverse method overcoming the limitations of other testing methods. Maximum heat transfers and temperature variation in various layers are only needed. The results revealed that the method provided the highest accuracy. Traditionally thermal inertia is enhanced by increasing the thickness of the building envelope. However, inserting insulating materials into the brick enclosures made the novel approach to gain thermal inertia in Mediterranean climates. Increasing energy performance and diminishing heat transfer, the brick enclosures are inserted with PCM and are coated with low emissivity and absorption paint (Principi & Fioretti, 2012). The results addressed shifting load peaks and reducing heat flux variations, and the paint improved the candidate thermal transmittance and conductance.

Proper utilization of the sun's perennial energy for conserving building energy can be a landmark for building energy savings. Various passive techniques are being integrated and explored in buildings in urban areas where solar energy is in great need of utilization. One of the methods was implemented by Saxena et al. (2019), in which PCM was incorporated within the building element (brick) in climatic conditions of Delhi to narrow down temperature fluctuations and heat flow and to enhance energy efficiency within the buildings. The authors exposed the developed PCM integrated bricks to direct and indirect solar irradiance. The study revealed substantial demotion ($\sim 10^\circ\text{C}$) of temperature fluctuation and heat gain with the incorporation of PCM in building envelopes. Moreover, results iterate Eicosane and OM35 are satisfactory for Delhi's climate. PCM integrated bricks find a viable solution for cooling in buildings during peak summer conditions. The authors addressed the impact of single and multi-layers of PCM in Delhi's climate escorted by analyzing the effect of PCM with fins in bricks. The results indicated a reduction in temperature and heat gain with PCM thickness of 1 – 1.3cm, suitable for the demotion of temperature around 6°C . The overall decline in heat gain varied from 16 – 20% for a stretch of 24hr. Moreover, the use of fins showed substantial enhancement in heat transfer. The following heat conduction equation can be used to determine the heat transmission through bricks.

$$\frac{\partial t_{brick}}{\Delta \tau} = \alpha \frac{\partial^2 t_{brick}}{\partial x^2} \quad (2.23)$$

$$Q_2 = Q_1 - Q_{s,i} \quad (2.24)$$

$$Q_{s,i} = mC_i \frac{dt}{d\tau}, \quad i = 1, \dots, n \quad (2.25)$$

where, Q_1 is the incoming heat absorbed by PCM and other building materials, Q_2 is the heat that flows inside, and C_i is the heat capacity of distinct brick layers.

The heat transfer across the composite is a function of several parameters. Saxena et al. (2020b) computed that the uncertainty of heat transfer across the brick is a function of the cross-sectional area (A), the brick's effective thermal conductivity (U_{eff}), and the temperature differential across the thickness of the brick (ΔT), described by the following equation.

$$U_Q = \sqrt{\left(\frac{\partial U_Q}{\partial \delta_{brick}} U_{\delta_{brick}}\right)^2 + \left(\frac{\partial U_Q}{\partial \delta_{air}} U_{\delta_{air}}\right)^2 + \left(\frac{\partial U_Q}{\partial \delta_{PCM}} U_{\delta_{PCM}}\right)^2 + \left(\frac{\partial U_Q}{\partial l_{brick}} U_{l_{brick}}\right)^2 + \left(\frac{\partial U_Q}{\partial b_{brick}} U_{b_{brick}}\right)^2 + \left(\frac{\partial U_Q}{\partial T_{outer}} U_{T_{outer}}\right)^2 + \left(\frac{\partial U_Q}{\partial T_{inner}} U_{T_{inner}}\right)^2} \quad (2.26)$$

A study conducted by Abbas et al. (2021) investigated the application of PCM-filled capsules as an insulating material within the walls consisting of hollow bricks. The research utilized both experimental and numerical approaches, employing an innovative plug-and-play wall system model

with two similar rooms to evaluate the performance of two southern walls in both PCM-integrated and PCM-free environments. The results demonstrated that the proposed PCM encapsulation within the wall significantly reduced the internal wall surface and indoor environment temperatures by approximately 4.7°C, enhanced the time lag by 2 hours, reduced temperature fluctuations by 23.84%, and achieved a decrement factor of 0.7.

On a related note, Kant et al. (2017) developed a thermal model that accounted for the heat and mass transmission of PCMs within the cylindrical hollows of bricks, aiming to utilize the substantial latent heat of PCM for improved comfort inside buildings. The study focused on analyzing heat movement in buildings, considering convective and radiative heat transfer within the PCM and to the outdoors. Three distinct scenarios were compared: conventional bricks, bricks with cylindrical cavities filled with air, and bricks with cylindrical cavities filled with PCM. Various PCMs were considered in the analysis, including different quantities of single and multiple PCM. The findings revealed that Capric acid exhibited higher effectiveness as a PCM compared to Paraffin and RT-25. The maximum heat transfer reduction achieved with Capric acid loaded in three cylindrical voids was 8.31%. The heat transfers across the brick's front side, back side, and inside the brick were determined using the following equations:

$$-k_{brick} \frac{\partial T}{\partial x} = h_o (T_{amb} - T_{brick}) + \varepsilon_{brick} \sigma (T_{amb}^4 - T_{brick}^4) + \alpha_{brick} E(t) \quad (2.27)$$

$$-k_{brick} \frac{\partial T}{\partial x} = h_i (T_{indoor} - T_{brick}) + \varepsilon_{brick} \sigma (T_{indoor}^4 - T_{brick}^4) \quad (2.28)$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \nabla T = -\nabla \cdot (-k \nabla T) \quad (2.29)$$

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = 0 \quad (2.30)$$

Where k_{brick} is bricks' thermal conductivity, h_o is the coefficient of heat transfer with a value of 20 W/m² K (Alawadhi, 2008), T_{amb} and T_{brick} is the ambient temperature and the temperature of the brick front wall, ε_{brick} is the bricks' emissivity, with a value of 0.8. The Stefan-Boltzmann constant, σ is assumed to have a value of 5.67 108 Wm². According to Yao & Yan, (2011), brick absorptivity α_{brick} is 0.65, and E stands for incident solar radiation. $\vec{u}$ is the velocity field for incompressible fluids while ρ and C_p representing density and specific heat capacity.

2.5.1.3 PCM Incorporated Mortar

By customizing building materials, such as mortar, by incorporating heat storage materials, it is possible to modify building envelopes and enhance their energy efficiency. This approach allows for better regulation of internal temperatures within buildings (V. V. Rao et al., 2018). Researchers have explored the use of PCM in cement and concrete-based mixtures, demonstrating the potential benefits of PCM in improving building energy efficiency. However, accurately quantifying the impact of PCM on building materials has remained a challenging question for many years. Recognizing the potential of PCM-enhanced materials Olivieri et al. (2018) formulated PCM-enhanced mortar for an active wall with water pipes, aiming to determine the optimal amount of PCM to be added to the matrix. In this study, thermal conductivity (λ), thermal effusivity (e), and thermal diffusivity (α) were the thermal characteristics analyzed, and their calculations were based on the following equations:

$$\alpha = \frac{\lambda}{\rho.C_p} \quad (2.31)$$

$$e = \sqrt{\lambda.\rho.C_p} \quad (2.32)$$

Results revealed higher values of thermal conductivity, thermal diffusivity, and thermal effusivity with higher increments of MEPCM, showing a density reduction of 1.7 kgm^{-3} for 20% PCM and 1.4 kgm^{-3} for 32% PCM. Moreover, thermal conductivity and thermal diffusivity decreased with increasing amounts of PCM, with a 17% reduction in λ and 31% in α while enhancement in C_p counterbalanced the former properties. Increasing the PCM content enhances the energy storage with constant thermal effusivity, suggesting the implication of suitable material based on diffusivity appropriate for heat flow rates.

In recent decades, there has been growing interest in incorporating PCMs into cementitious materials, but the interaction mechanism between the matrix and PCM requires further clarification. In the study conducted by Djamai et al. (2019), the goal was to enhance the impact of PCM-integrated mortars on the mechanical properties by evaluating the hydration mechanism through various tests such as TGA, SEM, FT-IR, and Calorimetry. The primary objective of this research was to characterize PCM-integrated mortars and accurately quantify the PCM content within the matrix. Experimental investigations revealed a reduction in compressive strength in composite mortars enhanced with PCM due to the interaction between PCM and the matrix, as well as the weak bonding with PCM. PCM can be mixed into building materials through pastes and mortars, with cement serving as the common binder in PCM-integrated mortars. In addition to using Nano inclusions, lightweight aggregates and cellulose fibers are being introduced to improve thermal properties by reducing mortar density and thermal conductivity.

In an effort to address the freeze-thaw durability of concrete and potentially enhance frost resistance, Yeon, (2020) explored the thermal behavior of cement mortar incorporating PCM with low-phase transition temperatures. The study found that adding PCMs with low-phase transition temperatures effectively increased the minimum material temperature. Moreover, the use of multiple PCMs-filled LWA showed the best performance in terms of thermal and mechanical characteristics when compared to other inclusion techniques. This research provides a promising approach to improving the thermal performance and mechanical properties of PCM-integrated cementitious materials.

In another study focusing on passive building conditioning, Saxena et al. (2020b) assessed the thermal efficacy of bricks containing galvanized steel capsules housing PCM. The selected PCMs for the investigation included Eicosane and OM35. Experimental trials using PCM-embedded bricks were conducted at an ambient temperature of 40°C. Results indicated that heat transfer through PCM walls was reduced by 40–60% when utilizing single or double-layer PCM bricks, resulting in 4–9.5°C temperature differentials across them. The thermal performance of PCM bricks remained consistent even with the addition of fins.

Recently, Al-Yasiri & Szabó, (2023) conducted experimental trials to evaluate the thermal performance and benefits of integrating PCMs into the building envelope, particularly in brick walls and the roof, amidst the challenging hot summer conditions prevalent in southern Iraq. The study analyzed crucial parameters such as the average heat gain reduction (AHGR) and potential electricity savings. Electricity Cost Savings (ECS) in Iraqi dinar (IQD)/day/m³ were calculated by considering the total AHGR for each day and the prevailing cost of each kWh in Iraq. The computed ECS results for each day amounted to 77.76, 80.64, and 78.77 IQD/day during the three experimental days. These findings suggest a relatively moderate return on investment when compared to the initial outlay for PCMs and their associated integration costs in the current market scenario.

2.5.2 PCM Enhanced Building Envelopes

2.5.2.1 Application of PCM in Floors

Among the various energy systems utilized in buildings, the floor radiant heating system stands out for its exceptional advantages, including low energy consumption, pleasant indoor temperature, elegant design, and space-saving features, making it suitable for meeting the heating requirements of diverse building types. TES systems, particularly employing PCMs, have garnered significant attention in floor radiant heating systems due to PCM's high thermal storage density and minimal

temperature-volume changes during phase transitions. The integration of TES technology with radiant floor heating not only reduces overall energy consumption but also enhances thermal comfort by mitigating interior temperature fluctuations. Study conducted by Su et al. (2020) has prompted several investigators to explore the use of PCM macrocapsules in heated floors. The study by González & Prieto, (2021), demonstrated that such integration can lead to a 10 to 18% reduction in heat transfer compared to systems without PCM. These findings have spurred further exploration and optimization of building designs, aiming to achieve superior energy performance and occupant comfort.

Integrating thermal mass into under-floor heating systems offers the potential for off-peak heat energy storage, enabling the shift of maximum energy demand to periods with lower power tariffs, typically during nighttime when electricity costs are reduced. This approach involves utilizing the phase change characteristics of SSPCM to achieve efficient thermal energy management. For instance, in many cities of China, nighttime electricity tariffs can be 1/3rd to 1/5th of daytime rates (K. Lin et al., 2005). A study conducted by X. Xu et al. (2005) focused on developing a novel floor system with SSPCM capable of capturing solar irradiance during the daytime and releasing stored heat energy during the night in winter. The researchers analyzed the impact of various factors, including PCM melting temperature, thickness of PCM layers, latent heat, and thermal conductivity, on the thermal performance of the SSPCM floor. They proposed an enthalpy-based model that integrated the SSPCM floor into passive solar structures. The findings suggested that for effective interior environment control, the PCM melting temperature should closely match the mean indoor air temperature, with a latent heat capacity of approximately 120 kJ/kg. Moreover, the optimal SSPCM plate should have a thickness not exceeding 20 mm and a thermal conductivity of 0.5 W/mK, ideally positioned beneath the ground to achieve desired thermal performance. The transient heat transfer equation of SSPCM plate can be expressed as:

$$\rho_{pcm} \frac{\partial H}{\partial \tau} = k_{pcm} \frac{\partial^2 T(x, \tau)}{\partial x^2} \quad (2.33)$$

$$\left. \begin{aligned} k_{pcm} \frac{\partial T(x, \tau)}{\partial x} &= -q_{gap}(\tau) + \varepsilon \sigma \left[(Tx_3, \tau)^4 - T(Tx_2, \tau)^4 \right] \quad \text{at } x = x_2 \\ k_{pcm} \frac{\partial T(x, \tau)}{\partial x} &= 0, \quad \text{at } x = x_1 \end{aligned} \right\} \begin{array}{l} \text{after applying} \\ \text{the boundary conditions} \end{array} \quad (2.34)$$

PCM-embedded concrete floors serve as effective thermal energy storage systems without the need for active cooling or heating mechanisms. However, thick concrete floors with a depth of

approximately 50mm have prolonged charging times due to their high energy storage capacity. To mitigate surface temperature fluctuations and heat fluxes, a dual-layer PCM floor has been proposed by (Entrop et al., 2011). Jin & Zhang, (2011) developed a numerical model based on a two-layer PCM floor to store hot or cold energy during off-peak hours and utilize it during peak periods. Their findings indicated that an optimal PCM melting temperature of 38°C for charging and 18°C for discharging, which may vary depending on the location. The PCM-enhanced floor showed a remarkable improvement of 41.1% and 37.9% in peak periods during melting and freezing of PCM, respectively, with a heat of fusion of 150 kJ/kg. In rural China, Lu et al. (2020b) proposed a dual pipe PCM radiant floor system with three heating modules for green energy heating. They conducted a 26-day experimental study to investigate the system's performance under four distinct operational strategies: partial power operation, energy storage during the day, energy storage at night, and phased energy storage. The results demonstrated that the suggested floor heating system could be operated effectively while maintaining comfortable interior temperatures, validated by the modest average daily temperature variations of 3°C. Additionally, Babaharra et al. (2022) conducted a mathematical analysis to evaluate the thermal efficiency of a heated floor integrated with PCM. A physical model was developed to assess the effectiveness of the PCM under-floor heating system, which involved underground tubes circulating hot water through multiple layers of the earth to provide the heating. The heat energy equation of the PCM integrated layer could be expressed as:

$$\varepsilon \left(\frac{\partial H}{\partial t} \right) = \varepsilon \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \varepsilon \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) \quad (2.35)$$

The primary objective of incorporating PCM into the floor system is to leverage the substantial storage capacity of PCMs to optimize energy usage in the heating system and maintain indoor temperatures at a desired comfort level for an extended duration. The study focuses on evaluating and addressing the influence of various factors, such as microcapsule inclusion, mass fraction, inter-tube distance, and PCM type, on the thermal efficiency of the heated floor. Based on the data, it is observed that adding 15% of microcapsules above the heating tubes yields the optimum performance for the heated floor. Compared to the heated floor without PCM, this integration results in a phase shift of 5 hours and 30 minutes, accompanied by a 4°C increase in amplitude. In another investigation by, Larwa et al. (2021), a hydronic radiant heated floor system integrated with macroencapsulated PCM was studied experimentally and numerically, employing both dry and moist sand. The results revealed that the performance of the PCM-integrated heated floor system significantly improves when high thermal conduction mortar is used. Moreover, the utilization of wet sand instead of dry sand led to a substantial 75% increase in heat flux across the floor surface.

2.5.2.2 Application of PCM in Wallboards

PCM-integrated wallboards, in particular, have been extensively explored. These wallboards can absorb excess solar energy during the daytime and release it during the night, effectively regulating the interior temperature and enhancing energy efficiency. Carbonari et al. (2006) proposed a 2D model based on finite element analysis to assess heat transfer across PCM-integrated pre-fabricated walls within sandwich panels. The results demonstrated accurate absorption of latent heat by the PCM, which proved beneficial for lightweight enclosures, enabling the intermediate wall layer to maintain a temperature similar to the PCM's melting temperature. Notably, concrete and PCM-integrated gypsum wallboard have been extensively investigated. Darkwa & O'Callaghan, (2006) proposed a model to analyze the thermal efficiency of a designed passive room integrated with randomly mixed and laminated PCM systems. The presented 3D energy equation and reduced 1D energy equation for randomly mixed and laminated type are given below:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = \rho \frac{\partial H}{\partial t} = \rho \frac{\partial y}{\partial t} \int C_{eff} dT \quad (2.36)$$

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) = \rho \frac{\partial H}{\partial t} = \rho \frac{\partial y}{\partial t} \int C_{eff} dT \quad (2.37)$$

Where, H is an enthalpy and C_{eff} is effective heat capacity is given by:

$$H(T) = \int \rho C_{eff}(T) dT \quad (2.38)$$

During the phase transition process throughout T_s and T_l , $H(T)$ is presented as:

$$\begin{aligned} H(t) &= \int_{T_j}^{T_s} \rho C_s(T) dT + \int_{T_s}^T \left[\rho \left(\frac{dQ_L}{dT} \right) + \rho C_m(T) \right] dT \quad ; (T_s < T \leq T_l) \\ H(t) &= \int_{T_j}^{T_s} \rho C_s(T) dT + \rho Q_L + \int_{T_s}^{T_l} \rho C_m(T) dT + \int_{T_l}^T \rho C_l(T) dT \quad ; (T \geq T_l) \end{aligned} \quad (2.39)$$

The experimental outcomes revealed that the wallboard integrated with a laminated PCM system demonstrated superior efficiency in harnessing the latent heat compared to the randomly-mixed PCM system, thereby leading to an enhancement in the minimum room temperature. Specifically, in comparison to the randomly-mixed PCM system, the wallboard with the laminated PCM integration increased the minimum indoor temperature during the night by approximately 17%.

A study conducted by Medrano et al. (2007) focused on high energy efficiency by integrating microencapsulated PCM into concrete walls. Concrete cubicles containing PCM with a melting point of 26°C were constructed in Lleida, Spain. The results demonstrated that microencapsulated

PCM could be effectively utilized in concrete without compromising its original characteristics. The study highlighted the potential for energy storage using PCM, leading to improved thermal inertia and reduced interior temperatures. The findings showcased PCM's capability to contribute to energy savings in building envelopes. The thermal inertia observed in the experiments indicated that each cycle of PCM contained in the cubicle walls underwent solidification and melting. Furthermore, the study emphasized the importance of nighttime cooling to complete the entire PCM cycle on a daily basis.

Furthermore, a study conducted by C. Chen et al. (2008) introduced a novel PCM technology, which was mixed with construction materials and applied to the internal surface of wallboards in China. The model discussed heat transfer of a PCM integrated wallboard Fig. 2.25 through heat capacity method and MATLAB.

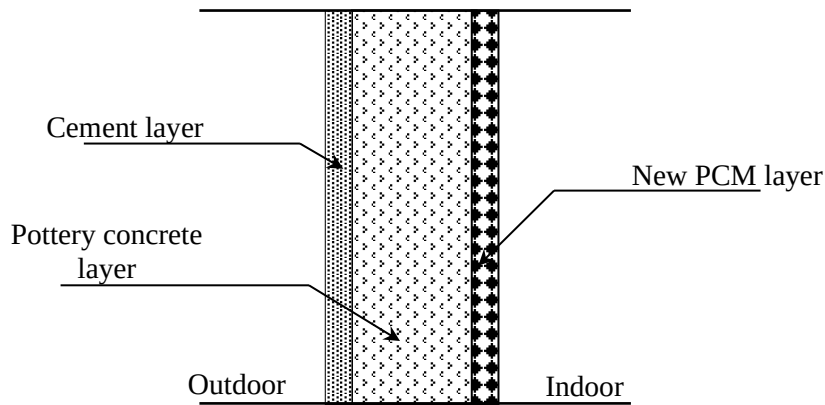


Fig 2.25 Schematic representation of new PCM integrated wallboard (C. Chen et al., 2008).

The parameters studied included the impact of PCM-embedded facades on energy usage and the rate of energy savings concerning phase transition temperature, enthalpy, and PCM thickness. The study found that the newly incorporated PCM exhibited the ability to store and release heat, which was highly influenced by the quantity of PCM present. The highest energy saving rate was observed with an optimal PCM thickness of 30mm and enthalpy of 60 kJ/kg. Furthermore, the PCM wallboard reduced the indoor air temperature by approximately 1°C compared to conventional rooms. The heat equation of PCM integrated wallboard is:

$$\rho c \frac{\partial t(x, \tau)}{\partial \tau} = \lambda \frac{\partial^2 t(x, \tau)}{\partial x^2} \quad (2.40)$$

The phase change problem is changed into a conductive problem with changing thermal characteristics when the thermal conductivity and equivalent heat capacity are thought of as functions of the nodal temperature.

$$C = \begin{cases} C_s(t) & t < t_f - \Delta t \\ \frac{\rho H}{2\Delta t} + \frac{C_s + C_l}{2} & t_f - \Delta t \leq t_f + \Delta t \\ C_l(t) & t > t_f + \Delta t \end{cases} \quad (2.41)$$

$$\lambda = \begin{cases} \lambda_s(t) & t < t_f - \Delta t \\ \lambda_s + \frac{\lambda_l - \lambda_s}{2\Delta T} [t - (t_f - \Delta t)] & t_f - \Delta t \leq t_f + \Delta t \\ \lambda_l(t) & t > t_f + \Delta t \end{cases} \quad (2.42)$$

A mathematical model developed by Voelker et al. (2008) utilized PCM in gypsum plaster to address this problem and showed that PCM effectively mitigates peak temperatures. Modified gypsum plaster and a combination of salt were employed to observe their impact on reducing room temperature. The thermophysical properties of wallboards significantly affected the thermal performance of buildings, with the highest temperature drop being at least 4K. Furthermore, if the PCM cannot be discharged overnight, it may be demonstrated that they lose their typical heat storing capability after some hot days in a row. Such effects can be mitigated by effective night ventilation. To mimic the regular activities of an office, the effect on the assessment of several factors, such as the air change rate, was modified. Unlike other materials, PCMs can be described by additional parameters viz. heat flux modifying factor (α) and heat storage (b) ratio besides time lag (ϕ) and decrement factor (f). Y. Zhang et al. (2008) through the theoretical analysis and simulation addressed new parameters for thermal efficiency of building envelopes incorporated with PCM viz. α & b respectively. The new parameters α and b are defined in the following equations:

$$\alpha = \frac{q_w}{q'_w} = \frac{U}{U'} \quad (2.43)$$

$$b = \frac{\int_0^\tau (q_w(\tau) - q_{in}) d\tau}{\rho H_m L} \quad (2.44)$$

Where, U' and q'_w are the overall heat transfer coefficient and inner surface heat flux of an external wall.

The authors highlighted that integrating PCM into external walls leads to energy savings for both heating and cooling when the thermal diffusivity (α) < 1, and the benefits are further enhanced by increasing the heat of fusion and achieving appropriate thermal conductivity. On the other hand, for internal walls with PCM integration, higher energy savings can be achieved by increasing the heat of fusion while adopting an appropriate melting temperature.

The integration of PCM into wallboards allows its feasibility to be evaluated during different seasons such as summer, winter, and mid-season. Kuznik & Virgone, (2009) conducted an experimental study on PCM-integrated wallboards, providing a rare analysis that controlled both thermal and radiative effects. The study revealed a reduction in temperature fluctuations, with a decrement factor of 0.7 for all cases when PCM was incorporated into the wall. PCM enhances natural convection, leading to a reduction in thermal stratification and improved human comfort. Another study by H. Liu & Awbi, (2009) investigated the behavior of PCM wallboards under natural convection and environmental conditions through experimental analysis. The results demonstrated a reduction in the internal surface wall temperature during the charging process with PCM wallboards, while the discharging process showed contradictory outcomes. PCM wallboards exhibited better heat insulation properties than ordinary walls, with double the heat flux capacity. Additionally, the convective heat transfer coefficient of PCM walls was considerably greater than that of ordinary walls.

To harness the potential of PCM in building envelopes, Izquierdo-Barrientos et al. (2012) proposed a 1D heat transfer model that analyzed various parameters, including wall configuration, position of PCM layers, PCM phase transition temperature, and outside environment. The findings revealed that there is no single optimum temperature that can optimize thermal load across the wallboard. Properly selecting the melting temperature of PCM can reduce heat flux across the wall and improve thermal load during the daytime, but the opposite effect occurs at nighttime. Beltrán & Martínez-Gómez, (2019) conducted a decision model analysis of PCM integrated wallboards, comparing the results of two methods: Building Energy Simulation (BES) and MCDM. The study highlighted that the thermal assessment of PCMs is crucial for understanding their behavior during operation. PCM exhibited good thermal behavior in cold regions, maintaining comfortable indoor temperatures, but the performance differed in warm places. Z. X. Li et al. (2019) conducted a numerical investigation to assess the performance of PCM in conventional walls in Iran. The study observed a reduction in temperature fluctuations and heat transfer across the wall when PCM was incorporated. Additionally, the use of low conductivity PCM led to decreased heat flow, and energy storage capacity increased with higher PCM quantities. Placing PCM externally and utilizing two layers of PCM resulted in a twofold reduction in heat transfer. However, achieving optimal PCM performance in building envelopes poses a significant challenge due to positioning considerations. Khan et al., (2020) conducted two experimental models to study the performance of PCM-integrated building walls. One model aimed to identify the optimum position for the PCM layer, while the other evaluated the impact of PCMs on heat transfer rates and thermal comfort within the building fabric. The results indicated that PCM inclusion in building walls led to the lowest temperature gain from external sources and a smaller peak heat flux compared to other materials. This suggests the potential of PCMs to improve indoor temperature conditions in buildings. Arıcı

et al. (2020) conducted a numerical study to investigate the contribution of PCM latent heat in building walls in Turkey. The results revealed that an optimum PCM thickness ranging from 1-20mm provided the largest annual energy savings, highlighting the economic aspect of PCMs in energy-efficient buildings. N. Zhu et al. (2022) evaluated the effectiveness of a unique double-layer phase transition humidity control material wallboard in a commercial building in Wuhan, China. The PCHCM was designed to absorb and release heat and moisture to regulate the interior climate. The study also explored altering the phase transition temperature of PCHCMs to enhance their overall performance in building applications. The authors' findings were as follows:

- The ideal melting temperature of PCHCM wallboards, reached by 2 layers with distinct PCMs in the given region, is 25°C and 17°C during summer and winter, respectively.
- In relative to a reference building, the PCHCM building saves energy at a rate of 8.3% in the summer and 24.9% in the winter.
- On the interior hygrothermal environment, the impact of PCHCM wallboards is astounding.
- However, compared to the reference building, the interior relative humidity dropped by around 5%.

A recent study, Kong et al. (2022) proposed a novel PCM Trombe wall consisting of two layers with multiple phase transition spots. To evaluate its thermal efficiency, the researchers compared it to a normal wall without PCM, a standard solo-PCM layer wall, and a standard duplex PCM-layer integrated Trombe wall. The comparative analysis used a validated computational fluid dynamics (CFD) model. The results demonstrated that the new dual PCM Trombe wall exhibited significant improvements in maintaining indoor temperatures during both winter and summer, with variations ranging from 0.3 to 6.6°C. Moreover, the peak indoor temperature during summer was significantly mitigated. The heat transfer through the wall was also substantially reduced, ranging from 9.1% to 92% during summer and 1.8% to 75.7% during winter. These findings highlight the potential of the proposed dual PCM Trombe wall to enhance buildings' energy efficiency and thermal performance.

2.5.2.3 PCM integrated glazing units

Glazing units play a critical role in buildings, offering visual access, natural light, ventilation, and passive energy gain. However, their relatively low thermal resistance compared to other building materials makes them crucial for energy requirements and indoor thermal comfort. Wide glazing surfaces significantly impact the energy consumption of the building envelope, with windows being responsible for a substantial portion (about 30%) of heat intake and loss. To address this issue, integrating PCMs into glazing units can be a viable solution to reduce energy transmission between the interior and exterior of structures. In a study by Q. Wang & Zhao, (2015). a commercialized PCM called $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ with a melting temperature of 29.9°C was incorporated into a rectangular canister installed between the curtains of a room in Shanghai. During the summer, adding a 15mm

PCM coating to the curtains effectively reduced the facade temperature by 30.9% (Fig. 2.26), demonstrating the significant impact of PCM on the thermal efficiency of the curtains. However, the $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ PCM showed a sub-cooling problem that might affect its cooling effectiveness. Another investigation by Alawadhi, (2012) employed the finite element approach to explore a method of reducing solar heat gain through openings in buildings using PCM-infused shutters instead of foam. By storing the heat gain until it reaches the interior environment, the high latent heat of the incorporated PCM in the shutters aims to limit heat gain. A parametric analysis was conducted to determine the impact of PCM type and loadings in the shutter. The results showed that PCMs with higher melting points performed better thermally, leading to a 23.29% reduction in heat gain through windows compared to using foam shutters during normal operating hours. These studies highlight the potential of PCM-integrated glazing units and shutters in enhancing the thermal performance and energy efficiency of buildings.

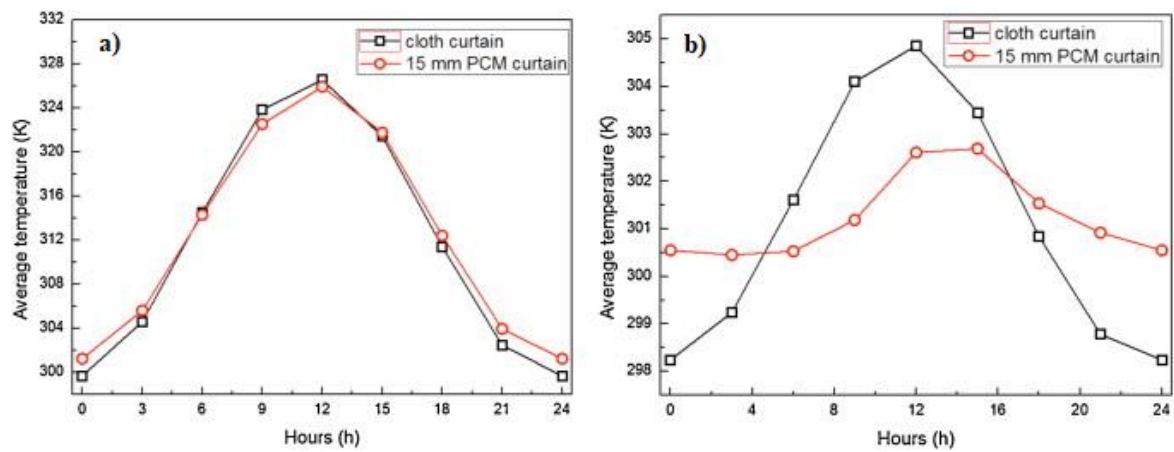
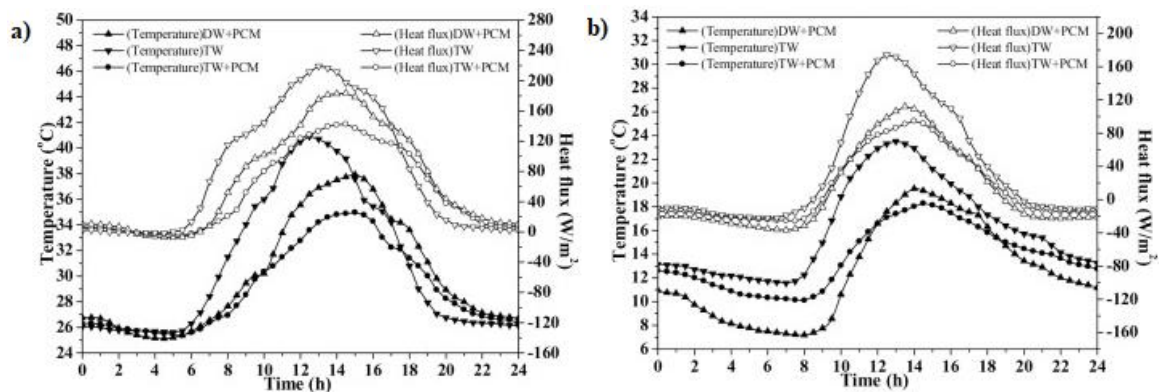


Fig. 2.26 The temporal fluctuations: a) average interior surface temperature and b) average air temperature (Qian Wang & Zhao, 2015).



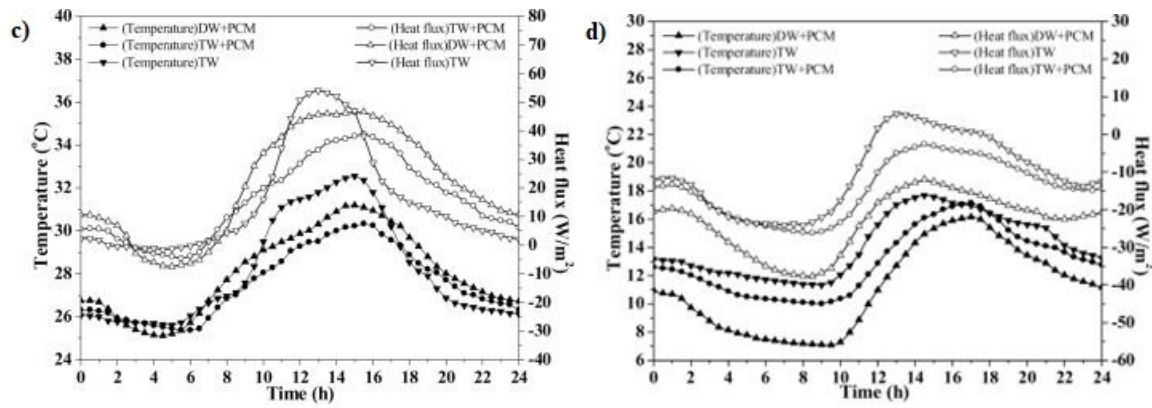


Fig. 2.27 Temporal variation of indoor surface temperature and heat flux during typical; a) sunny summer day, b) sunny winter day, c) rainy summer day, d) rainy winter day (S. Li et al., 2018).

Likewise, S. Li et al. (2018) proposed a configuration of trifold-glazed windows integrated with PCM (TW+PCM) to address the overheating issue associated with double-walled glazed windows. The researchers utilized simulations to evaluate the thermal performance of TW+PCM under dynamic conditions. Comparisons were made with DW+PCM and triple-glazed hollow windows (TW), and the results showed that, on an average bright summer day, the temperature decrement factors were 0.75 and 0.63, respectively. Moreover, TW+PCM exhibited energy savings of 21.30% and 32.80% compared to DW+PCM and TW, respectively. The TW+PCM arrangement also demonstrated efficient insulation and heat preservation during normal winter conditions [Fig. 2.27](#).

In a subsequent study by L. Wei et al., (2022), a quantitative examination of PCM-integrated multilayered glazing units ([Fig. 2.28](#)) was conducted to investigate their performance in terms of dynamically paired heat flux and energy efficiency. The evaluation of energy efficiency was based on heat flow estimation and a model that considers conduction, phase shift, and solar radiation transfer within the glazing units. A transient coupled heat transfer model was employed to account for conduction, phase shift, and solar radiation transfer in the glazing units. The study assessed the efficiency of energy conservation using heat transfer calculations. Based on the findings, the incorporation of PCM into multilayer glazing units can significantly reduce energy consumption compared to non-PCM glazing units. The energy savings rates for double, triple, and four glazing units are 14.55%, 33.89%, and 50.71%, respectively. A comprehensive investigation was carried out to assess the influence of PCM's thermal and optical properties on the thermal efficiency of the glazing modules. The results suggest that the proposed PCM-integrated glazing unit is a promising solution for energy-efficient transparent building envelopes.

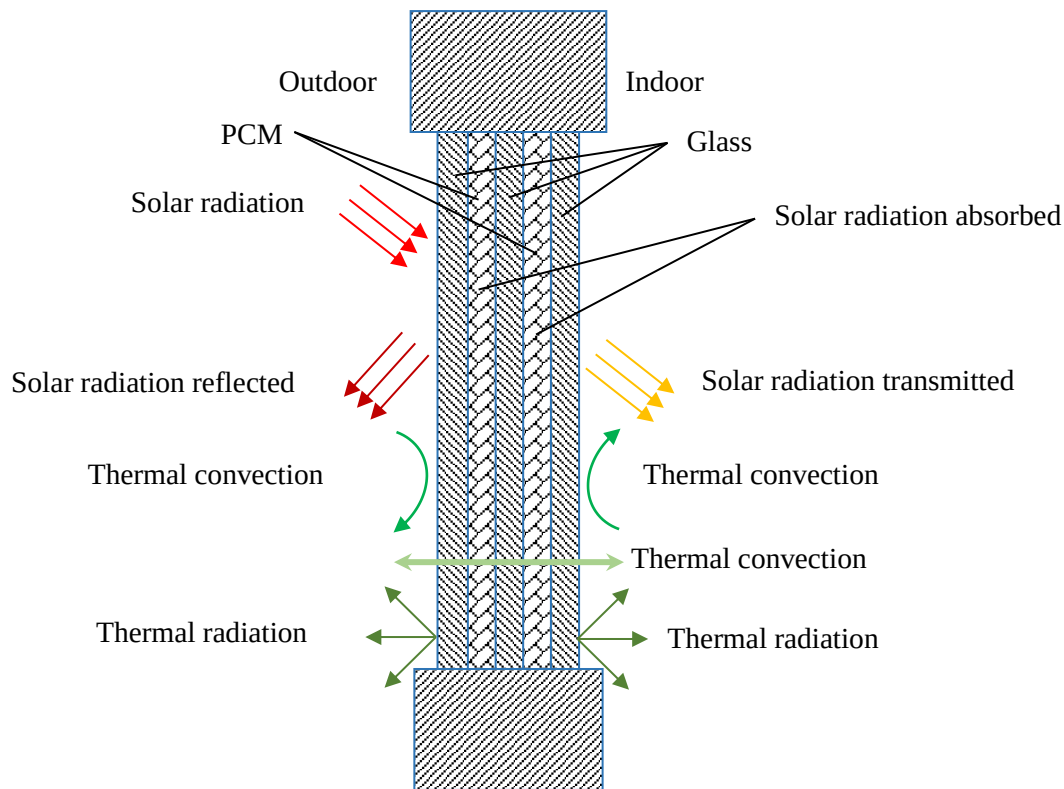


Fig. 2.28 Model of PCM integrated multilayered glazing unit (L. Wei et al., 2022).

In Bosnia, Duraković & Mešetović, (2019) conducted an experimental study on the thermal efficiency of glass-based energy storage devices utilizing different storage media, including water and PCM (Fig. 2.29) depicts the experimental setup's configuration. The authors compared and assessed several metrics based on the experimental results. To determine the disparities in performance between these materials, they performed analysis of variance (ANOVA) and post-hoc t-tests. Based on the experimental results, the authors discovered that the thermal performance of water and PCM filled glazing systems differs from that of conventional glazing systems. The temperature variance at the internal glass surface over a 48-hour period was found to fluctuate substantially for each material. They came to the conclusion that the PCM integrated glazing system outperformed the air – filled glazing system in terms of enhancing the thermal efficiency of building glazing systems.

Additionally, Changyu Liu et al. (2016) conducted a computational evaluation on the energy efficiency of PCM-integrated double-glazed roofs. The study investigated the impact of zenith angle, semi-transparency, and PCM layers' thickness on thermal efficiency. Optical parameters were established to analyze the heat transmission mechanism of PCM-integrated double-glazed roofs. The authors found that PCM integration lengthened the time lag and enhanced the thermal mass of the roof, resulting in improved thermal performance. The zenith angle had a more noticeable impact on solar transmission and temperature time lag than on the indoor thermal

environment. Moreover, as the amount of PCM increased, the temperature time delay also increased, while the thickness of the PCM layer affected the amount of solar radiation transmitted and the overall solar energy conveyed differently.

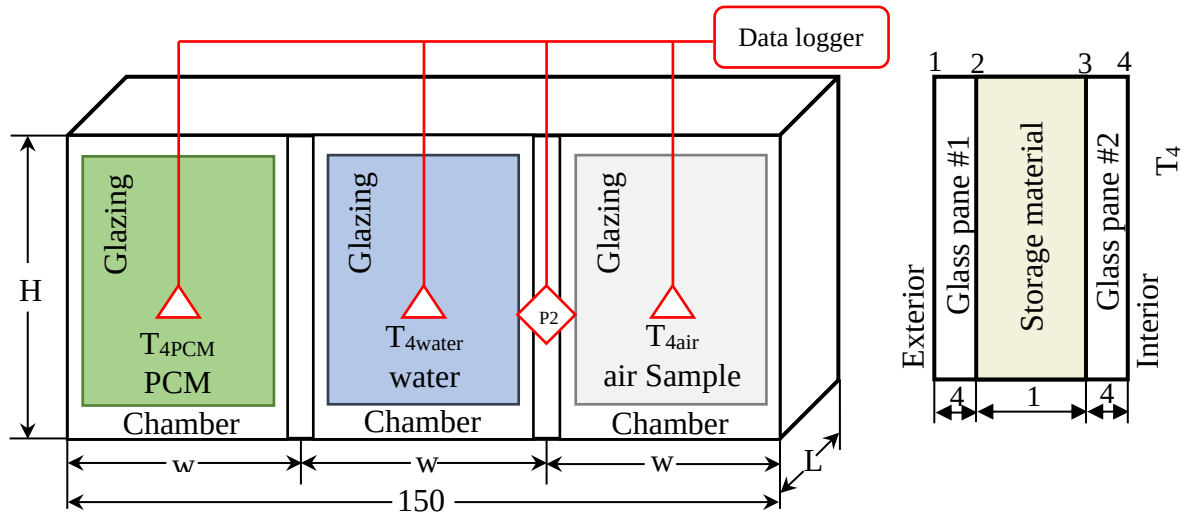


Fig. 2.29 Graphical illustration of the experimental setup and the glazing unit's cross section (Duraković & Mešetović, 2019).

The following equations define the PCMs and glasses optical properties:

The glass and PCM layer's transmittance were assessed by the following equation:

$$T_i = \frac{[(1 - \rho_{i1})(1 - \rho_{i2})\exp(-\alpha_i L_i)]}{[1 - \rho_{i1}\rho_{i2}\exp(-2\alpha_i L_i)]} \quad (2.45)$$

The following equation was used to compute PCM and glass layers absorptance:

$$A_i = \frac{1 - \rho_{i1} - [(1 - \rho_{i1})\rho_{i2}\exp(-2\alpha_i L_i)]}{[1 - \rho_{i1}\rho_{i2}\exp(-2\alpha_i L_i)] - T_i} \quad (2.46)$$

Between PCM and glass layers, the interface reflectance can be defined as:

$$\rho_{ij} = \frac{(n_i - n_j)^2}{(n_i + n_j)^2} \quad (2.47)$$

The authors concluded that the PCM integrated double glazing roof lengthened the time lag, enhanced the thermal mass, and showed substantial thermal performance because of the glazed roofs' semi-transparent characteristics. Zenith angle has a more noticeable impact on solar transmission and temperature time lag than it does on indoor thermal environments. As PCM doubles, the temperature time delay also goes up. However, the amount of solar radiation

transmitted and the overall amount of solar energy conveyed are affected by PCM layer thickness differently.

2.5.2.4 Application of PCM in Roofs/Ceilings

Roofs receive the highest solar radiation and experience the maximum heat energy transmission. (Suehrcke et al., 2008), have shown that solar radiation transmissions can reach up to 1000 W/m², with about 95% of it being collectible. Yet very limited experimental research has been conducted on integrating PCM into building roofs. To maintain comfort conditions and increase energy efficiency, the integration of PCMs in roofs can significantly limit the heat transfer across the building's roof. By incorporating thermal storage in the roof, traditional storage materials like bricks can be replaced, allowing for full utilization of the solar energy absorbed by the PCM integrated into the roof. This approach leads to benefits such as lower energy tariffs, reduced energy consumption, improved indoor air quality, lower maintenance costs, increased efficiency, and reduced carbon emissions.

The design of roofs integrated with solar heaters has become a cornerstone in building space heating strategies. For instance, Saman et al. (2005) proposed a 2D enthalpy model to analyze phase-change TES units in the roof of a house. The storage unit consists of multiple layers of PCM slabs. Warm air from a roof-integrated collector is channeled through voids between the PCM layers to charge the storage unit. The stored heat is then used to heat the ambient air before it enters the living room, providing space heating. Results show the sensible heat effect during both charging and discharging when the initial temperature of the PCMs is either above or below the transition temperature. The enthalpy-based mathematical model provides an example of the following energy conservation equation:

$$\frac{\partial H}{\partial t} + \nabla(uH) = \nabla(k(\nabla T)) \quad (2.48)$$

It is feasible to presume that the thermophysical characteristics of materials undergoing phase transition will not change. In this scenario, the above mentioned equation can be reduced to:

$$\frac{\partial H}{\partial t} = \nabla(k(\nabla T)) \quad (2.49)$$

$$\frac{\partial h}{\partial t} = \nabla \cdot (\alpha \nabla h) - \rho \lambda \frac{\partial f_1}{\partial t} \quad (2.50)$$

$$f_1 = \begin{cases} 1 & \text{if } T > T_m \\ 0 & \text{if } T < T_m \end{cases} \quad (2.51)$$

Where k is thermal conductivity (w/m°C); H is the total volumetric enthalpy (J/m³); latent heat of fusion (J/kg); u = velocity.

Later, (Elawady et al., 2022) investigated the long-term thermal characteristics of a PCM-integrated building roof by validating Enthalpy porosity models through experiments. The study compared the performance of a roof in Egypt's Aswan city with and without a PCM layer under various exterior weather conditions. The roof was integrated with a 40mm thick PCM layer encapsulated in a transparent capsule. The governing equation of the PCM layer can be defined as:

$$(\rho C)_{pcm} \frac{\partial T_{pcm}}{\partial t} = k_{pcm} \left(\frac{\partial^2 T_{pcm}}{\partial x^2} + \frac{\partial^2 T_{pcm}}{\partial y^2} \right) \quad (2.52)$$

The latent heat of melting L , PCM temperature T_{pcm} and the melting temperature range ΔT , are taken into account when determining specific heat capacity of a PCM layer.

$$(\rho C)_{pcm} = \begin{cases} (\rho C)_{solid} & T < T_m \\ \frac{(\rho C)_{solid} + (\rho C)_{liquid}}{2} + \frac{\rho_{solid} + \rho_{liquid}}{2} \left(\frac{L}{\Delta T} \right) & T_m \leq T \leq T_m + \Delta T \\ (\rho C)_{liquid} & T > T_m \end{cases} \quad (2.53)$$

The findings demonstrate that the incorporation of PCM in the roof structure reduces the interior heat flux and achieves an interior wall temperature close to the desired indoor air temperature. Moreover, the performance improves as the thickness of the PCM layer increases. Over a four-month modeling period, the average expected inside wall temperature for the roof without and with PCM was 32.5°C and 29.4°C, respectively. Furthermore, integrating the roof with a 40mm thick RT31-PCM resulted in a 40% reduction in overall energy gain during the summer months.

In the context of building energy conservation, thermal storage is a critical element, and latent heat storage integrated into building envelopes can be beneficial. The isothermal nature and high storage density of PCMs have drawn attention in this regard. Pasupathy & Velraj, (2008b) conducted an analysis of a building roof integrated with a double layer of PCM for thermal management in domestic buildings. They developed and verified a model using experimental data, demonstrating that the integration of a two-fold eutectic PCM in the building roof proved suitable for all seasons.

Another study by Pasupathy et al. (2008) focused on assessing the thermal efficiency of a building roof integrated with PCM using an active system that kept water storage outside the building in Chennai city. The study used a mathematical model to evaluate the effectiveness of the PCM integration. Moreover, Alawadhi & Alqallaf, (2011) investigated a macro-encapsulated PCM integrated building roof using both computational and experimental methods, considering conical

and cylindrical PCM designs. Their findings indicated that the integration of PCM led to a reduction in heat flux of up to 39% at the indoor surface. The study also identified that using N-Eicosane with a conical design significantly decreased heat transfer to the interior space. The optimal designs A32 and a conical design with dimensions of 0.1979 m in diameter and 0.0383 m in height demonstrated superior heat gain performance. Overall, the authors concluded that this roof structure could decrease internal heat flow by 9% to 17.26%. For both outdoor and indoor roof surfaces, the average heat fluxes can be through the following equations:

$$\overline{Q_{os}} = \frac{1}{W^2} \int_0^W \int_0^W [h_0 (T_o - T_{os}) + \alpha q_s] dx dy \quad (2.54)$$

$$\overline{Q_{is}} = \frac{1}{W^2} \int_0^W \int_0^W h_i (T_i - T_{is}) dx dy \quad (2.55)$$

By integrating the total heat flux, the total average heat flux can be computed for a specific period, given by:

$$\overline{\overline{Q_{is}}} = \frac{1}{t} \int_{t_o}^{t+t_o} \overline{Q_{is}} dt \quad (2.56)$$

Yahaya & Ahmad, (2011) conducted a study on the performance of gypsum board integrated with Phase Change Materials (PCMs) as ceiling panels in buildings. They used an explicit numerical approach to predict the interior air temperature of single-space homes and assess the impact of PCM-integrated ceiling panels. The findings demonstrated that the use of PCM-integrated ceiling panels, along with active cooling systems, could significantly reduce energy consumption. In a subsequent study, Alqallaf & Alawadhi, (2013) investigated the thermal effectiveness of a PCM-integrated roof. They observed that the diameter of the cylindrical holes in the PCM had a direct impact on the reduction of heat flux, which was also influenced by the melting point of PCM. The PCM effectively absorbed heat gain before it reached the interior environment. The study suggested a 9% to 17.26% decrease in heat transfer at the interior surface during working hours and operating months, depending on the PCM's melting temperature. Implementing TES helped in smoothing the peak load and reducing energy usage during both heating and freezing periods in HVAC systems. Another research by Navarro et al., (2014) analyzed the integration of macro-encapsulated PCM into hollow prefabricated concrete slabs. They found that the active slab effectively covered energy demand and reduced the consumed energy during both charging and discharging phases. Several models have been developed to simulate the thermal behavior of PCM, and time-dependent behavior of PCMs is being explored. Tokuç et al., (2015) conducted a comprehensive investigation

using numerical and experimental models to analyze the thermal behavior of PCM-integrated flat roofs in Istanbul, Turkey. Several laboratory studies were carried out, and the first field setup with PCM integration was installed on a complex roof in Reunion Island, characterized by a tropical and humid climate. Temperature measurements were taken on both sides of the PCM's melting temperature. Additionally, Guichard et al., (2015) conducted experimental and numerical studies that demonstrated the capability of PCMs to store heat energy during the daytime and release it during the nighttime. The addition of PCM resulted in a 2°C temperature reduction, along with a low R-value, which could be further enhanced by adding a thermal insulating layer.

(Figueiredo et al., 2016) addressed the contribution of PCM in reducing energy demand in buildings by analyzing PCM-integrated thermally active slabs and characterizing the thermal and mechanical properties of concrete. The results showed a reduction in the mechanical properties of concrete after integrating it with micro-encapsulated PCM. Despite the loss in compressive strength and bending (68% and 51%, respectively), PCM-integrated concrete is accepted for concrete applications due to its ability to reduce indoor air temperature and day-to-day temperature swings.

In the context of TES systems, Millers et al., (2019) proposed a model for integrated PCM thermally active concrete slabs, suggesting that a thickness of 25-90mm is optimum for thermally active slabs and 180mm thickness for non-thermally activated slabs. These panels not only provide energy storage but also contribute to human comfort. TES systems utilize sensible and latent heat storage methods, and in the case of hollow-core slabs, the passage of hot/cold heat through the supply ducts acts as sensible thermal storage in buildings. Experimentally validated computational models were developed to analyze PCM-integrated supply air ducts and hollow-core slabs. However, the use of macro-encapsulated PCM in concrete and its insertion into hollows does not appear practical for hollow-core systems in buildings. Regarding hollow-core systems in buildings, (Jamil et al., 2019) investigated the effectiveness of macro-encapsulated PCM in air supply ducts of hollow-core systems. They observed a reduction in diurnal temperatures with PCM integrated air supply ducts, and the magnitude of temperature variation varied with the placement of PCM inside the supply duct. However, the combined effect of PCM-integrated supply air ducts and hollow-core ducts did not align with the individual performances as expected.

Alim et al., (2020) conducted a study to evaluate the effectiveness of monocrystalline solar-cell-integrated mortar roof tiles with protective glass (Ref. [Fig. 2.30](#)). To regulate the temperature of the solar cells, a PCM was directly incorporated into the cement used to manufacture the roof tiles. To address the potential leakage issue, the authors developed form-stable PCM (FSPCM). A life cycle cost assessment study was carried out to assess the economic feasibility of solar roof tiles and to examine the impact of PCMs on the solar-to-electrical power output. The findings revealed that the electrical energy production from solar roof tiles with integrated PCM was approximately 4.1%

higher compared to those without PCM during winter days. However, during six summer days, the gain was within the range of 2.2% to 4.3%. The PCM-integrated solar roof tiles exhibited an affordable payback period, with an effective payback period of 5.7 years, considering the cost of the inverter. Additionally, when taking into account the overall 4.1% gain in energy production, the payback period was predicted to be reduced to 3 months compared to those without PCM. The utilization of PCM led to a preliminary cost increase of 1.2% for the roof tiles.

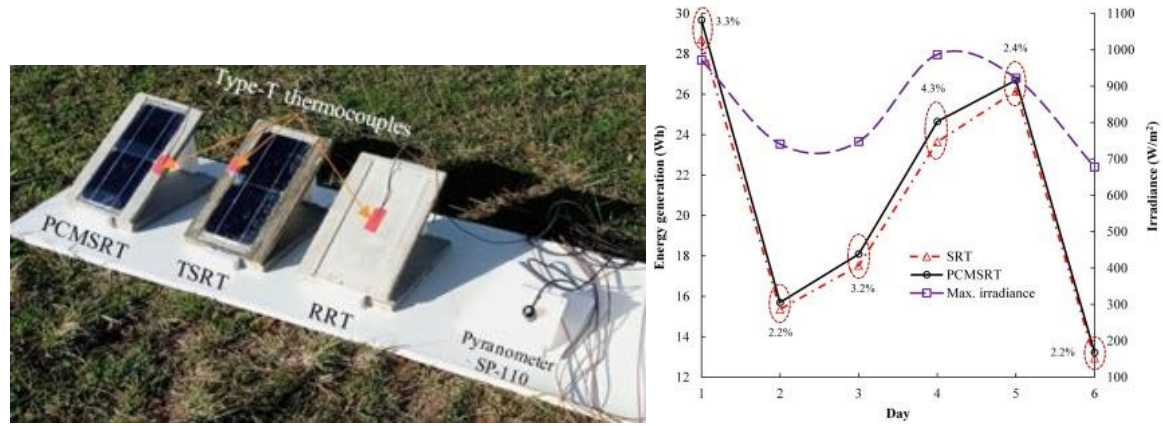


Fig. 2.30 Arrangement of roof tile and their performance during the period.

Triano-Juárez et al. (2020) conducted a numerical analysis of heat transfer in a concrete roof integrated with a PCM layer positioned in between. The study considered three different locations and thicknesses for the PCM layer, as well as two solar absorptance values for the roof (grey and white). The investigation focused on an average summer week in a Mexican metropolis characterized by warm and humid weather conditions. The authors employed an implicit methodology using the Finite Volume Method to solve the unsteady 2D model. The results showed that when a 2 cm thick PCM layer was placed adjacent to the inside surface of the grey roof, it resulted in the most significant temperature reduction of 6.4°C and reduced heat gains by up to 22.2%. However, variations in the highest indoor surface temperatures and heat gains were negligible for different PCM layer thicknesses and locations on the white roof. The unsteady 2D heat diffusion equation for the roof layers can be defined using the following equation:

$$\frac{\partial(\rho_j C_{pj} T)}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_j \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_j \frac{\partial T}{\partial y} \right) \quad (2.57)$$

Where, λ and ρ along with liquid fraction can be calculated as:

$$\begin{aligned} \rho &= f_{liq} \rho_l + (1 - f_{liq}) \rho_{sl} \\ \lambda &= f_{liq} \lambda_l + (1 - f_{liq}) \lambda_{sl} \end{aligned} \quad (2.58)$$

The value of f_{liq} is determined from the following equation if the PCM temperature (T_m) is within the phase transition range.

$$f_{liq} = \left(\frac{T - T_m}{\Delta T} \right) \quad (2.59)$$

The study observed an impact on the melting cycles of the PCM layer as it became thicker and closer to the roof's internal surface. Additionally, incorporating a white reflective coating on the roof significantly decreased the thermal loads and reduced the highest inner surface temperature by 58.1% to 62.7% and 7.4°C to 14°C, respectively.

To balance out energy absorbed or lost in facades, Xiao et al. (2021) devised a unique thermo-optically sensitive solid-solid PCM coating. Through a number of numerical simulations, the study explores the thermal and optical functions of the solid-solid PCM in addition to the interactions between the various layers of the enclosed system. The authors investigated how the optic and heat transfer processes are significantly impacted by the solar incoming angle and phase change temperature on the SS-PCM's absorptivity.

The heat transfer equation for the aforementioned SS-PCM coating [Fig. 2.31](#) is given by:

$$\rho_{pcm} C_p(T) = \frac{\partial}{\partial x} \left(k_{pcm} \frac{\partial T}{\partial x} \right) + \dot{q}_r(x, t) \quad (2.60)$$

$$C_p(T) = \frac{dH}{dT} \quad (2.61)$$

$$H = Q_s \hat{A} T + step \hat{A} Q_l \quad (2.62)$$

$$step = \begin{cases} 0, & T < T_o \\ \frac{T - T_o}{T_t - T_o}, & T_o \leq T \leq T_t \\ 1, & T > T_t \end{cases} \quad (2.63)$$

Where, ρ_{pcm} and k_{pcm} are density (kgm^{-3}) and thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$) of PCM, $C_p(T)$ is the specific heat capacity, $\dot{q}_r$ is the heat source, Q_s and Q_l are solid-solid PCMs specific heat ($\text{Jkg}^{-1}\text{K}^{-1}$) and latent heat (Jkg^{-1}).

The absorptivity for the transparent phase ($A_{pcm,t}$) is estimated using the following equation:

$$A_{pcm,t} = \frac{(1 - \rho_{12})(1 + \rho_{23}\tau)(1 - \tau)}{1 - \rho_{12}\rho_{23}\tau^2} \quad (2.64)$$

where,

$$\begin{aligned}\tau &= e^{-\epsilon_t \cdot d / \cos \theta_2} \\ \epsilon_t &= k_t + s_t \\ \rho_{12} &= \frac{1}{2} \left[\left(\frac{\cos \theta_2 - n \cos \theta_1}{\cos \theta_2 + n \cos \theta_1} \right)^2 + \left(\frac{\cos \theta_1 - n \cos \theta_2}{\cos \theta_1 + n \cos \theta_2} \right)^2 \right]\end{aligned}\quad (2.65)$$

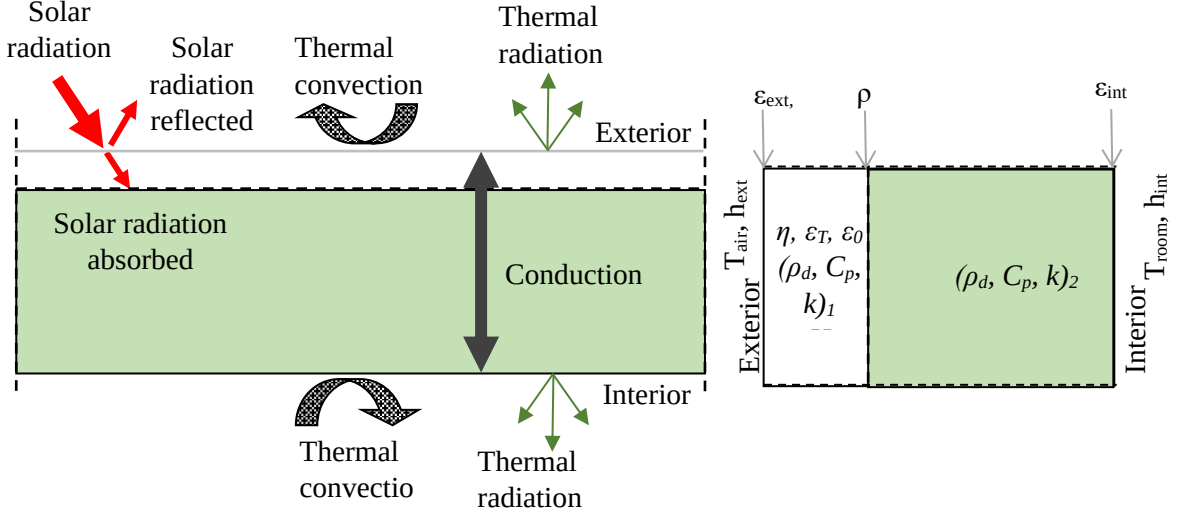


Fig. 2.31 Heat transmission mechanism of SSPCM-based coating system along with 2D wall section.

During the opaque phase the scattering effect is significant as it would interact with the polymeric chains to store and reflect solar light. Therefore, K–M theory is being used to calculate the absorptivity, $A_{pcm.o}$.

$$A_{pcm.o} = \left\{ \frac{(2\beta_{km} + 2\beta_{km}^2)e^{\alpha_{km}d/\cos\theta_2} + (2\beta_{km} - 2\beta_{km}^2)e^{-\alpha_{km}d/\cos\theta_2} - 4\beta_{km}}{\left[(1 + \beta_{km})^2 e^{\alpha_{km}d/\cos\theta_2} - (1 - \beta_{km})^2 e^{-\alpha_{km}d/\cos\theta_2} \right] (1 + \rho_{12})} \right\} \quad (2.66)$$

$$\begin{aligned}\alpha_{km} &= \sqrt{k_o (k_o + 2s_o)} \\ \beta_{km} &= \sqrt{\frac{k_o}{k_o + 2s_o}}\end{aligned}\quad (2.67)$$

where, τ is the SSPCMs transmittance, k_t , s_t , k_o , and s_o represent absorbing and scattering coefficients for transparent and opaque phases respectively. ϵ_t is the SSPCMs extinction coefficient, n is the refractive index. d is the thickness of coating; where the reflectance of the back reflector is denoted by ρ_{23} and the exterior surfaces' reflectance is denoted by ρ_{12} . The incidence angle and reflection angle, respectively, are θ_1 and θ_2 .

Shu Zhang et al., (2022) Investigated and contrasted the new roof with the conventional air-filled multiple-glazing roof both with and without low-e glass. Analysis was done on how two PCM's thickness ratio and melting point affected the roof's thermal performance. Additionally, the complete lifecycle energy-economy of the new roof and the conventional roof were compared. According to the findings, the new glass roof may offer outstanding thermal efficiency in both the summer and the winter, and is economically viable.

2.6 Improvement of Thermal Performance of PCMs

2.6.1 Nanoparticles

Nanoparticles are particles with sizes smaller than 100 nm, and they possess distinctive characteristics due to their exceptionally high surface-to-volume ratio. For example, multi-walled carbon nanotubes (MWCNTs) and graphene nanoparticles (GNPs) exhibit remarkable thermal conductivities of approximately 3000 and 5300 W/m. K, respectively. In contrast, substances like water, kerosene, vegetable and motor oil, ethylene glycol, and liquid paraffin have relatively lower thermal conductivities (Asadi et al., 2019).

2.6.2 Nano-Enhanced Phase Change Materials

The low thermal conductivity of PCMs affects the efficiency of charging and discharging cycles in PCM-based systems. To address this limitation, researchers are focusing on enhancing the thermal conductivity of PCMs. Several strategies have been investigated for heat enhancement, including encapsulating the PCM, using extended surfaces like fins or heat pipes, employing metallic foams, and dispersing highly conductive nanoparticles. In recent times, the incorporation of highly conductive nanoparticles into PCMs, known as Nano-enhanced Phase Change Materials (NePCMs), has gained significant attention due to the thermal characteristics of these nanomaterials.

By dispersing high conductive nanoparticles like *Graphene*, Al_2O_3 , *CNTs*, *GNPs*, *CuO*, TiO_2 , *Cu*, SiO_2 , and others into PCMs, their thermal conductivity can be significantly improved. This approach overcomes the issues of weight increase associated with metallic foams or fins and the increased manufacturing costs due to encapsulation. However, there are some drawbacks, such as agglomeration, sedimentation, and a potential decline in latent heat capacity with the use of nanoparticles. Nonetheless, the inclusion of nanoparticles in PCMs holds promise for enhancing heat transfer performance and represents a valuable direction for research in the field of NePCMs.

In a brief review study on the use of nanoparticles to improve PCMs, Agrawal et al. (2019) revealed their findings. According to the authors "*Nano embedded PCMs are the best and only option to address the key limitations to employ the PCMs in diverse thermal storage applications*".

2.6.3 Preparation and Thermal Characterization

2.6.3.1 Preparation of NePCMs

Two primary methods are used to prepare NEPCMs, namely the one-step approach and the two-step approach (Eanest Jebasingh & Valan Arasu, 2020a; Tariq et al., 2020). In one-step process, nanoparticles are synthesized and dispersed directly into the base PCM in a single step. On the other hand, in the two-step process, the nanomaterial is first created or acquired separately and then incorporated into the base PCM.

Table 2.13 Various preparation techniques used in experimental investigations by various researchers.

S.No.	Preparation technique	Melting point (°C)	PCM	Nanofiller	Reference
01	Stirring and sonication	28.91	Octadecane	xGnP	(Jeon et al., 2012)
		39.3	Paraffin	Exfoliated graphite sheet	(X. Liu & Rao, 2017)
		37.0	1-tetradecanol	Graphene (0.2-2 wt.%)	(L. W. Fan et al., 2014)
02	Kneader mixing technique	28.7	Octadecane	GNPs (0.5-3 wt.%)	(D. Kim et al., 2016)
03	Vacuum impregnation	28.99	CA	EG	(A. Sari et al., 2008)
		-	Erythritol	Carbon fiber sheets	(Dong et al., 2020)
		30.3	LA-MA-SA	Aluminum oxide (Al ₂ O ₃)	(H. Wei & Li, 2017)
04	Sonication and ultrasonication	25.37	RT22	Graphene	(Putra et al., 2017)
05	Autoclave technique	35.87	Tetradecanol	EG	(Yushi Liu et al., 2016)
06	Gravity die casting	30-35	Paraffin	CuO (0.25-1 wt.%)	(Mandal et al., 2020)

While the majority of studies have used the two-step procedure, some have designed and synthesized nanoparticles specifically to improve their dispersion in the base PCM within a temperature range of 20°C to 37°C. The one-step procedure is relatively less common due to its higher cost compared to the two-step approach. Many studies omit specifying the method used for preparing NePCMs. The preparation of NePCMs involves various techniques, as listed in [Table 2.13](#) based on different experimental investigations done by researchers.

2.6.3.2 Thermal Characterization

Additionally, researchers have employed diverse methods to characterize PCM/NePCMs, considering factors such as the shape, size, and loadings of nanoparticles. Commonly used methods for NePCM characterization are summarized in [Table 2.14](#). Among these methods, DSC is

frequently utilized to determine the fundamental thermal and physical characteristics of NePCMs. Moreover, both transient and steady-state techniques can be applied to analyze the thermal conductivity of PCMs.

Table 2.14 Various techniques used to characterize NEPCMs.

S.No	Characterization Methods	Purpose
1.	Scanning Electron Microscope (SEM)	It demonstrates the microscopic structure of prepared NEPCMs.
2.	Differential Scanning Calorimetry (DSC)	It demonstrates the material's thermal characteristics.
3.	Fourier Transform Infrared Spectrometer	It examines the nanoparticles' structures and establishes the chemical group.
4.	X-Ray Diffraction	Analyze the nano-structure and size of crystallites.
5.	Thermal gravimetric analyzer (TGA)	It analyzes NEPCMs weight variations over time following numerous cycles to evaluate their thermostability.
6.	Transmission electron microscopy (TEM)	It enables the observation of the nanoparticles' microscopic morphology and dissemination.
7.	Thermal conductivity analysis	It evaluates the thermal conductivity of NEPCMs.

2.6.4 Effect of nanoparticles on PCMs' thermophysical characteristics

The addition of nanoparticles alters both the thermal and physical characteristics of the base PCMs, with thermal properties being particularly crucial in phase change applications. This section focuses on the impact of nanoparticle incorporation and its effect on the overall characteristics of the materials.

2.6.4.1 Influence of nanoparticles on Thermal Conductivity

When nanoparticles are added to the base PCM, their inherent high thermal conductivity leads to an increase in the overall thermal conductivity of the composite material. Improving the thermal conductivity of base PCMs has been a subject of great interest to researchers due to its significance in various industries, as shown in [Table 2.15](#).

The noticeable increase in thermal conductivity observed in NePCMs can be attributed to several factors, including intermolecular interactions, Brownian motion, nanoparticle purity, high surface-to-volume ratio, interfacial thermal resistance, nanoparticle clustering, phonon movements, and the amount of nanofillers used. Of these factors, nanoparticle clustering is considered the primary reason behind the enhanced thermal conductivity of solid NePCMs. Clusters, consisting of

approximately 50 atoms, tend to form and can affect the material's stability and settling behavior. However, low loadings of nanofillers can still lead to stable structures. The continuous network structure formed by aggregated phonon mobility significantly contributes to the increased thermal conductivity in solid-state materials. It's noteworthy that high aspect ratio nanoparticles like MWCNTs and GNPs do not significantly contribute to the conductivity increase in the composites.

Table 2.15 Influence of nanoparticles on thermal conductivity.

Reference	NEPCMs		Findings
	Nanoparticle	PCM	
(C. Li et al., 2019)	EG (2, 6, 10 wt.%)	Stearic acid	The value of thermal conductivity got rose up by 9.6 times compared to base PCM
(Praveen et al., 2019)	GNPs (thickness = 5-20 nm)	Paraffin	3 % GNPs enhanced thermal conductivity by 97.4%.
(K. Sun et al., 2021)	PW-GAF	Paraffin wax	5.22 % enhancement in thermal conductivity.
(P. Li et al., 2020)	Graphene oxide sponge	Paraffin	12 % improvement in thermal conductivity due to the creation of interconnected network.
(C. Wang et al., 2022)	GO-co-Bdye	PEG	A 10.10 % improvement in thermal conductivity has been recorded
(X. Li et al., 2021)	CNT	Paraffin wax	The outcomes showed 2.9 times enhancement in thermal conductivity at 70 wt.%.
(C. Zhu et al., 2021)	CF (0, 1, 3, 5 wt.%)	Stearic acid	@5 wt.%, 2.22 times enhancement in thermal conductivity was seen.
(Rakkappan et al., 2021)	1-Decanol	EG (15 wt.%)	@15 wt.%, 16.33 times enhancement was seen.

2.6.4.2 Influence of nanoparticles on Latent Heat

The addition of nanoparticles to PCMs has been a topic of discussion among experts, with some suggesting that nanoparticle inclusion enhances the latent heat (positive effect). Conversely, some experts argue that nanoparticle incorporation reduces the volume of the PCM and, consequently, its latent heat (negative effect). Several studies indicate that the impact of nanoparticles on the latent heat is dependent on the nanoparticle loadings. Low loadings of nanoparticles tend to have a positive effect on the latent heat, while high loadings have a negative effect. [Table 2.16](#) provides a summary of the influence of nano inclusion on the latent heat.

2.6.4.3 Influence of nanoparticles on phase transition temperature

The influence of introducing nanoparticles on the phase transition temperature has not been thoroughly studied. Prior studies conducted by the researchers have nearly shown that the influence

of nanofillers is negligible. The results of earlier research on the impact of nanofillers are compiled in Table 2.17.

2.6.5 Applications of NePCMs in Buildings

Khodadadi & Hosseinizadeh, (2007) conducted a comprehensive investigation to explore the potential of PCMs as energy storage solutions, focusing on enhancing thermal conductivity and achieving high heat release rates through Nano-fluid dispersion. The research primarily revolved around the characterization and preparation of NePCMs. In this context, a 1D Stefan model was proposed by (L. Fan & Khodadadi, 2012) to test the unidirectional freezing behavior of NePCMs, specifically studying ice formation involving dynamic interfaces. The investigation led to significant benchmarks regarding the impact of Nanoparticles on thermal conductivity.

Table 2.16 Influence of nanoparticles on latent heat.

Reference	NEPCM		Findings
	PCM	Nanoparticle	
(Saeed et al., 2018)	Methyl palmitate and Lauric acid	Graphene platelets (10 wt.%)	The nanoparticle inclusion lowers the latent heat by 7.42%.
(Elbahjaoui & El Qarnia, 2017)	n-octadecane	Cu (2 – 8% vol.)	The result showed enhancement in latent heat by copper nanoparticles inclusion.
(Singh et al., 2019)	Eutectic salt	Cu, Ag, Al, Ni, Al ₂ O ₃ , TiO ₂ , GNPs, CuO	Among all the nanoparticles, graphene showed minimum reduction in latent heat.
(T. Wu et al., 2020)	MgCl ₂ -H ₂ O	MWCNTs (0.5, 1, 1.5, 2, 2.5, 3 wt.%)	At 3 wt.% loading of MWCNTs, latent heat showed highest (9.6%) decrease in latent heat
(Y. Chen et al., 2021)	SA	GNP (1, 3, 5 wt.%)	The GNPs at 5 wt.% showed maximum reduction in latent heat, 19.725 % and 22.36 % during melting and solidification.
(X. Wei et al., 2021)	PEG	GNP (0.5, 1, 2, 4 wt.%)	The composite showed 13.65 % reduction in latent heat at 4 wt.%.

It was observed that an increase in nanoparticles resulted in a linear enhancement of thermal conductivity in the liquid phase, which was in contrast to the solid phase, where a non-monotonic enhancement pattern was observed. Furthermore, the freezing process exhibited an expedited behavior by introducing more nanoparticles into the PCM solution. (Mishra et al., 2018) reported

an increase in thermal conductivity due to nano-inclusions, leading to the creation of Nano-crystalline needle-like microstructures in PCM during freezing. This study emphasized that Nano-inclusions significantly aided in intensifying thermal conductivity in PCMs, especially when used for indoor temperature applications.

In a study conducted by Yuan Liu et al. (2019), the inclusion of nano particles demonstrated a notable improvement in the thermal conductivity of PCMs, indicating good thermal stability of the new nanoparticle. Although graphite has been considered an inclusion in paraffin, its application is limited to PCMs with low melting temperatures (<150°C). Expanding natural graphite into the matrix has been identified as the sole effective method among various thermal transfer enhancement techniques to intensify thermal conductivity. (Pincemin et al., 2008) proposed a composite containing salts and graphite flakes within a temperature range of 200°C – 300°C, analyzing different characteristics such as thermal conductivity, thermal stability, and thermal capacity. The study revealed that the inclusion of graphite caused a slight reduction in latent heat and thermal conductivity at higher temperatures, emphasizing that the graphite content should be carefully adjusted to achieve the desired intensification. Furthermore, (Z. Ma & Lin, 2016) investigated the energy efficiency and thermal management of dispersed nano particles in the PCM base. They suggested that the inclusion of Nano particles led to high charging and discharging rates of NePCMs compared to pure PCMs, owing to the enhanced thermal conductivity provided by the nano particles. Modified Maxwell equation expresses thermal conductivity of NePCM given by:

$$k_{NEPCM} = \frac{k_{ep} + 2k_{PCM} + 2(k_{ep} - k_{PCM})(1 + \beta)^3 \phi}{k_{ep} + 2k_{PCM} - 2(k_{ep} - k_{PCM})(1 + \beta)^3 \phi} k_{PCM} \quad (2.67)$$

Whereas the equivalent thermal conductivity (k_{ep}) is expressed as:

$$k_{ep} = \frac{2(1 - \gamma) + (1 + \beta)^3(1 + 2\gamma)\gamma}{-(1 - \gamma) + (1 + \beta)^3(1 + 2\gamma)} k_{np} \quad (2.68)$$

The following equations give the density, specific heat, & latent heat of NePCM:

$$\rho_{NEPCM} = (1 - \phi)\rho_{PCM} + \phi\rho_{np} \quad (2.69)$$

$$(\rho C_p)_{NEPCM} = (1 - \phi)(\rho C_p)_{PCM} + \phi(\rho C_p)_{np} \quad (2.70)$$

$$(\rho L)_{NEPCM} = (1 - \phi)(\rho L)_{PCM} \quad (2.71)$$

In the context of buildings, the combination of PV and CPV technologies is utilized to create Building Integrated Photovoltaic (BIPV) and Building Integrated Concentrated Photovoltaic (BICPV) systems, which replace conventional building materials with solar technologies. In BICPV

systems, two methods are employed for thermal management. The first approach involves the adoption of nano particles to improve the poor thermal conductivity of PCMs used in building applications. The second method utilizes fins to enhance the thermal conductivity of PCMs.

A study conducted by S. Sharma et al. (2017) investigated the quantification of PCMs and the behavior of BICPV systems with combined passive mechanisms using Aluminum plate micro fins. Six configurations were tested, comparing micro-finned surfaces to unfinned surfaces, which resulted in reduced temperatures with the micro finned surface. Additionally, NePCM showed greater effectiveness compared to conventional PCM. Heat transfer enhancement was observed in all configurations. However, it was noted that n-PCM tended to agglomerate after charging and discharging cycles, yet still exhibited an improvement in effective thermal conductivity calculated using the Maxwell Garnett equation:

$$k_{n-PCM} = \frac{[k_n + 2k_p + 2(k_n - k_p)\phi] \cdot k_p}{k_n + 2k_p - (k_n - k_p)\phi} \quad (2.72)$$

Where k_{n-PCM} , k_n , and k_p are the thermal conductivities of NePCM, dispersed Nano-material, and dispersion medium while, ϕ is the particle volumetric concentration.

Table 2.17 Influence of nanoparticles on phase transition temperature.

References	NEPCM		Findings
	PCM	Nanoparticles	
(S. C. Lin & Al-Kayiem, 2016)	Paraffin wax	Cu	The results showed 2.61 °C decrease during melting and 1.29 °C increase during solidification.
(N. H. Mohamed et al., 2017b)	Petroleum waxes	A-Al ₂ O ₃	Phase transition temperature got reduced by 2.2 °C.
(Saeed et al., 2018)	Eutectic PCM	Graphene nanoplatelets (GNPs)	Melting temperature got reduced by 1.31 °C
(X. Li et al., 2021)	Paraffin wax	CNT	The results showed 6.6 °C increase during melting and 0.08 °C decrease during solidification.
(Habib et al., 2021)	Paraffin wax	SWCNTs (0.1, 0.5, 1, 3, 5 wt.%)	Melting: Decreased by 2.12 °C. Solidification: Decreased by 4.4 °C.
(Chi et al., 2021)	Tetradecanol	EG and graphene Oxide	Melting: decreased by 1°C. Freezing: increased by 1.8 °C.

In a study by Colla et al., (2017), NePCMs containing Carbon Black (CB) and Aluminum Oxide (Al₂O₃) nanoparticles were introduced to enhance PCM properties. The addition of Carbon Black

increased thermal conductivity, while Al_2O_3 had the opposite effect on thermal conductivity but positively affected the latent heat. However, Al_2O_3 inclusion showed thermal instability, while CB remained highly stable. Another study examined Coconut Oil as a PCM with CuO nanoparticles incorporated into an isoflux wall, while other walls were kept adiabatic. The researchers Al-jethelah et al., (2018) employed scale analysis and heat line techniques to evaluate different temperature regimes of nano PCMs. Top-side interface deformation indicated a mixed conduction-convection regime, while deformation across the entire interface represented a convection regime. The scale analysis and numerical technique aligned well with experimental results, validating the behavior of PCM. The use of nano-fluid suspensions as NePCMs has been explored, altering heat transfer characteristics and transport properties. MWCNT emerged as a favorable option due to its high thermal conductivity and lightweight. A study by Shafee et al. (2019) investigated a combination of MWCNT and liquid paraffin as NEPCM and found enhanced heat transfer and reduced solidification time by including nanoparticles.

NePCMs play a vital role in energy efficiency in buildings as 50% of building energy consumption is attributed to HVAC systems. TES systems doped with nanoparticles have shown increased thermal conductivity and nucleation process, enhancing energy efficiency. Fatty acids doped with silicon dioxide (nSiO_2) nanoparticles were examined by Martín et al., (2019) to study NePCM characteristics, indicating enhanced thermal conductivity with nSiO_2 addition. A linear relationship between viscosity and nanoparticles was observed, and the fatty acids demonstrated long-term performance.

The impact of pore diameter on the thermal conductivity of form-stable PCMs was investigated by Z. X. Li et al. (2019) through an experimental study of NePCM. Adding nSiO_2 led to a decrease in PCMs' phase change temperature. It was noted that decreasing Nano-pore size resulted in a relative decrement in the thermal conductivity of FSPCMs and reduced indoor peak temperature. The inclusion of Carbon Black nanoparticles (CBNP) in lauric acid led to an increment in thermal conductivity, as reported by (Mishra et al., 2020). This enhancement was attributed to the interconnected percolation network formed during PCM discharge. Additionally, the photothermal efficiency improved due to multiple scattering of incident radiance from the clusters of CBNP within the matrix, making PCMs attractive for TES systems.

While form-stable PCMs have been widely studied, the exploration of shape-stabilized PCMs presents new materials to be explored. SSPCM maintain their shape during the phase change process and possess a large specific heat. However, the prediction of thermal conductivities in PCM-Carbon nano-additive composites lacks a theoretical model. Several composite models, such as Kingery, Maxwell-Eucken, Maxwell-Garnet, Bruggeman, etc., have been reported to predict effective thermal conductivity, assuming the matrix as the continuous phase with Nano fillers of a

certain shape. Qu et al. (2020) investigated SSPCM for building study through experimentation based on the T-history method. Thermal conductivity enhancement of a composite was reported because of the synergistic effect and small thermal resistance of composites. The thermal conductivity of a solid PCM composite can be evaluated as:

$$k = \frac{\rho H_m R^2}{4t_f (T_m - T_\infty)} \quad (2.73)$$

where, T_m , T_∞ , ρ , H_m are melting temperature, ambient temperature, density of composite and latent heat of PCM. NePCM showed enhanced thermal conductivity with EG possessing beneficial structure and thermal stability by mixing n-Eicosane with nano-SiO₂ and EG. Nano-SiO₂ possesses high adsorption capacity and porous nature, while n-Eicosane contains non-toxic characteristics. The objective of adding EG was to improve thermal conductivity. Almousa et al., (2021) conducted an investigation on the properties of paraffin wax (PW) doped with nano-additives, specifically MWCNTs, resulting in the development of a nanocomposite PCM. The paraffin/MWCNT composite PCMs were specifically designed to cater to enhanced and efficient TES applications. Notably, the TES bed system exhibited a significant thermal storage efficiency of approximately 71%. The results indicated the successful physical incorporation of MWCNTs into the PW matrix, forming strong interfaces without micro cracks. Additionally, the experimental outcomes from FTIR and TGA demonstrated favorable chemical compatibility and thermal stability of the composite PCM. This was established based on the observed similar thermal mass loss profiles and identical chemical bond peaks among all tested samples, including PW, CNT, and PW/CNT composites.

In a study conducted by Amidu et al., (2023), a numerical model was developed and implemented to analyze the behavior of nanoparticles - NePCM. The model involved coupling an advanced two-phase model for NePCM with the enthalpy-porosity formulation to capture the transient behavior during the phase change process. The numerical simulations revealed significant heat transfer enhancement during both the charging and discharging cycles when assuming a homogeneous distribution of nanoparticles as the initial condition. Moreover, the results demonstrated that the predictions obtained using the two-phase model were superior to those obtained with the classical single-phase model. However, for NePCM with a high concentration of nanoparticles (> 1%), the melting performance during the second charging cycle was reduced by 50% compared to the first cycle. This decline in performance was attributed to a non-homogeneous distribution of nanoparticles at the beginning of the second charging cycle, primarily caused by sedimentation effects leading to the migration of nanoparticles.

2.7 Concluding remarks

A vast literature exists regarding PCMs intended for various applications. However, only a fraction of this literature adequately meets the requirements for practical implementation. Many PCMs have been developed and exhibit promise for use in efficient TES systems. Nonetheless, numerous challenges and issues persist in their respective technological applications that require attention. Some of these challenges are outlined below:

1. Making a choice is still a challenge for building constructors. A suitable PCM is able to regulate the comfort temperature limits within the building envelope.
2. Material degradation and long-term stability of PCM have not been given due consideration yet. This warrants further investigation.
3. Despite macro-encapsulation being the most common way of encapsulating PCMs, RCC compatible encapsulation techniques are not sufficiently explored.
4. Very few studies include incorporating PCMs into RCC roof slabs. This merits further investigation as roofing systems can have significant influence on the indoor environment.
5. Developing NePCMs with superior thermal properties can improve thermal energy storage capacity of integrated building components.

This study focuses on developing PCM/NePCM integrated biaxial voided RCC roof slab employing the macroencapsulation technique. The latent heat storage characteristics of the slab are investigated under an ambient environment and compared with a normal RCC roof slab. The novelty of the study comprises: identifying and characterizing suitable PCM/NePCMs; transforming containers into PCM/NePCM macroencapsulations; and conducting a thorough assessment of roof slab latent heat storage potential under an ambient environment. Such a biaxial voided RCC roof slab that is macroencapsulated with PCM/NePCMs and aimed to assist in the passive cooling of buildings has never been explored before. Few studies have explored the thermal performance of PCM integrated roofs in the Indian context, such (Baskar & Chellapandian, 2022; Rathore et al., 2020; Shanmuganathan et al., 2021). However, the current study is unique in the following aspects: PCM leakage has been completely prevented using a metal void former; PCM macroencapsulations are embedded in two directions within the concrete matrix; and a new PCM encapsulation typology has been introduced. PCM and two nanomaterials, MWCNT and GNP, are chosen based on the study area's historical weather data and the materials' thermodynamic properties. Further, the thermal properties of OM35 are examined individually, as well as in combination with 2% and 4% mass fractions of MWCNT and GNP. Four specimens are cast: conventional roof slab (CRS) without PCM and three biaxial voided RCC roof slab specimens, namely BVS with PCM, 2% and 4% GNP–NePCMs. The latent heat storage behaviour of the specimens is analyzed by examining variations in temperature, heat flux, thermal load, temperature decrement factor, and temperature time lag. In

addition, financial feasibility indicators, including electricity cost savings, simple and discounted payback periods, and CO₂ emission savings, are evaluated.

3.1 Introduction

It is crucial to adopt a systematic approach to ensure the selection of the most appropriate material, as an improper choice could lead to reduced product performance and efficiency. Several techniques have been proposed to tackle this challenge, with multi-criteria decision-making (MCDM) being a standard method for handling conflicting and analogous alternatives. MCDM evaluates alternatives based on a set of decision criteria, making it suitable for solving complex real-life problems. MCDM can be categorized into multi-attribute decision-making (MADM) and multi-objective decision-making (MODM), depending on the nature of the decision spaces. MADM deals with discrete decision spaces, while MODM deals with continuous ones. The literature proposes numerous MADM methods, further classified based on the type of data decision-makers use and the number of decision-makers involved. In this chapter, various decision-making methods are employed to facilitate material selection, including the Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and VlseKriterijumska Optimizacija Kompromisno Resenje (VIKOR). Table 3.1 summarizes the information on these methods.

Table 3.1 Summary of MCDM techniques with merits and demerits.

MCDM Technique	Working principle	Inventor	Merits	Demerits
AHP	The importance of criteria, alternatives, and hierarchical structure is the driving principle of AHP.	Thomas Saaty (1970)	No additional technique is required to determine the weight of the criteria.	The method turns out to be more intricate with the increase in criteria and alternatives.
TOPSIS	The optimum alternative is chosen based on the distance between positive and negative ideal solutions.	Hwang and Yoon (1981)	Simplicity and unchangeable behavior concerning criteria and alternatives	Correlation isn't considered between the criteria. Multi-dimensional problems may require vector normalization.
VIKOR	The optimum alternative is determined by measuring the closeness of alternatives to an ideal alternative.	S. Opricovic (1990)	This method is an updated version of TOPSIS	Facing contradictory scenarios, the method turns out to be challenging.

3.1.1 Background

A suitable PCM is pivotal in building design to address energy optimization needs. In this context, multi-criteria decision methods have been applied to rank PCMs in building roofs and wallboards (Beltrán & Martínez-Gómez, 2019). It is essential to consider environmental variables, as they can substantially impact PCM performance. The discrepancy between MCDM and Building Energy Simulations (BES) must be considered. To select appropriate PCMs for building envelopes, considering climatic factors, Mukhamet et al. (2021) integrated building energy simulation MCDM tools, such as AHP-TOPSIS and Fuzzy AHP-modified Fuzzy TOPSIS methods. Fuzzy MCDM methods are instrumental when decision-makers encounter uncertain or vague data. Fuzzy multi-criteria methods are described by membership functions comprising fuzzy numbers. These membership functions can represent discrete or continuous elements in fuzzy sets.

Furthermore, multi-criteria tools were employed in LTES systems, such as shells and tubes, to rank PCMs while considering fluctuating heat sources (X. Yu et al., 2021). (Loganathan & Mani, 2018) employed an innovative MCDM methodology by integrating Fuzzy AHP with VIKOR, TOPSIS, and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) techniques to facilitate the selection of PCMs for thermal management within electronic cooling systems. In building HVAC applications, (Rastogi et al., 2015) utilized the TOPSIS method to prioritize the optimal PCM candidates for performance evaluation. The Figure of Merits (FOM) derived from the Ashby approach was employed to assess the performance attributes of the PCMs quantitatively, and the PCM Express was leveraged to validate the resultant rankings. Using multi-criteria methodologies for material selection can foster sustainable development within building construction (Balali & Valipour, 2020). (H. Xu et al., 2017) unveiled that a multi-criteria approach demonstrated competence and applicability in selecting suitable materials for LHTES applications, particularly within the domain of solar air conditioning systems. By employing the AHP, it is possible to enhance system efficiency while mitigating the potential hazards associated with PCM selection.

Moreover, MCDM techniques such as TOPSIS and Fuzzy TOPSIS have been demonstrated as viable methodologies for effectively ranking the most suitable PCMs for utilization within solar water systems (Rathod & Kanzaria, 2011). Concurrently, (Venkataramaiah et al., 2012) applied AHP to determine the optimal polymer for producing solar plate collectors. In a distinct context, the rational application of AHP has been instrumental in material selection aimed at restoring chloride-deteriorated concrete (Do & Kim, 2012). Contrarily, (Uğur & Baykan, 2017) exercised AHP to select wall materials within a hotel building. Drawing from entropy weight and TOPSIS methodologies, (Oluah et al., 2020) conducted a ranking exercise for PCM integration into the Trombe wall, enhancing overall building performance.

Within the realm of construction projects, the evaluation of risks, a pivotal facet for the construction management team, can be effectively undertaken through the application of the MCDM framework (L. Wang et al., 2018). Within the realm of public buildings, the inherent complexity of green renovation initiatives can be effectively navigated through the strategic integration of multi-criteria tools (Yang Liu et al., 2021). Through the strategic integration of the TOPSIS methodology coupled with the Entropy method, (S.-S. Lin et al., 2021) presented a structured framework for assessing environmental impact and optimizing the siting of concrete mixing stations. The TOPSIS methodology is adept at evaluating a building's energy performance, leveraging available clusters of variables (E. Wang et al., 2017). The robustness of benchmarking makes it a precious instrument for comprehensive energy assessments of buildings.

The impetus behind this study is rooted in the existing research void concerning the selection of PCMs meticulously tailored for the specific demands of the given climatic conditions. Optimal PCM selection holds the potential to significantly enhance energy efficiency within buildings and concurrently reduce operational costs. The selection of appropriate PCMs is inherently contingent upon the specific intended application and functional objectives.

3.1.2 Materials and Selection Criteria

The principal objective of this study is to attain optimal indoor room temperatures conducive to human comfort by strategically choosing an appropriate PCM that aligns seamlessly with the temperature range of 30 – 40°C, specifically suited to an Indian city, Rupnagar. This study undertakes a comprehensive assessment of diverse PCMs, emphasizing two pivotal parameters: latent heat and density. The latent heat parameter contributes to the thermal stability of the PCM, while density profoundly influences its energy storage capacity. Despite the extensive assortment of documented PCMs, [Table 3.2](#) presents materials meticulously suited for regulating indoor room temperature within the unique confines of the Indian climatic conditions. Drawing from the existing literature, a set of 17 PCMs was thoughtfully chosen for meticulous scrutiny within this study. These PCMs were meticulously identified as apt for regulating indoor room temperature in Indian climates based on five distinct criteria: Latent Heat (ΔH), kJ/kg, Specific Heat (C_p), kJ/kg. K, Thermal Conductivity (K), W/m. K, Melting Point (T_m), °C, and Density (ρ), Kg/m³. Notably, these criteria significantly influence the overall energy performance of buildings.

The weights associated with each evaluation criterion were judiciously determined using the AHP methodology. Subsequently, the conclusive rankings and selection of the most appropriate PCM were accomplished by leveraging multi-criteria decision-making methodologies, specifically the TOPSIS and VIKOR methods. To our knowledge, no analogous study has been conducted previously in this domain. The hierarchical structure governing PCM selection is shown in [Fig. 3.1](#).

Table 3.2 Studied phase change materials with their thermo-physical properties.

PCM	Latent Heat, kJ/kg (ΔH)	Specific Heat, kJ/kg. K (C_p)	Thermal Conductivity, W/m. K (K)	Melting Point, °C (T_m)	Density, Kg/m ³ (ρ)
1-Decanol	200	2.55	1.07	9.03	830
Polyethylene glycol (PEG)	74	2.117	0.297	29.39	1117
Caprylic acid	140	1.95	1	15.64	910
OM35	160	2.71	0.2	35	870
Paraffin wax	153.3	2.4	0.4	64.5	920
Eicosane	247	2.46	0.15	38	815
CaCl ₂ .6H ₂ O	187.8	1.37	0.53	30	1910
Paraffin wax	230	2.4	0.123	32	906
OM37	218	0.16	0.16	40	960
Capric Acid	162.8	2.09	0.153	40	1004
RT50	240	1.5	0.15	50	750
OM 37	231	0.13	0.145	39.1	960
Paraffin wax	214	2.34	0.4	60	856
n-Eicosane	237.4	2.2	0.39	36.5	910
OM47	196	2.7	0.2	48	917
Erythritol	331	2.17	0.733	120	1480
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	64.75	2.23	0.38	20.02	1050
RT42	165	2	0.2	42	880
Paraffin wax	180	2.52	0.241	60	893
Paraffin	169	2.1	0.2	61.85	880
Eutectic	100	2.18	0.21	-3.15	766
Inorganic Salt Hydrate	188	1.44	1.64	27.85	109
Inorganic HS24	199	1.05	1.05	24	1621
OM32	157	3	0.026	32	928
RT27	184	2	0.2	27	880
OM50	223	3.33	0.21	49.85	961

3.2 Methodology

3.2.1 Analytical Hierarchy Process – AHP

The AHP was initially conceived by Thomas Saaty in 1960 during his involvement in a research project affiliated with the Arms Control and Disarmament Agency in the United States. AHP is grounded in a well-defined mathematical framework that employs consistent matrices, which subsequently facilitates the derivation of approximate weights by utilizing Eigenvectors. The

fundamental essence of AHP is delineating and narrowing down the problem domain. In pursuit of this, a foundational scale, validated through decision-making and empirical experiments, is harnessed to capture individual preferences about qualitative and quantitative criteria.

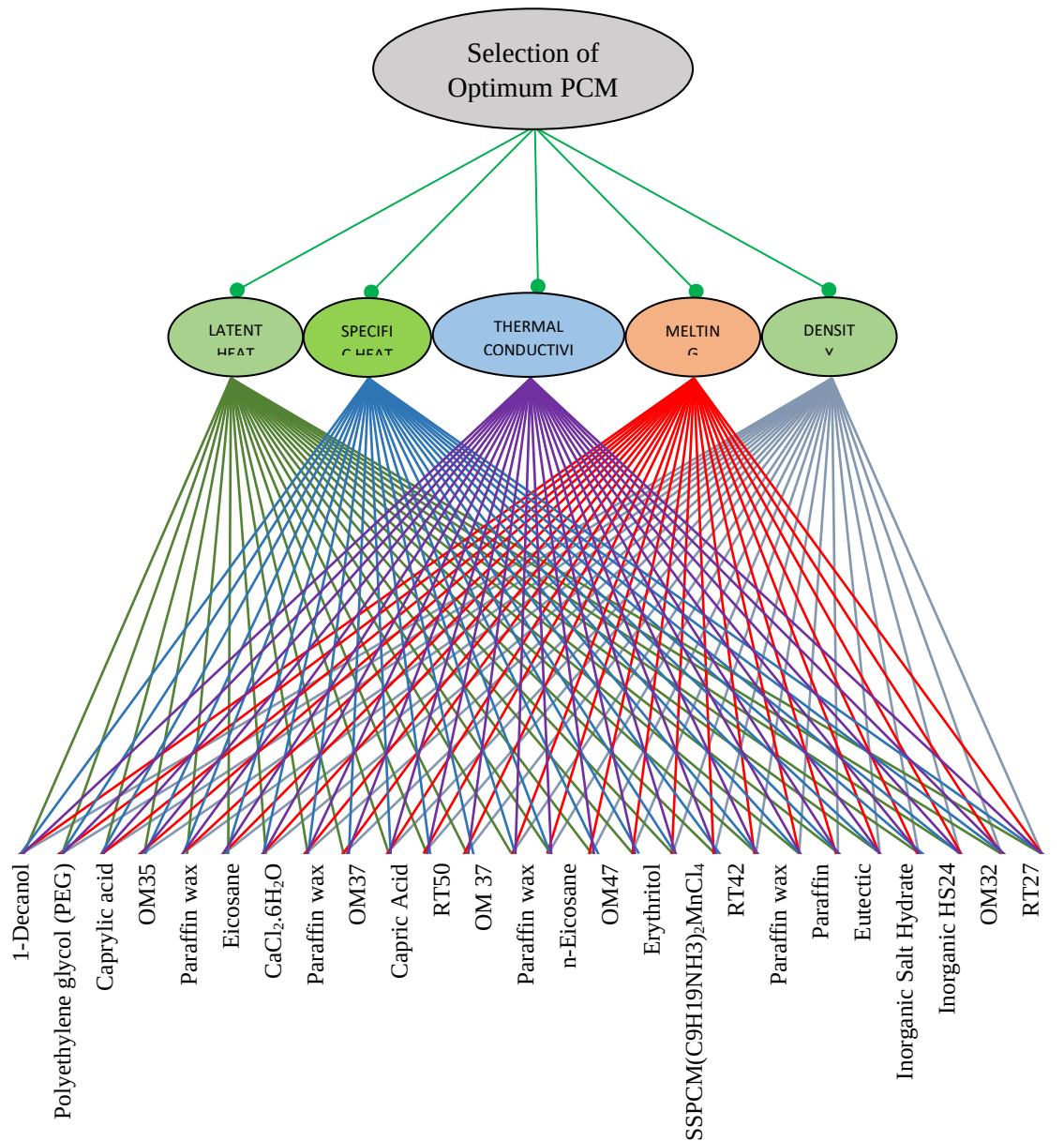


Fig. 3.1 The decision criteria for PCM selection.

The AHP methodology has emerged as one of the most extensively utilized prescriptive and descriptive tools in decision-making processes. The AHP can be conceptually elucidated through three primary functions: (a) the organization of complexity, (b) measurement utilizing a ratio scale, and (c) synthesis. Its endorsement as a standard approach by the American Society of Testing and Materials (ASTM) for multi-criteria decision-making concerning investments in the construction sector underscores its wide-reaching acceptance. The AHP technique adeptly amalgamates tangible

and intangible elements to assign weights to criteria, thereby enabling the prioritization of alternatives. The operational steps inherent to the AHP approach are delineated as follows:

1. The supreme goal, criterion, and alternatives are arranged in a hierarchal or network structure. The primary goal is at the top level, and the criterion is placed at the lower level, followed by the alternatives at the lowest level.
2. A pair-wise decision matrix is being created by an expert with the alternatives below criteria using a scale from 1 to 9. The evaluations are based on this scale, which comprises the comparison matrix, X .

$$X = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & \dots & a_{1n} \\ a_{21} & \dots & \dots & \dots & a_{25} & a_{2n} \\ a_{31} & \dots & a_{ij} & \dots & \dots & \dots \\ \dots & \dots & \dots & a_{ij} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & a_{n3} & \dots & \dots & a_{nn} \end{bmatrix}, a_{11} = 1, a_{ij} \neq 0, \text{ and } a_{ji} = 1 / a_{ij} \quad (3.1)$$

The comparison among criteria is made by the scale suggested by Saaty, in 1987, as given below in [Table 3.3](#).

Table 3.3 Hierarchy used by Saaty to convert linguistic terms into intensity.

Definition	Intensity of importance
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate values	2,4,6,8

3. After creating the comparison matrix, the normalized matrix is developed, and the geometric mean of each row is calculated.
4. The given equations normalize the geometric mean to obtain relative weights of each criterion.

$$GM_i = (a_{i1} * a_{i2} * a_{i3} * \dots * a_{in})^{1/n} \quad (3.2)$$

$$W_i = \frac{GM_i}{\sum_{j=1}^n GM_j} \quad (3.3)$$

5. The n -dimensional column vector is developed, representing each alternative's weighted sum while addressing each criterion.

$$A = X * W = \begin{pmatrix} 1 & a_{12} & a_{13} & \dots & \dots & a_{1n} \\ a_{21} & 1 & a_{23} & \dots & \dots & a_{2n} \\ \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & 1 & \dots \\ a_{n1} & a_{n2} & a_{n3} & \dots & \dots & 1 \end{pmatrix} * \begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ \dots \\ w_n \end{pmatrix} = \begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ \dots \\ \dots \\ C_n \end{pmatrix} \quad (3.4)$$

6. Calculate consistency value (CV):

$$CV_i = C_i / W_i \quad (3.5)$$

7. Calculate maximum Eigen value $\lambda_{\max}$.
8. Calculate the consistency index:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (3.6)$$

9. Calculate consistency ratio (CR):

$$CR = CI / RI \quad (3.7)$$

The RI values for different n given by Saaty are given below in [Table 3.4](#):

Table 3.4 Random index values.

N	3	4	5	6	7	8	9	10
Randomness Index (RI)	0.524	0.881	1.108	1.247	1.341	1.405	1.449	1.485

If the $CR \leq 0$, the decision matrix is considered consistent; otherwise, it is said to be inconsistent.

3.2.2 Technique for Order of Preference by Similarity to Ideal Solution, TOPSIS

The TOPSIS was initially proposed in 1981 by Ching-Lui Hwang and Yoon, but it was further refined by Lai, Lui, and Hwang in 1993. The foundational tenet is grounded in the principle that the selected alternative should exhibit the shortest Euclidean distance from the Positive Ideal Solution (PIS) while simultaneously having the farthest distance from the Negative Ideal Solution (NIS). In essence, the PIS accentuates advantageous criteria while attenuating non-advantageous

criteria, whereas the NIS accentuates non-advantageous criteria and reduces advantageous criteria. The fundamental underpinning of TOPSIS is as a compensatory aggregation technique, wherein alternatives are equated through an assumption of a monotonically increasing and decreasing behavior of attributes. This feature contrasts with non-compensatory methods, where a trade-off between criteria is absent. TOPSIS methodology finds applicability when the criteria values are numerically quantifiable and possess comparable units.

The stepwise methodology of TOPSIS implemented by Hwang and Yoon is mentioned as follows:

1. The initial step involved is forming a Decision matrix with attributes as columns and alternatives as corresponding rows.

$$\begin{array}{cccccc}
 & C_1 & C_2 & C_3 & \dots & \dots & C_n \\
 & w_1 & w_2 & w_3 & \dots & \dots & w_n \\
 A_1 & \left(\begin{array}{cccccc} a_{11} & a_{12} & a_{13} & \dots & \dots & a_{1n} \end{array} \right) \\
 A_2 & \left(\begin{array}{cccccc} a_{21} & a_{22} & \dots & \dots & \dots & a_{2n} \end{array} \right) \\
 A_3 & \left(\begin{array}{cccccc} \dots & \dots & a_{33} & \dots & \dots & \dots \end{array} \right) \\
 \dots & \left(\begin{array}{cccccc} \dots & \dots & \dots & a_{44} & \dots & \dots \end{array} \right) \\
 \dots & \left(\begin{array}{cccccc} \dots & \dots & \dots & \dots & \dots & \dots \end{array} \right) \\
 A_m & \left(\begin{array}{cccccc} a_{m1} & a_{m2} & a_{m3} & \dots & \dots & a_{mn} \end{array} \right)
 \end{array} \quad (3.8)$$

2. The second step in the TOPSIS methodology comprises normalizing a decision matrix. The normalized decision matrix is obtained by using the equation mentioned above, and the weighted normalized decision matrix is obtained by using the following equation:

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}} \quad (3.9)$$

$$V_{ij} = W_j * r_{ij} \quad (3.10)$$

3. After normalization, each criterion's positive and negative ideal solutions are obtained. The following equations are used to obtain ideal positive and negative solutions.

$$V_i^+ = \left[\left(\sum_i^{\max} v_{ij} / j \in J \right), \left(\sum_i^{\min} v_{ij} / j \in J' \right), i = 1, 2, \dots, m \right] = [v_1^+, v_2^+, \dots, v_n^+] \quad (3.11)$$

$$V_i^- = \left[\left(\sum_i^{\min} v_{ij} / j \in J \right), \left(\sum_i^{\max} v_{ij} / j \in J' \right), i = 1, 2, \dots, m \right] = [v_1^-, v_2^-, \dots, v_n^-] \quad (3.12)$$

where J and J' denote sets of beneficial and non-beneficial criteria.

4. The Euclidean distance or the separation measures from positive ideal and negative ideal solutions are evaluated by the equations defined below:

$$S_i^+ = \sqrt{\sum_{j=1}^n [v_{ij} - v_j^+]^2}, i = 1, 2, 3, \dots, m \quad (3.13)$$

$$S_i^- = \sqrt{\sum_{j=1}^n [v_{ij} - v_j^-]^2}, i = 1, 2, 3, \dots, m \quad (3.14)$$

5. After evaluating the Euclidean distance, the relative closeness of alternatives is assessed by using the subsequent equation:

$$P_i = \frac{S_i^+}{S_i^-} \quad (3.15)$$

6. The best alternative is evaluated by analyzing the closeness of alternatives concerning positive ideal solutions, and the final ranking is achieved according to the descending order.

3.2.3 Visekriterijumska Optimizacija I Kompromisno Resenje, VIKOR

Initially formulated by Serafim Opricovic in 1980, the VIKOR method was conceptualized as a solution to intricately structured systems characterized by multiple criteria. Visekriterijumska Optimizacija I Kompromisno Resenje embodies its essence, denoting multi-criteria optimization and compromise solution. This method finds its utility when confronted with scenarios encompassing conflicting criteria. Within the VIKOR framework, the optimal alternative is discerned by comparing their proximity to the ideal solution. Addressing the limitations observed in the conventional VIKOR approach, (Chang, 2010) proffered a refined rendition of the VIKOR methodology to alleviate these concerns.

The steps followed in the VIKOR method are listed:

1. To determine each criterion's best (X_i^+) and worst (X_i^-) :

$$\begin{aligned} X_i^+ &= \max(a_{ij}) \\ X_i^- &= \min(a_{ij}) \end{aligned} \quad \left| \begin{array}{l} \\ \end{array} \right. \quad \begin{array}{l} \\ \end{array} \quad (3.16)$$

... for beneficial criteria

$$\begin{array}{l} X_i^+ = \min(a_{ij}) \\ X_i^- = \max(a_{ij}) \end{array} \quad \left| \begin{array}{l} \\ \end{array} \right. \quad \dots \text{for non-beneficial criteria} \quad (3.17)$$

2. Framing normalization matrix and weighted normalized decision matrix.

$$r_{ij} = \frac{X_i^+ - a_{ij}}{X_i^+ - X_i^-} \quad (3.18)$$

$$V_{ij} = W_j \times r_{ij} \quad (3.19)$$

3. Evaluating S_i and R_i values:

$$S_i = \sum_{j=1}^n W_j \cdot \frac{X_i^+ - a_{ij}}{X_i^+ - X_i^-} \quad (3.20)$$

$$R_i = \max \left[W_j \cdot \frac{X_i^+ - a_{ij}}{X_i^+ - X_i^-} \right] \quad (3.21)$$

4. Calculate Q_i values:

$$Q_i = \beta \cdot \frac{(S_i - S_i^+)}{(S_i^- - S_i^+)} + (1 - \beta) \cdot \frac{(R_i - R_i^+)}{(R_i^- - R_i^+)} \quad (3.22)$$

where β is taken as 0.5 to provide a compromise solution.

5. Ranking alternatives according to descending order.
6. Acceptable advantage and acceptable stability conditions are determined. Providing the conditions below, A_1 finds the compromised solution.

$$Q(A_2) - Q(A_1) \geq DQ \quad (3.23)$$

$$DQ = \frac{1}{1 - m} \quad (3.24)$$

3.3 Results and Discussion

3.3.1 Evaluation of Weights by AHP

Initially, numeric values were allocated to each criterion, and subsequently, these values were subjected to pairwise comparisons, as illustrated in [Table 3.5](#). The process of establishing criterion

weights involves the utilization of the AHP. About the phase change temperature criterion, a weight of 9 was assigned to latent heat, whereas a reciprocal weight of $1/9^{\text{th}}$ was assigned to the phase change temperature. Analogously, thermal conductivity was accorded a weight of 5 vis-à-vis density, and density was endowed with a reciprocal weight of $1/5^{\text{th}}$ compared to thermal conductivity. The proportional weights corresponding to each criterion are detailed in Table 3.6, which emerges from the normalization procedure applied to the pairwise decision matrix (see Reference Table 3.5).

Table 3.5 Pairwise decision matrix of criterion.

	ΔH	C_p	K	T_m	ρ
ΔH	1.000	5.000	3.000	9.000	7.000
C_p	0.200	1.000	0.333	5.000	3.000
K	0.333	3.000	1.000	7.000	5.000
T_m	0.111	0.200	0.142	1.000	0.333
ρ	0.142	0.333	0.200	3.000	1.000

The graphical depiction of criterion weights is illustrated in Fig. 3.2. Subsequently, the calculation of the consistency ratio yields a value of 0.05, residing below the threshold of 0.1, thus signifying an acceptable level of consistency.

3.3.2 Evaluation by TOPSIS Method

Following AHP, a decision matrix was formulated, encompassing the array of PCMs as potential alternatives and the quintet above of evaluative criteria. After the assignment of the criterion weights, as outlined previously, the decision matrix underwent normalization. The resultant normalized matrix is provided in Table 3.7.

Table 3.6 Relative weightings of each criterion by AHP.

	ΔH	C_p	K	T_m	ρ	Criteria weights
ΔH	0.559	0.524	0.641	0.360	0.428	0.502
C_p	0.111	0.104	0.071	0.200	0.183	0.134
K	0.186	0.314	0.213	0.280	0.306	0.260
T_m	0.062	0.021	0.030	0.040	0.020	0.034
ρ	0.079	0.035	0.042	0.120	0.061	0.067

Subsequently, the procedure advances to identifying the optimal solutions, namely the ideal best and ideal worst solutions, within the normalized matrix. These solutions respectively embody the utmost and lowest values for each advantageous criterion, whereas the converse holds for non-advantageous criteria such as melting point. With this, the calculation determines the Euclidean distances for each alternative from the ideal best and ideal worst solutions, a process delineated in Table 3.8.

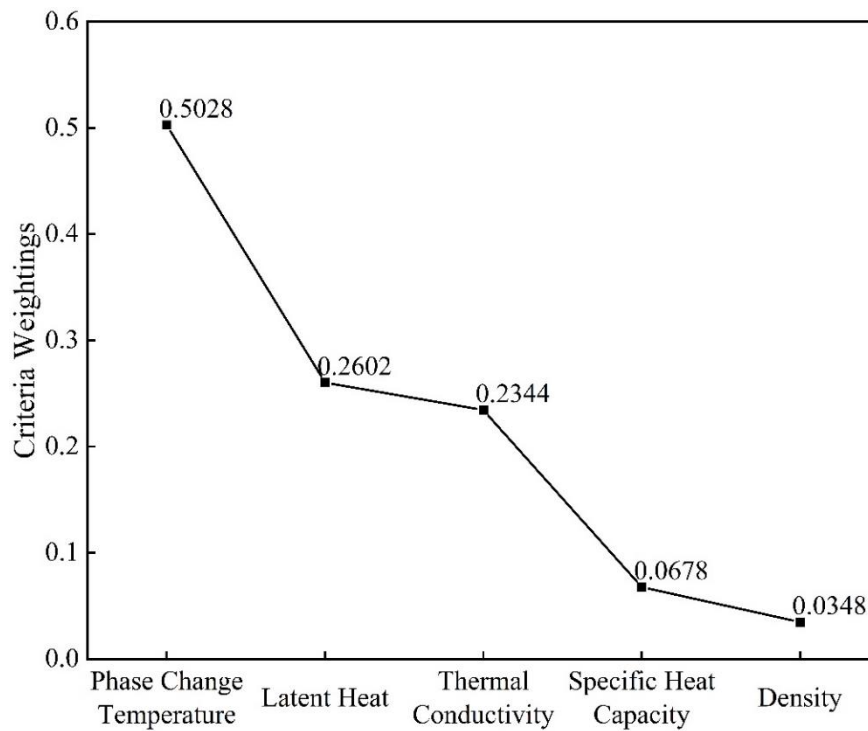


Fig. 3.2 Criteria weightings by the AHP method.

Upon calculating the Euclidean distances from the ideal best and ideal worst solutions, it is evident that inorganic salt hydrate has the shortest distance from the ideal best solution and the longest distance from the ideal worst solution. The Euclidean distances from the ideal best (S_i^+) and ideal worst (S_i^-) solutions of each alternative are presented in Fig. 3.3. Their comparison is graphically illustrated in Fig. 3.4. The rankings are predicated on performance ratings, where a rating approximating 1.0 signifies proximity to the ideal best solution. Conversely, a rating nearing zero conveys affinity with the ideal worst solution.

Table 3.7 Normalized matrix of PCMs.

PCM	ΔH	C_p	K	T_m	ρ
1-Decanol	0.202	0.231	0.380	0.039	0.161
Polyethylene glycol (PEG)	0.075	0.191	0.105	0.126	0.216
Caprylic acid	0.141	0.176	0.355	0.067	0.176
OM35	0.161	0.245	0.071	0.151	0.168
Paraffin wax	0.155	0.217	0.142	0.278	0.178
Eicosane	0.249	0.222	0.053	0.164	0.158
CaCl ₂ .6H ₂ O	0.189	0.124	0.188	0.129	0.369
Paraffin wax	0.232	0.217	0.044	0.138	0.175
OM37	0.220	0.014	0.057	0.172	0.186
Capric Acid	0.164	0.189	0.054	0.172	0.194
RT	0.242	0.136	0.053	0.215	0.145
OM 37	0.233	0.012	0.051	0.168	0.186
Paraffin wax	0.216	0.212	0.142	0.258	0.166
n-Eicosane	0.239	0.199	0.138	0.157	0.176
OM47	0.198	0.244	0.071	0.207	0.177
Erythritol	0.334	0.196	0.260	0.516	0.286
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	0.065	0.202	0.135	0.086	0.203
RT42	0.166	0.181	0.071	0.181	0.170
Paraffin wax	0.181	0.228	0.086	0.258	0.173
Paraffin	0.170	0.190	0.071	0.266	0.170
Eutectic	0.101	0.197	0.075	-0.014	0.148
Inorganic Salt Hydrate	0.190	0.130	0.582	0.120	0.021
Inorganic HS24	0.201	0.095	0.373	0.103	0.313
OM32	0.158	0.271	0.009	0.138	0.179
RT27	0.185	0.181	0.071	0.116	0.170
OM50	0.225	0.301	0.075	0.215	0.186

Among the examined PCMs, the inorganic salt hydrate PCM registers the highest performance rating of 0.6714, signifying its suitability for the intended deployment (Ref. [Table 3.9](#)). Notwithstanding, it is prudent to consider pre-selection criteria encompassing temperature range, availability, desired thermophysical properties, and cost. This analysis recommends the utilization of two commercially accessible PCMs, characterized by melting points of 35°C and 37°C. Furthermore, [Fig. 3.5](#) visually communicates the performance ratings assigned to each PCM by the TOPSIS methodology in descending order of magnitude.

Table 3.8 Normalized decision matrix for an ideal best and ideal worst solution.

PCM	ΔH	C_p	K	T_m	ρ
1-Decanol	0.101	0.031	0.099	0.001	0.011
Polyethylene glycol (PEG)	0.038	0.026	0.027	0.004	0.015
Caprylic acid	0.071	0.024	0.092	0.002	0.012
OM35	0.081	0.033	0.018	0.005	0.011
Paraffin wax	0.078	0.029	0.037	0.010	0.012
Eicosane	0.125	0.030	0.014	0.006	0.011
CaCl ₂ .6H ₂ O	0.095	0.017	0.049	0.004	0.025
Paraffin wax	0.117	0.029	0.011	0.005	0.012
OM37	0.110	0.002	0.015	0.006	0.013
Capric Acid	0.083	0.025	0.014	0.006	0.013
RT	0.122	0.018	0.014	0.007	0.010
OM 37	0.117	0.002	0.013	0.006	0.013
Paraffin wax	0.108	0.028	0.037	0.009	0.011
n-Eicosane	0.120	0.027	0.036	0.005	0.012
OM47	0.099	0.033	0.018	0.007	0.012
Erythritol	0.168	0.026	0.068	0.018	0.019
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	0.033	0.027	0.035	0.003	0.014
RT42	0.084	0.024	0.018	0.006	0.012
Paraffin wax	0.091	0.031	0.022	0.009	0.012
Paraffin	0.086	0.026	0.018	0.009	0.012
Eutectic	0.051	0.026	0.019	0.000	0.010
Inorganic Salt Hydrate	0.095	0.018	0.151	0.004	0.001
Inorganic HS24	0.101	0.013	0.097	0.004	0.021
OM32	0.080	0.036	0.002	0.005	0.012
RT27	0.093	0.024	0.018	0.004	0.012
OM50	0.113	0.040	0.019	0.007	0.013
v_j^+	0.168	0.040	0.151	0.000	0.025
v_j^-	0.033	0.002	0.002	0.018	0.001

The robustness of this selection procedure is buttressed by analogous research endeavors employing the TOPSIS methodology for PCM selection across diverse applications, encompassing HVAC systems (Rastogi et al., 2015), Trombe wall systems (Oluah et al., 2020), solar AC systems, and ground source heat pumps (H. Xu et al., 2017; K. Yang et al., 2018). This ranking signifies the preferred order based on the considerations given in [Eq. 3.15](#).

Table 3.9 Performance rankings of PCMs.

PCM	S_i^+	S_i^-	$S_i^+ + S_i^-$	P_i	Rank
1-Decanol	0.086	0.123	0.209	0.588	3
Polyethylene glycol (PEG)	0.180	0.039	0.220	0.180	26
Caprylic acid	0.115	0.101	0.217	0.468	5
OM35	0.159	0.061	0.221	0.279	20
Paraffin wax	0.147	0.064	0.211	0.304	18
Eicosane	0.145	0.098	0.243	0.404	7
CaCl ₂ .6H ₂ O	0.127	0.083	0.211	0.395	9
Paraffin wax	0.150	0.090	0.240	0.375	12
OM37	0.153	0.080	0.234	0.343	14
Capric Acid	0.162	0.058	0.221	0.265	22
RT50	0.147	0.092	0.239	0.383	11
OM 37	0.152	0.086	0.239	0.361	13
Paraffin wax	0.130	0.088	0.219	0.403	8
n-Eicosane	0.126	0.098	0.224	0.437	6
OM47	0.150	0.076	0.227	0.337	15
Erythritol	0.087	0.153	0.240	0.637	2
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	0.179	0.045	0.224	0.203	24
RT42	0.158	0.059	0.218	0.273	21
Paraffin wax	0.151	0.069	0.220	0.314	16
Paraffin	0.157	0.061	0.219	0.280	19
Eutectic	0.177	0.040	0.218	0.185	25
Inorganic Salt Hydrate	0.079	0.162	0.242	0.671	1
Inorganic HS24	0.090	0.119	0.210	0.568	4
OM32	0.173	0.060	0.234	0.259	23
RT27	0.153	0.068	0.222	0.308	17
OM50	0.143	0.092	0.235	0.390	10

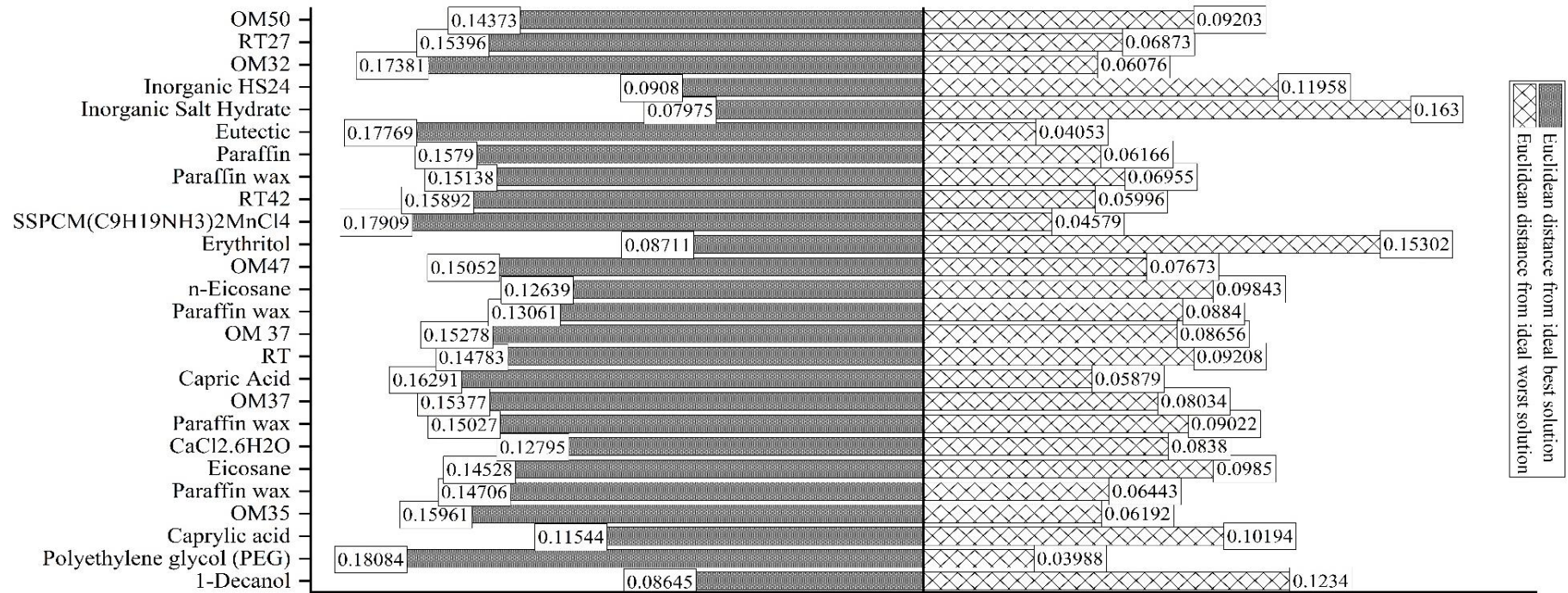


Fig. 3.3 Euclidean distances of alternatives from ideal best and worst solution.

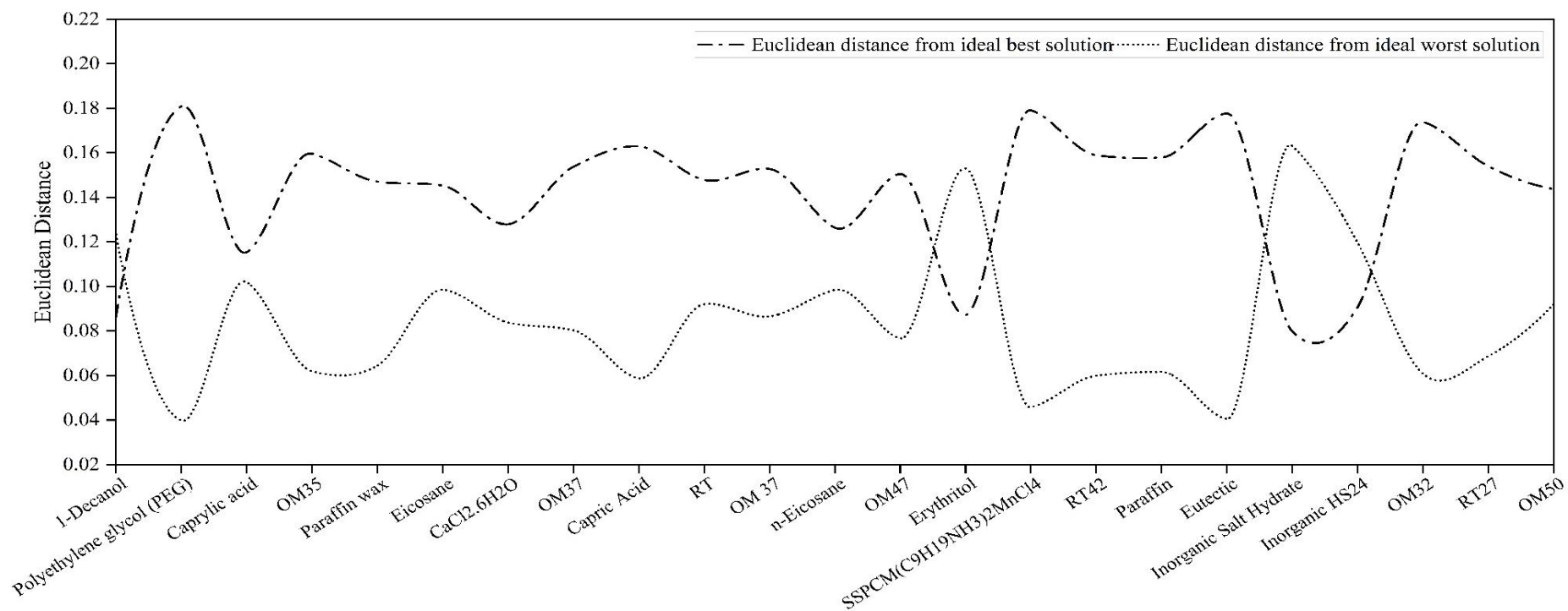


Fig. 3.4 Comparison graph of ideal best and ideal worst solution.

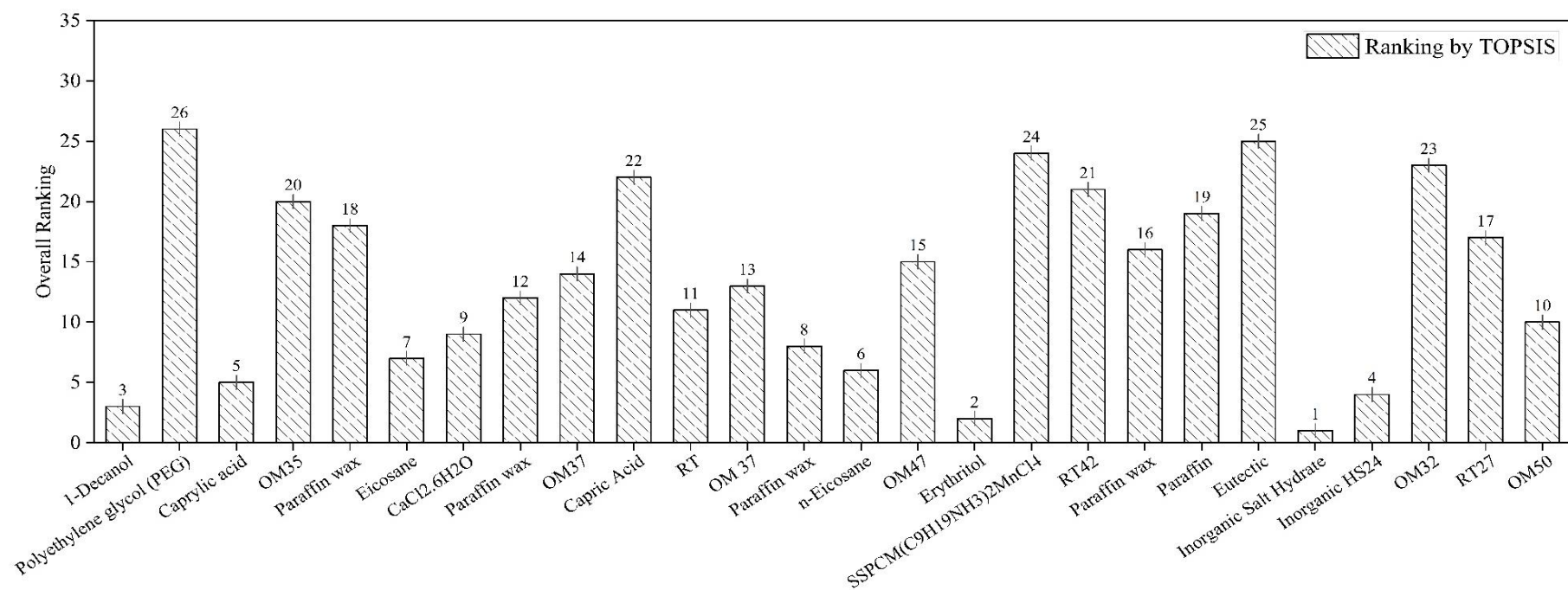


Fig. 3.5 Performance ranking of PCMs by TOPSIS method.

3.3.3 Evaluation by VIKOR Method

The VIKOR methodology entails the construction of a decision matrix that encompasses the stipulated evaluation criteria delineated within the investigation. The most favourable and least favourable values are identified for each criterion. In instances involving advantageous criteria, the zenith value represents the optimal outcome, while the nadir value signifies the minimal outcome, regardless of the specific alternative under consideration.

Table 3.10 Normalized weighted matrix of PCMs using the VIKOR method.

PCM	ΔH	C_p	K	T_m	ρ
1-Decanol	0.247	0.033	0.092	0.003	0.038
Polyethylene glycol (PEG)	0.485	0.051	0.217	0.009	0.028
Caprylic acid	0.361	0.058	0.103	0.005	0.036
OM35	0.323	0.026	0.232	0.011	0.037
Paraffin wax	0.336	0.039	0.200	0.019	0.035
Eicosane	0.159	0.037	0.240	0.012	0.039
CaCl ₂ .6H ₂ O	0.270	0.082	0.179	0.009	0.000
Paraffin wax	0.191	0.039	0.245	0.010	0.036
OM37	0.213	0.133	0.239	0.012	0.034
Capric Acid	0.318	0.052	0.240	0.012	0.032
RT	0.172	0.077	0.240	0.015	0.041
OM 37	0.189	0.134	0.241	0.012	0.034
Paraffin wax	0.221	0.042	0.200	0.018	0.037
n-Eicosane	0.177	0.047	0.202	0.011	0.036
OM47	0.255	0.026	0.232	0.014	0.035
Erythritol	0.000	0.049	0.146	0.035	0.015
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	0.503	0.046	0.203	0.007	0.031
RT42	0.313	0.056	0.232	0.013	0.037
Paraffin wax	0.285	0.034	0.226	0.018	0.036
Paraffin	0.306	0.052	0.232	0.018	0.037
Inorganic Salt Hydrate	0.270	0.079	0.000	0.009	0.068
Inorganic HS24	0.249	0.096	0.095	0.008	0.010
OM32	0.329	0.014	0.260	0.010	0.035
RT27	0.278	0.056	0.232	0.009	0.037
OM50	0.204	0.000	0.231	0.015	0.034
Eutectic	0.436	0.048	0.231	0.000	0.041

Conversely, the conceptual orientation is inverted for non-advantageous criteria such as melting point, where the minimal value signifies the most favourable, and the maximal value signifies the least favourable. This study categorizes melting point as a non-advantageous criterion, and its utmost (X_i^+) and worst (X_i^-) values are stipulated as 9.03 and 120, respectively.

Table 3.11 Performance ranking of studied PCMs using the VIKOR method.

PCM	S_i	R_i	Q_i	Rank
1-Decanol	0.414	0.247	0.297	3
Polyethylene glycol (PEG)	0.790	0.485	0.976	25
Caprylic acid	0.563	0.361	0.592	19
OM35	0.629	0.323	0.600	18
Paraffin wax	0.629	0.336	0.618	22
Eicosane	0.486	0.240	0.353	7
CaCl ₂ ·6H ₂ O	0.541	0.270	0.446	12
Paraffin wax	0.520	0.245	0.390	9
OM37	0.631	0.239	0.484	14
Capric Acid	0.654	0.318	0.615	21
RT	0.545	0.240	0.407	10
OM 37	0.610	0.241	0.468	13
Paraffin wax	0.518	0.221	0.355	8
n-Eicosane	0.472	0.202	0.286	2
OM47	0.563	0.255	0.444	11
Erythritol	0.245	0.146	0.000	1
SSPCM(C ₉ H ₁₉ NH ₃) ₂ MnCl ₄	0.789	0.503	0.999	26
RT42	0.651	0.313	0.607	20
Paraffin wax	0.599	0.285	0.519	15
Paraffin	0.645	0.306	0.591	17
Inorganic Salt Hydrate	0.426	0.270	0.340	5
Inorganic HS24	0.458	0.249	0.340	6
OM32	0.647	0.329	0.625	23
RT27	0.611	0.278	0.520	16
OM50	0.483	0.231	0.337	4
Eutectic	0.756	0.436	0.875	24
S^+, R^+	0.245	0.146		
S^-, R^-	0.790	0.502		

The decision matrix is subsequently normalized (Ref. [Table 3.10](#)), a process facilitated by the weightings ascribed to each criterion. Employing the equations inherent to the VIKOR methodology, the positive ideal and negative ideal solutions corresponding to each criterion are established. The performance of each alternative is evaluated based on the specific criteria, yielding performance scores duly presented in [Table 3.11](#). These scores, derived by applying the VIKOR method, are systematically ordered in a descending sequence.

For assessing the performance of PCMs using the VIKOR method, a visual representation is presented in [Fig. 3.6](#). However, when considering factors such as availability, pricing, desired temperature range, and desired thermophysical properties, the recommended options within the desired temperature range are OM35 and OM37, with melting temperatures of 35°C and 37°C, respectively. The final ranking of PCMs is as follows: OM35 > OM37 > n-Eicosane. This ranking signifies the preferred order based on the considerations given in [Eq. 3.23](#).

The overall rankings of all PCMs by TOPSIS and VIKOR is as follows:

TOPSIS:

Inorganic Salt Hydrate > *Erythritol* > *1-Decanol* > *Inorganic HS24* > *Caprylic acid* > *n-Eicosane* > *Eicosane* > *Paraffin wax* > *CaCl₂.6H₂O* > *OM50* > *RT50* > *Paraffin wax* > *OM 37* > *OM47* > *Paraffin wax* > *RT27* > *Paraffin wax* > *Paraffin* > *OM35* > *RT42* > *Capric Acid* > *OM32* > *SSPCM(C₉H₁₉NH₃)₂MnCl₄* > *Eutectic* > *Polyethylene glycol (PEG)*.

VIKOR:

Erythritol > *n-Eicosane* > *1-Decanol* > *OM50* > *Inorganic Salt Hydrate* > *Inorganic HS24* > *Eicosane* > *paraffin wax* > *paraffin wax* > *RT50* > *OM47* > *CaCl₂.6H₂O* > *OM 37* > *OM 37* > *paraffin wax* > *RT27* > *paraffin* > *OM35* > *Caprylic acid* > *RT42* > *Capric Acid* > *paraffin wax* > *OM32* > *Eutectic* > *Polyethylene glycol (PEG)* > *SSPCM(C₉H₁₉NH₃)₂MnCl₄*.

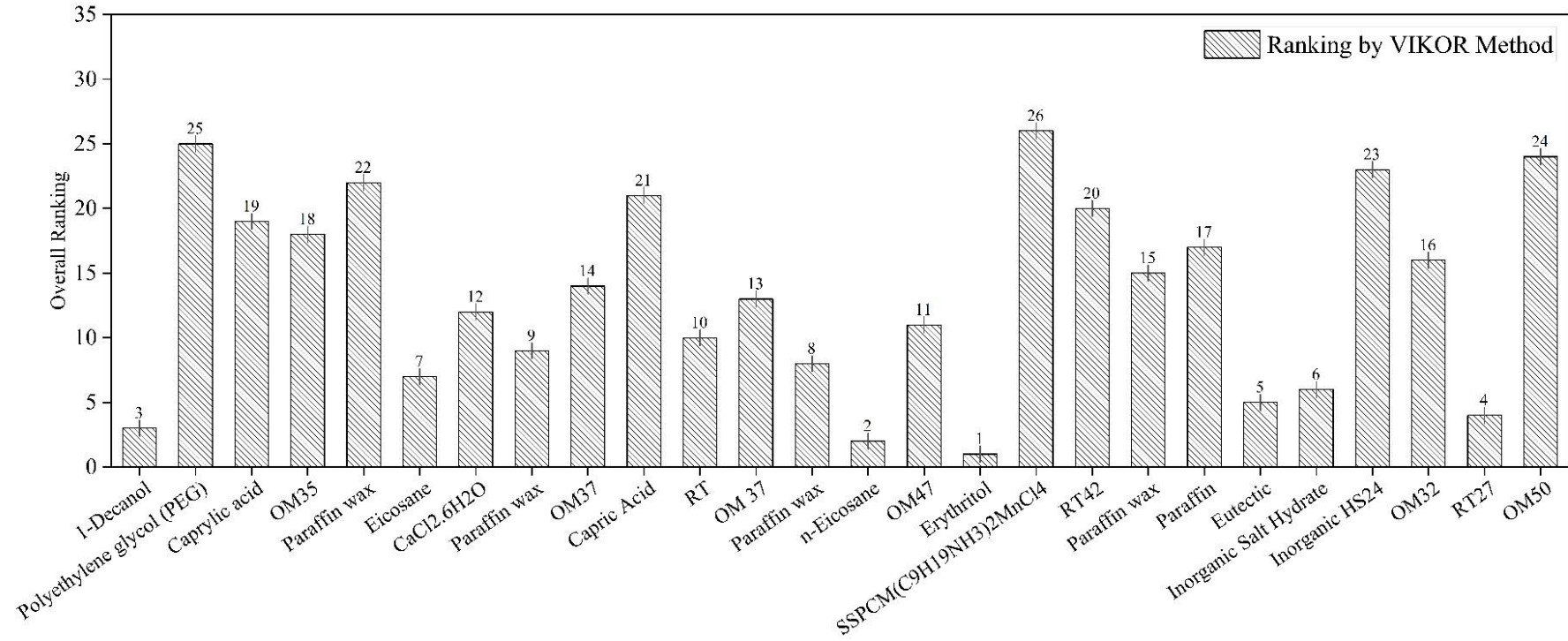


Fig. 3.6 Performance ranking of PCMs using the VIKOR method.

The summary of the application of multi-criteria decision-making methods in material selection is presented in Table 3.12. The table depicts the primary objective of the MCDM method adopted besides application area, country, and critical criteria.

Table 3.12 Summary of the application of MCDM methods in material selection.

Primary Objective	MCDM Methods	Criteria	Application Area	Country	Authors
Selection of PCM for building envelopes	AHP, COPRAS-G, TOPSIS, VIKOR	The heat of fusion, Melting point, Specific heat capacity in solid state and liquid state, Thermal conductivity in solid and liquid state, density in solid state	Buildings	Ecuador	[(Beltrán & Martínez-Gómez, 2019)]
Using a dynamic analytic hierarchy process to improve the business objectives of a company	DHAP	Stock level, supply term reliability, cost, repair term	Production Company	Spain	[(González-Prida et al., 2012)]
Ranking of PCMs using a novel approach for building facades	AHP-TOPSIS, Fuzzy AHP-Modified Fuzzy TOPSIS	Melting point, Heat of fusion, Density, Thermal conductivity, Specific heat capacity, Cycling stability, cost	Buildings	Kazakhstan	[(Mukhamet et al., 2021)]
Selection of optimal PCM implemented in ground source heat pump (GSHP)	AHP, TOPSIS	Thermal properties, physical properties, kinetic properties, chemical properties, economic properties	GSHP systems	China	[(K. Yang et al., 2018)]
Selection of materials for engineering applications	AHP VIKOR	Tensile strength, density, Young's modulus of elasticity, corrosion resistance	Manufacturing	India	[(R. V. Rao, 2008)]

PCM selection for solar domestic hot water system	AHP, TOPSIS, Fuzzy TOPSIS	Latent heat, density, specific heat capacity in solid and liquid state, thermal conductivity, and cost	Energy	India	[(Rathod & Kanzaria, 2011)]
Selection of materials for solar flat plate connector	AHP	Density, thermal conductivity, safety level temperature, cost, coefficient of thermal expansion, notch impact strength, and tensile strength	Solar collectors	India	[(Venkataramaiah et al., 2012)]
Material selection for a manufacturing hacksaw blade	AHP PROMETHEE	Brinnell hardness, yield stress, tensile stress, Young's modulus of elasticity, density, elongation	Manufacturing	India	[(Chothani, H. G., Kuchhadia, B. B., & Solanki, 2015)]
Selection of material for sustainable design	AHP, GRA	Economic, environmental, and social	Design	China	[(R. Zhao et al., 2016)]
The material selection process for walls	AHP	Cost, fire resistance, earthquake resistance, heat insulation, recycling, strength, workability, void ratio, sound insulation, density weightless, prod. En. Amount	Buildings	Turkey	[(Uğur & Baykan, 2017)]
Material selection for an axle	AHP, ANP	Cost, hardenability, chemical composition, availability of raw materials, and mechanical properties	Manufacturing	India	[(ta, R. K. Srivastava, 2015)]
Material selection for screw making process	AHP	Carbon footprint, air acidification, total energy consumed, water Eutrophication	Manufacturing	Malaysia	[(Sia et al., 2013)]
Material selection using AHP for Robot Arm	AHP	Strength, Young's modulus, density, cost	Robotics	India	[(Ankit Kumar & Kumar, 2019)]

Material selection process using AHP for concrete repair	AHP	Tensile and compressive strength, tensile bond strength, elasticity, thermal expansion, alkali resistance, electrical resistivity, drying shrinkage, chloride permeability	Construction	Korea	[(Do & Kim, 2012)]
PCM selection under steady and un-steady sources	TOPSIS	Melting point, density, latent heat of fusion, Thermal conductivity, Specific heat capacity	Shell and tube LTES	China	[(X. Yu et al., 2021)]
Phase change material selection for AC systems	AHP, TOPSIS	Melting point, latent heat, thermal conductivity, specific heat capacity, and density	AC systems	France	[(H. Xu et al., 2017)]
PCM selection in maintaining the comfort of occupants in vehicles	AHP	Melting point, density, latent heat of fusion, Thermal conductivity, Specific heat capacity, maximum operating temperature, density of solid, density of liquid	Vehicles	Romania	[(Socaciu et al., 2016)]
PCM selection for HVAC	Ashby, TOPSIS	Melting point, density, latent heat of fusion, Thermal conductivity, Specific heat capacity, figure of merits	Buildings	India	[(Rastogi et al., 2015)]
Selection of PCMs in Trombe wall systems	Entropy method, TOPSIS	The heat of fusion, thermal conductivity, density, cost	Buildings	South Africa	[(Oluah et al., 2020)]
PCM selection in electronic cooling systems	FAHP, TOPSIS, VIKOR, PROMETH EE	The heat of fusion, Melting point, Specific heat capacity in the solid state and the liquid state, Thermal conductivity in the solid state and the liquid state, density, cost	Electronic devices	India	[(Loganathan & Mani, 2018)]

Selection of innovative materials for building facades	AHP	Technical and executive, economic, social, environmental, and energy consumption factors	Buildings	Iran	[(Balali & Valipour, 2020)]
Selection of materials using MCDM for natural FRP composites	AHP	Tensile strength, density, Young's modulus	Automotive	Malaysia	(Sapuan et al., 2011)
Prioritizing trust parameters in cloud computing	Fuzzy-AHP	Quality of service, social relationships, recommendation, quality of security, and past reputation	Cloud computing	Nigeria	(Ogundoyin & Kamil, 2020)
Evaluating the performance of airports using BWM-VIKOR	BWM, VIKOR	Green building and infrastructure, air and noise control, waste management and recycling practices, green operation and transportation, green policies and regulation, environmental monitoring and control, and employee green training	Aviation	India	(Ashwani Kumar et al., 2020)
Ranking OEMs for performance measurement of manufacturers	Fuzzy VIKOR	Marginals, intermediators, and prominent	Management	India	(Parvez, 2020)
Risk evaluation for construction projects	Fuzzy VIKOR	Probability of risk influence, risk urgency, unpredictability, and risk occurrence	Construction	China	(L. Wang et al., 2018)
Solving maritime transportation industry problems using a multi-criteria approach	AHP VIKOR	Installation and maintenance cost, flexibility, operation mechanism, physical durability, opening/closing duration, operation mechanism, user friendly, water tightness	Transportation	Turkey	(Soner et al., 2017)
Material selection for	VIKOR	Tensile and fatigue strength, modulus of elasticity, cost,	Materials	Malaysia	(Jahan et al., 2011)

biomedical application using VIKOR		specific gravity, relative wear, corrosion resistance, relative toughness, tissue tolerance, density			
Election of materials for an automotive application using the MCDM tool	Fuzzy VIKOR	Elongation, tensile strength, toxicity level, thermal conductivity, recyclability, cost, and maximum temperature limit.	Automotive	India	(Jeya Girubha & Vinodh, 2012)
Selection of magnetic materials using MCDM tools	VIKOR, TOPSIS	Coercive field, remanence value, electrical resistivity, max. Magnetic permeability, magnetic induction, Curie temperature, magnetic energy, and operating temperature.	Materials	India	(Chauhan & Vaish, 2012)
Material selection using MCDM techniques for connecting rod	VIKOR, TOPSIS, COPRAS, MOORA, ARAS FAHP	Cost, machining, fatigue limit, tensile strength, fracture toughness, and fracture brittleness	Manufacturing	India	(Sen et al., 2016)
Using MCDM methods to solve material selection problems for pipes used in the sugar industry	VIKOR, FAHP ELECTRE, FAHP TOPSIS, FAHP PROMETHEE	Ultimate tensile strength, hardness, corrosion rate, elongation percentage, wear rate, yield strength, and cost	Manufacturing	India	(Anojkumar et al., 2014)
Evaluation of buildings' green renovation schemes using the TOPSIS method	TOPSIS	Energy saving and utilization, indoor environment, land saving outdoor environment, water savings and water resource utilization	Energy	China	(Yang Liu et al., 2021)
Evaluating the environmental impact on CMS	TOPSIS	Construction unit, environmental impact, pollution reduction	Construction	China	(S.-S. Lin et al., 2021)

using MCDM methods		management, and geographical environment			
Using TOPSIS methodology to benchmark the energy performance of a building	TOPSIS	Heating/cooling degree day efficiency, total degree day efficiency, total room-oriented efficiency, bathroom, and occupant-oriented efficiency, and the energy use intensity	Energy	USA	(E. Wang et al., 2017)

3.4 Concluding Remarks

The selection of suitable materials holds paramount significance in building applications as it directly influences overarching objectives and bolsters building performance. This investigation centers on the meticulous selection of appropriate PCMs tailored specifically for building comfort applications, targeting a desired phase change temperature range of 30-40°C. To accomplish this task, a MCDM approach was adopted, integrating the AHP, TOPSIS, and VIKOR methods. The AHP method was employed to assign weights to various criteria, ensuring a systematic consideration of their relative importance. The outcomes of the AHP analysis revealed that latent heat garnered a global weight of 50.28%, while the phase change temperature obtained the least weight (3.48%). Following this, the TOPSIS and VIKOR methods were invoked to rank the PCMs based on their performance ratings. These ratings were ascertained by evaluating the proximity of each PCM to the ideal best and worst solutions on a scale ranging from 0 to 1.

Remarkably, OM35 and OM37 PCMs emerged with the highest performance ratings, considering factors such as availability, pricing, and desired thermophysical properties. This suggests that their integration into building envelopes would yield optimal performance outcomes. The findings underscore the efficacy and applicability of employing MCDM tools for the purpose of ranking and selecting PCMs in building applications.

Introduction

In this subsequent section of the thesis, the PCMs selected based on MCDM methods and local climatic factors in the preceding chapter underwent thorough characterization. The following section (section 4.1) entails a comprehensive discourse on the techniques employed for the characterization process. The PCMs used for this study were procured from PLUSS Advanced Technologies Pvt. Ltd., in Gurugram–122101, India. To offer a comprehensive insight into the PCMs, Table 4.1 provides an all-encompassing compilation of their thermophysical attributes. The lack of well-defined standards for characterizing PCMs has resulted in inconsistent documentation of PCM properties within the scientific literature (Singh et al., 2019). Therefore, PCM characterization procedures were meticulously performed in this study to determine its thermophysical properties. Characterizing PCMs plays a crucial role in understanding their thermal behavior and performance. PCMs are substances capable of storing and releasing large amounts of thermal energy during the process of melting and solidification, making them valuable for various thermal energy storage applications. Characterization involves systematically assessing the physical, chemical, and thermal properties of PCMs to determine their suitability for specific applications.

Accurate characterization allows researchers to select the most appropriate PCM for a given application and design efficient energy storage systems. Furthermore, it provides valuable insights into the PCM's performance under different operating conditions, helping optimize its use for maximum energy efficiency and reliability. Furthermore, ongoing research efforts in PCM characterization aim to develop new materials with enhanced properties, such as higher energy storage capacity, improved thermal conductivity, and increased durability, further advancing the field of thermal energy storage and contributing to the transition toward sustainable energy systems.

Table 4. 1 Thermophysical properties of PCMs.

Thermal properties	Melting/Freezing Temp (°C)	Latent heat (kJ/kg)	Liquid/Solid Density (kg/m ³)	Liquid/Solid Specific Heat (kJ/kg.K)	Thermal Conductivity, liquid/solid (W/m.K)
OM35	35/34	171	870/900	2.78/2.57	0.16/0.20
OM37	37/36	179	860/973	2.63/2.55	0.13/0.16

4.1 Characterization Techniques

The characterization of PCMs typically involves assessing various thermo-physical properties. One of the primary properties evaluated during PCM characterization is the phase change temperature, which refers to the temperature at which the PCM transitions between solid and liquid states. This parameter is critical for determining the operational temperature range of the PCM-based system and ensuring that it operates effectively within this range. Additionally, the latent heat of fusion, which represents the amount of energy absorbed or released during the phase transition, is another essential parameter that influences the energy storage capacity of the PCM. Thermal conductivity is another key property that characterizes the ability of a PCM to conduct heat. High thermal conductivity allows for efficient heat transfer within the PCM, facilitating rapid charging and discharging of thermal energy. Density, specific heat capacity, and thermal stability are other important properties that affect the overall performance and durability of PCM-based systems.

Thermal conductivity and diffusivity can be determined using a thermal constants analyzer, allowing for simultaneous thermal conductivity and heat capacity measurement. DSC is employed to ascertain transition temperatures and latent heat of fusion. FT-IR Spectroscopy evaluates the chemical compatibility between the PCM and the container or supporting material. XRD is a robust technique for identifying crystallinity and associated crystal phases. TGA is employed to assess the thermal stability of macroencapsulated PCMs. Additionally, the utilization of Fe-SEM for morphological analysis was considered. Further details regarding the characterization of thermo-physical properties of PCMs are elaborated upon in this chapter.

4.1.1 Thermal conductivity

The knowledge of PCM's thermal conductivity is essential for designing and optimizing LHTES systems tailored to specific applications. The thermal conductivity of PCMs can be determined through steady-state and non-steady-state methods (Memon, 2014). In the steady-state method, measurements are conducted when the material's temperature remains constant over time, maintaining a consistent signal. Hence, signal analysis is relatively straightforward. On the other hand, the non-steady state method involves measurements taken during the heating process, with the signal analyzed as a function of time. Although this method allows for quicker measurements, the mathematical analysis of the data tends to be more complex.

In this study, the thermal conductivity of PCMs was determined by employing a transient plane source-based thermal constants analyzer (Model: TPS 500) developed by Gustafsson, 1991, as depicted in [Fig. 4.1](#). The tests follow the thermal conductivity and thermal diffusivity methods outlined in ISO 22007-2:2022. The specific methodology and underlying principles have been

detailed in previous work (Xie et al., 2006). An aluminum mould is used to prepare PCM specimens in the solid state. The dimensions of each specimen were measured to be 50 mm in diameter and 10 mm in thickness. The experiment employs a Kapton-insulated sensor. The sensor comprises a small nickel foil sheet arranged in a dual spiral configuration and placed between protective films, which was employed as the sensor/heater. Two identical PCM discs, measuring 20 mm in diameter and 6 mm in thickness, were positioned between the sensor/heater, and a steady power of 3 W was applied for 40 seconds, allowing generated heat within the dual spiral to transmit into the samples. The change in temperature over time is monitored at short intervals to ascertain the thermal conductivity of PCMs.



Fig. 4.1 Thermal conductivity setup of the PCM.

Three measurements were carried out for each sample, and the statistics presented here are the mean values with a standard deviation of $< 1\%$. The PCMs exhibit average thermal conductivity values of 0.226 W/mK and 0.206 W/mK, respectively. The thermal conductivity, thermal diffusivity, and specific heat capacity findings of PCMs are documented in [Table 4.2](#).

Table 4.2 Thermal conductivity values of PCMs.

PCM	Thermal conductivity (W/mK)	Thermal Diffusivity (m ² /s)	Specific heat capacity (J/kg.K)
OM35	0.2258	0.0893	2526
	0.2271	0.0854	2656
	0.2270	0.0850	2656
	<i>Avg.</i> 0.2266	0.0865	2612
OM37	0.2073	0.1018	2.036
	0.2064	0.0935	2.207
	0.2072	0.0946	2.190
	<i>Avg.</i> 0.2069	0.0966	2.144

The measured thermal conductivity and specific heat capacity values of OM35 showed deviations of approximately 13% and less than 2%, respectively, from the manufacturer-provided values. On the other hand, OM37 demonstrated deviations of 20% and 16% for thermal conductivity and specific heat capacity, respectively. However, these measured values closely align with data reported in existing literature (Chelliah et al., 2021; Saxena et al., 2020b).

4.1.2 Chemical Characterization

4.1.2.1 Fourier Transform Infrared Spectroscopy

FT-IR spectroscopy proves highly advantageous in verifying the identity of individual compounds, particularly when they are in a pure state. However, its utility diminishes when applied to compound mixtures. The methodology relies on discerning functional groups within molecules, which exhibit vibrational modes (either stretching or bending) when subjected to specific wavelengths of light. These vibrational frequencies, along with their intensity (% transmission), are graphed against the frequency of light (cm^{-1}) to generate an FT-IR spectrum (Daéid, 2005). The actual photograph of FT-IR is shown in Fig. 4.2. FTIR spectroscopy is characterized by its rapidity, cost-effectiveness, simplicity, and non-destructive nature.

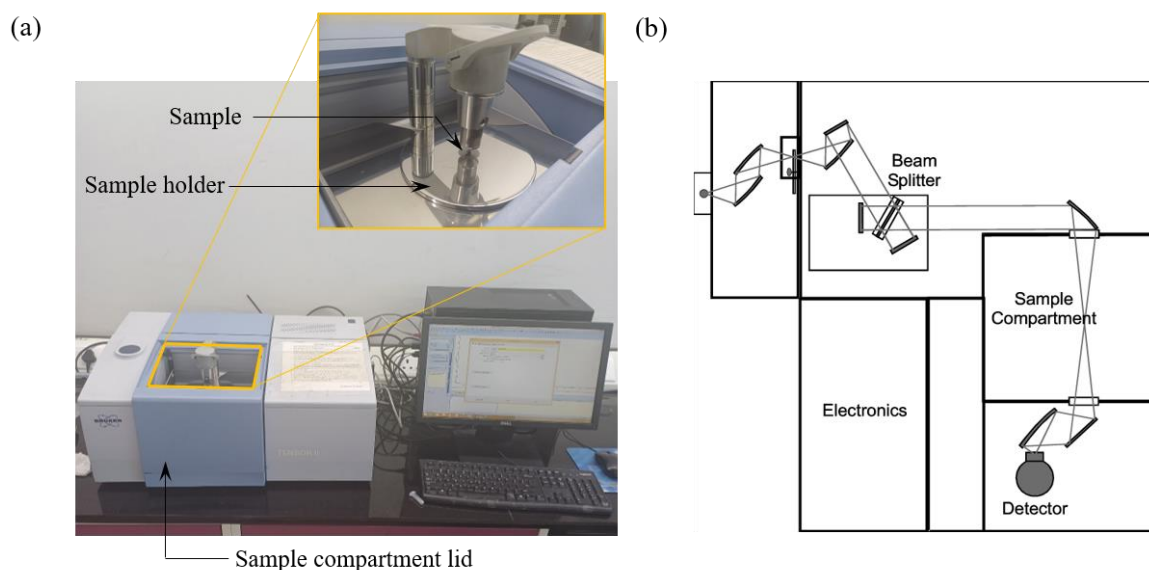


Fig. 4.2 FT-IR representation: (a) Experimental setup; and (b) Schematic diagram of FT-IR.

This study investigated the chemical composition of PCMs with FT-IR spectroscopy (Model: Bruker Tensor-27) employing a KBr disc. The spectrum range covered was from 400 cm^{-1} to 4000 cm^{-1} , with a resolution of 4 cm^{-1} . The FT-IR spectra of both PCMs are presented in Fig. 4.3. Both the PCMs exhibited identical spectra. The distinctive peaks at 2915 and 2848 cm^{-1} in the FT-IR spectra of PCMs are ascribed to C–H asymmetric stretching and symmetric vibration of CH_3/CH_2

groups. The absorption peak at 1693 cm^{-1} suggests a C=O bond stretching within the –COOH group. The characteristic peaks observed at 1300 cm^{-1} and 730 cm^{-1} indicate specific molecular vibrations. The peak at 1300 cm^{-1} corresponds to the bending vibration of C–H bonds, while the peak at 730 cm^{-1} corresponds to the in-plane deformation rocking vibration of the CH₂ group. Moreover, a peak at 930 cm^{-1} indicates the vibration of the –OH group (Fu et al., 2015; S. Y. Wu et al., 2016b).

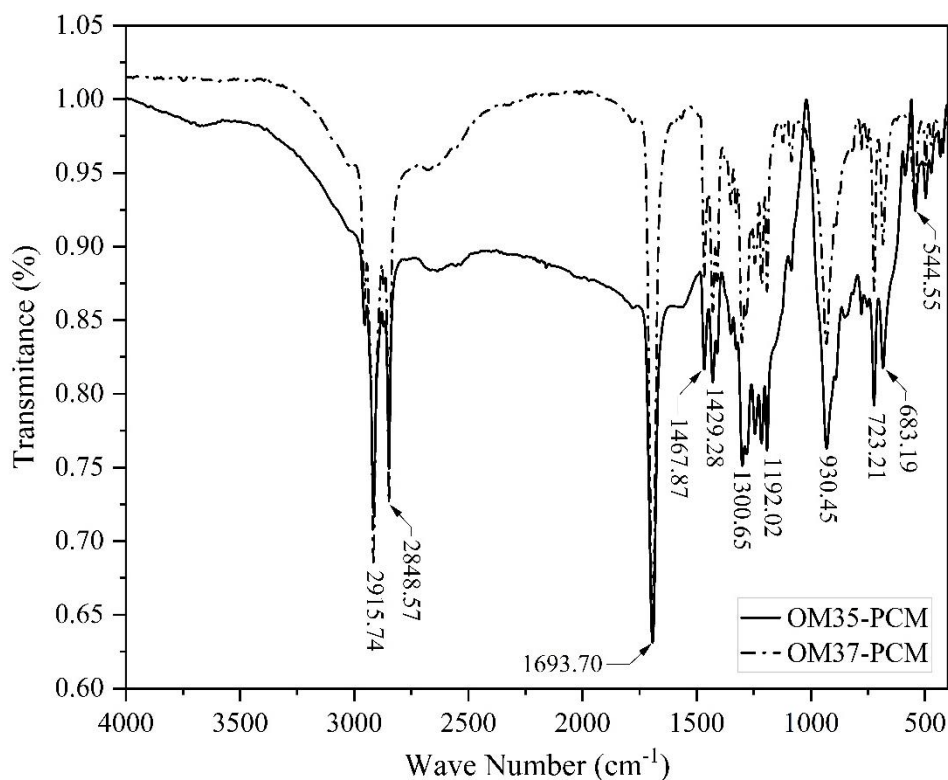


Fig. 4.3 FT-IR spectra of OM35 and OM37 PCMs.

4.1.2.2 X-Ray Diffraction Analysis

XRD is a non-destructive testing (NDT) method employed to discern the compositions, microstructures, and atomic or molecular morphology of coatings. The standard experimental arrangement for XRD analysis is depicted in Fig. 4.4. XRD patterns encompass insights across various length scales. While XRD has conventionally been utilized for analyzing bulk samples, advancements in optical systems now permit thin film analysis using XRD techniques. While XRD is commonly recognized for its qualitative and quantitative analyses of crystalline phases in materials, a meticulous examination of diffraction patterns can yield a wealth of additional information.

The crystallization behavior of PCMs was investigated by analyzing their XRD spectrum. The XRD diffractometer (Model: Bruker D8 Venture) is employed in this research. It utilizes Cu K–Alpha radiation with a wavelength of 0.154 nm , operating at 45 kV and 40 mA . The range of $2\text{-}\theta$

analyzed is from 5° to 70° . Bragg's equation calculates the interlayer spacing, commonly called d-spacing.

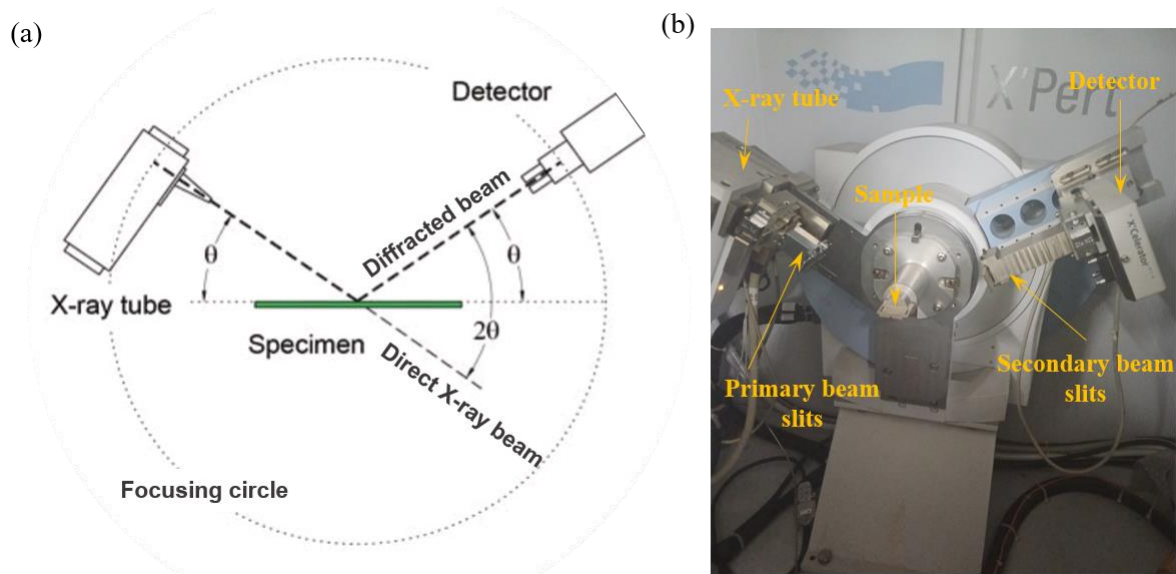


Fig. 4.4 XRD setup: (a) Diffraction geometry; (b) X-ray diffractor.

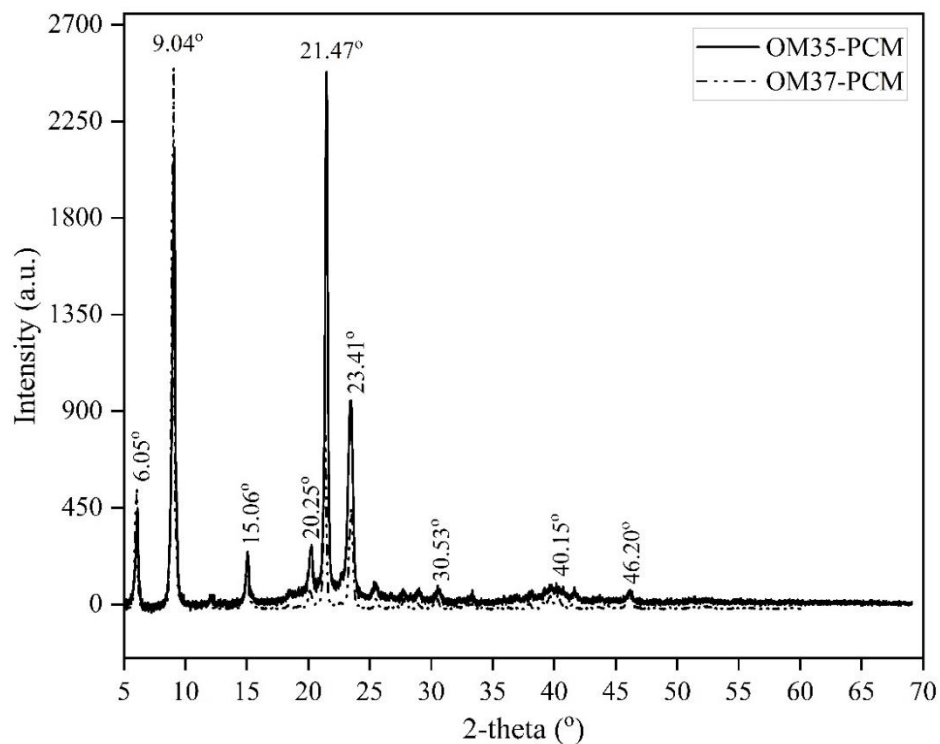


Fig. 4.5 XRD results of OM35 and OM37 PCMs.

The XRD pattern obtained at ambient temperature is illustrated in Fig. 4.5. The peaks indicate the specific arrangement and orientation of the crystal lattice within the material under investigation. The presence of six distinct diffraction peaks at specific angles, namely 6.05° , 9.04° , 15.06° , 20.25° ,

21.47°, 23.41°, and 39.62°, is a clear indication of PCM crystallization. Sharp peaks between 20° and 25° in PCM suggest that PCM exhibits good crystallization behavior. The observed peaks in the PCM pattern can be attributed to the diffraction indices of different crystal planes, namely (002), (004), (012), (110), (002), and (022).

4.1.3 Differential Scanning Calorimetry

The analysis of the melting, crystallization, and heat storage characteristics of the PCMs was performed using a NETZSCH–DSC (Model: STA 449 F1 Jupiter). A DSC NETZSCH (Model: STA 449 F1 Jupiter) having $\pm 2\%$ precision and 0.001 °C temperature resolution is used for testing. When a PCM undergoes physical or chemical transformations, such as melting, vaporization, solidification, endothermic, or exothermic reactions, it absorbs or emits corresponding heat. The PCM and reference samples are maintained at the same temperature to ensure uniform conditions before commencing measurements. The PCMs are carefully weighed and securely sealed in aluminum pans. An identical empty aluminum pan, sealed in the same manner, serves as a reference sample to eliminate the influence of the aluminum pan in the measurements. Three 5mg PCM samples are analyzed using DSC. The testing is done at a ramp rate of 1 °C/min over 25 °C–60 °C. A constant flow rate of 50 ml/min of pure nitrogen was used in the experiment. Prior to analyzing the samples, the DSC instrument is calibrated using indium as a standard calibrating sample for enthalpy and temperatures. The phase change temperature of the PCMs was ascertained by tracing a line along the steepest slope of the DSC peak and projecting the baseline onto the same side as the peak's leading edge. The latent heat associated with the phase transition process was quantified through numerical integration of the area beneath the peaks. Notably, the calorimeter employed exhibited an accuracy of $\pm 2\%$, while the temperature resolution achieved was 0.001 K.

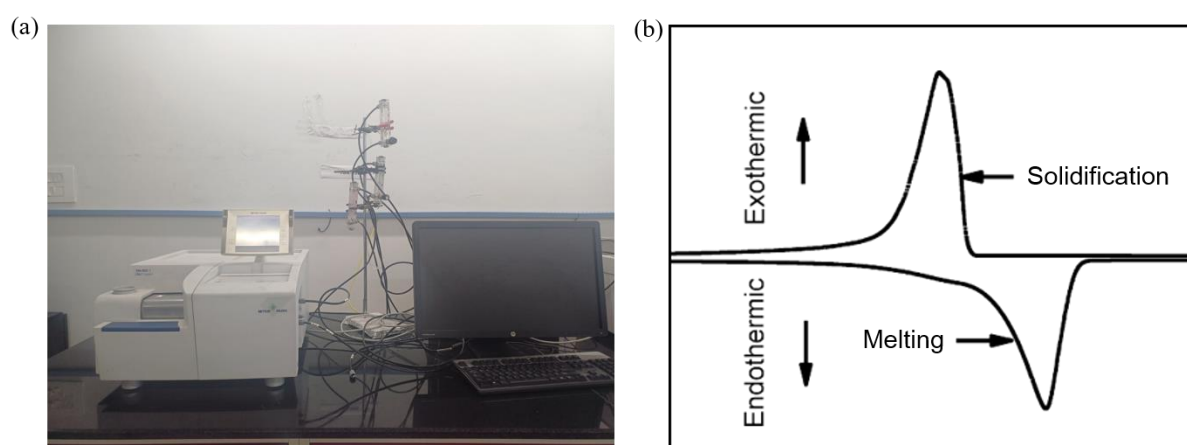


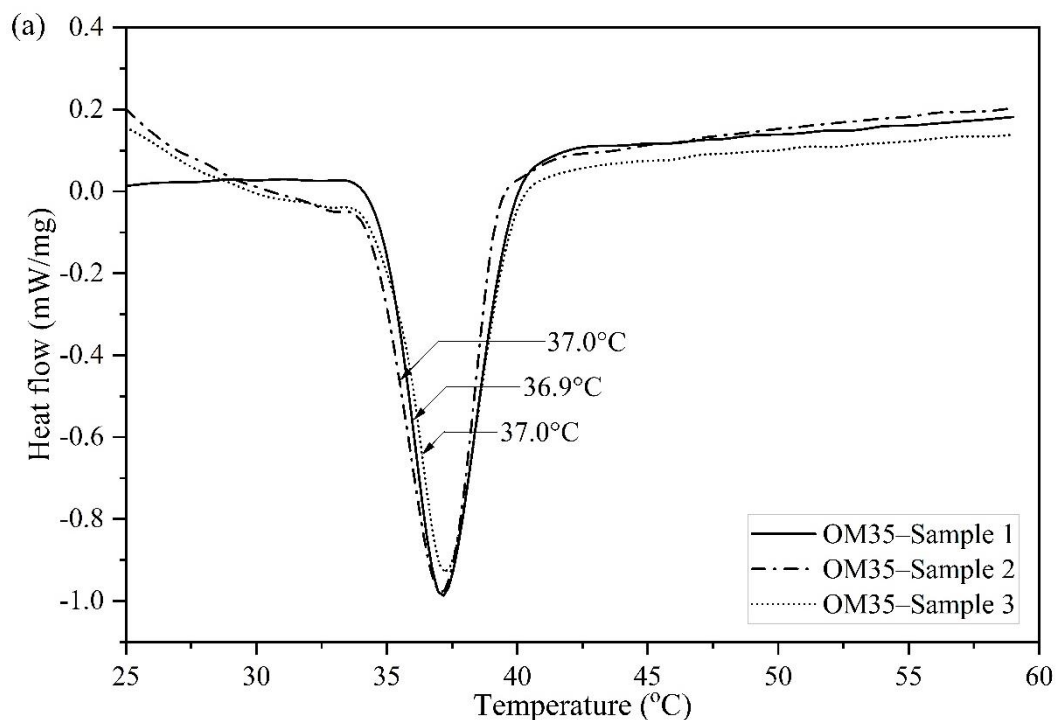
Fig. 4.6 DSC setup: (a) DSC instrument; and (b) DSC thermogram explaining melting and solidification process.

The DSC instrument, as depicted in Fig. 4.6a, is used to evaluate the thermophysical properties of PCMs. The schematic of the DSC thermogram illustrating both melting and solidification phase changes is illustrated in Fig. 4.6b.

4.1.3.1 Phase Transition Temperature

During the cyclic sequences of melting and cooling, the DSC analysis discloses that both PCMs manifest a singular peak, indicative of the transition from solid to liquid phase. This transformation arises from the amalgamation of alkanes possessing varying carbon chain lengths intrinsic to paraffin wax. This transition is observed to occur over a wide temperature span. The DSC curves exhibit discernible inflection points, encompassing the initiation and apex of both solid-solid and solid-liquid phase transitions. Figs. 4.7(a and b) show DSC thermograms during the heating cycle. The ascertained onset temperatures for melting were approximately 34°C for OM35 and 37.06°C for OM37, which closely aligns with the findings reported by (Saxena et al., 2020b).

The peak temperature corresponding to the melting phase for OM35 was roughly 37 °C, while for OM37, it was approximately 40 °C, a result consistent with the outcomes presented by (Rathore et al., 2020). Interestingly, the heating curve of the second sample of OM37 PCM exhibited two distinct phase transition peaks. The first peak, centered at around 36.073 °C, denoted the solid-solid phase transition and was of relatively lower magnitude. The second peak, significantly higher in magnitude, was centered around 40.073 °C, corresponding to the solid-liquid phase transition. PCM's average melting temperature deviated by around 5% and 7.5% from the manufacturer's specified value. The deviation is acceptable and within expected limits.



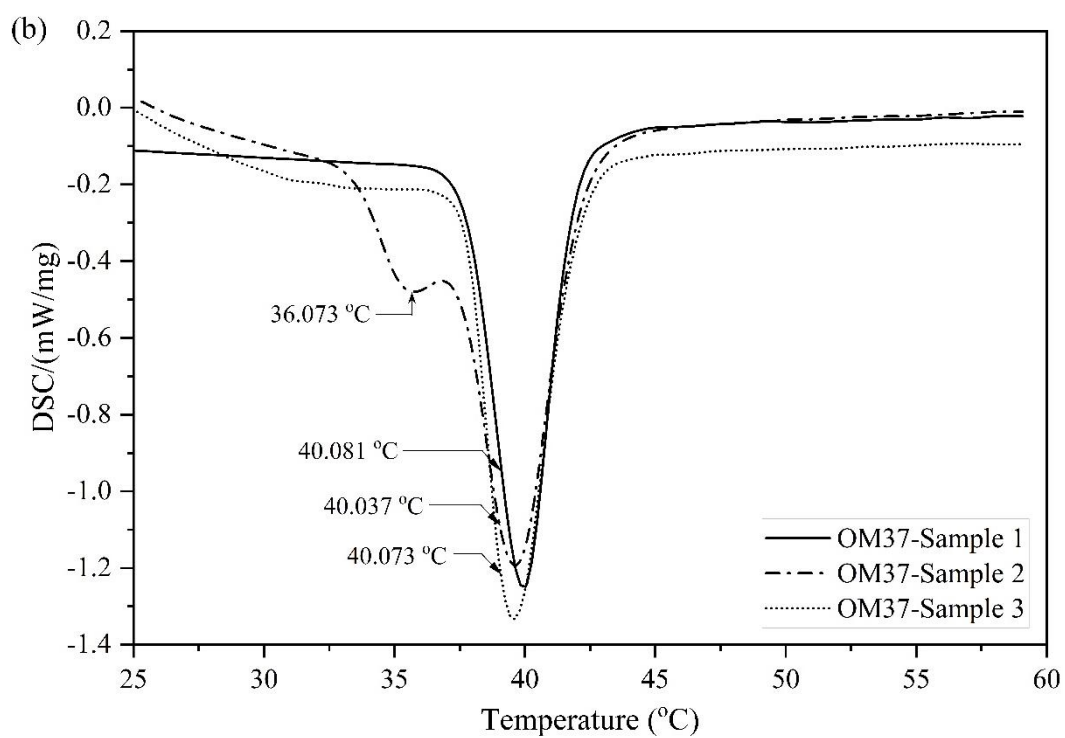
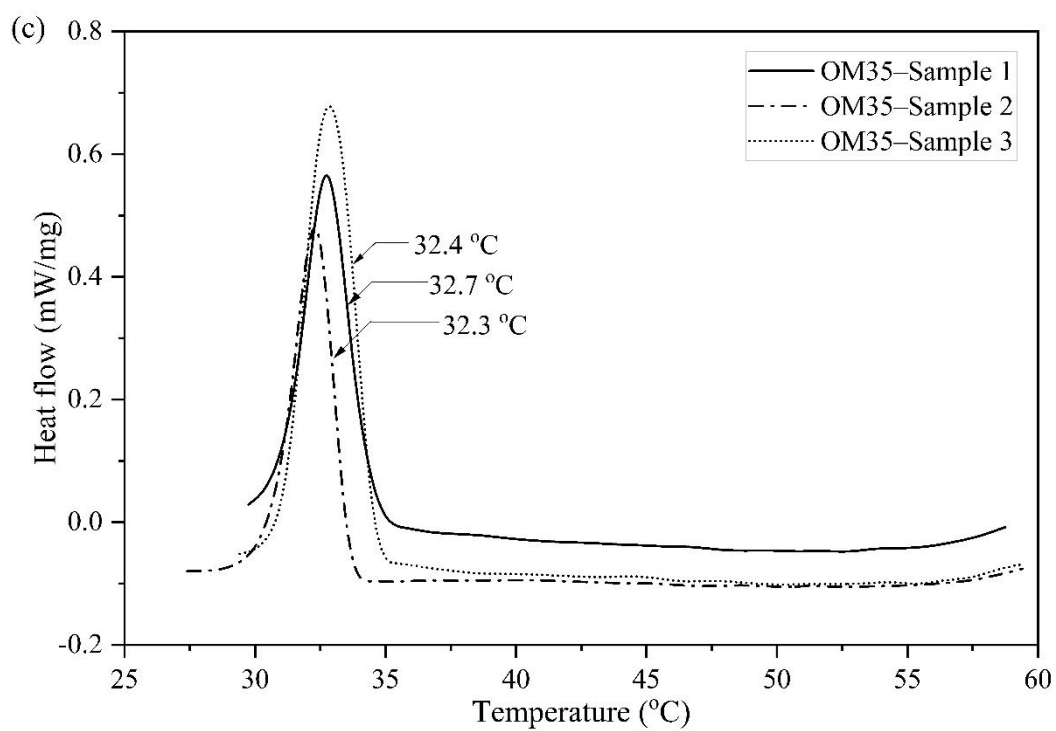


Fig. 4.7 DSC melting thermograms: (a) OM35; and (b) OM37.



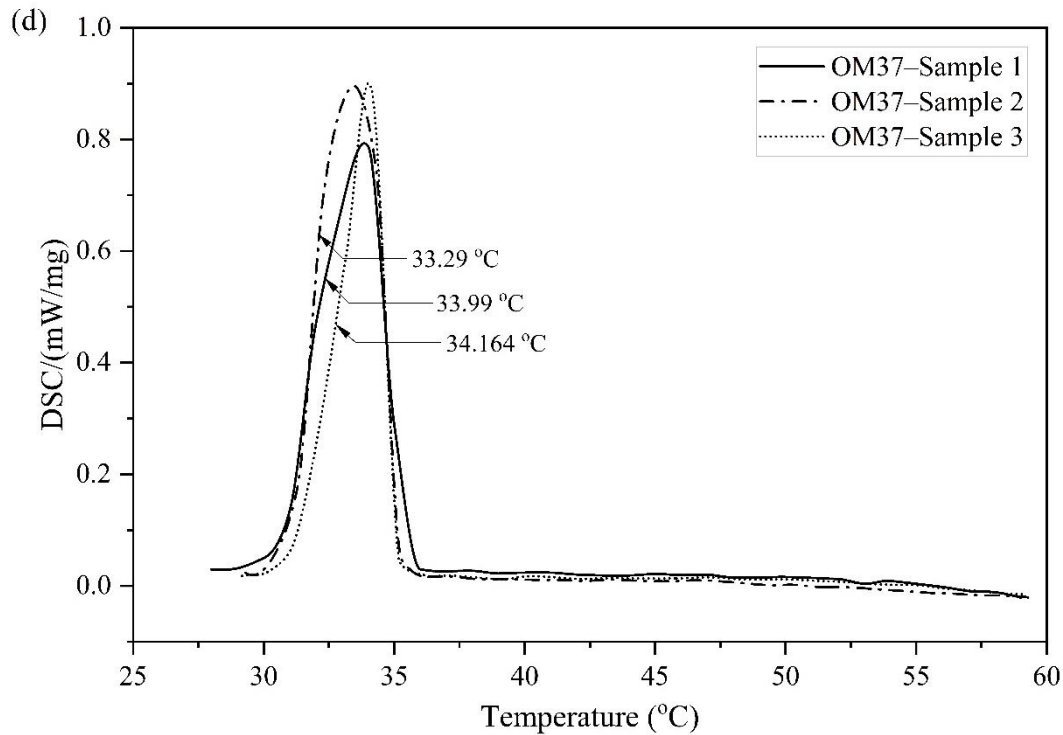


Fig. 4.8 DSC solidification thermogram: (c) OM35; and (d) OM37.

Figs. 4.8(c and d) show DSC thermogram during the cooling cycle. The outcomes elucidate that the solidification temperatures of these PCMs are approximately 32.5 °C for OM35 and 34 °C for OM37. During the solidification phase, an onset temperature of 34.51°C and 35.47°C is observed. Upon juxtaposing the peak melting and solidification temperatures of OM35 and OM37, a discernible sub-cooling effect of 4.5°C and 6.2°C is noted. This sub-cooling level is notably lower than salt hydrates, as reported by (Saxena et al., 2018). Importantly, it is noteworthy that the solidification process is fully completed by the time the temperature reaches 30°C for both PCMs.

4.1.3.2 Phase Change Enthalpy

Phase change enthalpy, another DSC measure, quantifies PCM efficiency. Table 4.3 summarizes the melting and solidification enthalpies. The mean enthalpies for OM35 during melting and solidification are 191.4 J/g and 159.6 J/g, respectively. Conversely, the average melting and solidification enthalpies for OM37 are determined as 189.2 J/g and 158.62 J/g.

PCM's thermal reliability is critical, requiring it to maintain its heat storage capabilities after multiple melting and solidification cycles. In this study, DSC analysis is performed on two samples: one extracted from the dismantled macroencapsulated PCM unit after one year of exposure to ambient conditions and the other on the base sample for various cycles ranging from 200 to 1000. The sample extract from the dismantled unit is assumed to represent the 150 cycles of charging and discharging.

Table 4.3 Summary of Thermal characteristics of PCMs.

PCM	Solidification Cycle		Melting Cycle	
	Solidification temperature (°C)	Solidification enthalpy (Jg ⁻¹)	Melting temperature (°C)	Melting enthalpy (Jg ⁻¹)
OM35	32.411	158.6	37.038	191.8
	32.751	159.4	36.987	189.7
	32.397	160.8	37.028	192.6
	<i>Avg.</i>	32.519	37.028	191.4
OM37	33.29	150.06	40.081	190.2
	33.99	180.0	40.037	188.4
	34.164	145.8	40.073	189.0
	<i>Avg.</i>	33.814	40.063	189.2

Table 4.4 Melting and solidification enthalpies of OM35.

Thermal cycles	Solidification cycle		Melting cycle	
	Solidification Temperature (°C)	Solidification enthalpy, ΔH_m (Jg ⁻¹)	Melting temperature (°C)	Melting enthalpy, ΔH_m (Jg ⁻¹)
1	32.5	159.6	37.0	191.4
150	33.6	154.2	34.5	184.86
200	33.6	150.42	34.4	160.08
300	33.7	145.9	34.4	154.01
500	33.6	137.69	32.7	139.48
700	33.6	137.69	32.7	134.4
1000	33.1	122.5	33.5	125.4

Fig. 4.9 displays the DSC thermographs following 150, 200, 300, 500, 700, and 1000 cycles. Table 4.4 includes relevant melting and solidification temperatures and corresponding melting and solidification enthalpies. The results indicate PCM's melting and solidification temperatures remain stable after 1000 cycles. Moreover, the melting and solidification enthalpies are decreasing with increased thermal cycles. Between 1 and 1000 cycles, there is a decrease of 34.5% in the melting enthalpy and 23.2% in the solidification enthalpy. The reduction in enthalpies can be attributed to the deterioration of PCM during repeated phase transitions. In addition, the thermophysical characteristics at 150 and 200 cycles also demonstrate minimal variations, which showcases the stable thermal performance of the macroencapsulated PCM. Thus, the selected PCM shows good thermal stability even after undergoing multiple thermal cycles. Moreover, it has been reported that

OM35 demonstrates negligible changes in its melting, solidification, and associated enthalpies even after 2000 cycles (Patel et al., 2023). However, the thermal stability of PCM throughout a building's lifespan is crucial for consistent thermal performance and energy efficiency. Key factors include thermal degradation, phase separation, and encapsulation integrity. Ensuring long-term performance requires high-quality encapsulation techniques and regular quality checks.

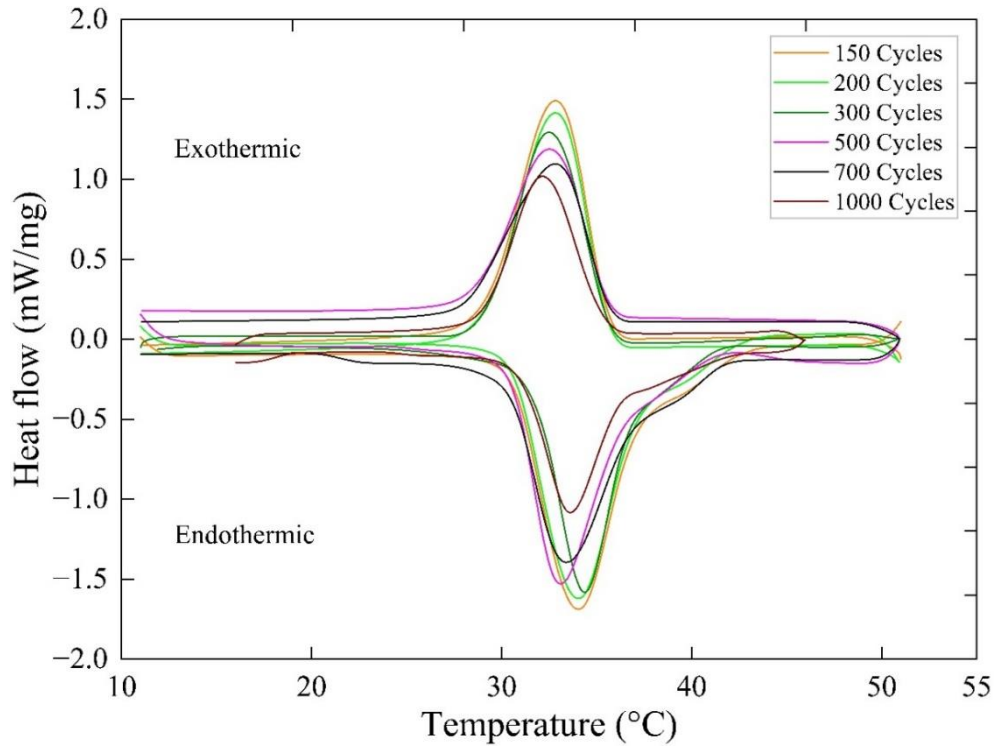


Fig. 4.9 DSC thermogram of OM35 for higher thermal cycles

4.1.4 Thermal Stability Analysis

TGA is a thermal analysis technique employed to assess the alterations in the physical and chemical properties of PCM materials. Concurrently, the mass of the sample is continuously monitored throughout the analysis. Typically, TGA measurements are conducted by incrementally raising the temperature at a constant rate or monitoring mass changes over time while maintaining a constant temperature. [Fig. 4.10](#) illustrates the TGA setup along with its block diagram. Various physical phenomena, such as second-order phase transitions, vaporization, desorption, and chemical processes, like decomposition and dehydration, can be investigated through TGA. TGA facilitates determining PCM sample mass loss or gain resulting from decomposition, degradation, oxidation, or loss of volatile compounds. Moreover, standardized TGA testing procedures enable the evaluation of PCM thermal stability in terms of their resistance to thermal decomposition or degradation.

Thermal stability assessment was conducted using TGA (Model: Mettler Toledo TGA 1 HT 1600). The temperature gradually increased from 27 °C to 500 °C at a rate of 5 °C/min. PCM starts losing weight at 126 °C and undergoes almost complete weight loss (97%) by 234 °C, as depicted in Fig. 4.11. Notably, the PCM exhibits slight weight loss within the temperature range of 27 °C to 126 °C, probably due to the apparatus used. Subsequently, 96.7%, 96.2%, and 96.9% weight losses were observed for samples 1, 2, and 3 until reaching 230 °C. Deviation in weight loss in PCM samples can be attributed to physical degradation resulting from melting-freezing cycles.

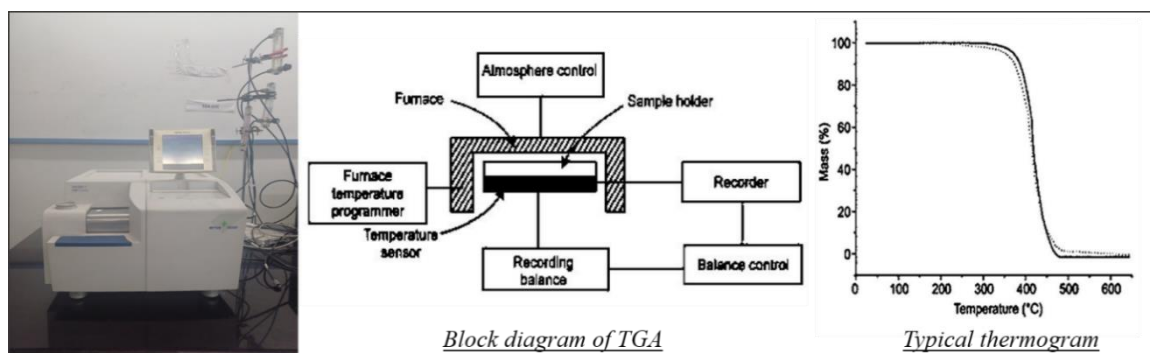


Fig. 4.10 Thermogravimetric analysis setup.

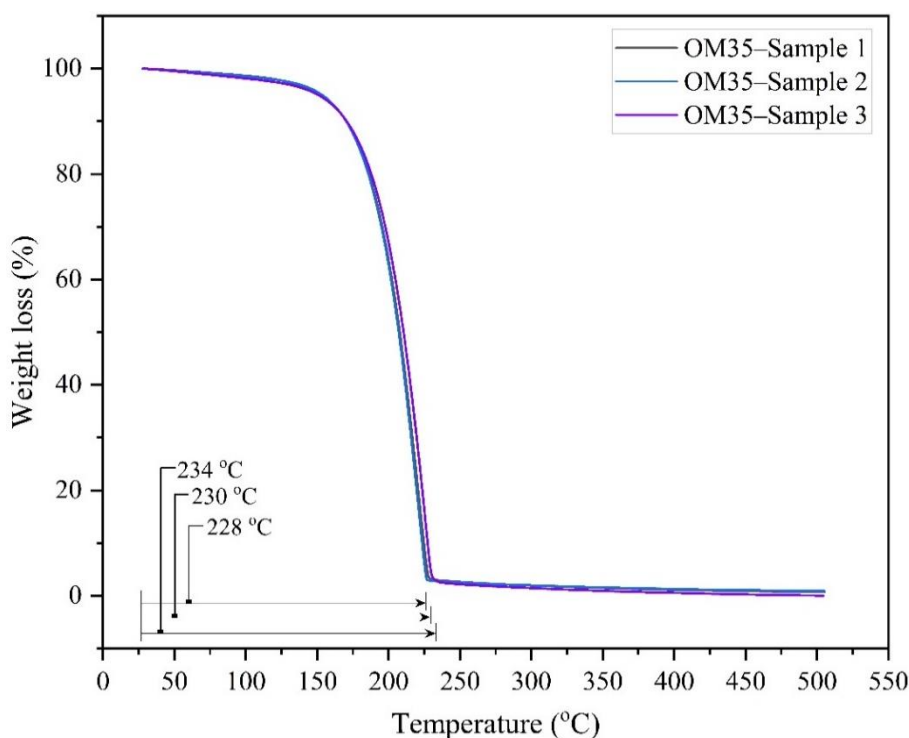


Fig. 4.11 TGA curves of PCM.

The TGA curves that portray the alterations in weight of the PCMs near the mean temperature (melting temperature range) are depicted in detail in Figs. 4.12(a and b). The in-depth examination

illuminated that both the PCMs underwent a rapid weight loss till phase change temperatures. Notably, the considerable reduction in mass for the PCMs amounted to 1.76% and 2.72%, as visually demonstrated in the figures. This discernible reduction in mass is attributed to the evaporation of the paraffin constituents inherent in the PCM composition. Rather intriguingly, a minor increment in mass (0.095%) was recorded between the temperature range of 35 °C and 40 °C for OM37. It is pertinent to highlight that a marginal increase in mass was observed at the initial stage for Sample 3rd of OM35 PCM, possibly attributable to factors such as the buoyancy effect of the TGA apparatus or sample oxidation.

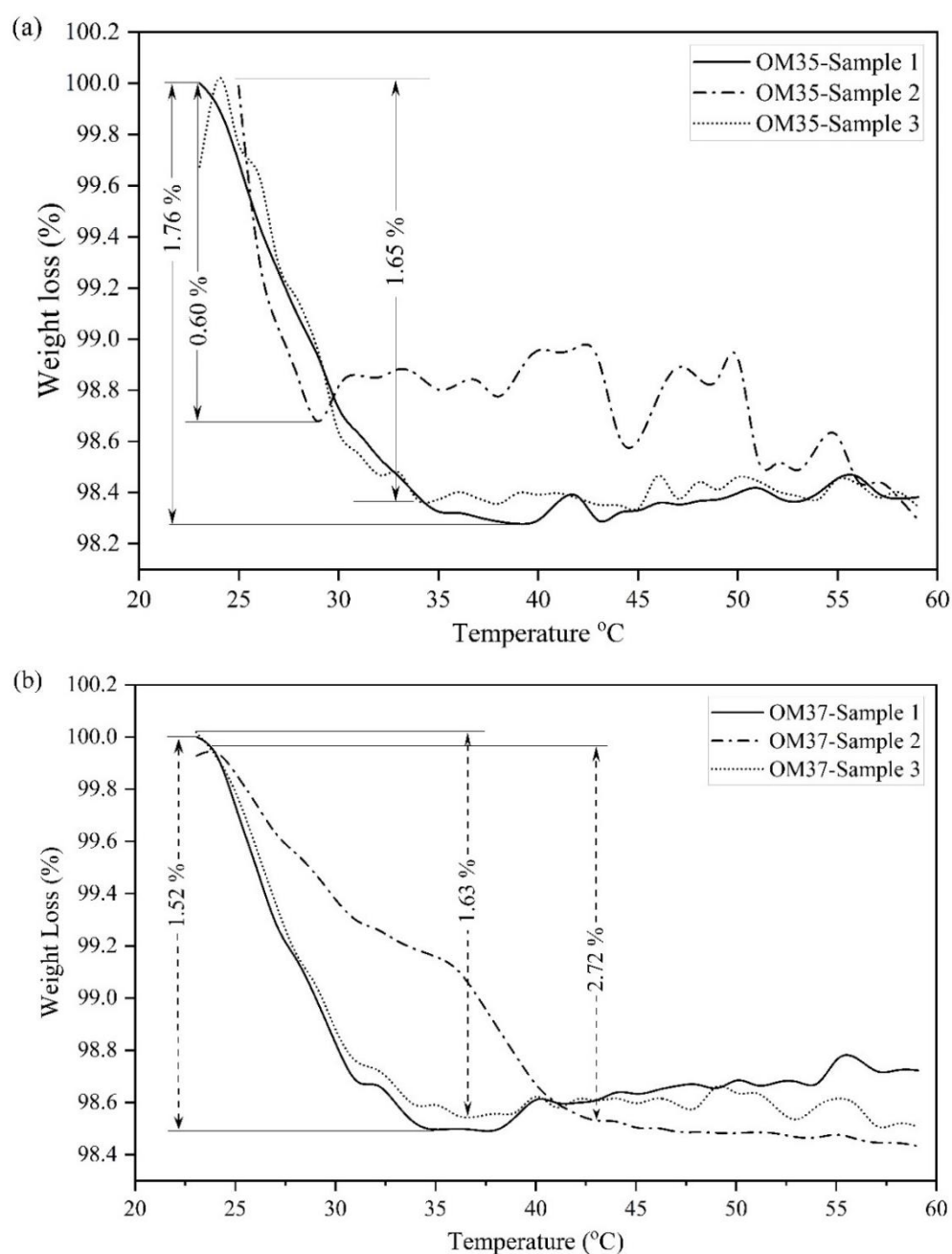


Fig. 4.12 TGA curves near phase change temperature: (a) OM35; and (b) OM37.

4.1.5 Microstructural analysis

Fe-SEM is employed for microstructural analysis, particularly examining crystallite structures and surfaces by scanning the material surfaces. Fig. 4.13a displays the Fe-SEM instrument installed at the Central Research Facility IIT Ropar, while Fig. 4.13b illustrates the schematic structure of the Fe-SEM. Controlling the operating parameters is essential to achieve the desired depth of field and resolution, thereby enabling the acquisition of high-quality SEM images.

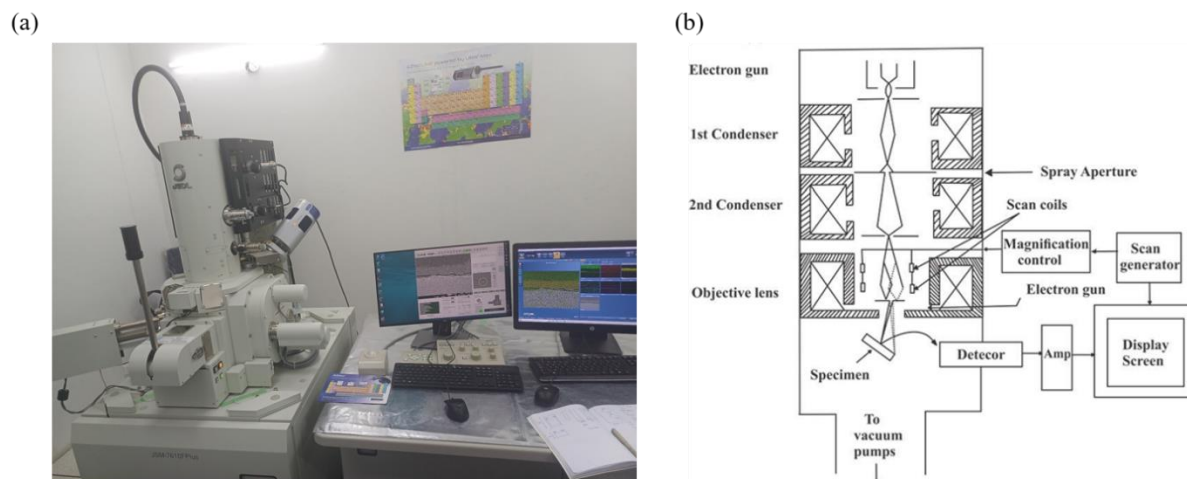
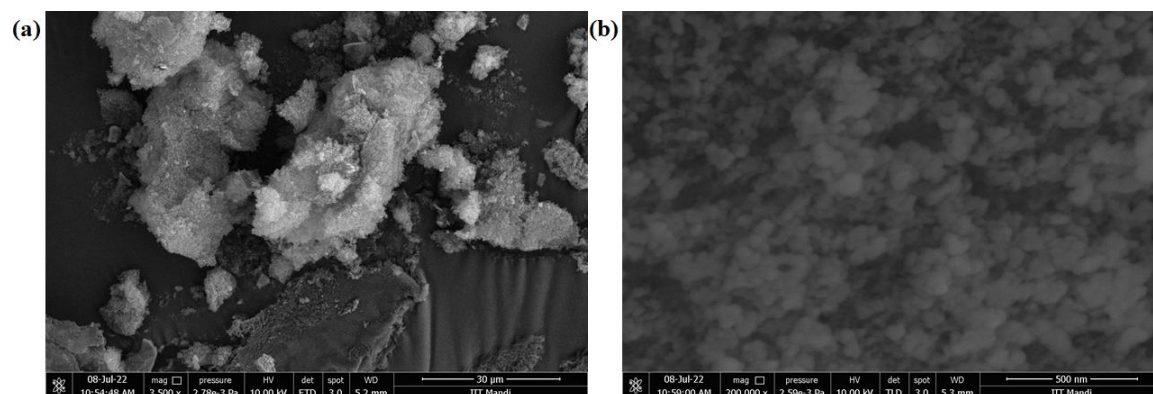


Fig. 4.13 Fe-SEM analysis: (a) Instrumental setup; and (b) Schematic diagram of Fe-SEM.

Figs. 4.14(a–c) shows the fractographic images of PCMs as observed through Fe-SEM (model: JSM7610F Plus), operating at an acceleration voltage of 15 kV. The captured SEM images of the PCMs distinctly unveil a profoundly porous structure. Fig. 4.14a shows the smooth surface of three-dimensional lamellar structures, indicating the adhesive nature of a PCM. Further, it can be seen that PCM crystallizes, leading to the formation of randomly aligned microplates. This particular structural arrangement, characterized by a lamellar internal structure, is commonly observed in alkanes possessing a linear molecular structure and an extended carbon chain.



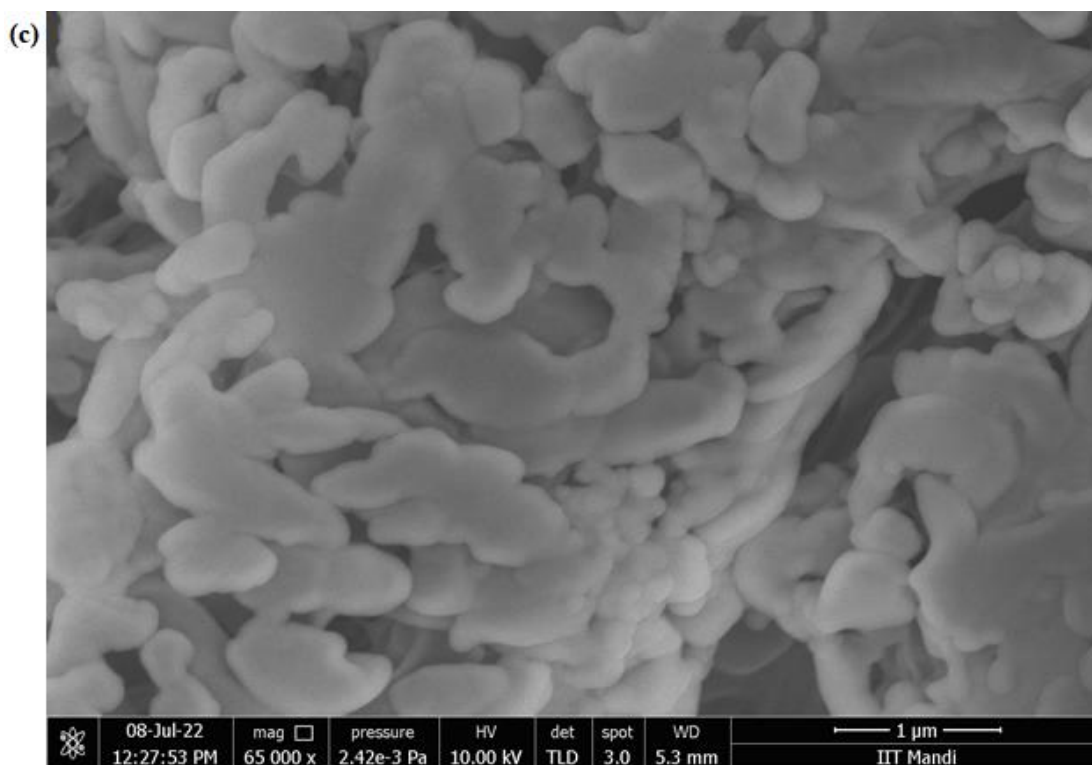


Fig. 4.14 Fe-SEM images of PCMs at lower and higher magnification.

4.2 Concluding remarks

The investigation conducted in this study delved into the comprehensive thermophysical properties of PCMs. By leveraging the experimental data provided within this study, the thermal behavior of PCMs within a TES system can be readily anticipated and simulated. The thermal conductivity of the PCM was determined to be 0.22 and 0.20 W/mK, respectively, which represents a 13% increase compared to the manufacturer's specifications. Morphological examinations revealed the presence of smooth surfaces within three-dimensional lamellar structures, suggesting the adhesive nature of the PCM. Analysis of FT-IR spectra indicated significant physicochemical compatibility of the PCMs. XRD spectra exhibited favorable crystallization behavior of the PCMs.

Experimental outcomes from DSC demonstrated that both PCMs exhibited a singular melting/solidification peak, signifying the transition between solid and liquid phases, occurring at temperatures of 37.02, 32.51, and 40.06, 33.81 °C, with corresponding latent heat of fusion values measuring 191.4, 159.6, and 189.2, 158.62 J/g, respectively. Furthermore, the PCMs demonstrated minimal alterations in their melting and solidification behavior and associated enthalpies even after undergoing 1000 cycles. TGA thermogram indicated that the PCMs initiated weight loss at 126 °C, followed by rapid decomposition leading to nearly complete weight loss (97%) by 234 °C. Overall thermal characterization suggests that the PCMs hold promise for applications in energy storage within building envelopes.

Energo-Economic Evaluation Of PCM-Integrated Concrete Roof Under Ambient Conditions

5.1 Introduction

Researchers have extensively studied incorporating PCMs into building materials and components to control indoor climate using experimental, analytical, and numerical methods. Examples of building materials that have been studied extensively include wallboards, tiles, bricks, cement mortars, and concrete, as they offer a large heat transfer surface area and a high heat transfer rate. PCM-integrated roofing systems are considered to be one of the various methods for energy refurbishment in all types of buildings due to their ability to accommodate large amounts of PCM as structural elements, high heat exchange surface-to-depth ratio, and the ability to be applied to all building types. The preponderance of research in this field has centered on the utilization of PCM-integrated roofs, with no reports to date in the literature concerning the incorporation of commercially available PCMs into BVS roofing systems, despite several studies identifying PCM-integrated roofs as a potential technology for enhancing indoor thermal comfort. Moreover, the preceding chapter of this thesis substantiated the appropriateness of the PCM used in the BVS roofing system for construction due to its highly adequate thermal energy storage capacity.

The main objective of this chapter is to assess the thermal performance enhancement of PCM-incorporated BVS roofs in buildings to improve indoor thermal comfort. The research primarily focuses on investigating the impact of enhanced roofs on indoor thermal comfort conditions, peak indoor temperature reduction, and diurnal temperature fluctuations. Experimental research is conducted on laboratory-scale test modules exposed to the outdoor environment, which includes PCM-incorporated roof slabs and conventional roof slab units. The roof slabs were subjected to environmental conditions that were similar to the weather patterns in the Main campus of the Indian Institute of Technology, located in Ropar, India. The study, which aimed to evaluate the thermal performance of PCM concrete roofs in the spring, summer, and autumn seasons, lasted three months from April 15, to September 15.

5.2 Materials and Methods

5.2.1 Materials

The performance of PCMs is intricately linked to the thermal fluctuations in their surrounding environment. In essence, PCMs operate by absorbing thermal energy during periods of solar

exposure, transitioning from a solid to a liquid state, and releasing this stored energy during non-sunny hours as they revert from a liquid to a solid state. Consequently, consistent cycling between these two phases, known as charging (solid-to-liquid transition) and discharging (liquid-to-solid transition), is indispensable for the efficient thermal regulation of building envelopes integrating PCM technology. The selection of an appropriate PCM is paramount, and this selection process is facilitated through a technique called PCM mapping and benchmarking. This method considers a range of PCM characteristics, including their thermophysical properties, thermal cycle stability, environmental conditions, and heat transfer capabilities (Bhamare et al., 2020; Saxena, Agarwal, et al., 2019).

The daily charging and discharging of PCMs are contingent upon two primary factors: the inherent thermophysical attributes of the PCM itself and localized temperature variations. Local temperature fluctuations are influenced by many climatic variables, encompassing temperature, wind speed, air humidity, sky conditions, precipitation, and solar radiation (Saxena et al., 2020b). Given the substantial variance in local climatic conditions and the limited operational temperature range of PCMs, it becomes imperative to ascertain the optimal melting point for a PCM in accordance with the specific local climate. Rupnagar, India, was chosen as the study location in this study. Rupnagar is geographically situated at coordinates 30.9661°N and 76.5231°E, with an average elevation of 260 meters above mean sea level. It is characterized by a humid subtropical climate featuring dry winters. Meteorological data were employed to obtain mean daily maximum and minimum temperatures, which are graphically depicted in Fig. 5.1. The months of May and June typically register the highest temperatures, while December and January experience the lowest. Temperature fluctuations in the city can span from a scorching maximum of 47 °C during summer to a chilly minimum of 0 °C in winter. Notably, during summer, the building encounters significant temperature oscillations, with average daily temperatures ranging from 43 °C during the day to 27 °C at night.

It's worth noting that Fig. 5.1 emphasizes that selecting a PCM with a melting point closely aligned with the thermal comfort temperature might not be ideal. This is primarily since Rupnagar often experiences mean temperatures exceeding 32 °C during the summer season. Furthermore, to maximize the potential for daily charging and discharging, the phase change temperature of the PCM must fall within the established range of maximum and minimum temperatures. Failure to meet this criterion may result in the PCM's incapability to function effectively as a latent heat thermal energy storage system. In this study, a commercially available organic PCM named OM35 has been chosen. OM35 is non-paraffin-based and exhibits a phase transition temperature of 35 °C (Ref. Table 4.1). Importantly, a numerical investigation (Saxena, Agarwal, et al., 2019) has indicated a PCM melting temperature of 34 °C for a study location with similar climatic conditions.

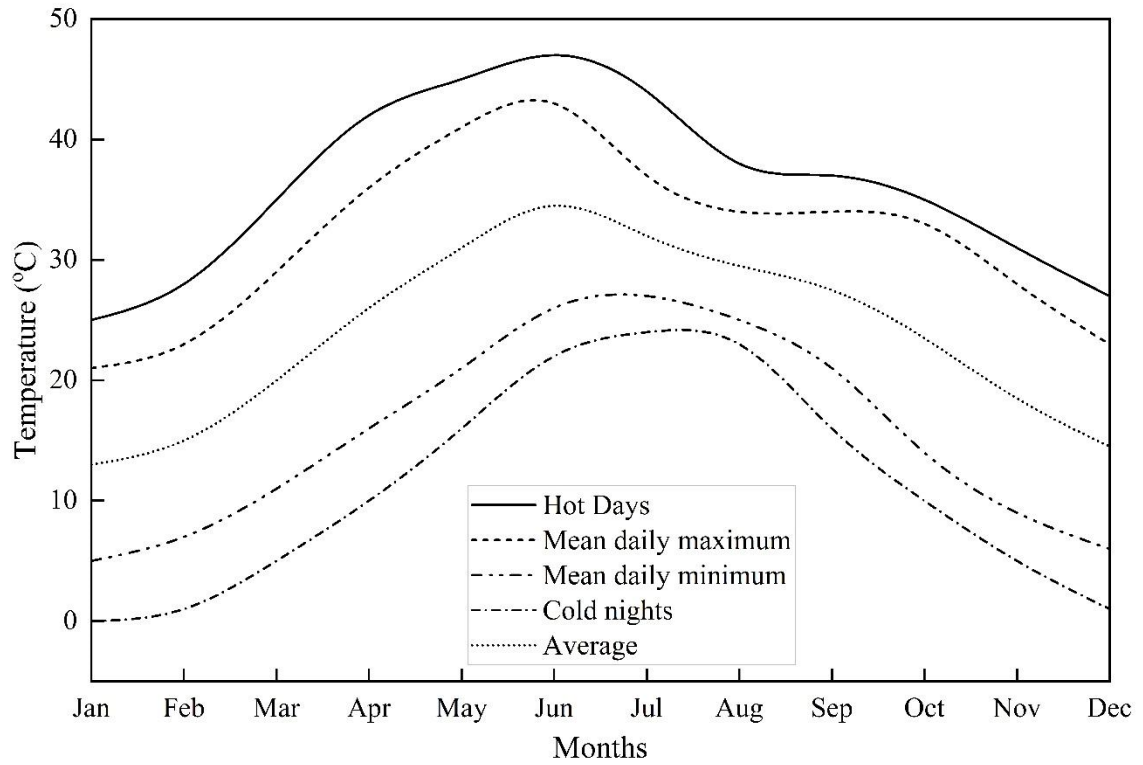


Fig. 5.1 Monthly temperature variation in the study area (*Simulated historical climate & weather data for Ropar - meteoblue, n.d.*).

The Indian subcontinent receives an average annual global solar irradiance of 5 kWh/m²/day, with approximately 58% of the region receiving this amount (Ramachandra et al., 2011; Rathore et al., 2019). The intense solar radiation leads to increased solar heat gain in the building envelope, causing thermal discomfort and a rise in energy consumption for space cooling (De La Flor et al., 2005; Gueymard & Thevenard, 2009). In tropical countries like India, space cooling requirements are often higher than space heating requirements due to the high solar radiation levels. As such, the experimental site's location is well-suited to assess the effects of increasing latent heat storage capacity using MPCM on the building's indoor thermal behavior. The high atmospheric temperature leads to complete melting of the PCM, resulting in maximum utilization of its latent heat.

Thermocouples were utilized for recording the indoor temperature of the building envelope and sol-air temperature. Additionally, the global solar radiant energy of the experimental site was measured using a Pyranometer. The collected data was analyzed to assess the effect of various factors on the indoor thermal condition of the building envelope on an hourly, monthly, and seasonal basis. The peak indoor temperature, peak heat flux across the building envelope walls, sol-air temperature, and global solar radiation were measured and analyzed. During the year-long data monitoring, the experimental site experienced various weather conditions and seasons, including summer and winter, along with sudden rainfall and thunderstorms. This study can be useful in predicting the

potential of incorporating PCM into building envelopes to develop energy-efficient buildings in locations with different weather conditions and seasons.



Fig. 5.2 Meteorological station positioned at the Main campus of IIT Ropar.

Table 5.1 Specification of sensors used in the weather (station (Automatic & Station, 1962).

Specification		
Data logger	Channel:	12 flexible digital channels
	Resolution:	18-bit resolution
	Operating temperature:	-45° to + 70 °C
Ambient temperature sensor	Sensing:	standard PT-RTD element
	Range:	-40° to + 60 °C
	Resolution:	0.1 °C
	Accuracy:	+0.2 °C
Solar radiation sensor	Sensor:	72 element thermopile
	Sensitivity:	~ 20 micro volts/W/M ²
	Time constant:	< 30 seconds
	Range:	0 – 1500 W/m ²
	Output:	0 – 25 mV

A Wireless automatic weather station, manufactured by Aimil Ltd. India, was utilized to measure the local weather conditions. The weather monitor was installed on a pole at precisely 2 and 8 meters above the ground, [Fig. 5.2](#). It was strategically located to avoid any shading effects caused by nearby plants and structures. The weather station has a digital thermometer, a humidity meter, a

solar sensor, an anemometer to measure wind speed, and a wind vane to determine wind direction. Additionally, it measures relative humidity and horizontal global radiation.

Table 5.1 summarizes the weather station's sensors and their relevant precision. At predetermined intervals of 30 minutes, the sensors for measuring the aforementioned weather variables electronically record their readings and transmit them to a console unit. The console unit must be placed in a secure location to avoid theft or damage, and it can be situated up to 300 meters from the weather monitor. In this investigation, the console unit was installed in a room approximately 60 meters from the weather monitor. Additionally, the console unit includes two extra sensors for measuring indoor thermal parameters, specifically dry bulb temperature and relative humidity.

The aforementioned measurements served as the fundamental data for assessing various metrics in both experiments involving the roof slab. These metrics include:

1. Temperature profile,
2. Heat transfer,
3. Thermal loadings
4. Time lag,
5. Decrement factor,
6. Electricity cost savings,
7. Payback period,
8. CO₂ emissions
9. Thermal comfort analysis

5.2.2 Macroencapsulated Void former

Void formers are hollow inclusions that are integrated into RCC structural components, such as slabs found in various infrastructure projects like buildings and bridges. By introducing these inclusions, the total volume of concrete can be significantly reduced, resulting in a decrease in the structural self-weight. Typically, void formers are fabricated from materials like plastics or recyclable substances. They can be integrated into various parts of buildings, including floors, roofs, walls, and ground-level slabs. It's essential to note that these void formers are often positioned on the tension side of a structure's roof, where traditional concrete alone is less effective while maintaining both flexural strength and load transfer to support structures uncompromised.

The utilization of these void formers, typically empty inclusions, provides an opportunity to incorporate PCMs within them, effectively converting them into macroencapsulations. To serve effectively as macroencapsulations, void formers are expected to meet the following specific criteria: made of a material that is impermeable, compatible with the PCM that has been stored, and does not interact with either concrete or reinforcing enables effective melting of the encased PCM

and has higher heat transfer properties, has sufficient strength and rigidity to handle the imposed stresses before, during, and after concrete casting. In real applications, it is essential to completely stop PCM leakage into concrete during the PCM change from solid to liquid state. This prevents PCM from being mixed with concrete. As PCM changes its volume periodically throughout the charging and discharging cycles, mixing might weaken the compressive strength of concrete. For instance, it was shown that a 0.5% increase in PCM mass ratio resulted in a 32% reduction in compressive strength (Z. Zhang et al., 2013).

The choice of void former material significantly impacts PCM's heat transferability. In this perspective, metals are a superior void-forming material as compared to plastics. Aluminium was considered the void former material in this study because of its higher thermal conductivity and comparatively low corrosion rate. It is crucial to note that phase transition in PCM results in a volume change that, if it happens quickly, might distort the void former. An aluminum alloy, Al 1100, that complies with ASTM-B-209, is employed as the void former material for this study. The alloy's properties include a density of 2710 kg/m³, a melting temperature of 643-657.2°C, a yield strength of 70 MPa, an ultimate strength of 110 MPa, a modulus of elasticity of 68.9 GPa, and a 12% elongation at break. Note that [Table 5.2](#) lists the thermal and mechanical characteristics of Al 1100. Due to its improved thermal conductivity, compatibility with different PCMs, and low corrosion rate, aluminum has been employed extensively for numerous building energy storage applications (e.g. (Ferrer et al., 2015; Fukai et al., n.d.; Soares et al., 2021).

Table 5.2 Thermal and mechanical properties of Al 1100.

Thermal Conductivity (W/mK)	Brinell Hardness	Thermal Expansion (K ⁻¹)	Specific heat capacity (J/kg °C)	Coefficient of thermal expansion (µm/m-°C)	Modulus of Elasticity (GPa)	Electrical Resistivity (Ω.m)	Fatigue strength (MPa)
222	23	24×10 ⁻⁶	904	23.6	68.9	.0282×10 ⁻⁶	34.5

Some studies (e.g., (Caes et al., 2023; Kinoshita et al., 2013)) propose that aluminum might experience corrosion when embedded within concrete, particularly during the initial stages when the concrete exhibits high alkalinity. However, when conditions are favourable, aluminum can be compatible with the alkaline building materials present in concrete (Pitts, 1967). Nonetheless, research regarding aluminum corrosion within concrete is an ongoing endeavour, and substantial knowledge gaps persist in this domain (Herting & Odnevall, 2021). It's essential to highlight that phase transitions within PCMs can induce changes in volume, which, if occurring rapidly, could lead to deformations in the void former. The material selected for this study meets this criterion due to its higher strength.

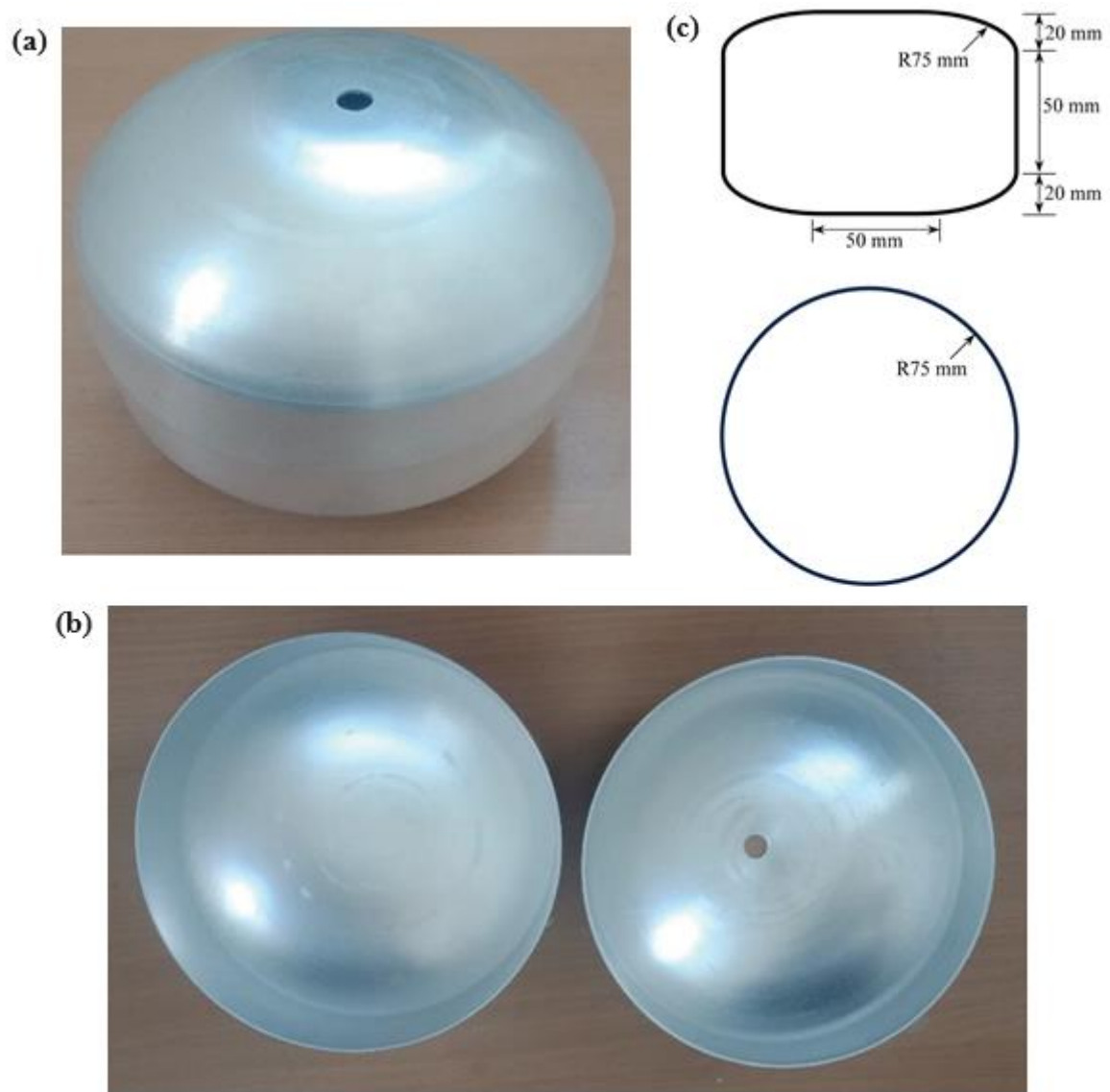


Fig. 5.3 Void former: (a) shape; (b) segments; and (c) dimensions.

It's worth noting that the geometries of the void formers can significantly impact the melting and solidification processes of PCMs, despite being chosen for their suitability in engineering applications. For instance, unstable supercooling phenomena have been observed at the sharp edges of rectangular geometries (G. Zhou & Han, 2017). On the other hand, shell and tube geometries have been identified as enhancing energy efficiency by over 70%. It's important to mention that spherical, cylindrical, and rectangular geometries are frequently employed for macroencapsulating PCMs (Zayed et al., 2020a).

Fig. 5.3 displays the void former created in this study using Al 1100. It has a symmetrical geometry and features a truncated spherical segment at either end and a cylindrical section in the middle. The cylindrical portion has a 150 mm diameter and a 60 mm height. The flat portion has a diameter of 50 mm, while the spherical portion has a radius of 75 mm. The two halves of the void former, as

depicted in (Ref. [Fig. 5.3b](#)), are produced via the process of cold forging, employing a sheet of Al 1100 with a thickness of 1.3 mm. These halves are subsequently interconnected to create a single unit. It's important to note that the design of the void former incorporates a hybrid structure characterized by the fusion of shell and cylinder geometries. This hybrid structure is engineered to optimize the processes of both melting and solidification of the PCM. The most common geometries for microencapsulating PCMs are spherical, cylindrical, and rectangular (Zayed et al., 2020b).

The developed void former is subjected to a compression test without PCM to ascertain its mechanical strength. Following the guidelines provided in ASTM-F9, the specimen is put through a compression test on the universal testing machine 1150KS housed in the Mechanical Engineering Department IIT Ropar. To ensure quasi-static compression, the specimen is subjected to a uniaxial deflection-controlled test at a speed of 0.15 mm/s. A curve, such as OABCDEF in [Fig. 5.4](#), may be used to illustrate the equivalent load-axial displacement relation. Between points O and A, most of the deflection occurs in the spherical section of the specimen. The specimen deforms axisymmetrically as the load increases up to point A. The maximum load the specimen can support before buckling is shown at point A. It's crucial to remember that point A denotes the buckling load, or the load at which the axial compressive force causes the top of the cylindrical portion to bend laterally.



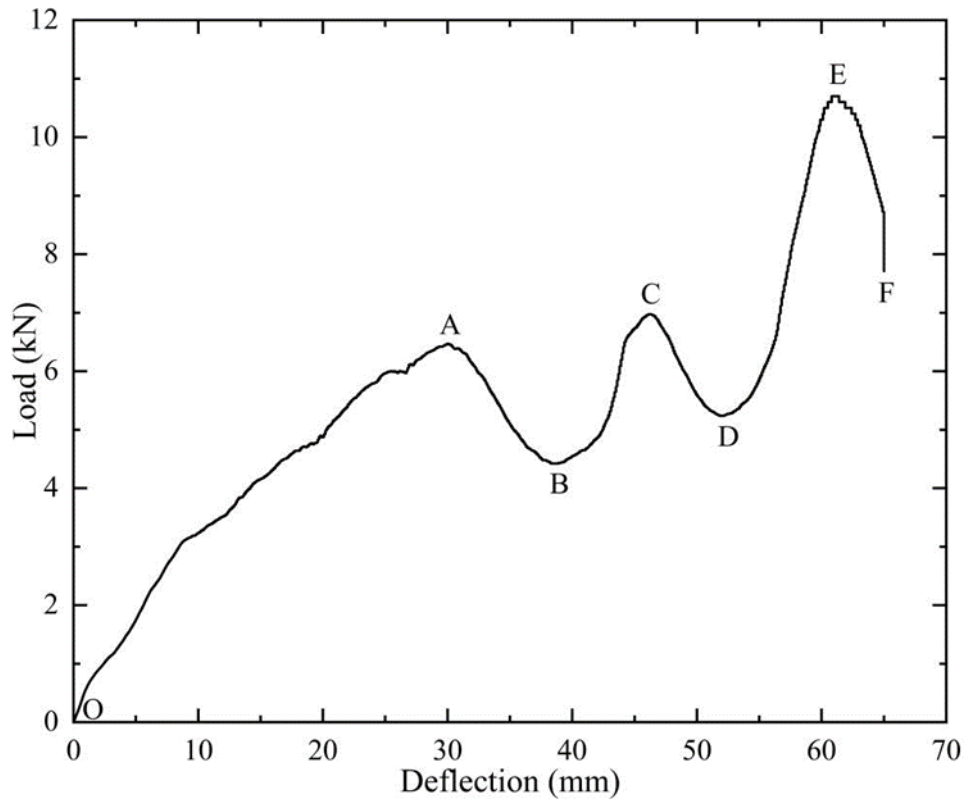


Fig. 5.4 Compression behaviour of void former.

The section ABCDEF of the curve (Ref. Fig. 5.4) depicts the specimen's post-buckling conduct. Reduced load bearing capacity is caused by increasing lateral deformation from buckling, which is represented by Part AB. Additionally, between B and C, strength is seen to be increasing due to the subsequent cylindrical part resisting the strain. Notably, the specimen has a load that is almost 16% larger at C than it is at A. This is due to the fact that the weight is now being resisted by the cylindrical component that is less thin. Point C, serves as a visual cue for the second buckling load, as another cylindrical component segment begins to bend laterally. Section CD illustrates how this causes more profound lateral distortion. For the same reason, points D and E show a rising trend in strength. However, the specimen at point E now resists load higher by about 57% than at point C due to a further reduction in the slenderness of the cylindrical section. The specimen starts to buckle once again at point E, and at point F, it fully crumbles. The void former's post-buckling strength has been found to be almost 70% higher than its initial buckling load.

Following an extensive investigation aimed at assessing the strength and stiffness characteristics of the developed void former, the process of macroencapsulation has been executed. Historically, PCM encapsulation has been conducted in either liquid form, as evidenced in previous studies (e.g., (Rathore et al., 2020)), or in solid form (e.g., (Yaping Cui et al., 2017)), contingent upon the specific geometry and integration configuration. In the present study, the PCM is encapsulated in its solid state within the lower half of the void former. This results in a total encapsulation thickness

of 50 mm within the void former, distributed as 20 mm in the lower truncated spherical portion and 30 mm in the cylindrical portion. Notably, the selection of PCM thickness aligns with established literature. A parametric analysis on building integration has identified an optimal range for PCM thickness spanning from 12 mm to 30 mm (Changyu Liu et al., 2017). Furthermore, experimental studies (Reference (Pasupathy & Velraj, 2008b)) have investigated the effects of incorporating 25 mm thick PCM into building roofs. Additionally, other research (Reference (Shanmuganathan et al., 2021)) has observed that increasing PCM thickness from 30 mm to 100 mm results in a 28% reduction in indoor temperature. Following the encapsulation of PCM within the lower half, the void former is affixed to its upper counterpart. The opening initially designed in the upper portion for liquid PCM filling has been sealed. Consequently, the process of macroencapsulation of PCM within the void former has been successfully completed, and the encapsulated PCM has been stored with care. This PCM-encapsulated void former is now poised for integration into the biaxial voided roof slab.

5.2.3 Biaxial Voided Roof Slab

A biaxial voided slab is a RCC two-way hollow slab structure. Its construction involves the incorporation of void formers within the concrete matrix, positioned both longitudinally and transversely between the upper and lower reinforcement grids. Void formers utilized in the construction of biaxially voided slabs can take various shapes, such as spheres, cylinders, donuts, cuboids, and hexagons with rounded edges (Chung et al., 2018; Sagadevan & Rao, 2020). The primary advantage conferred by this type of slab is a notable reduction in self-weight. In practical terms, a biaxial voided slab weighs significantly less than a solid slab of equivalent thickness. This reduction in self-weight can reach up to 35%. In real-world applications, this translates into the biaxial voided slab's ability to efficiently support heavier loads across similar span lengths or provide extended spans for prescribed superimposed loads (Yaping Cui et al., 2017). Furthermore, the diminished self-weight of the slab directly influences the material costs associated with structural components such as columns, beams, and load-bearing walls. These costs are notably reduced. Additionally, reducing self-weight has implications for seismic considerations, leading to decreased earthquake forces and influencing the design of elements responsible for resisting seismic forces. It's important to note that incorporating PCMs within the otherwise empty void formers compromises the self-weight reduction, with reductions ranging from 28% to 72% in general and a 36% reduction in the specific context of this study. These percentages are calculated by comparing the typical density of concrete, which is approximately 2500 kg/m³, with the varying densities of PCMs, which can range from 700 to 1800 kg/m³ (Yaping Cui et al., 2017).

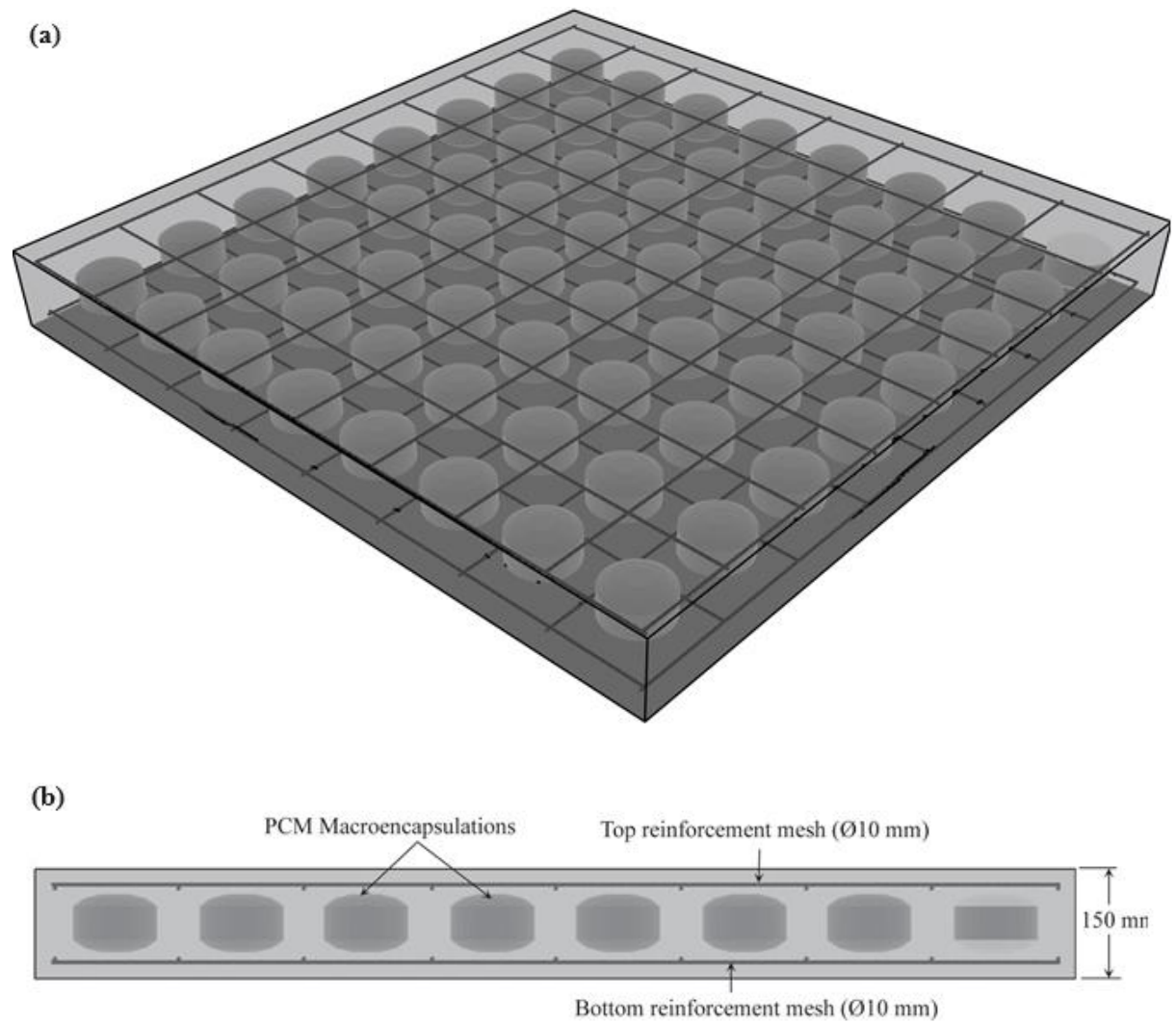


Fig. 5.5 Biaxial voided slab: (a) typology; (b) cross-section.

The design of the biaxially voided slab, the guidelines specified in ACI 318:2019, EN 1992-1-1:2004, and IS 456:2000 were followed with necessary modifications that consider the impact of voids on flexure and shear capacities. As the void formers are located beneath the neutral axis, the voided slab can withstand loads similar to those of a solid slab. However, the initial flexural stiffness of the voided slab may vary significantly. Therefore, the flexural stiffness of the voided slab was estimated using the maximum void ratio at a segment, following the recommendations given in (Philosophy, 2020). A theoretical design of a biaxially voided slab measuring $2\text{m} \times 2\text{m} \times 0.15\text{m}$ was carried out considering self-weight and superimposed load (2 kN/m^2). The 3D typology of the slab and its cross-section are shown in Fig. 5.5(a and b), respectively. The maximum void ratio at a section has been used to determine the flexural stiffness of the voided slab. The concrete and steel grades used were M20 and Fe415, respectively. The design process yielded a configuration of square meshes, positioned at both the upper and lower sections, featuring reinforcing bars with a diameter of 10 mm spaced at intervals of 150 mm in both

horizontal and vertical directions. The construction sequence for a building's roof employing a biaxial voided slab typically comprises several distinct phases. Initially, the lower reinforcement mesh is positioned onto the supporting formwork. Subsequently, void formers are strategically arranged in two orthogonal directions. Following this, a secondary reinforcement mesh layer is placed atop the void formers. Fig. 5.6(a and b) illustrates the plan and schematic cross section of biaxial voided slab. Finally, the entire slab is cast using fresh concrete.

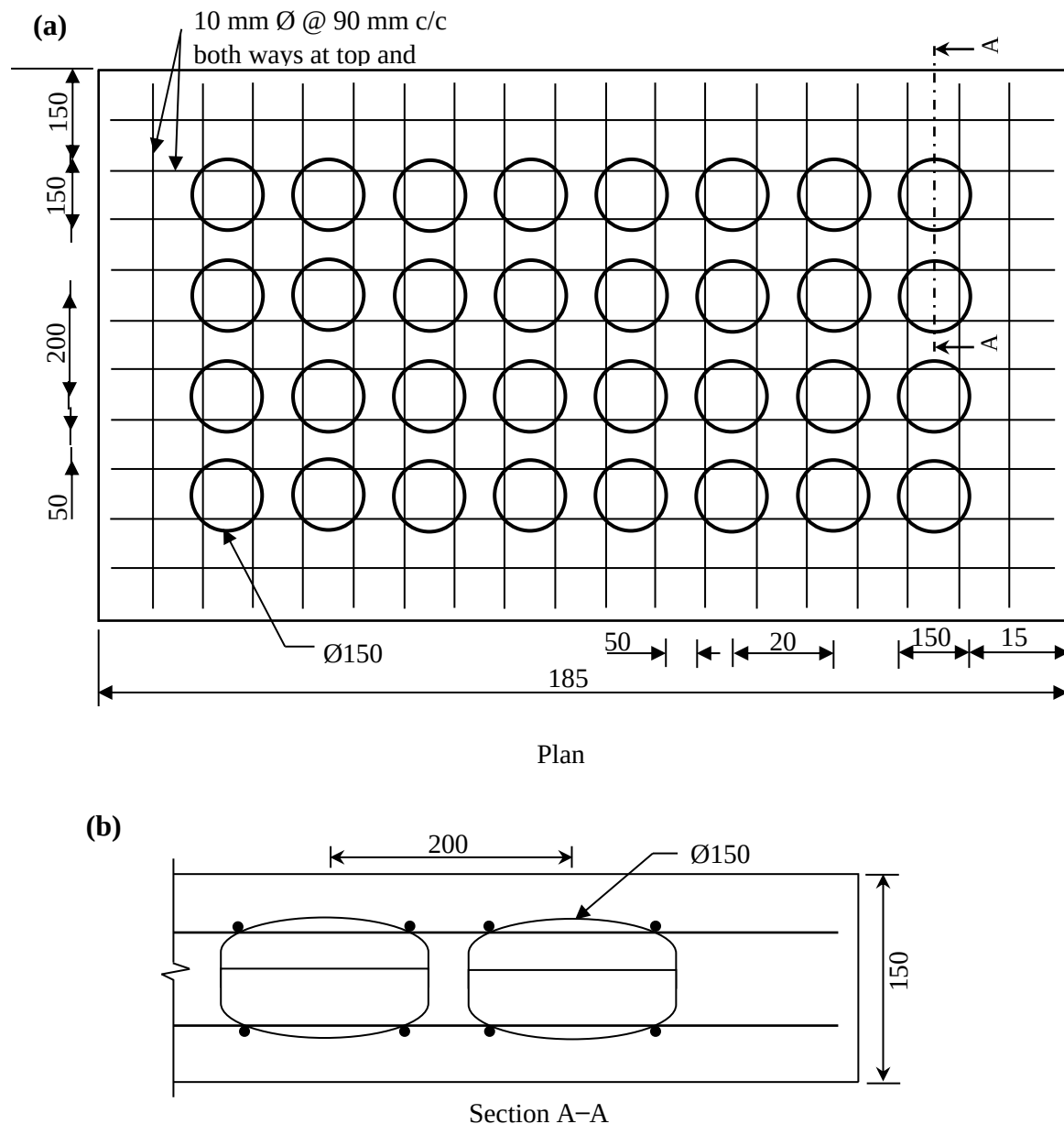


Fig. 5.6 Biaxially voided slab: (a) plan and (b) schematic cross-section.

5.2.4 Experimental Procedure

The structural arrangement of a biaxial voided slab can be conceptualized as a repetitive pattern of individual voided segments arranged both longitudinal and transversely. The term "unit cell" is

commonly employed to describe a single segment within this pattern. A unit cell serves as a practical means to investigate the thermal characteristics of the entire biaxial voided slab. In the study, experiments are conducted utilizing a unit cell. Fig. 5.7 illustrates a unit cell schematic. The unit cell comprises a slab segment measuring 300 mm long, 300 mm wide, and 150 mm deep, along with one OM35-filled aluminium void former. The unit cell is also equipped with two square mesh reinforcements consisting of 10mm steel bars at the top and bottom. The core region of the biaxially voided slab can be theoretically constructed by horizontally stacking several unit cells in opposite directions. The unit cell effectively simulates the thermal behavior of a voided slab during one-dimensional heat transfer, and the adoption of unit cell models has gained widespread acceptance, primarily due to their economic feasibility. The utilization of unit cell models has gained extensive recognition primarily because of their economic viability. However, it is crucial to recognize that the unit cell approach does not precisely replicate the mechanical loading conditions. Given that the principal aim of this study is to assess thermal performance rather than the effects of mechanical loading conditions, the adoption of the unit cell methodology is justifiable. Subsequent sections will elaborate on the unit cell casting procedure.

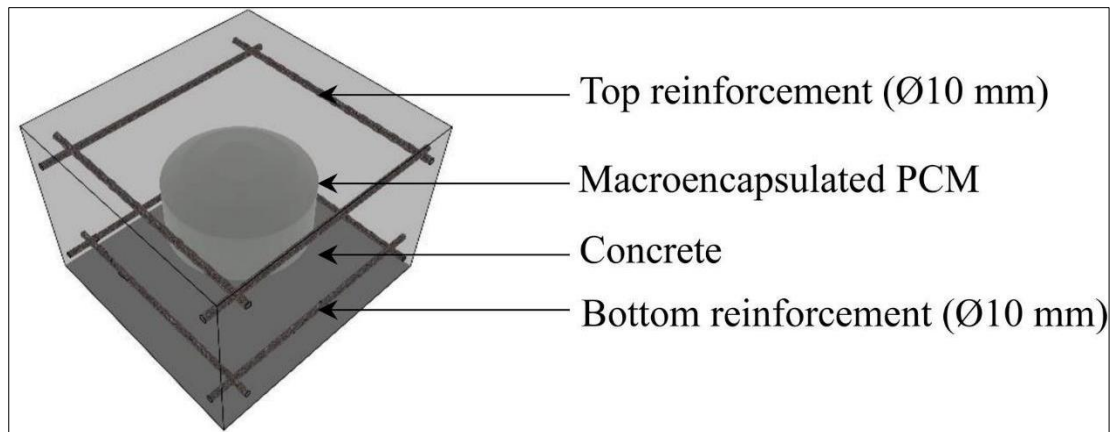


Fig. 5.7 Unit cell of biaxial voided slab.

Fig. 5.8 depicts a schematic of the unit cell casting procedure. Two wooden moulds, measuring $300 \times 300 \times 150$ mm, are used to cast two concrete specimens, one of which is regular concrete and the other reinforced concrete with a 1 cm-filled void former. The conventional method is used to cast the former, which involves mixing M20-proportioned (1:1.8:3.1:0.5) cement, fine aggregate, coarse aggregate, and water, then pouring the fresh concrete slurry into the wooden mould in layers and compacting it appropriately. To cast the latter, four 15 mm thick concrete cover blocks are used to position the bottom reinforcement mesh in the centre of the wooden mould. Up to 50% of the volume of the aluminium void former is filled with OM35 in the solid state, with the spherical and cylindrical parts of the void former having maximum and minimum thicknesses of 75 mm and 30 mm, respectively. The PCM thickness used in the experiment is based on existing studies, with

PCM thickness ranging from 12 to 30 mm according to parametric research on building integration. In this experiment, a PCM thickness of 25 mm was chosen, which was reported in reference (Pasupathy & Velraj, 2008b). Moreover, increasing the PCM thickness from 30 mm to 100 mm reduced the interior temperature by 28%, according to both theoretical and experimental studies (Shanmuganathan et al., 2021). The bottom 15 mm of the wooden mould's thickness is filled with concrete slurry and compacted. Then, using a dumpy level, the aluminium void former filled with OM35 is placed horizontally on top of the bottom concrete, and further concreting is done to achieve the desired depth. The top reinforcement mesh is then placed, and concrete is poured and levelled to the top of the mould. After 24 hours, the specimens are removed from the moulds and given 28 days to cure.

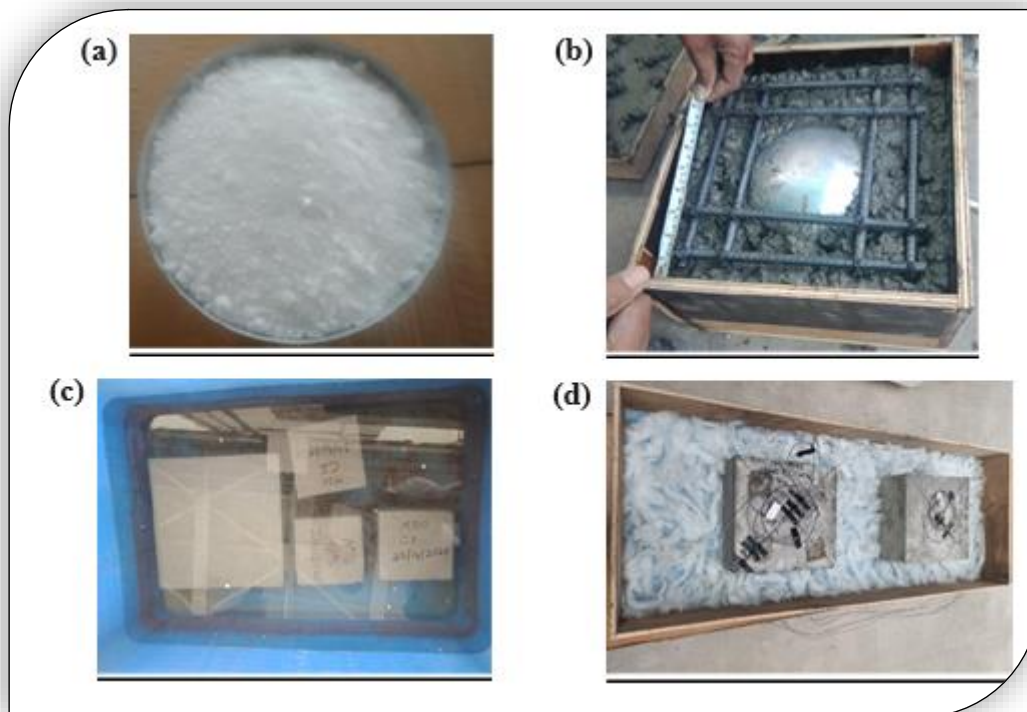


Fig. 5.8 Casting procedure: (a) PCM filled void former; (b) unit cell casting; (c) curing; and (d) wooden moulding with insulation.

The specimens are transferred to a second wooden mould measuring 1380×540×175mm. To prevent heat transmission from all sides except the top, the specimens are carefully packed with layers of extruded polystyrene and glass wool fibers to prevent heat transfer from all sides except the top (Ref. Fig. 5.8). Nine thermocouples are affixed to the specimens for temperature measurement. Two thermocouples are placed at the top and bottom of the PCM concrete specimen, one at the top and bottom of the regular concrete specimen, and three at the bottom of the PCM integrated concrete specimen, just beneath the void former aluminum in a triangular shape. The

thermocouples utilized in the experiment have a temperature precision of $\pm 0.1^{\circ}\text{C}$ and have undergone prior calibration in a lab using boiling water and ice. In the experiment, one-dimensional heat transfer is assumed to occur initially through the top layer of concrete and top reinforcement mesh, followed by the void former aluminum material, air gap in the top 50%, PCM, bottom reinforcement mesh, and bottom concrete layer. The temperature data is recorded every minute using a 16-channel auto-recording data logger. Fig. 5.9 displays the experimental setup and schematic. Except during rainy days, the entire experimental setup is exposed to the sun every day and is covered with a thin, transparent, waterproof sheet.

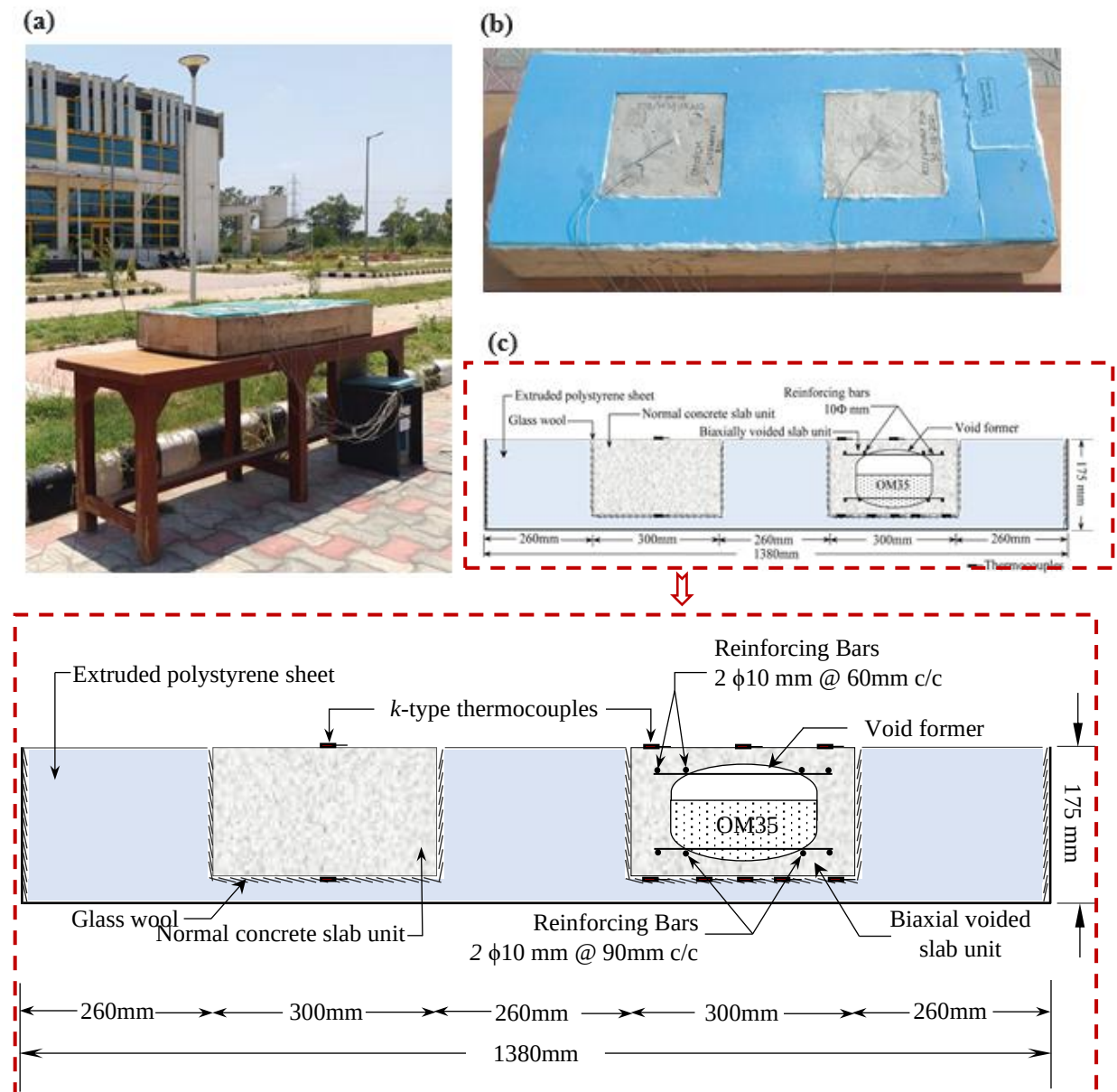


Fig. 5.9 Experimental setup: (a) atmospheric exposure; (b) top view; and (c) schematic cross-section.

5.3 Parameter Estimation

5.3.1 Heat Transfer

The assessment of heat transfer into the interior is a crucial parameter in evaluating a building's thermal insulation capacity against external environmental conditions. It's imperative to underline that the intricate study of heat transfer holds paramount significance in precisely ascertaining the cooling energy demands and appropriately sizing cooling systems within buildings. The analysis of heat transmission through unit cells, including regular concrete and PCM integrated concrete, utilizes the Fourier law. The governing differential equation for heat transfer is expressed as follows:

$$\rho C_p \dot{T} = \vec{\nabla} \cdot (K \vec{\nabla} T) \quad (5.1)$$

Here ρ , C_p , and K refer to the density (kg/m³), specific heat (J/kg K), and thermal conductivity (W/m K) of the material, respectively. For regular concrete, K represents the PCM's thermal conductivity (-1.4 W/m K). However, since PCM-integrated concrete is a composite material, evaluating its thermal conductivity requires considering the K values of concrete, aluminum, air, and PCM. The thermal resistance network is a commonly used method for this purpose. This method divides the composite material into several layers, similar to electrical resistance. The K values of all the layers are then combined to obtain the effective thermal conductivity (K_{eff}). The thermal resistance network for the concrete with PCM inclusion is computed using the following equation:

$$\frac{1}{K_{\text{eff}}} = \frac{1}{h_{\text{es}}} + 2 \times \frac{\delta_c}{k_c} + 2 \times \frac{\delta_{\text{Al}}}{k_{\text{Al}}} + \frac{\delta_{\text{Air}}}{k_{\text{Air}}} + \frac{\delta_{\text{PCM}}}{k_{\text{PCM}}} + \frac{1}{h_{\text{is}}} \quad (5.2)$$

where δ_c , δ_{Al} , δ_{Air} , and δ_{PCM} denote represent the thickness of concrete, aluminium (=222W/mK), air (=0.275 W/mK), and PCM (=0.2 W/mK), respectively, while h_{es} and h_{is} denote the outer and inner convective surface coefficients (W/m² °C). Fig. 5.10 shows the thermal resistance network used in the current study. It should be noted that the Fourier law relies on several assumptions to predict heat transfer in PCM-integrated concrete, including 1 D heat transfer, heat transfer only from the top surface, and a square cross-section for the void former. The heat transfer is computed as follows:

$$Q = K_{eff} A (T_{es} - T_{is}) \quad (5.3)$$

where A is the area over which heat flow occurs (m^2), T_{es} and T_{is} are the surfaces' respective inner and exterior temperatures ($^{\circ}C$).

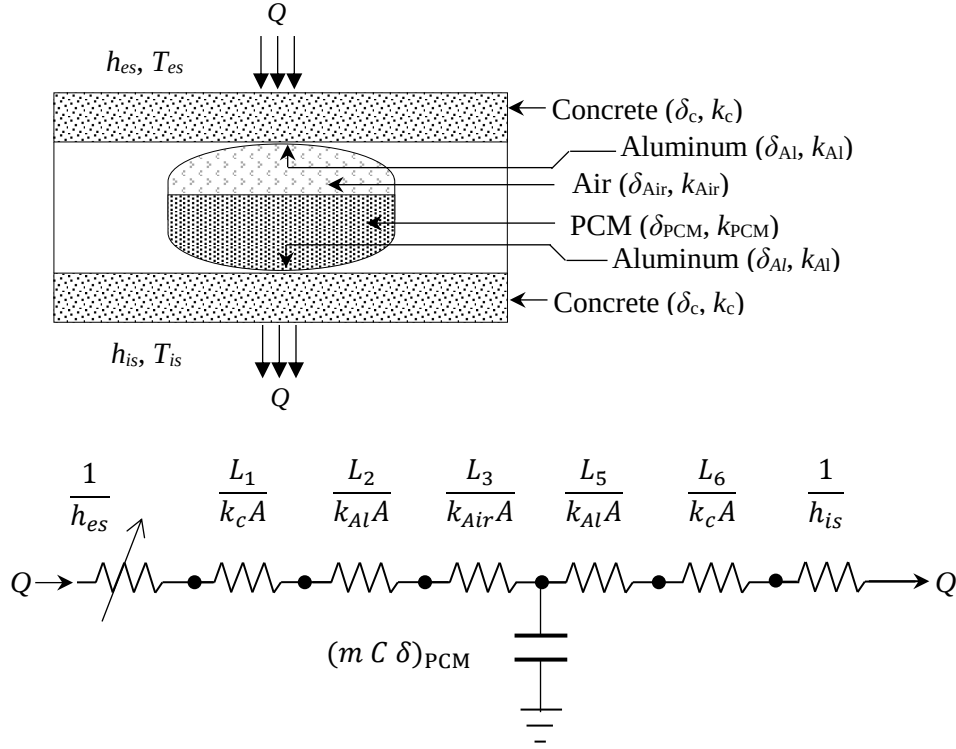


Fig. 5.10 Thermal resistant network.

Peak heat flux reduction is an important parameter that signifies reduction in the size of space cooling equipment. Due to significant latent heat storage capacity and thermal regulation PCM/NePCMs specimens offer substantial heat flux reduction. It can be evaluated as:

$$\Delta H_f = H_f^{CRS} - H_f^{PCM/NePCM} \quad (5.4)$$

where ΔH_f represents heat flux reduction, H_f^{CRS} and $H_f^{PCM/NePCM}$ represent heat flux in CRS and PCM/NePCM specimens. Based on heat flux estimates, cooling and heating thermal load through the testing units during the two testing periods can be calculated. To calculate thermal loads, the heat flux values are integrated over time employing the following equation (Eq. 5.5):

$$H_L = \int H_f \cdot dt \quad (5.5)$$

where H_L corresponds to the thermal load measured in Wh/m². The thermal load has a significant impact on the indoor thermal environment and the functioning of the air conditioning system.

5.3.2 Time Lag and Decrement Factor

The temperature profiles at a specified cross-section of the test specimen exhibit diurnal variations spanning 24 hours. These fluctuations are primarily driven by the dynamic interplay between interior and exterior temperatures and are further influenced by the inherent thermophysical properties of the specimen. Heat transmission within the specimen follows a transient pattern, resulting in alterations in both amplitude and wavelength of the temperature profile between its external and internal surfaces. Here, amplitude corresponds to temperature variations, while wavelength signifies the temporal aspect. Variations in temperature on the exterior surfaces can be attributed to factors such as solar radiation and convective air currents at the surface. Conversely, interior surface variations arise due to heat transfer driven by the evolving thermophysical characteristics of the constituent materials. Consequently, it is anticipated that the amplitude of the heat wave will be more pronounced at the outer surface compared to the inner surface. In this context, "time lag" pertains to the duration taken for the heat wave to propagate from the outer to the inner surface, whereas the "decrement factor" signifies the reduction in the amplitude ratio of this wave. It's worth noting that both time lag and the decrement factor are pivotal parameters in evaluating the heat storage capacity of a material.

Fig. 5.11 shows a schematic of the specimen's time lag and decrement factor. The reduction factor (f) and time lag (ϕ) are evaluated using following equations, as detailed references (Igs, 1998; Toure et al., 2019).

$$\phi_{\text{CRS}} = t_{T_{\text{is,CRS}}^{\text{max}}} - t_{T_{\text{es}}^{\text{max}}} \quad (5.6)$$

$$\phi_{\text{BVS}} = t_{T_{\text{is,BVS}}^{\text{max}}} - t_{T_{\text{es}}^{\text{max}}} \quad (5.7)$$

$$f_{\text{CRS}} = \frac{T_{\text{is,CRS}}^{\text{max}} - T_{\text{is,CRS}}^{\text{min}}}{T_{\text{es}}^{\text{max}} - T_{\text{es}}^{\text{min}}} \quad (5.8)$$

$$f_{\text{BVS}} = \frac{T_{\text{is,BVS}}^{\text{max}} - T_{\text{is,BVS}}^{\text{min}}}{T_{\text{es}}^{\text{max}} - T_{\text{es}}^{\text{min}}} \quad (5.9)$$

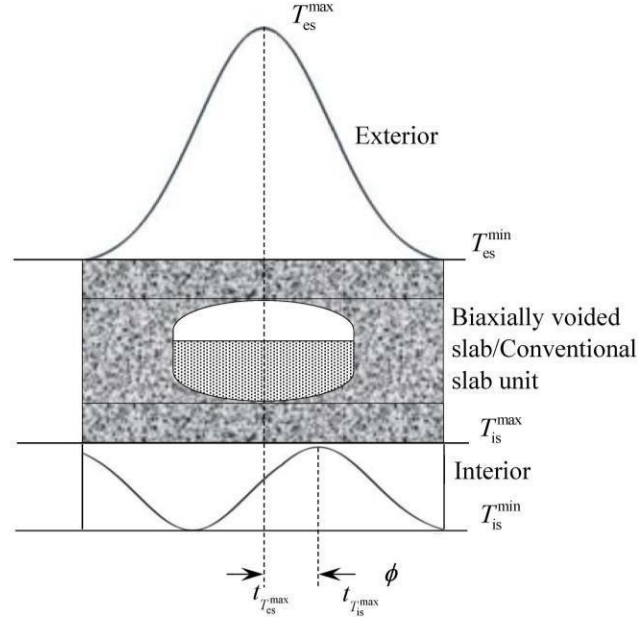


Fig. 5.11 Schematic of time lag and decrement factors.

where $T_{is,CRS}$ denotes the interior temperature °C of regular concrete measured, $T_{is,BVS}$ stands for the temperature measured at the interior surface of the PCM integrated biaxially void slab unit (°C), ϕ_{CRS} and ϕ_{BVS} indicate time lags in normal RCC and biaxial voided slab units, respectively, while f_{CRS} and f_{BVS} denote the corresponding decrement factors.

5.3.3 Electricity Cost Savings

Incorporating PCM into biaxial voided slabs can yield reductions in electricity consumption, leading to cost savings for residential consumers. Additionally, it offers advantages such as peak load shifting, energy conservation, and a reduction in peak demand for utility companies. Furthermore, assessing the potential cost savings in electricity constitutes a crucial economic metric for evaluating the feasibility of this proposed technology. The building that releases less carbon into the environment can be described as carbon minus building. Undoubtedly, there has been a significant rise of 16% in investments, amounting to USD 237 billion, in energy-efficient building materials in 2021 (*The Carbon Footprint Of The Construction Industry In India*, n.d.). However, recent reports indicate that carbon dioxide (CO₂) emissions have not declined despite these investments. The construction and building sector, encompassing processes such as lighting, cooling, and heating of building materials, accounts for approximately 40% of the overall carbon footprint (*Buildings & Built Infrastructure* | EESI, n.d.). This study calculates electricity cost savings by considering the reduction in peak heat flux achieved through integrating PCM into the

voided slab. Heat flux denotes the rate of heat transfer per unit area of a surface. Heat flux significantly influences the thermal performance of a building envelope, subsequently impacting heating and cooling demands. The peak heat flux value disparity between the normal RCC unit and the PCM-integrated voided slab unit signifies a reduction in peak heat flux. Supposing that the tariff for electricity in India is 7.3 Indian rupees (Bhawan & Puram, 2022; *Tariff for FY 2022-23*, n.d.), the daily cost-saving during peak loads can be estimated by (Rathore et al., 2020):

$$E_s = \Delta H_f^{\max} \times U_p \times 24hr \quad (5.10)$$

where E_s represents daily cost savings (Rupees/USD), $\Delta H_f^{\max}$ is peak heat flux reduction, and U_p represents the unit price of electricity. Among the three variables, U_p is region-specific and primarily influenced by the fuel consumption of combined heat and power generated by a power station. It's important to note that Eq. 5.8 has been deduced assuming that radiation losses can be effectively neglected. To compute cost savings, you can derive an estimate by substituting the peak heat flux values, along with the unit electricity price into Eq. 5.8.

5.3.3.1 Payback Period

The payback period is a widely used indicator for assessing the feasibility of an investment. The payback period is a quantitative measure to determine the time required to recoup the initial investment costs. In the current study context, it is the time required to amortize the initial investment costs of PCM or NePCM macroencapsulations in the roof. It is worth acknowledging that the recovery rate is contingent upon the annual energy savings achieved by reducing cooling and heating loads. The simple payback period (S_p) is a widely employed approach to determining the duration required to recoup the initial investment cost through annual cost recovery. S_p (year) is calculated as:

$$S_p = \frac{C_1}{E_s} \quad (5.11)$$

where C_1 represents direct investment cost of the PCM or NePCM specimens (Rupees/USD). It is essential to highlight that S_p fails to consider various factors commonly considered in financial analysis, including inflation, the time value of money, and the presence of uneven cash flows over time. To consider these factors, it is advisable to compute the discounted payback period (D_p). D_p incorporates the time value of money by using a discount rate to calculate the annual net cash flow.

This approach provides a more accurate evaluation of the investment's profitability. The D_p assessment involves comparing the HRS cost increase due to the inclusion of PCM or NEPCM with the annual electricity savings resulting from decrease in cooling and heating loads. Further, P_v represents the present value of anticipated future benefits adjusted for time effects and discounted at an appropriate rate. The current value of energy savings in the n -th year is (Panayiotou et al., 2016):

$$P_v = \frac{E_s}{(1-r)^n} \quad (5.12)$$

where r represents the rate of discount. The calculation of the net present value ($P_{v,net}$) allows for an estimation of the overall cost benefits that will be derived from future energy savings (Panayiotou et al., 2016):

$$P_{v,net} = \frac{E_s \left[(1+r)^n - 1 \right]}{r(1+r)^n} \quad (5.13)$$

The discount rate accounts for the time value of investment returns. However, it is worth noting that inflation can affect the annual income from energy savings. To account for inflation in financial analysis, it is necessary to replace r with the modified rate of discount (r_m):

$$r_m = \frac{(1+r)}{(1+i)} - 1 \quad (5.14)$$

where i is annual inflation rate. Finally, D_p is determined by comparing the net present value of energy savings to the investment cost of integrating PCMs/NePCMs into the roof. D_p evaluated as (Agarwal & Prabhakar, 2023):

$$D_p = \frac{\ln \left(\frac{E_s}{E_s - r_m \times C_I} \right)}{\ln(1-r_m)} \quad (5.15)$$

5.3.4 CO₂ Emission Savings

Global electricity production (approximately 63.3%) predominantly relies on the combustion of fossil fuels, specifically coal, natural gas, and oil. Among these fuels, coal exhibits significantly higher carbon emissions than others used for electricity generation. Specifically, coal power plants emit 2,249 pounds of CO₂ per megawatt-hour of electricity produced. In comparison, oil emits 1,672 pounds per megawatt-hour, while natural gas emits 1,135 pounds (*Carbon Dioxide Emissions*

From Electricity - World Nuclear Association, n.d.-b; Carbon Dioxide Emissions From Electricity | How You Can Help, n.d.). The primary contributor to India's power production is derived from coal's thermal power plants, constituting approximately 75% of the overall power generation capacity (*Ministry of Coal, Government of India, n.d.*). The Central Electricity Authority of India estimates that 1 million kWh of electricity produced from coal produces 975 tonnes of CO₂, while the same amount of power generated from natural gas results in 475 tonnes of CO₂ emissions. A power plant fueled by lignite, also known as brown coal, emits approximately 1,280 tonnes of CO₂ to produce an equivalent amount of power (*India's power output grows at fastest pace in 33 years, fuelled by coal | Reuters, n.d.*). According to the (2022 *Global Status Report for Buildings and Construction | UNEP - UN Environment Programme, n.d.*), CO₂ emissions stemming from building operations have escalated to a record-breaking level of around 10 GtCO₂, indicating a 5% rise compared to 2020 and a 2% increment over the previous peak recorded in 2019. Despite having relatively low per capita CO₂ emissions, India ranks as the third-largest emitter of CO₂ globally (*Energy in India today – India Energy Outlook 2021 – Analysis - IEA, n.d.*).

To mitigate overall emissions, the sector must enhance buildings' energy performance, reduce building materials' carbon footprint, and augment investments in energy efficiency. Consequently, the potential electricity savings resulting from implementing biaxial voided slabs can be directly associated with reductions in the consumption of fossil fuels. This, in turn, reduces carbon emissions released into the atmosphere during the electricity production phase. These savings harbor the potential to mitigate the risks linked to global warming and climate change. One conventional approach for estimating CO₂ emissions savings resulting from electricity consumption is outlined in (Psomopoulos et al., 2010).

$$C_s = EF_{CO_2} \times E_s \quad (5.16)$$

Where C_s represents CO₂ emissions savings in Kg CO₂, EF_{CO_2} is the CO₂ emission factor, also referred to as carbon intensity in KgCO₂/kWh, and E_s represents electricity savings in kWh.

EF_{CO_2} is a critical metric that quantifies the quantity of carbon released into the atmosphere for each unit of electricity generated. In the context of an isolated power generation plant, it can be directly computed by analyzing the plant's fuel consumption and power output. However, in a multi-plant generation system where electricity is supplied through a shared grid, it's evident that the level of carbon emissions depends on the presence and operational status of various generation plants at any given time (Psomopoulos et al., 2010; Voorspools & D'Haeseleer, 2000). Therefore, a

'weighted average' emission factor is typically employed to estimate EF_{CO_2} . This factor represents the average CO₂ emissions per unit of electricity generated within the grid and is calculated by dividing the total CO₂ emissions from all power stations by the total net generation. Importantly, this ratio encompasses net generation from low-cost and must-run sources. In the Indian context, it's essential to distinguish hydroelectric and nuclear power stations as low-cost and must-run sources of electricity. For the fiscal year 2021-22, the calculated weighted average values of EF_{CO_2} related to fossil fuel-based power stations are as follows: 1.19 for coal, 1.32 for lignite, 0.42 for natural gas, 0.59 for diesel, and 0.61 for naphtha. It's noteworthy that when assessing the EF_{CO_2} for gas-fired power stations, only those stations that exclusively utilize natural gas as their primary fuel source are considered (Bhawan & Puram, 2022). By substituting the estimated electricity unit savings outlined in Section 5.2.5.3 into Equation 5.16 and incorporating the relevant weighted average values of EF_{CO_2} for distinct fuel types, the potential reductions in CO₂ emissions resulting from implementing biaxial voided slabs can be accurately calculated.

5.3 Results and Discussions

The experimentation conducted outdoors spanned over three months, starting from 15 April–15 May, May 16 to June 09, and August 14 through September 14. The temperature data is recorded using the thermocouples. Note that T_{AMB} represents the ambient temperature (°C).

5.3.1 Short Duration Analysis

In Fig. 5.12, the study illustrated the phases of the PCM phase transition for 24 hours that started from April 9, at 6:00 AM, to April 10, at 6:00 AM. The figure presented variations in T_{es} , $T_{is,CRS}$, and $T_{is,BVS}$. The T_{es} trend exhibited an almost monotonous ascending and descending character, while the $T_{is,CRS}$ trend pattern was comparable to T_{es} in terms of monotonic behavior, with a few expected variations. However, the study identified the PCM phase transition inside the aluminum void former, indicated by discrete plateaus (A-D) in the $T_{is,BVS}$ trend. During the heating phase, the first plateau A indicates a solid-liquid phase transition at about 33.4°C, closely matching the DSC-predicted average melting onset temperature of 34.017°C. This demonstrates the consistency between the DSC measurements and the observed melting during the outdoor exposure. This stage

is known as the pure conduction regime, where heat transmission through diffusion plays a significant role during the phase change. Thermal buoyancy causes the liquid PCM near the surface of the void former to heat up sufficiently, causing it to dissolve and overcome the viscous force, allowing it to rise to the top of the container. Previous studies have reported this phenomenon (Huang et al., 2020b; Shokouhmand & Kamkari, 2013a). Compared to the DSC average peak temperature of 37.017°C, the second phase change, or plateau B, occurs at about 36.6°C and lasts for 1 hour and 42 minutes, 15 more minutes than plateau A. During this period, the main heat transfer processes are conduction and natural convection, known as the mixed regime. The remaining heat during this phase rises along the heated surface until it reaches the container top, with the heated PCM liquid increasing the local heat transfer rate and melting rate due to its impact on contact. A brief plateau C is observed at 43.3°C for 30 minutes, similar to the DSC's average inset temperature of 43.0°C, indicating the end of melting at C. The $T_{is,BVS}$ inclination between B and C is steeper than between A and B, as shown in Fig. 5.12, indicating a quicker heat flux resulting from PCM melting after the mixed regime compared to the diffusion-dominated regime.

During the cooling phase, the PCM integrated biaxially voided slab undergoes its first plateau (i.e., D) at 34.1°C, close to the DSC average onset solidification temperature of 34.2°C. The liquid-solid phase change peak lasts for about 2 hr 30 mins, during which the solidification process begins near the void former surfaces and develops at different rates at the top and bottom of the container due to the higher density of the fluid causing the colder fluid to sink to the bottom. Unlike the melting process, solidification mainly follows a mixed regime (Hekmat et al., 2022). Plateau D is observed during the early morning hours of 10 April, a few hours before sunrise. Thus, the solidification process may not have been fully completed, which could result in subsequent melting. It should be noted that Fig. 5.12 is provided as an illustration of the phase transition stages occurring within the unit cell and the presence and duration of various plateaus are strongly influenced by local meteorological conditions. For instance, on a hot day, solidification may not be complete and the PCM may undergo melting again.

It is important to note that during the phase change, PCM generally experiences three states: solid, liquid, and a transient state where the PCM exists in a solid-liquid state with varying level of solid-to-liquid fraction. In particular, liquid fraction (l_t) is often used to describe the thermodynamic state of the PCM.

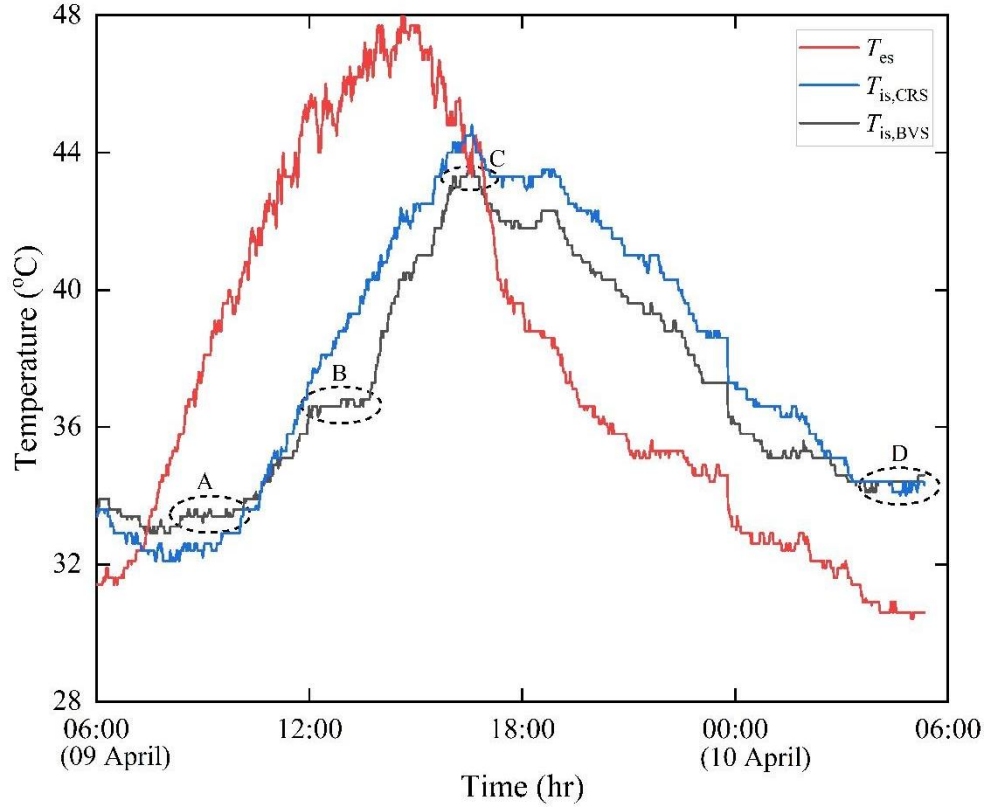


Fig. 5.12 Illustration of stages of PCM phase change.

The liquid fraction can be analytically estimated as (Thonon et al., 2020):

$$l_f = \begin{cases} 0 & T_{is} \leq T_s \\ \frac{T_p - T_s}{T_l - T_s} \left[\operatorname{erf} \left(\frac{2\sqrt{2}(T_{is} - T_p)}{T_p - T_s} \right) + 1 \right] & T_{is} \leq T_p \\ \frac{T_p - T_s}{T_l - T_s} + \operatorname{erf} \left(\frac{2\sqrt{2}(T_{is} - T_p)}{T_l - T_p} \right) \left(\frac{T_l - T_p}{T_l - T_s} \right) & T_{is} > T_p \\ 1 & T_{is} > T_l \end{cases} \quad (5.10)$$

where T_p , T_s , and T_l represent phase change, solidus, and liquidus temperatures (°C), respectively.

Further, erf represents mathematical error function. Using Eq. (5.10), the liquid fraction for the temperature profiles shown in Fig. 5.13 is computed. The application of Eq. (5.10) for estimating l_f relies on a few assumptions: (i) heat flux is parallel, (ii) T_{is} represents PCM temperature; and (iii) specific heat capacity varies linearly between solid and liquid during phase transition (Thonon et al., 2020).

Fig. 5.13 depicts the variation in l_f with temperature. As observed, l_f takes a value of below the melting point of PCM and progressive increases to reach the maximum value of 1 at 41.3 °C. With further increase in temperature, l_f maintains the value of 1.0 until favorable weather onsets solidification.

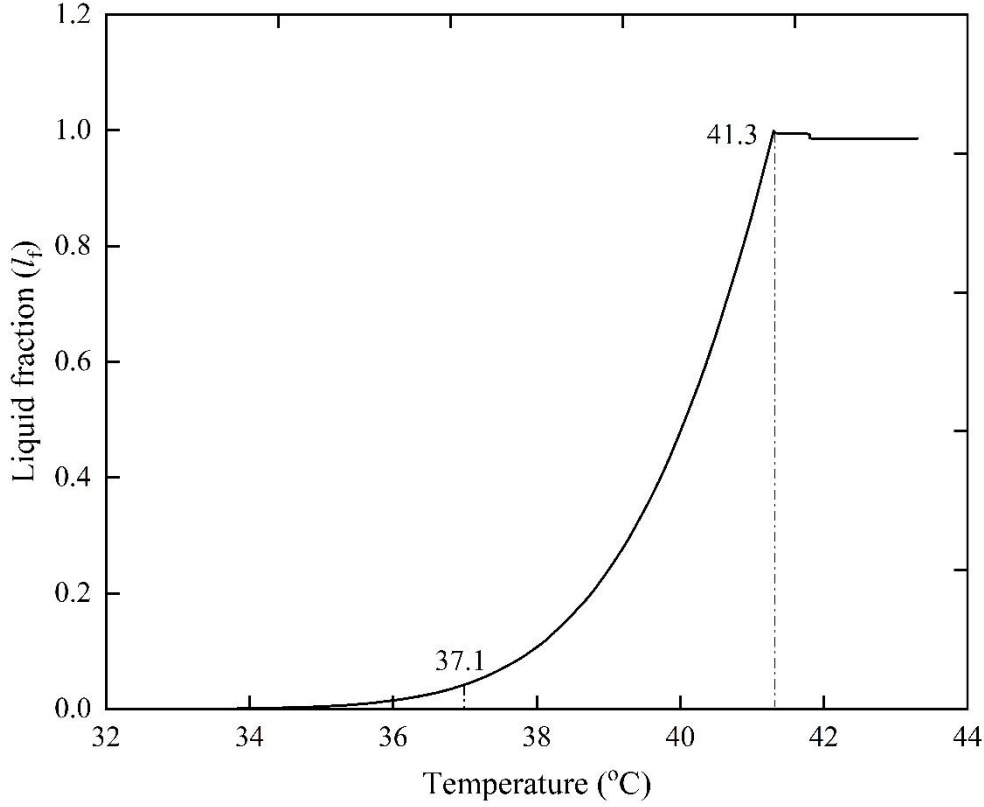


Fig. 5.13 Evolution of liquid fraction.

5.3.2 Long Duration Analysis

5.3.2.1 Temperature profiles

In Fig. 5.14, the temperature profiles of T_{es} , $T_{is,CRS}$, $T_{is,BVS}$, and T_{AMB} are compared with variations in solar radiation from April 15 to May 15. This illustration also incorporates data on the fluctuation in solar radiation. Notably, there are instances where T_{es} tends to exceed $T_{is,BVS}$ during the peak sunny hours, subsequently falling below $T_{is,BVS}$ during non-sunny periods. This intriguing observation implies a temperature reduction during sunny hours, attributable to the PCM's heat absorption capability. Conversely, a discernible temperature increases during non-sunny hours as the PCM liberates stored heat. Consequently, macroencapsulated PCM introduces valuable thermal

control to the roof, a vital factor in ensuring occupants' thermal comfort. Notably, on several days, the PCM undergoes a phase transition from solid to liquid during the daytime and from liquid to solid during the nighttime. This substantiates the biaxial voided slab unit's proficiency in absorbing thermal energy during the day and releasing it at night. This cyclic charging and discharging mechanism is a pivotal functional criterion for PCM suitability in building applications, and the selected PCM has been determined to meet this criterion effectively. During the period, the highest average daily temperatures for T_{es} , $T_{is,CRS}$, $T_{is,BVS}$, and T_{AMB} were 44.4°C, 44.3°C, 40.3°C, and 40.2°C, respectively, while the lowest average daily temperatures were 27.3°C, 29.7°C, 27.8°C, and 24.8°C, respectively.

Throughout the testing period (April 15 to May 15), an utmost temperature differential of 7.2°C becomes evident between T_{es} and $T_{is,BVS}$ during sunny hours. Furthermore, an average temperature disparity of 4.8°C is consistently noted. These observations distinctly signify that the implementation of the biaxial voided slab unit leads to a notable decrease in interior temperature, amounting to a maximum reduction of 7.2°C and an average reduction of 4.8°C. This decline in temperature can be attributed to the PCM's capacity to absorb thermal energy in the form of latent heat during its transformation from a solid to a liquid state. It's vital to recognize that the latent heat storage within the PCM is intricately linked to its phase transition characteristics. As the PCM undergoes the melting process, it traverses a semi-transient phase within regions that initially encounter this phase change. In this semi-transient state, the PCM exists in a state that is neither entirely solid nor fully liquid but rather exhibits characteristics akin to a mushy consistency. As the heat influx intensifies, the proportion of liquid within this mushy zone gradually increases until it eventually transforms into a completely liquid state. The phase transition mechanism within the PCM is inherently complex, involving the coexistence of diverse phases, encompassing solid-mushy, liquid-mushy, or hybrid solid-mushy- liquid phases (Mirzaei & Haghighat, 2012).

During sunny hours, the temperature differential between $T_{is,BVS}$ and $T_{is,CRS}$ was the highest, at 6.1°C, indicating that the biaxially voided slab unit resulted in a 6.1°C decrease in internal temperature compared to a normal RCC slab unit. A thorough analysis of temperature disparities between the voided and normal RCC testing units can be readily discerned. Notably thermal characteristic observed is the protracted elevation in temperature witnessed in the voided unit when juxtaposed with the standard RCC unit. As depicted in Fig. 5.14, the temperature within the regular RCC unit exhibits a relatively swift ascent, usually culminating during the late afternoon hours. Conversely, the temperature upsurge within the voided slab unit transpires over an extended timeframe, typically reaching its zenith well into the evening hours. This observation underlines that the biaxial voided slab unit also delivers sustained thermal regulation and insulation to the

interior environment throughout the phase transition. It's noteworthy to emphasize that sustained fluctuations in thermal energy are generally deemed more advantageous for maintaining thermal comfort than abrupt fluctuations that the voided unit could potentially induce.

During non-sunny hours between April 15 and May 15, it's observed that the temperature within $T_{is,BVS}$ surpasses that of $T_{is,CRS}$ by a maximum of 3.1°C, suggesting that heat release from the PCM inside the room with the biaxially voided block would cause a 3.1°C increase in internal temperature over the course of the night. The augmentation in thermal energy within the interior generally contributes to the occupants' thermal comfort and concurrently diminishes the energy requisites for space heating. As illustrated in Fig. 5.14, $T_{is,BVS}$ consistently outpaces $T_{is,CRS}$ during non-sunny hours across multiple days. However, it's worth noting that while this indicates the liberation of latent heat into the interior, it becomes undesirable if the temperature exceeds the established threshold for thermal comfort. In such unfavourable scenarios, measures need to be implemented to dissipate this excess heat into the surrounding atmosphere.

During the testing period, April 22 and May 3–4 were rainy days, resulting in a significant drop in temperature of 6.5°C and 5.3°C, respectively, observed at T_{es} and T_{AMB} locations, attributable to the prevailing local climatic conditions, Fig. 5.14. Conspicuously, T_{es} registers notably lower values than T_{AMB} during these periods, which is attributed to the dampness of the rooftop's upper surface.

Notably, on April 21, during daylight hours, $T_{is,BVS}$ exhibited a peak temperature that was 4.1 °C higher than T_{AMB} but 2.3 °C lower than $T_{is,CRS}$. From the empirical data, it can be ascertained that the PCM initiated its melting process during the morning hours of April 21, primarily driven by the elevated ambient temperatures. However, it's important to note that complete melting wasn't achieved instead, the PCM began to revert to its solid state during the afternoon of the same day due to declining temperatures. Consequently, the PCM underwent an extended period of discharging. This extended discharging phase plays a pivotal role in enabling the PCM to fully solidify, enabling it to be fully charged on a subsequent sunny day. This phenomenon was notably evident in the temperature profiles observed on April 22, where a substantial interior temperature drop of 6.5 °C was recorded. This temperature decrease can be elucidated by the favourable climatic conditions that facilitated solidification on April 21.

A similar weather pattern repeated itself on May 5, following two consecutive rainy days on May 3 and 4. The adverse weather conditions on May 3 and 4 favored the solidification process,

resulting in a significant reduction in the interior temperature of the voided slab unit, amounting to 7 °C on May 5. It's important to emphasize that while alternating periods of rainy and sunny weather prove conducive to the solidification and melting processes, consecutive rainy days can impede the PCM's charging capacity. This pattern is also evident from the data presented in Fig. 5.14. For instance, on May 4th, the voided slab unit experienced a slight decrease in interior temperature, about 1.1 °C. This decrease can be attributed to unfavorable weather conditions that hindered the PCM from reaching its melting point. Consequently, the effective thermal performance of the biaxial voided slab is intricately tied to the cyclical charging and discharging of the PCM, a process strongly influenced by the prevailing local climatic conditions.

Conversely, the greatest disparity in daily peak temperatures between the CRS and OM37 integrated roof slab occurs primarily in August to September, with a significant difference of 10.5°C, followed by April to May, with a difference of 6°C, and lastly May to June, a difference of 5.8°C. Conversely, the smallest distinction is observed in May to June, where the lowest difference of 0.6°C is recorded. In contrast, the largest difference of 2.1°C is documented in August to September. The indoor performance of the PCM integrated slab unit, compared to the conventional slab, exhibits a similar trend as observed in relation to the outside temperature.

During the testing period of April-May (Ref. Fig. 5.15), the average daily temperatures for T_{es} , $T_{is,CRS}$, and $T_{is,BVS}$ reached their highest points at 43.26°C, 42.65°C, and 40.28°C, respectively. Conversely, the lowest average daily temperatures were recorded at 32.5°C, 34.9°C, and 34.1°C, respectively. $T_{is,BVS}$ and $T_{is,CRS}$ experienced an average temperature decrease of 4.4°C during heating hours, while an average temperature increases of nearly 1.2°C was observed during cooling hours. During sunny hours, there was a notable temperature difference of 6°C between $T_{is,BVS}$ and T_{es} , indicating that the biaxially voided slab unit resulted in a 6°C reduction in internal temperature compared to a traditional concrete slab unit. On the other hand, during non-sunny hours, the highest temperature differential of 2.9°C between $T_{is,BVS}$ and T_{es} was observed, suggesting that the release of heat from the PCM within the room with the biaxially voided block would cause a 2.9 °C increase in internal temperature throughout the night.

Table 5.3 summarizes the calculated values of OM35 and OM37 integrated roof slabs for each testing period. The empirical observations strongly suggest that the biaxial voided slab unit integrated with OM35 demonstrated superior thermal performance than OM37 integrated BVS during (April 15 to May 15) and 16th May – 09th June while 14th August –14th September favoured OM37 integrated roof.

Table 5.3 Summary of calculated results for OM35 and OM37 integrated roofs.

Testing period	Sunny hours						Non-sunny hours					
	$T_{es} / T_{is,BVS}$			$T_{is,BVS} / T_{is,CRS}$			$T_{es} / T_{is,BVS}$			$T_{is,BVS} / T_{is,CRS}$		
	max	min	Avg.	max	min	Avg.	max	min	Avg.	max	min	Avg.
OM37												
15 th April – 15 th May	6	1.3	3.2	4.4	0.8	2.43	2.9	0.1	1.16	3.1	0	1.22
16 th May – 09 th June	5.8	0.6	3.34	7.3	0.4	2.61	2.0	0	0.99	2.5	0.2	1.16
14 th August – 14 th September	10.5	2.1	7.52	6.9	3	5.02	4.5	0.2	2.05	3.7	0.3	1.67
OM35												
15 th April – 15 th May	7.2	2.6	5.01	5.3	3.2	4.0	2.7	0.1	0.8	3.4	0	1.9
16 th May – 09 th June	6.03	0.1	3.32	4.1	0.7	2.09	3.0	0	1.59	3.1	0.2	1.10
14 th August – 14 th September	7.02	0.2	2.5	3.8	0.7	2.5	3.5	0.1	1.3	2.3	0.4	1.22

5.3.2.2 Heat flux profiles

Fig. 5.16 graphically depicts the time-varying heat flux (W/m^2) for both the normal RCC unit ($H_{f,CRS}$), and the biaxially voided slab unit ($H_{f,BVS}$), during the period spanning from April 15 to May 15. It's essential to note that negative heat flux values signify heat being emitted by the units, while positive values indicate heat being absorbed by the units. Temporal synchronization is notably observed between the heat flux profiles $H_{f,CRS}$ and $H_{f,BVS}$ during the early morning and late evening hours on various days. However, a substantial reduction in the $H_{f,BVS}$ values in comparison to $H_{f,CRS}$ is evident during the sunny hours.

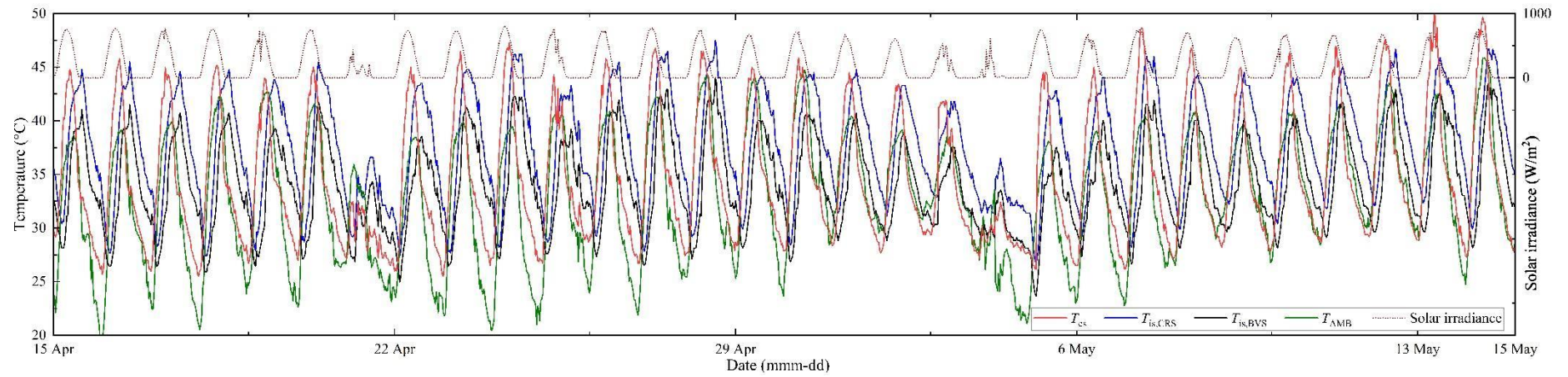


Fig. 5.14 Temperature variation of OM35 Integrated roof from 15 April to 15 May.

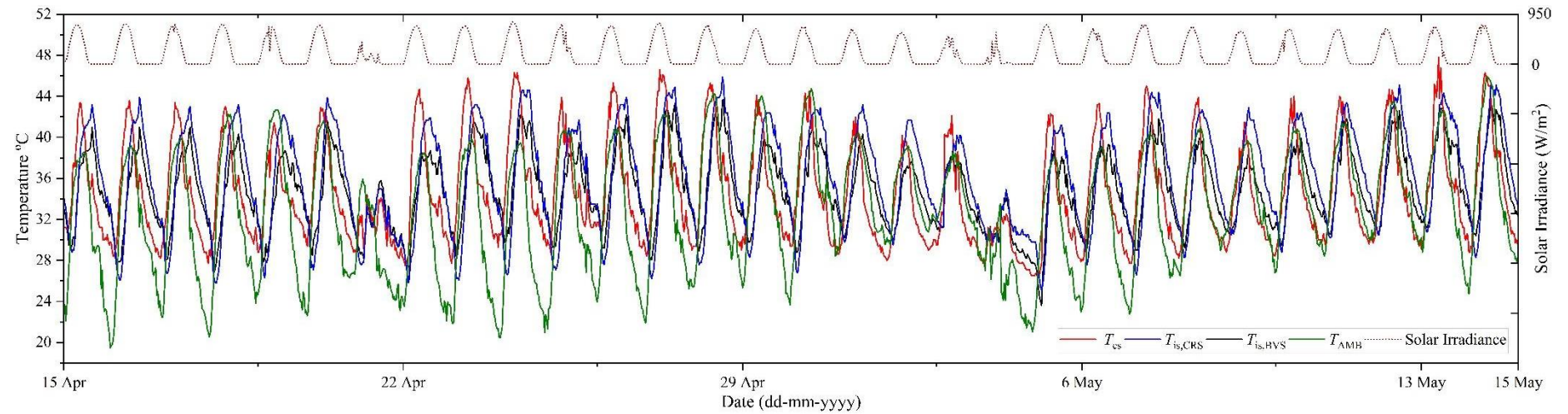


Fig. 5.15 Temperature variation of OM37 Integrated roof from 15 April to 15 May.

The normal RCC unit exhibits a substantially higher heat gain, reaching up to 32.5%, when contrasted with the voided slab unit, which conversely undergoes a substantial 32.5% decrease in heat gain. Conversely, for the OM37 integrated roof, the graphical representation in Fig. 5.17 demonstrates the daily average heat transfer rate for $H_{f,CRS}$ is 14.64 W/m² per day, while that of $H_{f,BVS}$ is 10.24 W/m² during the testing period which resulted in a 30.1 % decrease in heat transmission to the interior during the daytime. This discernible reduction in heat flux can be attributed to the thermal inertia of the PCM material contained within the void former. The findings illustrate that roof slabs integrated with OM37 exhibit a 50% reduction in heat transfer compared to those with OM35 for the entire testing period.

The difference in heat gain and release processes between the two units can be understood in Fig. 5.16 and 5.17. The daily heat flux profile manifests two distinct transition points. The first transition point occurs when an ascending $H_{f,BVS}$ profile shifts from the $H_{f,CRS}$ profile during the early morning hours. This transitional heat flux value typically falls within the range of 1 W/m² to 5 W/m², averaging around 1.8 W/m². The second transition point is located where a descending $H_{f,CRS}$ profile transits from $H_{f,BVS}$ in the late afternoon hours. Notably, the heat flux values at these transition points consistently fall within the same range. These transition points, along with their associated heat flux values, effectively denote the threshold heat flux levels that trigger the phase change of the PCM material. This phase change can either involve the transition from a solid to a liquid state or from a liquid to a solid state. Furthermore, it's worth noting that the $H_{f,CRS}$ profile exhibits a consistent slope at these transition points, signifying a constant rate of heat flux within the normal RCC unit.

Negative heat flux values are prominently evident during periods characterized by non-sunny hours, including the early morning, late afternoon, and nighttime. Particularly, during both the early morning and late afternoon intervals, there is a substantial three-fold amplification in the heat flux magnitude within the $H_{f,CRS}$, when juxtaposed with the corresponding $H_{f,BVS}$ values. Furthermore, during the night-time, $H_{f,CRS}$ exhibits an escalation of up to 2.5-fold concerning magnitude compared to $H_{f,BVS}$. Additionally, it has been empirically determined that $H_{f,BVS}$ maintains a daily average of approximately -2.1 W/m², in contrast to -6.7 W/m² of $H_{f,CRS}$, which is a rise of a factor

of 3.2. while OM37 integrated roof resulted in a difference of 2.9 times and a reduction of 9.4%, respectively.

Consequently, the utilization of macroencapsulated PCM within the voided slab unit has yielded a substantial reduction in the release of heat into the interior when contrasted with the conventional RCC unit. This highlights the superior heat storage capacity inherent in the voided slab unit, which, in turn, results in diminished rates of both cooling and heat discharge. A negative heat flux reading signifies a reversal in the direction of heat flow since the nighttime surface temperature is lower than the PCM temperature. Negative curves indicate that the discharge rate is greater for normal concrete than for voided slab units since normal concrete has a lower ability to store heat. Nevertheless, negative heat flow is crucial for a voided slab unit since it signifies the discharge of heat stored during the day (Saxena et al., 2020b).

Table 5.4 presents the computed heat flux values across all testing periods for both PCMs. The average heat flux values observed from August 14th to September 14th showed notable improvement compared to previous periods. Additionally, the OM35 integrated roof slab demonstrated superior performance from May 16th to June 9th, while OM37 excelled in the remaining testing periods. Furthermore, during non-sunny hours, the heat flux values of PCMs were comparable. $H_{f,BVS}$ of OM35 integrated roof slab demonstrates a daily average of approximately -4.52 W/m², whereas OM37 registers a daily average of about -2.8 W/m² recording a substantial reduction of 38%, respectively.

5.3.2.3 Thermal loading

Utilizing the energy flux dynamics within the roofing system, it was postulated to derive the comprehensive cooling and heating thermal loads encompassing a complete diurnal cycle. Fig. 5.18a presents the empirical data, elucidating the discernible impact of PCM integration on the cooling load engendered by the roof. Specifically, during the 15th April to 15th May test period, the PCM integrated slab unit exhibited almost a 24% reduction in cooling load compared to the normal RCC slab unit. Between the period of 16th May to 9th June, the configuration incorporating PCM demonstrates a substantial 54.27% reduction in the total thermal load compared to the base case. Among all the testing periods, this phase registers the most substantial reduction in cooling load, reaching 28%. Conversely, from 14th August to 14th September, the cooling load with PCM saw a comparatively modest reduction of 15.34% compared to the scenario without PCM. In contrast, Fig. 5.18b presents the empirical findings, delineating the conspicuous effect of OM37 integration on the cooling load generated by the roof over the entire testing period. Throughout the testing period, the slab unit equipped with PCM demonstrated an impressive reduction in thermal load, ranging from 60 to 70%, compared to the conventional slab unit. Notably, the testing period spanning from 14th August to 14th

September exhibits the most substantial reduction in cooling load, culminating at an impressive 73.19%. In contrast, during the period extending from 15th April – 15th May, the cooling load experienced a relatively moderate reduction of 47%, while 16th May to 9th June experienced the least at 41.50% when PCM was introduced, compared to the scenario without PCM. These findings can be ascribed to PCM's augmented latent heat storage capacity, particularly favoured by the prevailing local climatic conditions.

Table 5.4 Monthly comparisons of peak and average heat fluxes for conventional and PCM integrated roof slab units.

Testing Period	Parameters	Sunny hours		Non-sunny hours	
		$H_{f,CRS}$	$H_{f,BVS}$	$H_{f,BVS}$	$H_{f,CRS}$
		(W/m ²)	(W/m ²)	(W/m ²)	(W/m ²)
————— OM35 —————					
15 th April – 15 th May	Daily average	12.7634	8.6147	-4.1733	-11.69
	Maximum	16.505	11.633	-6.07	-15.32
16 th May – 09 th June	Daily average	12.855	8.612	-4.927	-12.792
	Maximum	17.5	11.83	-6.42	-15.47
14 th August – 14 th September	Daily average	10.437	6.887	-4.484	-11.851
	Maximum	13.76	09	-6.72	-14.86
————— OM37 —————					
15 th April – 15 th May	Daily average	14.6458	10.2410	-1.6819	-8.2706
	Maximum	19.7500	12.2800	-3.0000	-10.6100
16 th May – 09 th June	Daily average	11.68	8.26	-3.31	-10.84
	Maximum	16.98	6.14	-4.71	-15.17
14 th August – 14 th September	Daily average	12.5357	5.7584	-3.4141	-10.1053
	Maximum	17.8300	8.4700	-4.2000	-11.8900

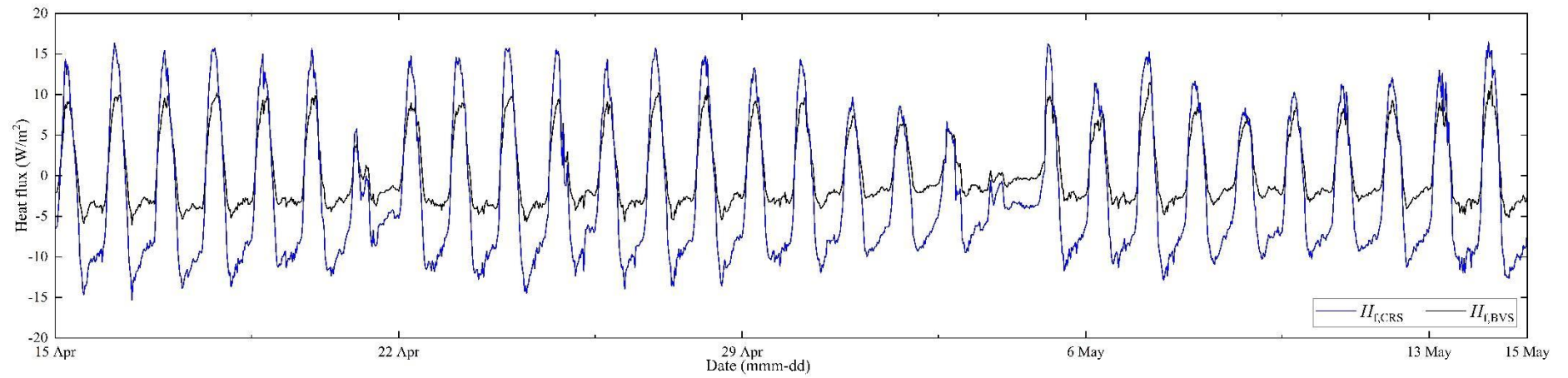


Fig. 5.16 Heat transfer during 15 April to 15 May.

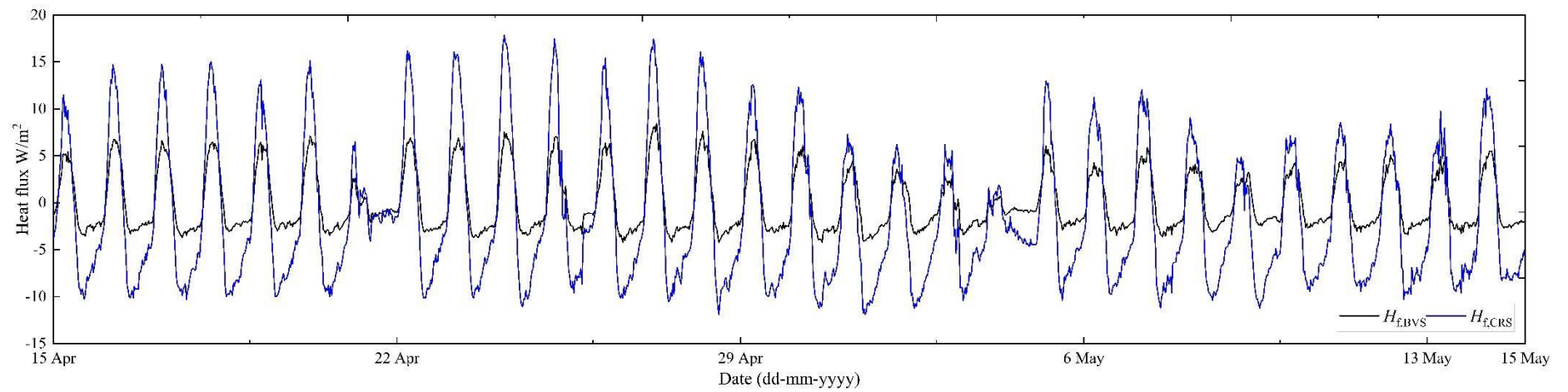


Fig. 5.17 Heat transfer from 15 April to 15 May.

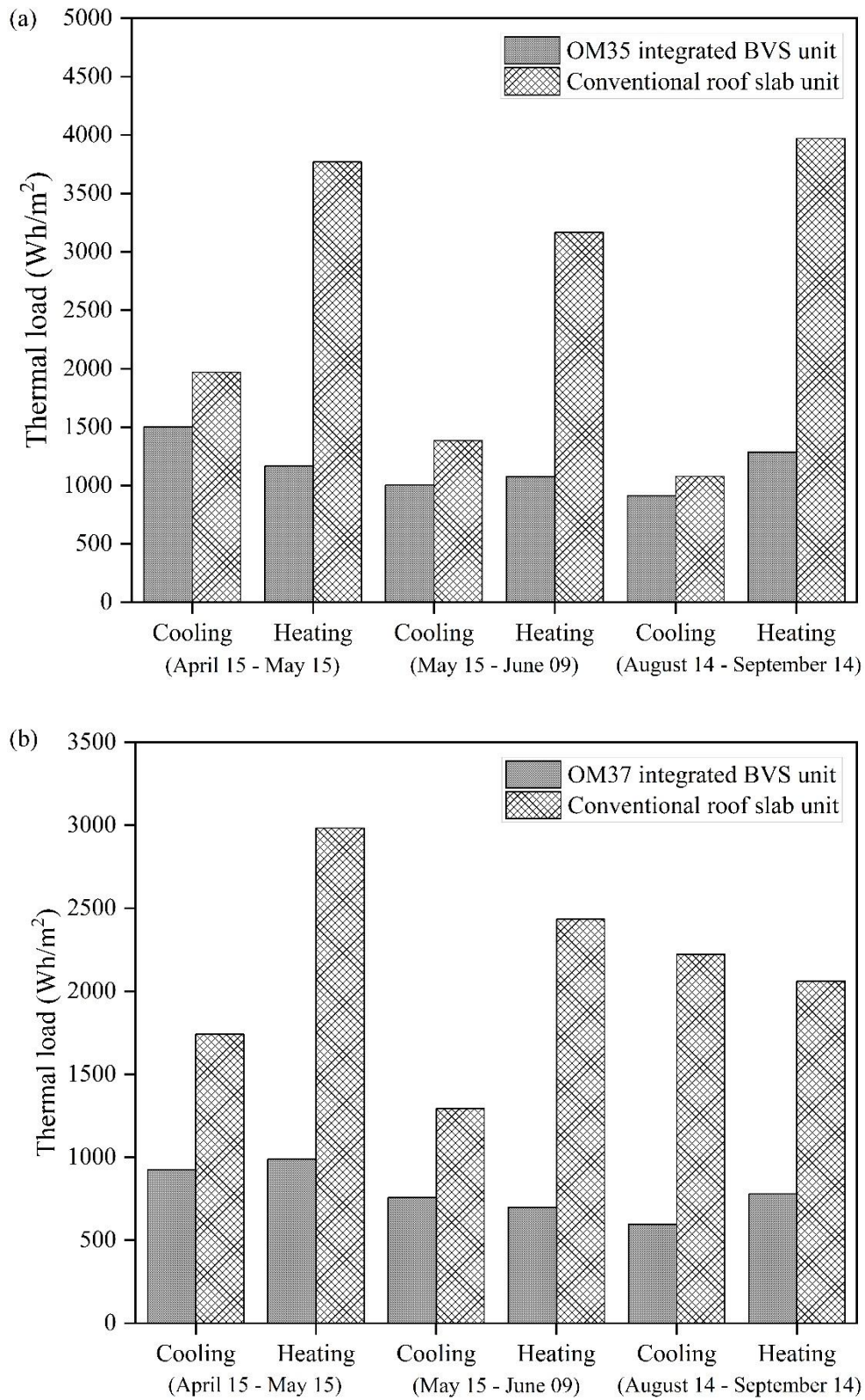


Fig. 5.18 Thermal load distribution of OM37 integrated BVS unit.

As per the data in [Table 5.5](#), it is discernible that the heating loads for the PCM slab unit exhibit significant reductions compared to the normal RCC slab unit. To be specific, during the period from

15th April to 15th May, the heating loads for the OM35 integrated slab unit are approximately 3.2 times lower; during the period from 16th May to 09th June, they are roughly 2.9 times lower, and 3.1 times during 14th August to 14th September, respectively. Consequently, during the period from May 16 to June 9, the heating loads within the OM37 slab unit are approximately 3.4 times lower, while the period spanning from August 14 to September 14 reflects the least reduction in thermal load, amounting to about a 2.6-fold decrease. A moderate reduction in heating load by a factor of 3.0 is observed between April 15 to May 15. Furthermore, over a specific testing period, the cumulative thermal load in the OM35 slab unit is roughly 55% lower while 67% lower for the OM37 slab unit compared to that in the normal RCC slab unit.

Table 5.5 Thermal loads for conventional and PCM integrated roof slab units.

Testing period	Thermal loads	CRS unit (Wh/m ²)	BVS unit (Wh/m ²)
————— OM35 —————			
15 th April – 15 th May	Cooling load	1970	1502.6
	Heating load	3769.15	1165.3
	Total load	5739.15	2667.9
16 th May – 09 th June	Cooling load	1386	1005.72
	Heating load	3165.36	1075.42
	Total load	4551.36	2081.14
14 th August – 14 th September	Cooling load	1078.3	912.87
	Heating load	3970.65	1286.08
	Total load	5048.95	2198.95
————— OM37 —————			
15 th April – 15 th May	Cooling load	1741.56	925.89
	Heating load	2983.1	989.11
	Total load	4724.66	1915
16 th May – 09 th June	Cooling load	1292.63	756.14
	Heating load	2434.21	698.75
	Total load	3726.84	1454.89
14 th August – 14 th September	Cooling load	2224.44	596.16
	Heating load	2060.77	779.25
	Total load	4285.21	1375.41

These outcomes substantiate that adopting the macroencapsulated PCM-integrated slab unit substantially enhances comfort by diminishing operative temperatures and refining thermal load regulation. Note that, compared to OM35, the thermal load reduction achieved by OM37 exhibited a 1.2-fold increase.

5.3.2.4 Time lag and Decrement factor

The assessment of (ϕ) and (f) is critical for improving the thermal performance of a building (Fathipour & Hadidi, 2017; Jin et al., 2012). ϕ and f are important variables that determine the extent of established indoor thermal stability and the potential for reducing energy consumption for space cooling. In hot and tropical climates, building envelopes with long time delays and low decrement factors promote indoor thermal comfort. These factors are dependent on the thermophysical properties and wall thickness of the building construction (Asan & San&tar, 1998). It is essential to design the building envelope with a high time lag and low decrement factor to achieve strong thermal stability and prevent the indoor environment from being affected by external temperature variations. The appropriate decrement factors, f_{CRS} and f_{BVS} , and time lags, ϕ_{CRS} and ϕ_{BVS} , respectively, are evaluated for concrete and biaxially voided slab units. The histogram of the time-lag variables ϕ_{CRS} and ϕ_{BVS} for the testing period (15 April to 09 June) is presented in [Fig. 5.19a](#). The average value of ϕ_{CRS} is 4.2 hours, while that of ϕ_{BVS} is 3.9 hours. The time-lag component of 3 hours accounted for the most days, or 16% of the testing span. A time lag factor of 4 hours or less was present in approximately 62.5% (35 days) of the testing period, while a time lag factor of more than 4 hours was observed in 21 days. On May 5, a time gap of 0.5 hours was observed, but there was none on May 4, the day after the wet day. It is worth noting that the rainy day of April 21, witnessed the largest time-lag factor ever recorded. Due to the poor thermal conductivity of PCMs, the measured values of time lag factors are relatively high (Rathore et al., 2020). Similarly, from 14 August to 14 September, the average value of ϕ_{CRS} is 4.01 hours, while that of ϕ_{BVS} is 4.33 hours, respectively [Fig. 5.19b](#). The time-lag component of 2:30 hours accounted for the most days, or 19% of the testing span. A time lag factor of 5 hours or less was present in approximately 56.25% (18 days) of the testing period, while a time lag factor of more than 5 hours was observed in 14 days.

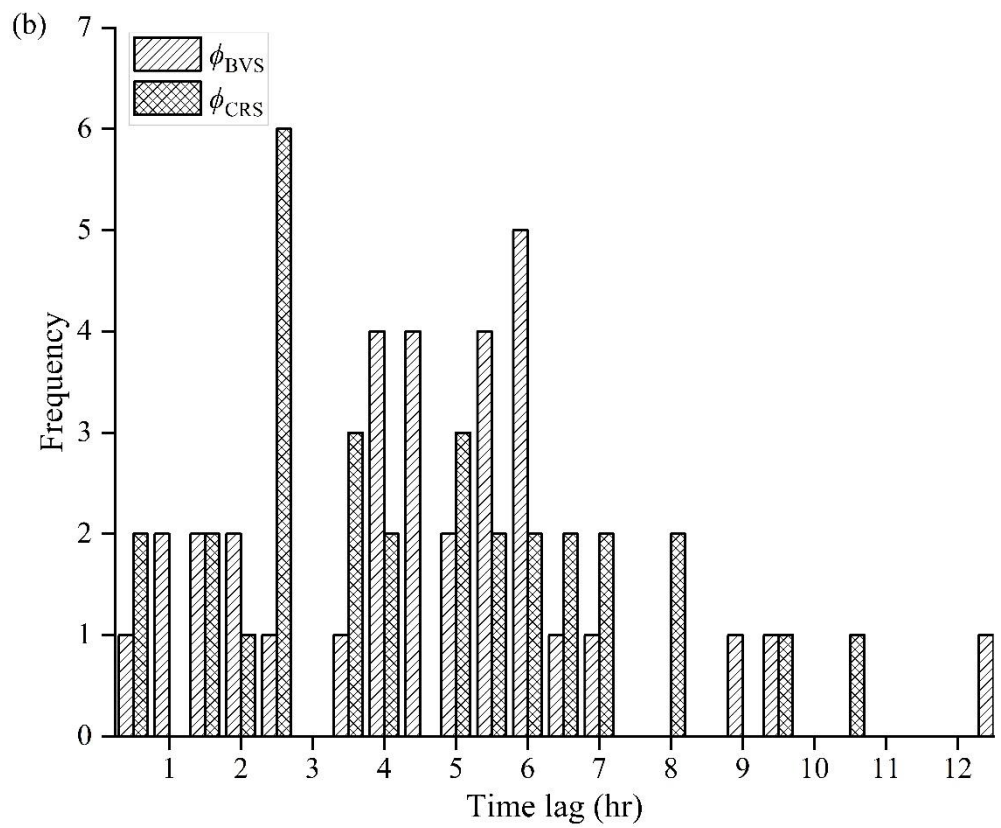
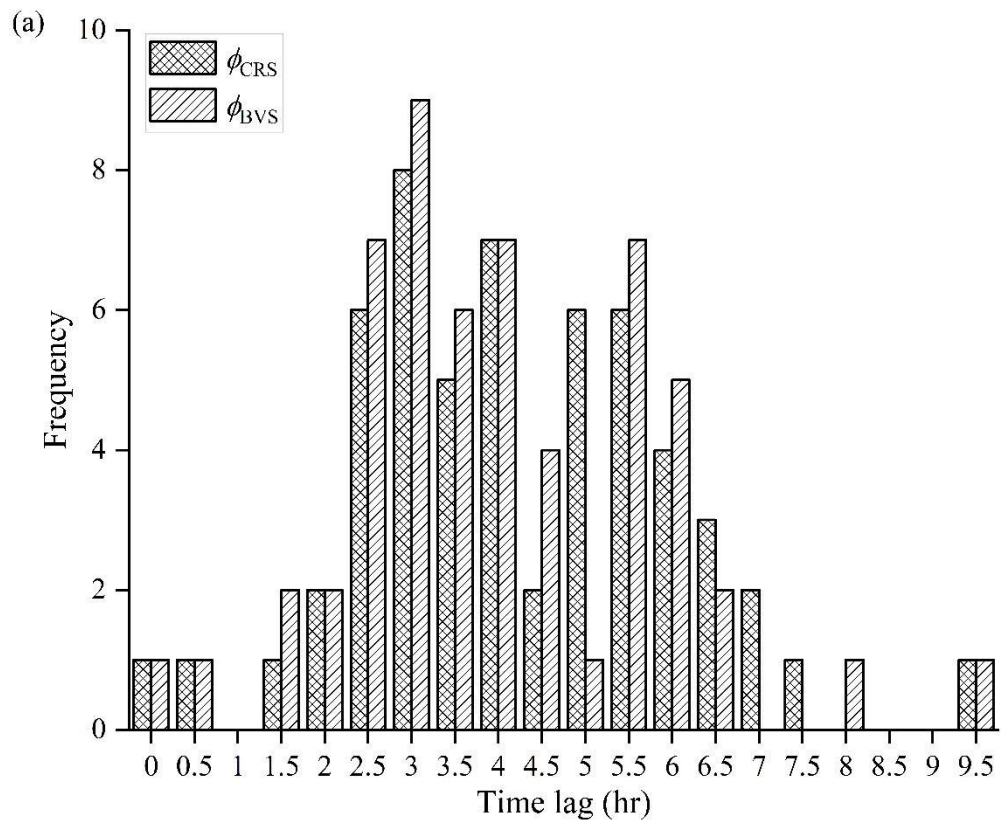
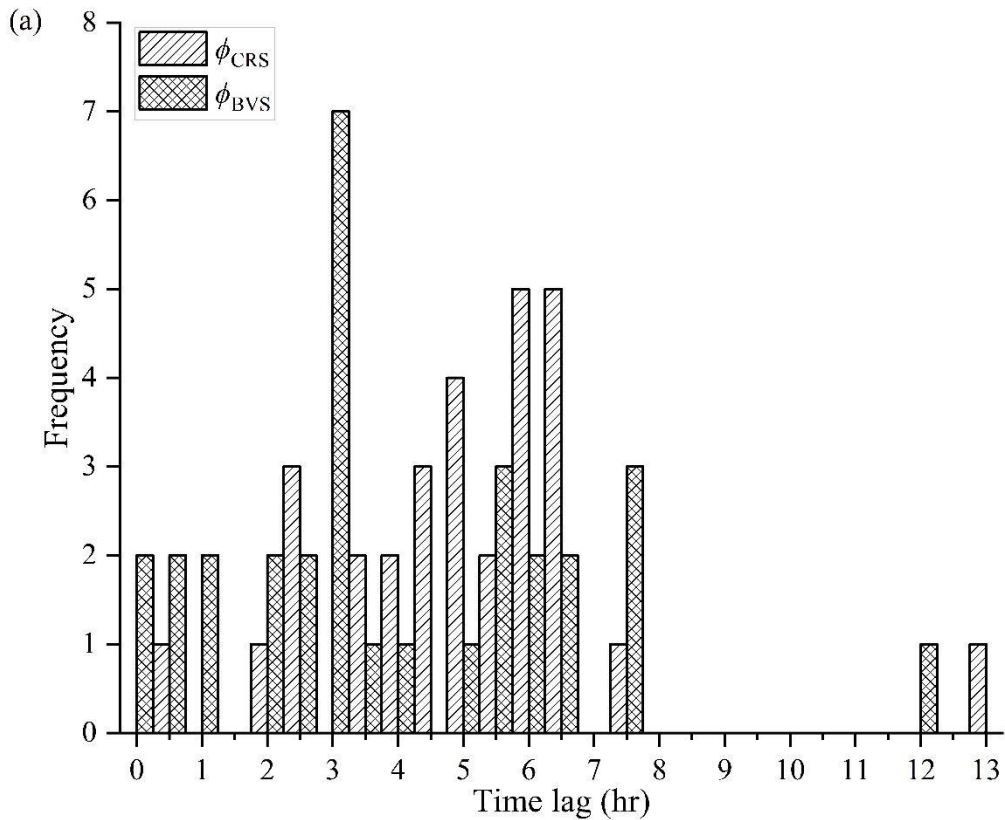


Fig. 5.19 Histogram of time lag factors during: (a) 14 April to 09 June; (b) 14 August to 14 September.

Conversely, in OM37 roofs, the average value of ϕ_{CRS} varies from 4.25 to 5.02 hours, while that of ϕ_{BVS} is 4.12 to 5.48 hours during the given testing period, with the highest ϕ of 5.48 hours observed between August-September. The ϕ component of 2.3 hours accounted for the most days, or 16.09% of the testing span. A ϕ factor of 5 hours or less was present in approximately 65.5% (57 days) of the testing period, while a ϕ factor of more than 5 hours was observed in 30 days. It should be emphasized that on days when it is raining or not sunny and the $T_{\text{AMB}} = 30.7$ to 35 °C, there was either no time gap or a gap of 0.5 hours. Additionally, after rainy days, the longest recorded time delay factor was observed, which was 7 to 8 hours. Fig. 5.20(a–c) illustrates the histogram of the time-lag variables ϕ_{CRS} and ϕ_{BVS} for the OM37 roof during the whole testing period (15 April to 14 September).



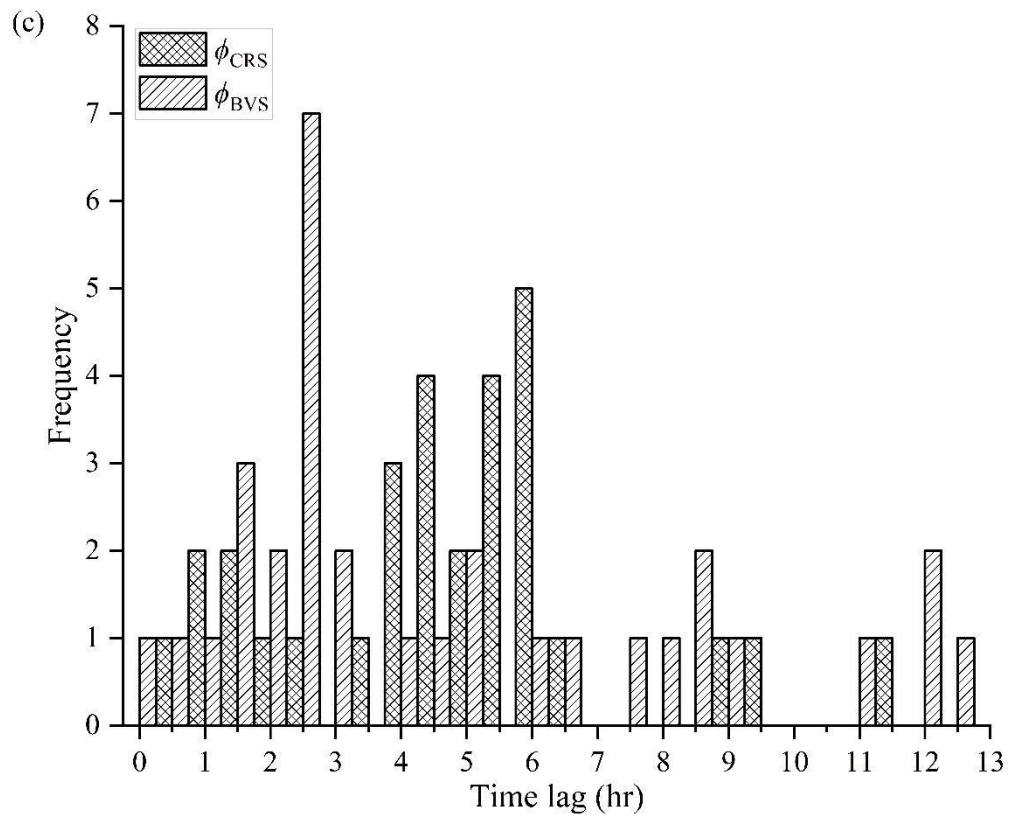
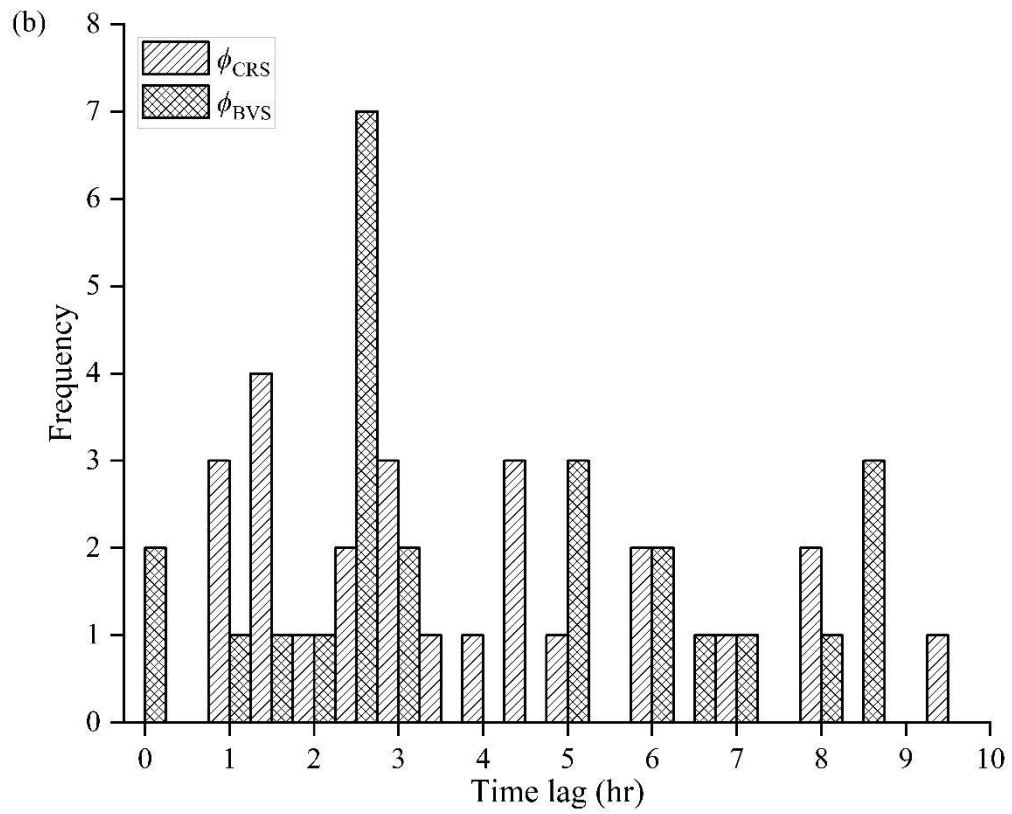


Fig. 5.20 Histogram of time lag factors for: (a) 15th April – 15th May; (b) 16th May – 09th June; and (c) 14th August – 14th September.

The distribution of decrement factors f_{CRS} and f_{BVS} from (15 April to 09 June) is shown in [Fig. 5.21a](#). The average value of f_{CRS} is 0.846, while the average value of f_{BVS} is 0.751. The standard deviations for f_{CRS} and f_{BVS} are remarkably low, at 0.22 and 0.18, respectively. On May 24, when precipitation occurred, the lowest f_{BVS} value of 0.378 was recorded. In contrast, the highest value of f_{BVS} , which was 1.793 on April 21, another rainy day, was recorded on that day. For approximately 36 days or 64% of the testing period, f_{BVS} values varied between 0.6 and 0.8, while for 21 days, or 37.5% of the tests, f_{CRS} was between 0.6 and 0.8. Moreover, for 30 days, or 53% of the measurement period, f_{CRS} was between 0.8 and 1.0, indicating that most decrement factors are between 0.6 and 1.0. Similarly, during the August-September period, the average value of f_{CRS} is 0.833, while the average value of f_{BVS} is 0.684, respectively. The distribution of decrement factors f_{CRS} and f_{BVS} throughout the testing period is shown in [Fig. 5.21b](#). The standard deviations for f_{CRS} and f_{BVS} are remarkably low, measuring 0.11 and 0.20, respectively. On September 01, a day after precipitation, the lowest f_{BVS} value of 0.13 was recorded. In contrast, the highest f_{BVS} value of 1.03, also on a rainy day, was observed on August 24. Approximately 18 days, or 56.25% of the testing period, had f_{BVS} values ranging between 0.6 and 0.8, while for 19 days, or 59.37% of the tests, f_{CRS} fell within the range of 0.6 and 0.8. Furthermore, for 12 days or 37.5% of the measurement period, f_{CRS} was between 0.8 and 1.0, indicating that most decrement factors were within the range of 0.6 and 1.0. Additionally, the average value of f_{CRS} is approximately 13% higher than that of f_{BVS} , suggesting that using a biaxially voided slab unit is more effective in reducing interior overheating.

Conversely, in OM37 roofs, during April – May, f_{BVS} showed a maximum decrement factor of 1.49 and a minimum of 0.389 for August- September, respectively. Standard deviations for f_{CRS} and f_{BVS} are remarkably low, at 0.169 and 0.158, respectively. On May 24, when precipitation

occurred, the lowest f_{BVS} value of 0.378 was recorded. The highest value of f_{BVS} , which was 1.49 on April 21, a rainy day, was recorded on that day. For approximately 68 days or 78% of the testing period, f_{BVS} values varied between 0.58 and 1.0, while for f_{CRS} the count is 70 days, or 80%, indicating that most decrement factors are within the range of 0.6 and 1.0. Additionally, decrement factors of 1 or higher occurred during 20 to 23% of the measurement period. The distribution of decrement factors f_{CRS} and f_{BVS} for the testing period is shown in Fig. 5.22(a and b).

Additionally, the average number of f_{CRS} is about 23.77% higher than that of f_{BVS} , suggesting that a biaxially voided slab unit integrated with OM37 is more effective than OM35 in reducing interior overheating.

5.3.2.5 Electricity Cost Savings

Fig. 5.23(a and b) presents the distribution of cost savings associated with electricity usage during the experimental test periods for cooling and heating purposes. It's essential to note that these cost savings estimations are predicated on the assumption that electrical energy sufficiently fulfills the energy demands for indoor space cooling via air conditioning and space heating through heating systems. The data in Fig. 5.23a indicate that the savings related to space cooling are more substantial than those for space heating. This divergence can be attributed to the inherent capacity of the PCM-integrated voided slab unit to store latent heat, thus diminishing the need for indoor space cooling. Conversely, the cost savings linked to the application of voided slab units for space heating appear to be somewhat lower, potentially influenced by localized climatic conditions. It's pertinent to acknowledge that passive houses, designed for minimal heating requirements and shorter heating periods, might not necessitate substantial space heating. Consequently, their capability to regulate space heating energy is constrained to the coldest hours of the day rather than encompassing transitional periods.

The monthly cost savings can be computed by substituting the measured value into Eq. 5.8. Table 5.6 summarizes the electricity cost savings over the test periods. The daily cost savings related to space cooling from April 15 to May demonstrate noteworthy figures, peaking at 3.98 Rupees/kWh/m², with an average of 3.33 Rupees/kWh/m². These savings align closely with the daily savings observed from May 16 to June 09 and August 14 to September 14.

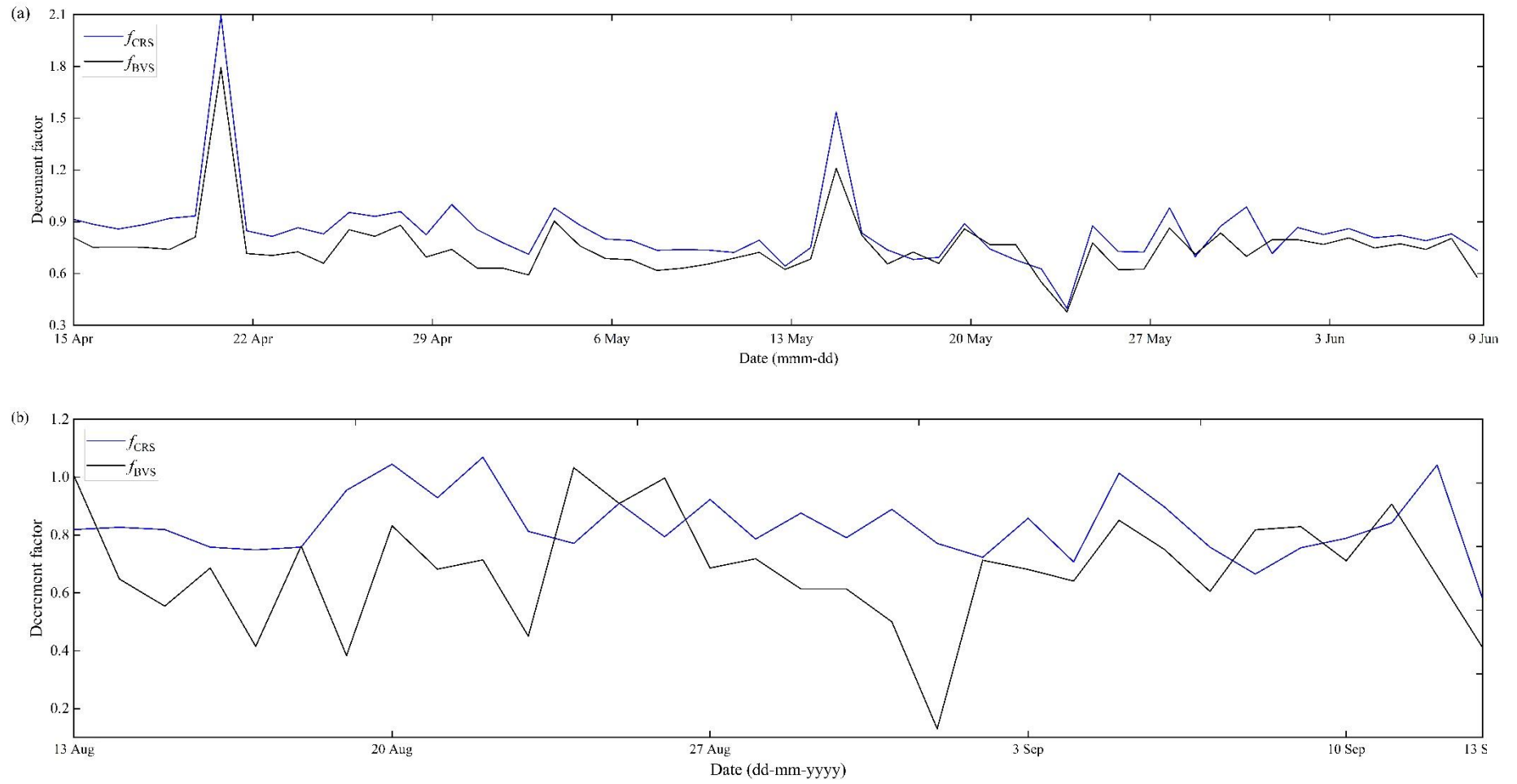


Fig. 5.21 Decrement factor during: (a) 15th April – 09th June; and (b) 14th August – 14th September.

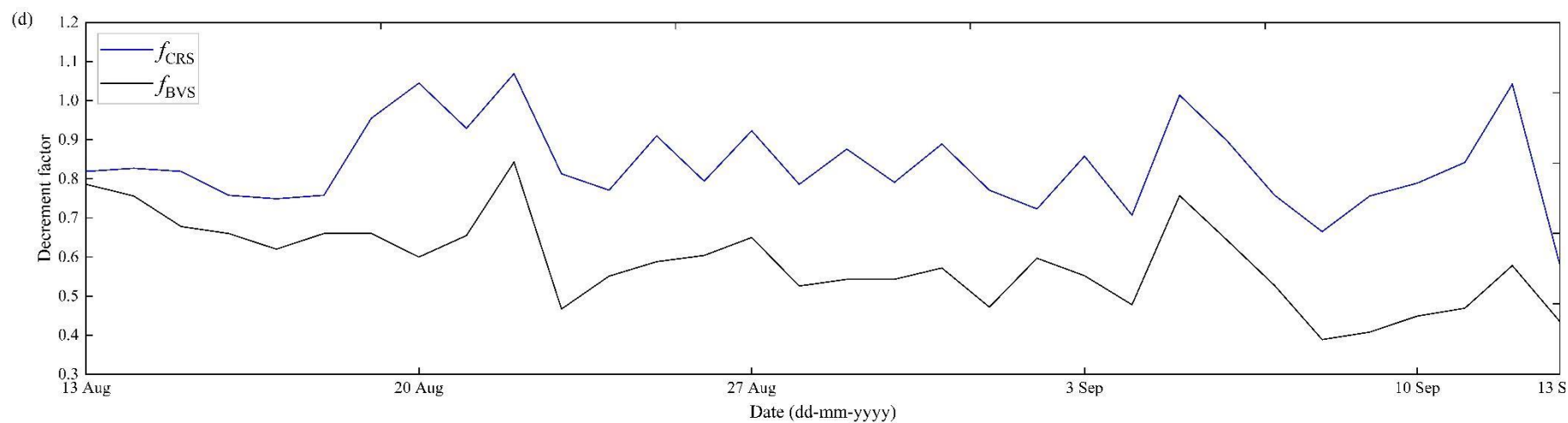
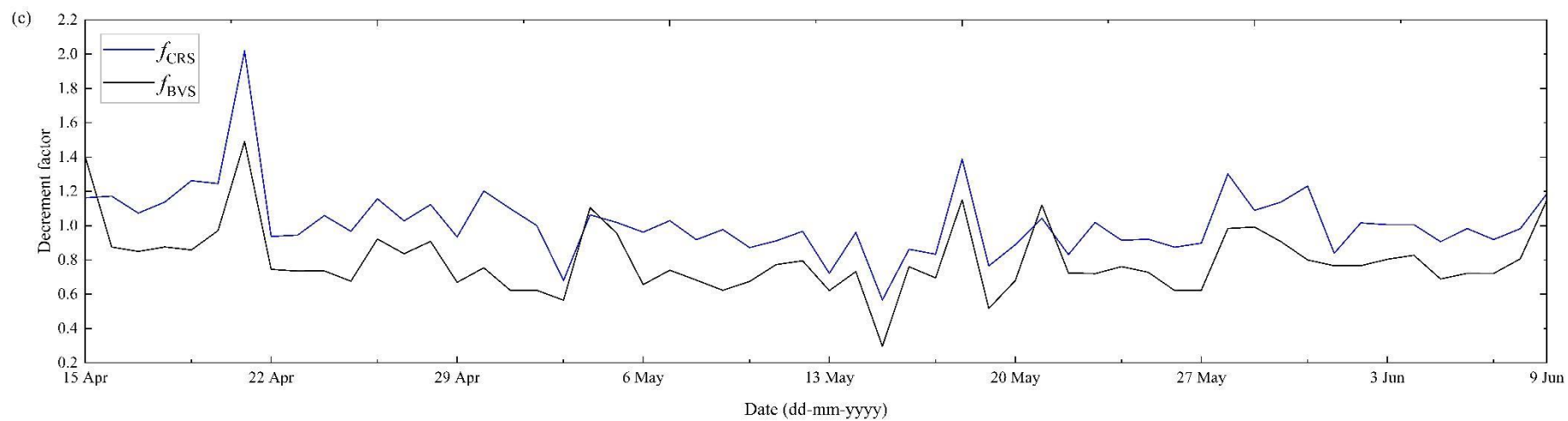


Fig. 5.22 Decrement factor during: (c) 15th April – 09th June; and (d) 14th August – 14th September.

Regarding space heating, the savings from August 14 to September 14 exhibit a slightly better performance, averaging at 1.62 Rupees/kWh/m², in comparison to the 1.57 Rupees/kWh/m² observed from May 16 to June 09 and 1.49 Rupees/kWh/m² from April 15 through May 15. Notably, significant peaks in space cooling savings, such as the 3.98 Rupees/kWh/m² observed from April 15 to May 15, particularly following rainfall. This underscores the importance of weather conditions that facilitate complete PCM discharge in the voided slab unit, as it leads to effective charging and subsequently improved cost savings. The results imply that most of the cost savings occur in the spring and autumn seasons during cooling thermal cycles.

Table 5.6 Comparison of daily cost savings for different months of roof slab units.

Testing Period	Thermal cycle	Cost savings per day (Rs/kWh/m ²)			
		Maximum	Average	Minimum	Monthly
————— OM35 —————					
15 th April – 15 th May	Heating	2.00	1.496	0.610	44.88
	Cooling	3.98	3.33	2.971	100.17
16 th May – 09 th June	Heating	1.918	1.754	0.925	37.77
	Cooling	3.307	3.00	2.773	72.00
14 th August – 14 th September	Heating	2.093	1.621	0.695	50.241
	Cooling	3.663	3.058	2.663	94.80
————— OM37 —————					
15 th April – 15 th May	Heating	3.013	2.497	1.602	74.909
	Cooling	3.799	3.241	2.343	97.233
16 th May – 09 th June	Heating	1.918	1.595	1.108	38.270
	Cooling	3.307	3.004	2.773	72.105
14 th August – 14 th September	Heating	1.841	1.441	1.229	44.66
	Cooling	4.760	3.927	3.339	121.741

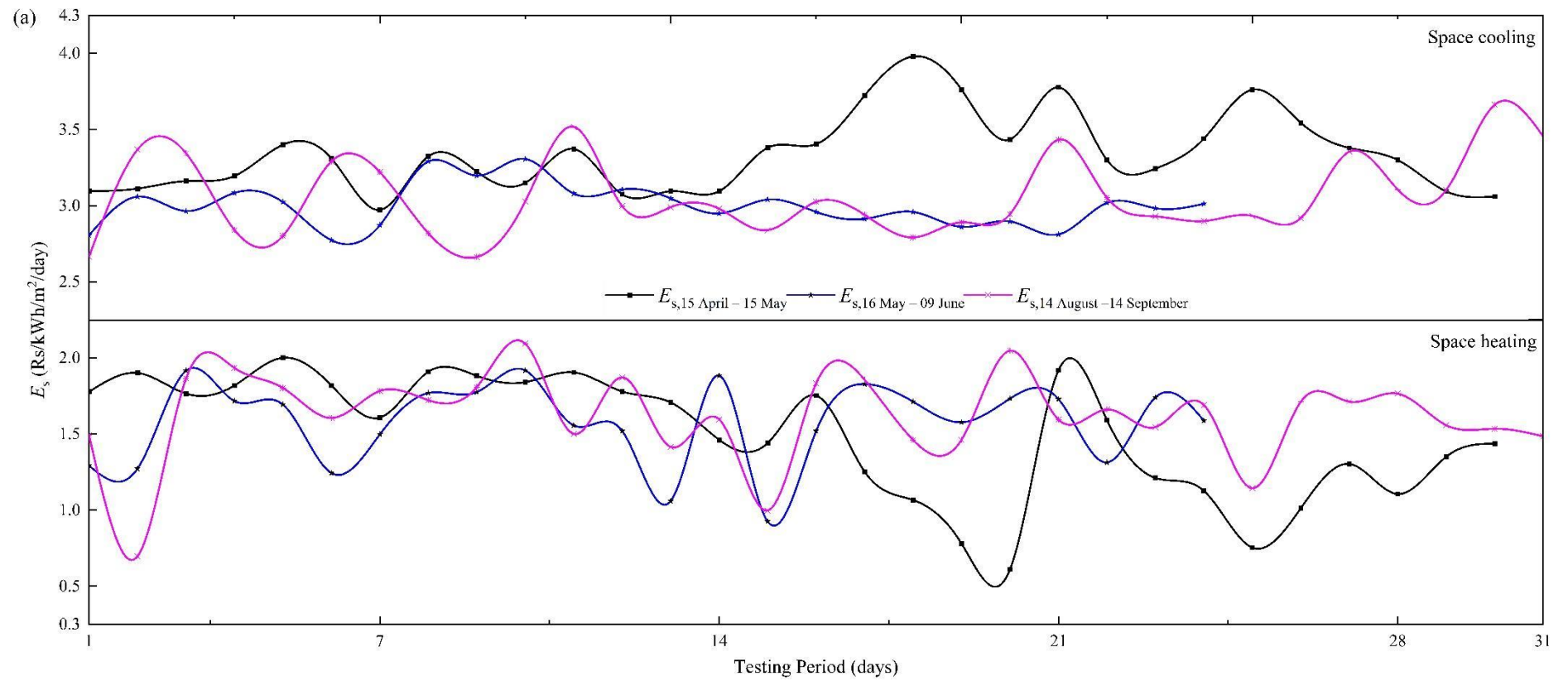
Conversely, similar trends were observed in OM37 integrated roof slabs (Ref. [Fig. 5.23b](#)) in which the daily savings on space cooling from April 15 to May are significant, with a maximum of Rupees 4.76/kWh/m² and an average of 3.97. The estimated daily savings from May 16 through June 9 and

August 14 to September 14 are 20% lower as compared to the prior testing period. Space heating savings from April 15 to May 15 averaging 2.5 Rupees/kWh/m², are 1.6 and 1.8 times better compared to 1.98 from May 16 – June 9 and 1.84 from August 14 to September 14. The cost savings achieved per day, as determined in this investigation, surpass those of (Rathore et al., 2020) during the former and later testing periods. The observed cost savings are approximately 1.5 times higher. The results imply that the majority of the cost savings occur in the spring and autumn during cooling thermal cycles. Monthly variation of 23 – 63% between heating and cooling cycles was observed for all the months. In comparison to the OM35 integrated roof slab, cost savings showed 32.4 % and 17.7 % more savings with the OM37 roof slab during heating and cooling for the whole testing period.

5.3.2.6 Payback period

In this study, the SPBP methodology was employed to ascertain the economic feasibility of PCM integration within the climatic conditions of Ropar, along with an extensive economic evaluation of the PCM-integrated slab unit. In the current study, the initial investment cost encompasses the expenses of procuring the aluminium void former and PCM. The unit cost of a single void former is 170 Rupees/2 USD. PCM incurs costs of 450 Rupees/kg or 5.4 USD/kg. Each void former seamlessly incorporates 600g of PCM. Consequently, the PCM expenditure per square meter of roof area is calculated as 3960 Rupees/47.6 USD.

The annual cost recovery is intrinsically linked to the amount of electricity saved, which inherently relies on the thermal performance of the PCM throughout the entire year. It's important to note that the average daily savings, encompassing both space heating and cooling for an entire test period, amounted to 4.69 Rupees/day, as elucidated in [Table 5.6](#). The number of potential PCM operational days can be approximated by utilizing the temperature profile of the study location, Rupnagar city, given the unavailability of test results for an entire year. As per the temperature profile (Ref. [Fig. 5.1](#)), there are approximately 148 days with temperatures exceeding 35°C, indicating their suitability for PCM operation. These days are distributed as follows: 23 between March and April, 28 between April and May, 30 between May and June, 21 between June and July, 18 between July and August, 22 between August and September, and 6 between September and October. To compute the payback period, it is assumed that PCM functions for 148 days, resulting in an average daily electricity savings of 4.69 Rupees. Consequently, the simple payback period per square meter of roof area is estimated at 3960 Rupees/4.69×148, equivalent to 5.7 years. This implies that the initial investment incurred in employing PCM-integrated biaxial voided roof elements can be recuperated in approximately 5.7 years. Thus, asserting that the proposed PCM-integrated biaxial voided roof exhibits promise and commercial viability is reasonable.



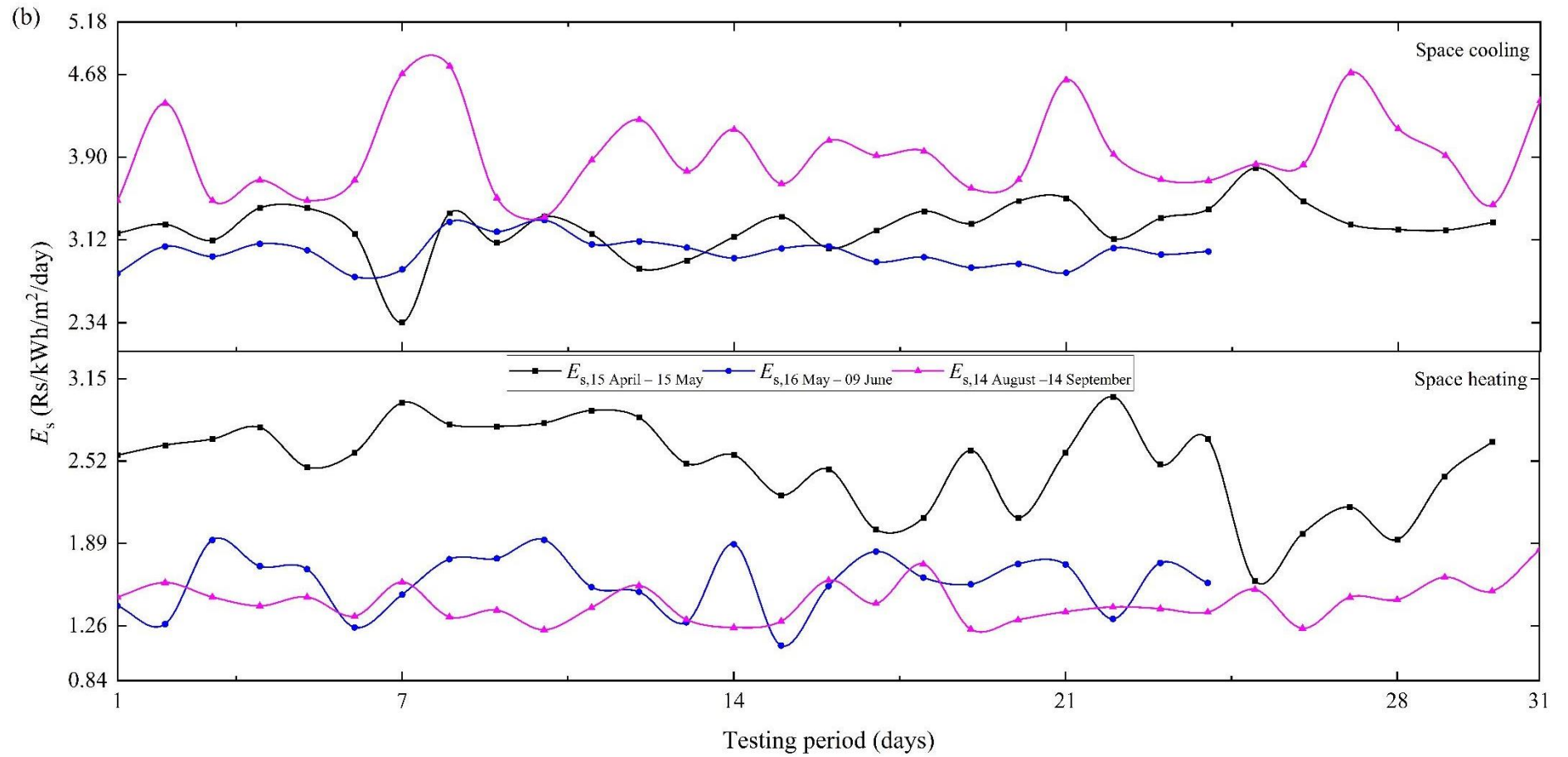


Fig. 5.23 Monthly electricity cost savings comparison: (a) OM35 integrated roof slab; and (b) OM37 integrated roof slab.

5.3.2.7 Savings in CO₂ Emissions

Fig. 5.24(a and b) illustrates the fluctuation in CO₂ emissions reductions concerning space cooling throughout the testing period. It's noticeable that lignite-based electricity generation results in the most substantial savings, while natural gas-based generation produces the lowest. This translates to potential CO₂ emissions reductions of up to 17.14 kgCO₂/kWh for power plants running on lignite and 3.3 kgCO₂/kWh for those powered by natural gas when utilizing PCM-integrated voided slabs. Coal-based electricity generation plants exhibit a similar savings figure of 15.45 kgCO₂/kWh, comparable to coal's performance. In contrast, integrating OM37 into voided slabs can lead to CO₂ emissions reductions of up to 22 kgCO₂/kWh for lignite-powered electricity generation plants and 4.1 kgCO₂/kWh for those powered by natural gas. Coal-powered electricity generation plants achieve a savings rate of 19.8 kgCO₂/kWh, aligning with coal's performance. It's important to highlight that the savings achieved from 14th August to 14th September exhibit an approximate increase of 39.3% in comparison to those observed from April 15 to May 15 and a 20.2% increase in comparison to the period from 15th of May to 09th of June. The same trend was observed in the OM37 integrated slab unit. However, the savings from August 14 to September 14 are 40% higher than those from May 16 to June 9 and 20% higher than those from April 15 to May 15. This difference can be attributed to variations in the thermal behavior of the biaxial voided unit between these testing periods.

Fig. 5.25(c and d) illustrates the fluctuations in CO₂ emissions savings related to space heating during the various test periods. Similar patterns in savings for space heating, akin to those depicted in Fig. 5.24(a and b), are evident here. Nonetheless, it's worth noting that, in general, space heating savings tend to be lower than those associated with space cooling. An approximate decline of 47% was observed from August 14 to September 14, succeeded by a reduction of 41% from April 15 to May 15, and approximately 34% between May 16 and June 09. Similarly, in the OM37 integrated roof, a substantial reduction of approximately 63% was observed between 14th August and 14th September, while the period from April 15 to May 15 exhibits the least reduction at 23%. A 47% reduction is noted between May 16 and June 9 (Ref. Fig. 5.25b) This trend can be explained within the Indian context, where space heating requirements tend to be relatively minimal compared to space cooling and given the prevailing global warming trends, it's anticipated that space heating requirements will further diminish. The CO₂ emissions savings have substantial practical implications, encompassing the reduction of direct emissions stemming from fossil fuel combustion or consumption, indirect emissions linked to electricity generation, and the broader mitigation of global warming and climate change by curbing carbon emission intensity.

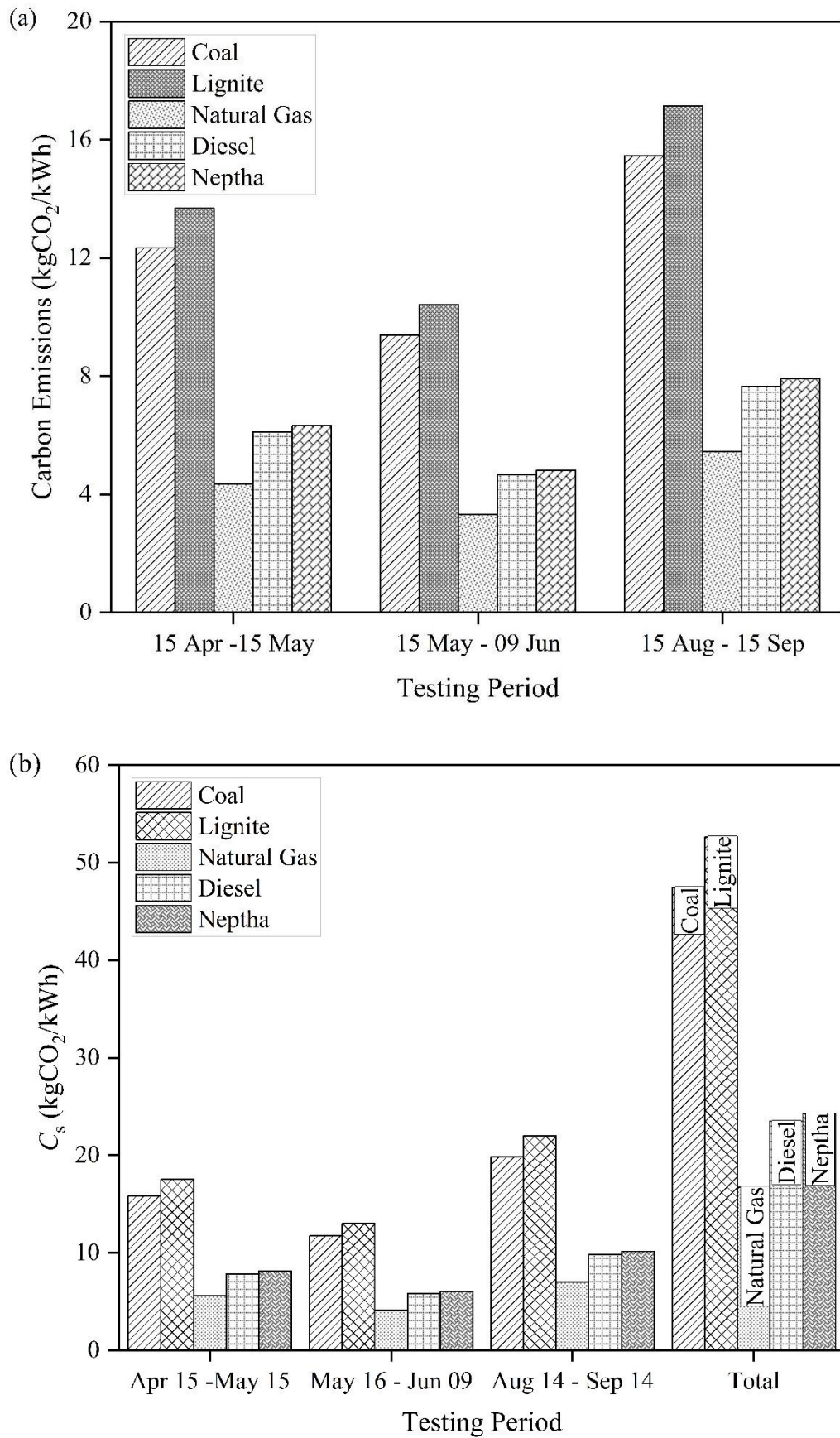


Fig. 5.24 CO₂ emission savings during cooling: (a) OM35 roof; and (b) OM37 roof.

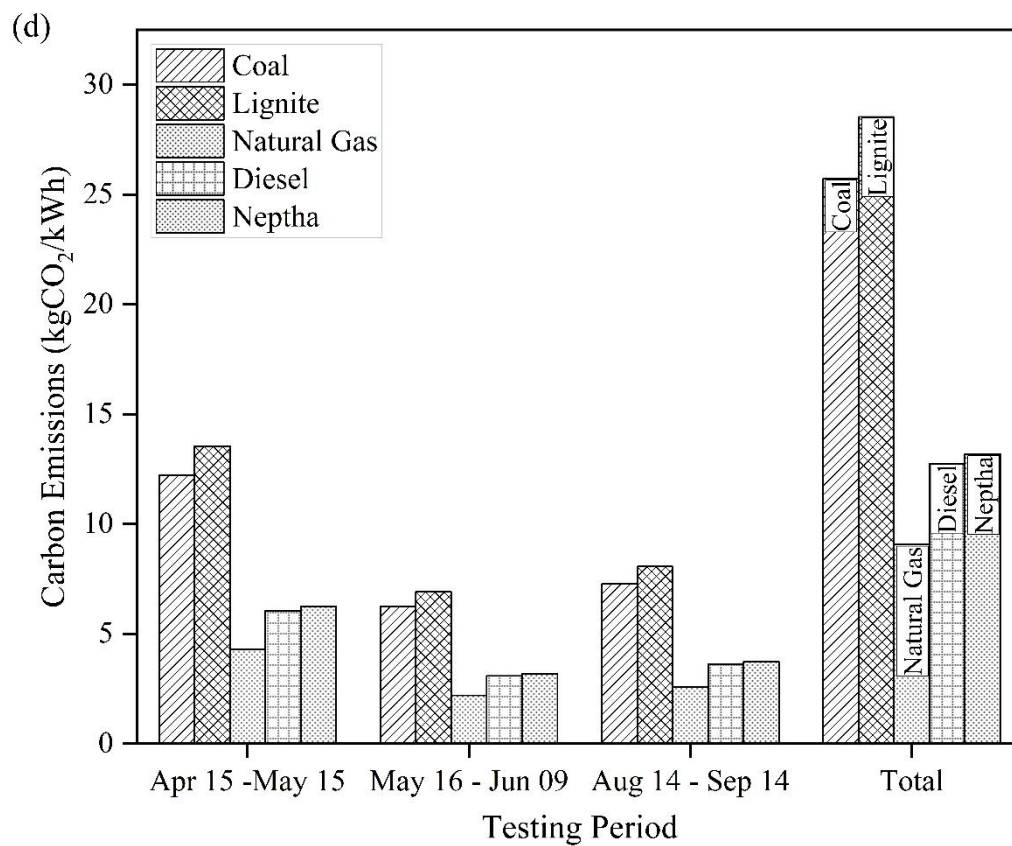
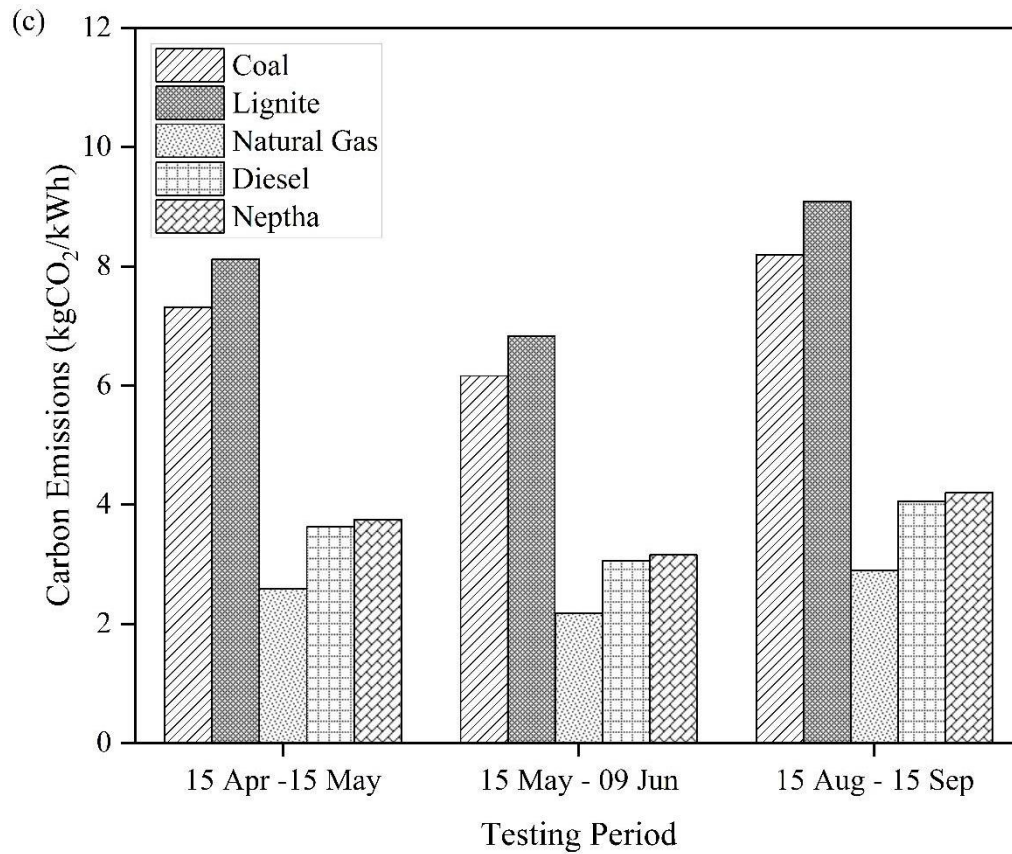


Fig. 5.25 CO₂ emission savings during heating: (a) OM35 roof; and (b) OM37 roof.

The comprehensive computation of carbon emissions for various fuel types is delineated in [Table 5.7](#) for categorical analysis. Notably, the integration of OM37 PCM leads to an almost 20% greater carbon emissions reduction than OM35. During the testing period, a substantial portion of total emissions, exceeding 65%, is attributed to the cooling load, and heating loads make 40%. Given that the cooling load represents a significant share of overall energy consumption during this stage, any reduction in the cooling load has the potential to yield a substantial decrease in life cycle carbon emissions.

Table 5.7 Carbon emissions reduction during heating and cooling loads.

Testing period	Heating loads					Cooling loads				
	Coal	Lignite	Natural Gas	Diesel	Neptha	Coal	Lignite	Natural Gas	Diesel	Neptha
————— OM35 —————										
15 th April – 15 th May	7.315	8.114	2.582	3.627	3.750	12.336	13.683	4.354	6.116	6.323
16 th May – 09 th June	6.158	6.831	2.174	3.053	3.157	9.390	10.416	3.314	4.656	4.814
14 th August – 14 th September	8.190	9.084	2.890	4.060	4.198	15.453	17.142	5.454	7.662	7.921
Total	21.66	24.02	7.64	10.74	11.10	37.17	41.24	13.12	18.43	19.05
————— OM37 —————										
15 th April – 15 th May	12.211	13.545	4.310	6.054	6.259	15.850	17.581	5.594	7.858	8.125
16 th May – 09 th June	6.238	6.919	2.202	3.093	3.198	11.754	13.038	4.148	5.827	6.025
14 th August – 14 th September	7.279	8.074	2.569	3.609	3.731	19.844	22.012	7.004	9.839	10.172
Total	25.72	28.53	9.08	12.75	13.18	47.44	52.63	16.74	23.52	24.32

5.4 Concluding Remarks

The following points provide a summary of the comparison between the two PCMs used in the BVS unit w.r.t the conventional roof slab unit:

- i. During the testing period of 15th April – 15th May, when comparing the calculated values for $T_{es}/T_{is,BVS}$ and $T_{is,BVS}/T_{is,CRS}$, OM35 outperformed OM37 in both sunny and non-sunny hours. The average improvement for $T_{es}/T_{is,BVS}$ and $T_{is,BVS}/T_{is,CRS}$ with OM35 PCM ranged from 36.12% to 39.25%, during both sunny and non-sunny hours with an average enhancement of 36.84% for $T_{is,BVS}/T_{is,CRS}$ during non-sunny hours compared to OM37. The summary of calculated data is computed in (Ref. [Table 5.3](#)). During the 16th of May – 09th June period, OM37 performed better during sunny hours, exhibiting an average improvement of 1% to 20% for $T_{es}/T_{is,BVS}$ and $T_{is,BVS}/T_{is,CRS}$. During non-sunny hours, OM35 dominated with an average improvement of 37.73% for $T_{es}/T_{is,BVS}$. Throughout the entire testing period from 14th August to 14th September, OM37 showed substantial improvement in both sunny and non-sunny hours compared to OM35. The improvements calculated were 36.58 to 66.75% and 26.94 to 50.19% for $T_{is,BVS}/T_{is,CRS}$ and $T_{es}/T_{is,BVS}$ during sunny and non-sunny hours.
- ii. During the entire testing period, the utilization of OM37 for heat transfer into the BVS showed a noteworthy improvement of 13% to 59% compared to OM35 specifically during sunny hours. However, during non-sunny hours, the heat flux values for OM37 to OM35 increased by a factor of 0.3 to 1.7.
- iii. Compared to OM35, the thermal load reduction achieved by OM37 exhibited a 1.2-fold increase.
- iv. During both sunny and non-sunny hours throughout the entire testing period, the electricity cost savings per day achieved with OM37 were almost 1.5 times higher than those obtained with OM35.
- v. Integration of OM37 PCM leads to an almost 20% greater reduction in carbon emissions than OM35. During the testing period, a substantial portion of total emissions, exceeding 65%, is attributed to the cooling load, and heating loads make 40%.
- vi. The average time lag of OM37 is 4.58 hrs while that of OM5 is 3.9 hrs, a rise of a 1.17 factor. A time lag factor of 5 hours or less was present in approximately 65.5% (75 days)

of the testing period, while a time lag factor of 4 hours or less was observed in 62.5% (35 days) for OM37 and 35 respectively.

- vii. The decrement factors of 0.728 and 0.717 were achieved for f_{OM37} and f_{OM35} respectively throughout the testing period.

6.1 Nano-Enhanced Phase Change Materials

The inadequate thermal conductivity of PCMs is a notable drawback, hampering the efficiency of their energy-charging and discharging processes (Khodadadi et al., 2013a). To surmount this constraint, diverse strategies have been investigated to bolster the effective thermal conductivity of these materials. Integrating nanoparticles, metallic foam structures, and fin configurations into PCMs has demonstrated notable enhancements in their thermal conductivity, as indicated in references (Ashraf et al., 2017; N. H. Mohamed et al., 2017a). Nevertheless, when considering metal foams and fins as additives to PCMs, it becomes apparent that this can lead to increased system weight and heightened design complexity for thermal storage applications (Leong et al., 2019). Historical research in the NePCMs domain has utilized various nanomaterials, including copper, copper oxide, aluminum, alumina, titanium, silver, silica, carbon nanotubes, and graphite nanofibers. Research studies by (Yanbin Cui et al., 2011; Fikri et al., 2022; Hekimoğlu et al., 2022; Khodadadi et al., 2013b; Teng et al., 2013) exemplify the growing interest in this area.

The selection of nanomaterials significantly influences the thermophysical characteristics of NePCMs, including thermal conductivity, latent heat capacity, supercooling, phase change duration, phase change temperatures, density, viscosity, and thermophysical properties after thermal cycles. In particular, the thermal conductivity of nanoparticles is an important parameter and is higher than that of PCM. Carbon-based nanomaterials, such as MWCNTs and GNPs, have emerged as favorable choices due to their notably elevated thermal conductivity coupled with a relatively low density exhibiting thermal conductivities over 3000 W/m K and 5300 W/m K, respectively. However, heavy replacement of PCM with nanomaterials could deteriorate the latent heat of NePCMs (Bahiraei et al., 2017). In the current study, MWCNT and GNP nanomaterials are selected. GNPs, characterized by their unique two-dimensional planar arrangement, have demonstrated a superior capacity to augment engineered suspensions' thermal conductivity compared to wire-shaped carbon nanomaterials like CNFs and CNTs (Z. T. Yu et al., 2013). The latent heat improvement in NePCM can be attributed to changes in the interaction between PCM and nanomaterials. However, heavy replacement of PCM with nanomaterials could deteriorate the latent heat of NePCMs. Detailed information regarding the purity, dimensional details, and manufacturers of nanoparticles is provided in [Table 5.1](#).

Table 6.1 Properties of Nanomaterials.

Nanoparticles	Supplier	Purity (%)	Dimensions
MWCNTs	Ultrananotech Pvt. Ltd. Bangalore – 560048, India	>97	$\phi^* = 10 - 15\text{nm}$ $L = 3 - 10\mu\text{m}$
GNPs	Ultrananotech Pvt. Ltd. Bangalore – 560048, India	>99.9	$d = 10 - 15\text{nm}$

* ϕ , L, and d stand for diameter, length, and thickness, respectively.

6.2 Preparation of NePCMs

NePCMs are typically synthesized using either a one-step or two-step technique. The one-step technique involves the simultaneous production and dispersion of nanomaterials in the base fluid of PCM. The one-step technique minimizes the agglomeration of nanoparticles. It is essential to recognize that this technique is only suitable for liquids with low vapour pressure (Bahiraei et al., 2017). The two-step technique involves the independent synthesis of nanomaterials, which are then dispersed in the base fluid of the PCM. The two-step technique is commonly employed for NePCM synthesis due to its cost-effectiveness compared to the one-step technique (X.-Q. Wang & Mujumdar, 2007).

The current study uses a two-step technique. The schematic of the technique is illustrated in Fig. 6.1. Four NePCM samples for each PCM are prepared with 2% and 4% weight fractions of MWCNT and GNP nanoparticles. First, the base solid PCM is preheated to a temperature range of 50–60 °C using a hot plate for 40 minutes. This process facilitates the conversion of PCM into a uniform base fluid. Subsequently, nanomaterials with mass fractions in each sample of 2% and 4% MWCNT and GNP are evenly dispersed in the base fluid. Each sample is prepared by shear mixing using a magnetic stirrer for 45 minutes. This process ensures that the nanomaterials are mixed homogeneously in the PCM base liquid. Further, each sample is subjected to ultrasonic shaking for 1 hour. This step is implemented to enhance the dispersion of nanomaterials in the PCM base fluid and prevent any potential agglomeration. Since nanomaterials have a very irregular structure, dispersion under magnetic stirring and subsequent ultrasonic shaking leads to isotropic NePCMs. However, the success in preventing agglomeration depends on several factors including the type and size of nanoparticles, the viscosity of the PCM, the mixing intensity and duration, and the effectiveness of the mixing equipment used e.g., shear mixing speed and time affect the size of agglomerates, which has an impact on the mechanical properties of the composite (Pullicino et al., 2017). similarly, sonication during the initial seeding phase may aid in nucleation generation and prevent particle agglomeration (Gielen et al., 2017). Finally, the molten NePCM is poured into

cylindrical aluminum moulds (20 mm × 10 mm), ensuring no air is entrapped. It is then allowed to solidify at room temperature. These samples were left to naturally solidify at room temperature, culminating in the formation of solid NePCM samples designated for subsequent thermal conductivity measurement. The complete solidification process took approximately 1.5 hours. The resultant samples generated via this procedural approach inherently demonstrate isotropy due to the pronouncedly irregular characteristics of nanoparticles.

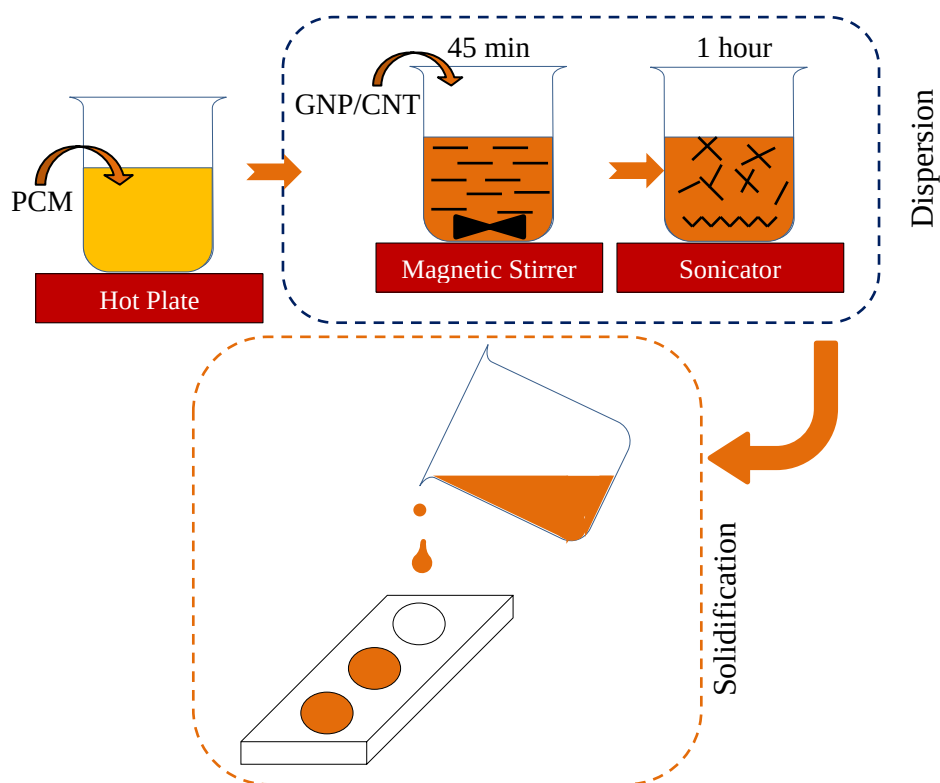


Fig. 6. 1 Diagrammatic representation of the experimental setup and methodology.

6.3 Characterization of NePCMs

Characterization of NePCMs involves various techniques to assess their properties comprehensively. Thermal conductivity, a critical parameter, is typically determined using the transient method. DSC measures phase change temperatures and latent heat of fusion, providing insights into thermal behavior. TGA evaluates thermal stability and decomposition characteristics by monitoring weight changes with temperature. FT-IR elucidates chemical composition and molecular structure through vibrational spectra analysis. XRD identifies crystal structure and phase composition, while FE-SEM offers high-resolution imaging of surface morphology and nanoparticle distribution. Together, these techniques enable a thorough understanding of NePCMs for diverse applications.

6.3.1 Thermal Conductivity

A transient plane source-based thermal constants analyzer was used to determine the thermal conductivity of PCMs and NePCMs. The tests follow the procedures outlined in ISO 22007-2:2022 for measuring thermal conductivity and thermal diffusivity. PCMs and NePCMs samples in the solid state are prepared using an aluminum mould. The dimensions of each sample were meticulously determined to be consistent, measuring 50 mm in diameter and 10 mm in thickness. The test setup is shown in Fig. 6.2. Note that the pure PCM sample is white, whereas the MWCNT–NePCM specimen exhibits a distinct black coloration due to carbon, and the GNP–NePCM specimen manifests as grey, as represented in Figs. 6.3(a–c). The thermal conductivity distribution of PCMs, MWCNT–NePCM, and GNP–NePCM, each with 2% and 4% mass fractions, are depicted in Fig. 6.4. The experiments were carried out on three samples, and the reported outcomes are average values, exhibiting a standard deviation of $< 1\%$.

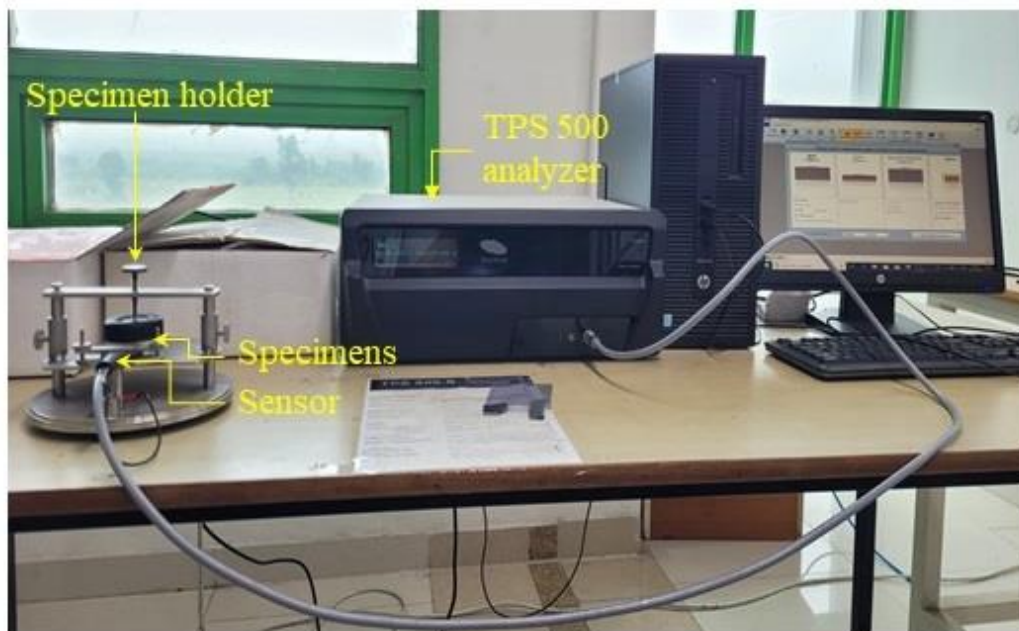


Fig. 6.2 Thermal conductivity setup.

The interaction between nanoparticles and PCMs can significantly enhance the effective thermal conductivity of NePCMs through: (i) GNP/MWCNTs embedded within the PCM matrix create additional pathways for heat transfer. These nanoparticles have high thermal conductivity compared to the PCM, allowing them to efficiently conduct heat through the material. (ii) Nanoparticles typically have a high surface area-to-volume ratio. When dispersed in the PCM, this large surface area facilitates improved contact between the PCM and the nanoparticles. This enhanced interface promotes heat transfer between the PCM and nanoparticles, thereby increasing overall thermal conductivity. iii. The nanoparticles act as bridges for heat conduction.

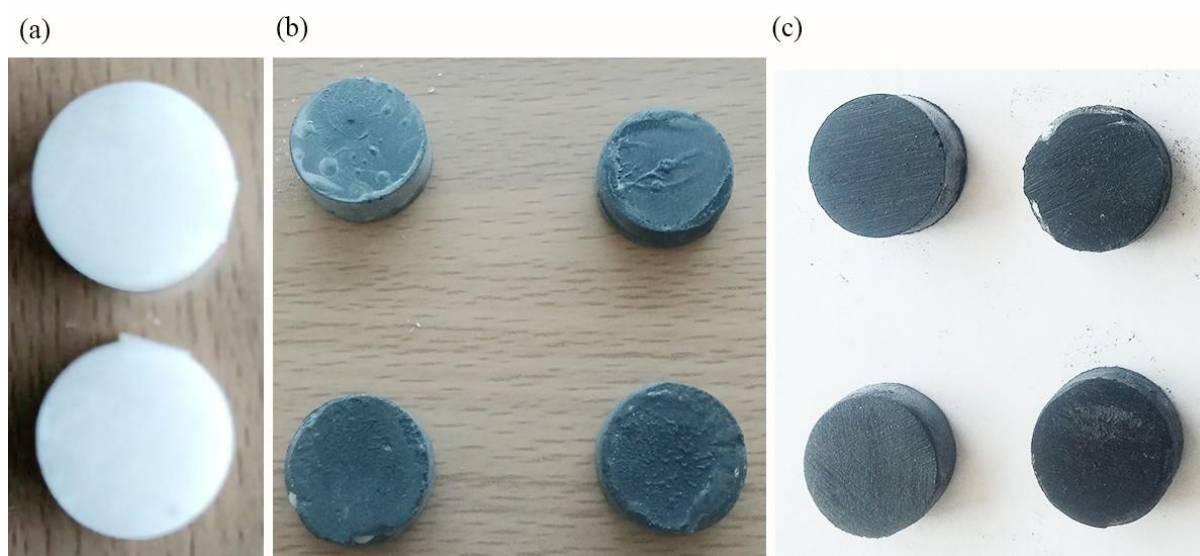


Fig. 6.3 Thermal conductivity samples: (a) PCM; (b) GNP-NePCM; and (c) MWCNT-NePCM.

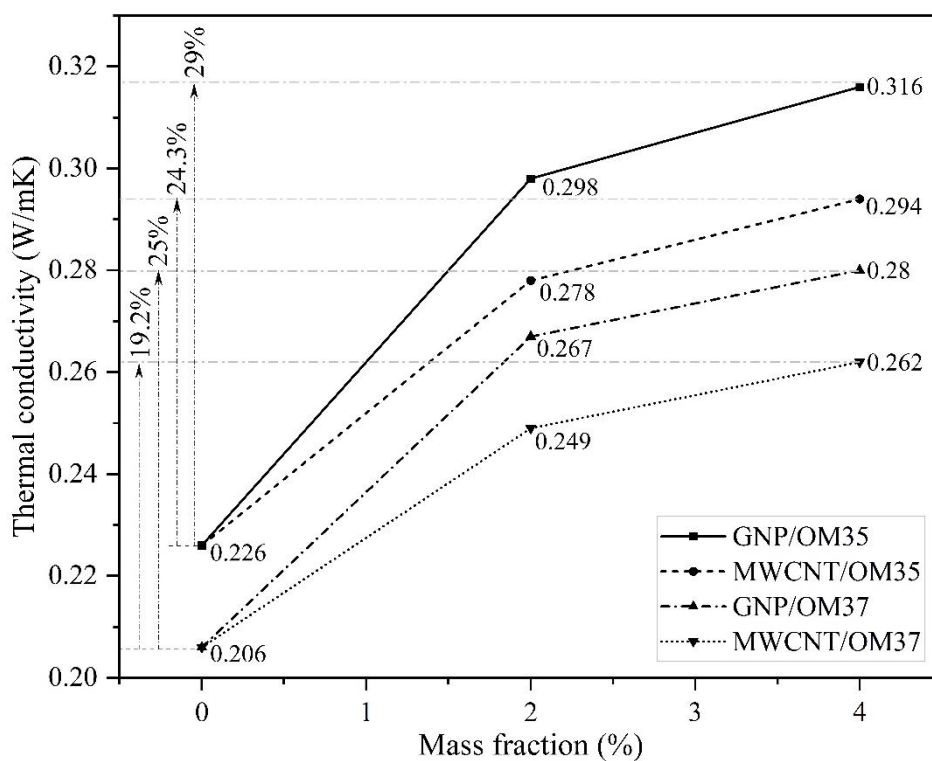


Fig. 6.4 Thermal conductivity of PCM and NePCMs.

The thermal conductivity assessment of the OM35/MWCNT – NePCMs yielded values of 0.278 and 0.294 W/mK for mass fractions of 2 and 4 wt.%, respectively. The values corresponding to 2% and 4% mass fractions exhibit an increase of 21.4% and 24.1%, respectively, compared to OM35. This notable upsurge in thermal conductivity can primarily be attributed to the elevated thermal conductivity range of MWCNTs and their well-dispersed disposition within the NePCM, which engenders a larger surface area for efficient heat transfer. These outcomes resonate with prior

investigations conducted by (Ting Xian Li et al., 2013; J. Wang et al., 2009) elucidating the constructive impact of MWCNTs on thermal conductivity. Conversely, the OM37/MWCNTs NePCMs exhibited enhancements of 20 % and 26 % at 2 and 4 wt.% loading levels, respectively, in contrast to base PCM, OM37.

In contrast, the performance of planar GNPs surpassed their wire-shaped counterparts in terms of thermal conductivity enhancement, as demonstrated in Fig. 6.4. The 2% GNP-NePCMs and 4% GNP-NePCMs demonstrated a thermal conductivity of 0.3 W/mK and 0.32 W/mK, exhibiting increments of 36.4% and 45.5%, respectively, compared to OM35. In comparison to OM37, GNP-NePCMs showed 26% and 28.5% increments. This enhanced performance can be ascribed to the unique two-dimensional planar configuration of GNPs, which results in a larger contact area and diminished thermal interface resistance between GNPs and the paraffin matrix. The diminished thermal interface resistance arises from the minimized geometric contribution to phonon scattering at the interfaces, as expounded by (A. Yu et al., 2007). The superior efficacy of GNPs compared to other carbon fillers like MWCNTs and CNFs in liquid paraffin-based suspensions has also been established by (Z. T. Yu et al., 2013).

Following the demonstration that GNPs exhibit superior performance as thermal conductivity enhancers due to their inherent geometry-induced lowered thermal interface resistance, the association with prior findings is of considerable interest. Fig. 6.5 provides a juxtaposition of the current findings with data documented in the literature (L. W. Fan et al., 2013; S. Kim & Drzal, 2009; J. N. Shi et al., 2013; X. Wu et al., 2022; Xiang & Drzal, 2011; Yavari et al., 2011).

Tables 6.2 and 6.3 present the average values for thermal diffusivity and specific heat capacity of PCMs, with 2% and 4% mass fractions of MWCNT-NePCM and GNP-NePCM. Both MWCNT-NePCM and GNP-NePCM exhibit higher thermal diffusivities compared to base PCMs. Specifically, the thermal diffusivity of GNP-NePCM surpasses that of OM35 by 75% for a 2% mass fraction and 112.5% for a 4% mass fraction. Similarly, MWCNT-NePCM demonstrates a 50% increase in thermal diffusivity for a 2% mass fraction and a 75% increase for a 4% mass fraction. Consequently, GNP-NePCM displays a 21.4% higher thermal diffusivity than MWCNT-NePCM for a 2% mass fraction and 23.07% higher for a 4% mass fraction. A comparable pattern is noted in the OM37 NePCMs, although there are marginal improvements in diffusivity values. Specifically, GNP-NePCM exhibits a 7.14% increase in thermal diffusivity compared to MWCNT-NePCM for a 2% mass fraction and a 3.65% increase for a 4% mass fraction. This suggests that GNP-NePCM facilitates a superior heat transfer rate compared to MWCNT-NePCM, allowing for efficient transfer of variations in boundary heat flux. It's noteworthy that OM35 NePCMs demonstrated superior thermal diffusivity values when contrasted with OM37. It is important to

highlight that a decline in thermal diffusivity leads to a diminished heat transfer rate, consequently limiting the thermal energy absorption rate.

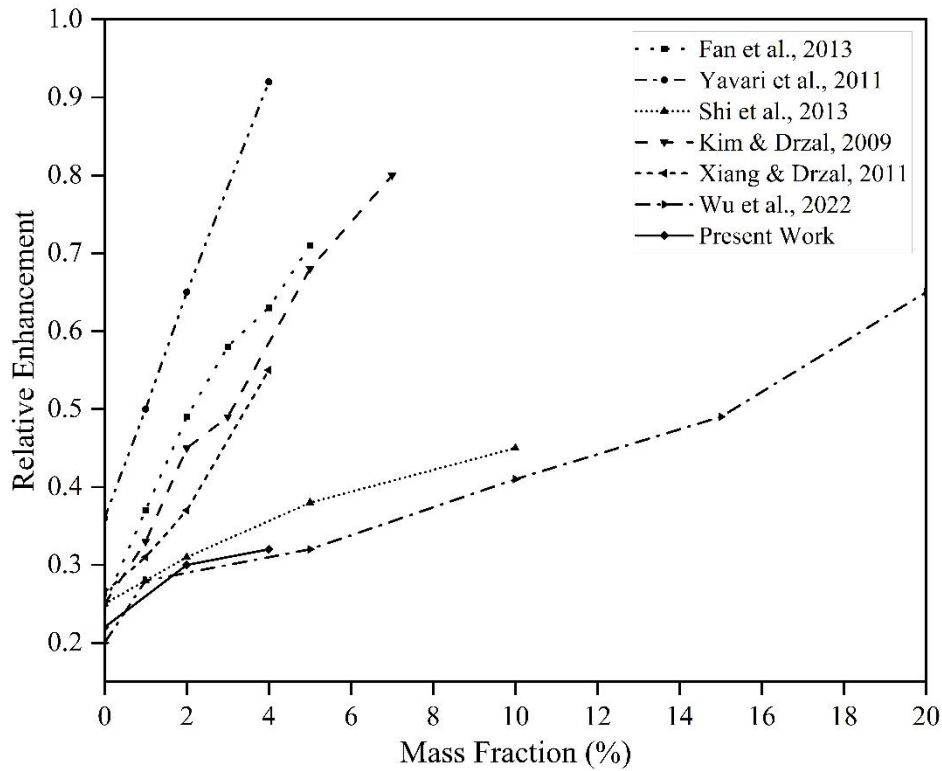


Fig. 6.5 Comparison of thermal conductivity values with the data in the literature.

Tables 6.2 and 6.3 delineate the samples' average specific heat capacity value fluctuations. The specific heat capacity of MWCNT–NePCM and GNP–NePCM manifests a decrease compared to PCMs. Specifically, the specific heat capacity of GNP–NePCM is 17.8% lower than OM35 for a 2% mass fraction and 25.6% lower for a 4% mass fraction. Conversely, MWCNT–NePCM exhibits a 10.0% reduction for a 2% mass fraction and a 6.2% reduction for a 4% mass fraction. Consequently, the specific heat capacity of GNP–NePCM is 14.1% lower than that of MWCNT–NePCM for a 2% mass fraction and 26.0% lower for a 4% mass fraction. Utilizing OM37, a reverse phenomenon was noted, indicating that the specific heat capacity of MWCNT–NePCM is 6.6% lower than that of GNP–NePCM for a 2% mass fraction and 3.0% lower for a 4% mass fraction. This suggests that GNP–NePCM has a lower heat storage capacity than MWCNT–NePCM. The amalgamation of higher thermal conductivity and low specific heat capacity observed in GNP–NePCM results in elevated thermal diffusivity, thereby enhancing the effectiveness of the NePCM and facilitating rapid heat transfer, especially in thicker NePCM configurations. Consequently, regarding thermal properties, GNP–NePCM emerges as a more favorable candidate than MWCNT–NePCM.

Table 6.2 Thermal conductivity values of OM35-based NePCMs at 2 and 4% loading.

Specimen	Thermal conductivity (W/mK)	Diffusivity (m ² /s)	Specific heat capacity (J/kg.K)
OM35-PCM	0.2258	0.0893	2526
	0.2271	0.0854	2656
	0.2271	0.0854	2656
	Avg. 0.2266	0.0865	2612
2%GNP/OM35	0.2992	0.148	2021
	0.3011	0.147	2046
	0.2956	0.1272	2325
	Avg. 0.29863	0.14073	2130.66
4%GNP/OM35	0.3175	0.1606	1977
	0.3237	0.1772	1827
	0.3096	0.1563	1981
	Avg. 0.31693	0.1647	1928.33
2%MWCNT/OM35	0.2787	0.1124	2479
	0.2795	0.1148	2434
	0.278	0.1188	2378
	Avg. 0.27873	0.11533	2430.33
4%MWCNT/OM35	0.2853	0.1256	2721
	0.2864	0.1324	2162
	0.3106	0.1467	2117
	Avg. 0.2941	0.1349	2333.33

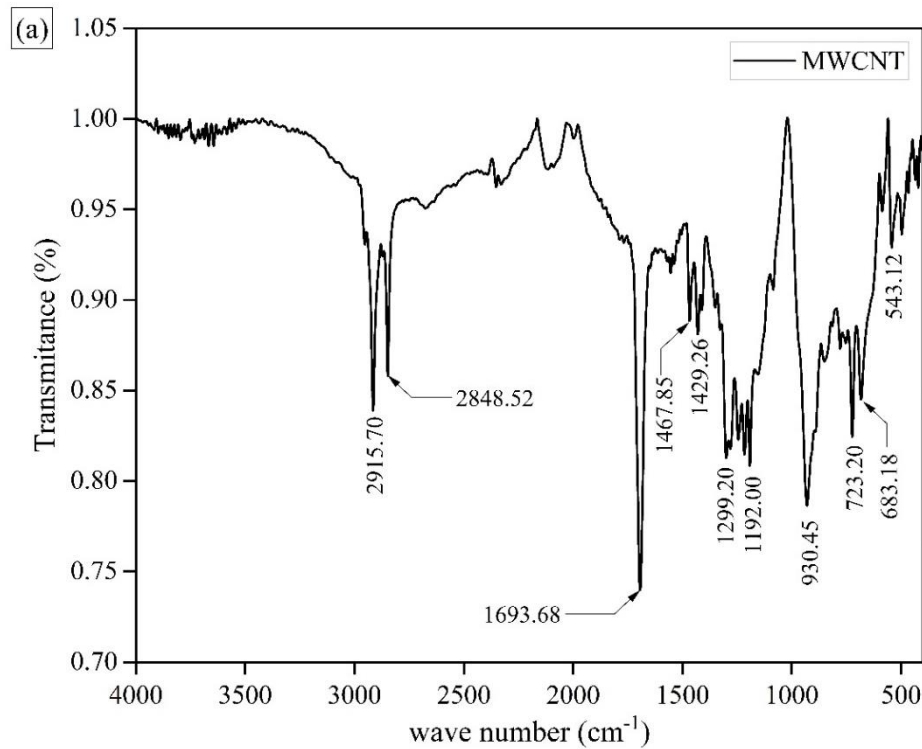
6.3.2 Chemical Characterization

6.3.2.1 FT-IR analysis

The chemical interactions between PCMs and MWCNT/GNP in NePCMs were meticulously examined through FT-IR using a KBr disc. The spectral analysis encompassed a range from 400 cm⁻¹ to 4000 cm⁻¹, maintaining a resolution of 4 cm⁻¹. Notably, the spectra of both NePCMs exhibited noteworthy similarities. The FT-IR spectra of MWCNTs and GNPs are depicted in Figs. 6.6(a, b) while the prepared NePCMs are presented in Fig. 6.7 and Fig. 6.8. The incorporation of MWCNTs and GNPs into PCMs did not give rise to the emergence of novel peaks or noteworthy shifts in existing peaks. Instead, the resulting NePCMs exhibited a blend of peaks characteristic of the PCMs and NePCMs. This observation indicates the absence of chemical interaction between the PCMs and MWCNT or GNP. The observed behavior can instead be attributed to physical phenomena such as capillary adsorption and van der Waals forces.

Table 6.3 Thermal conductivity values of OM37-based NePCM at 2 and 4% loading.

Specimen	Thermal conductivity (W/mK)	Diffusivity (m ² /s)	Specific heat capacity (kJ/kg.K)
OM37-PCM	0.207	0.101	2.036
	0.206	0.093	2.207
	0.207	0.094	2.190
Avg.	0.206	0.096	2.144
2%GNP/OM37	0.267	0.148	1.809
	0.267	0.147	1.817
	0.267	0.127	2.102
Avg.	0.267	0.140	1.909
4%GNP/OM37	0.281	0.160	1.756
	0.279	0.177	1.576
	0.280	0.156	1.794
Avg.	0.280	0.164	1.708
2%MWCNT/OM37	0.248	0.140	1.771
	0.249	0.139	1.791
	0.249	0.139	1.791
Avg.	0.249	0.139	1.783
4%MWCNT/OM37	0.262	0.158	1.658
	0.264	0.157	1.681
	0.261	0.159	1.641
Avg.	0.262	0.158	1.658



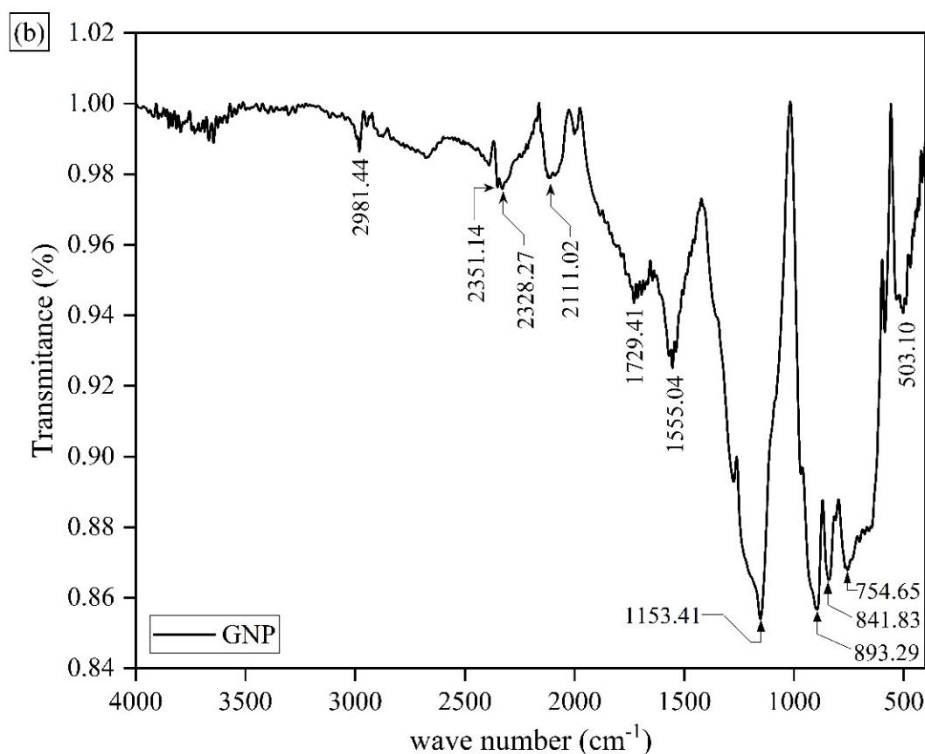


Fig. 6.6 FT-IR spectra: (a) MWCNT; and (b) GNP.

The FT-IR spectra of the NePCMs displayed distinctive peaks at 2915 and 2848 cm⁻¹, corresponding to C–H asymmetric stretching and symmetric vibration of CH₃/CH₂ groups, following findings reported by (S. Y. Wu et al., 2016a). The absorption peak at 1693 cm⁻¹ signifies the stretching of the C=O bond of the –COOH group. Notably, the characteristic peaks at 1300 and 730 cm⁻¹ are associated with C–H bending vibration and in-plane deformation rocking vibration of CH₂, respectively. Furthermore, the peak at 930 cm⁻¹ is attributed to –OH group vibration. Conversely, the absorption band for GNP emerged at around 2981 cm⁻¹ in the spectra, corresponding to the symmetric stretching vibration of the C–H bond. Based on the FT-IR data, it can be concluded that the constituents of the NePCMs demonstrate a high degree of physicochemical compatibility.

6.3.2.2 XRD analysis

Examining the crystallization behavior of PCMs and NePCMs involves a detailed analysis of their XRD spectra, employing a specialized XRD diffractometer. The apparatus utilizes Cu K- α radiation with a precise wavelength of 0.154 nm, operating under 45 kV and 40 mA conditions. The analysis spans a comprehensive range of 2- θ values, specifically from 5° to 70°. Fig. 5.9 displays the X-ray diffraction patterns of nanomaterials.

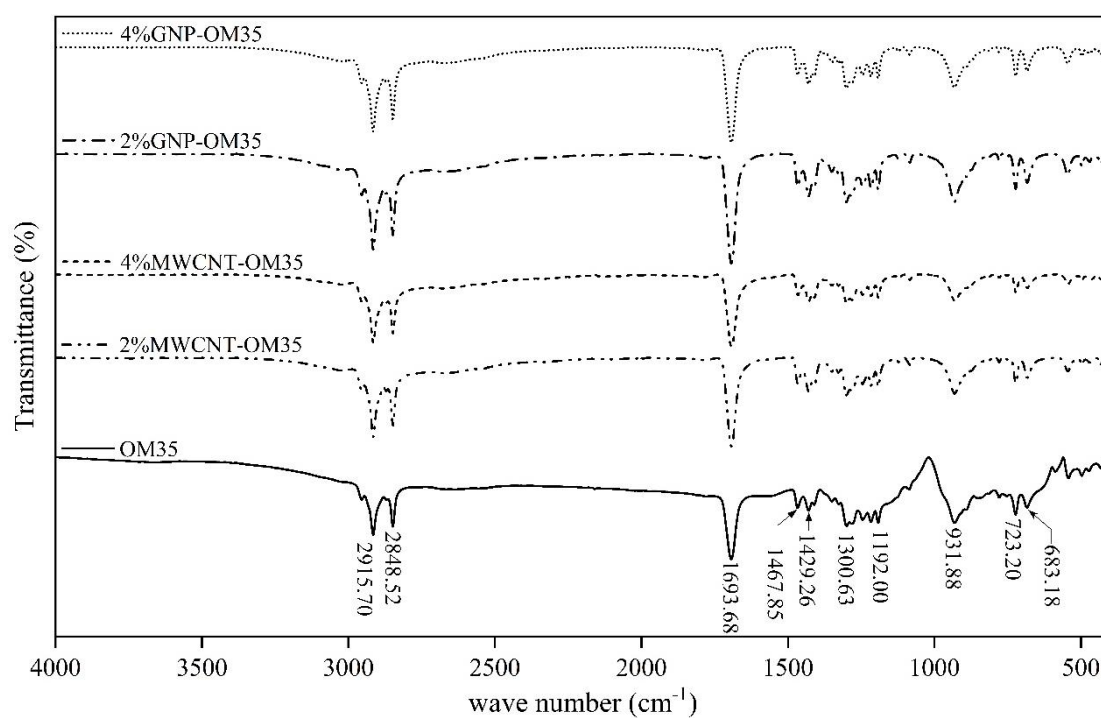


Fig. 6.7 FT-IR spectra of OM35 and OM35-based NePCMs.

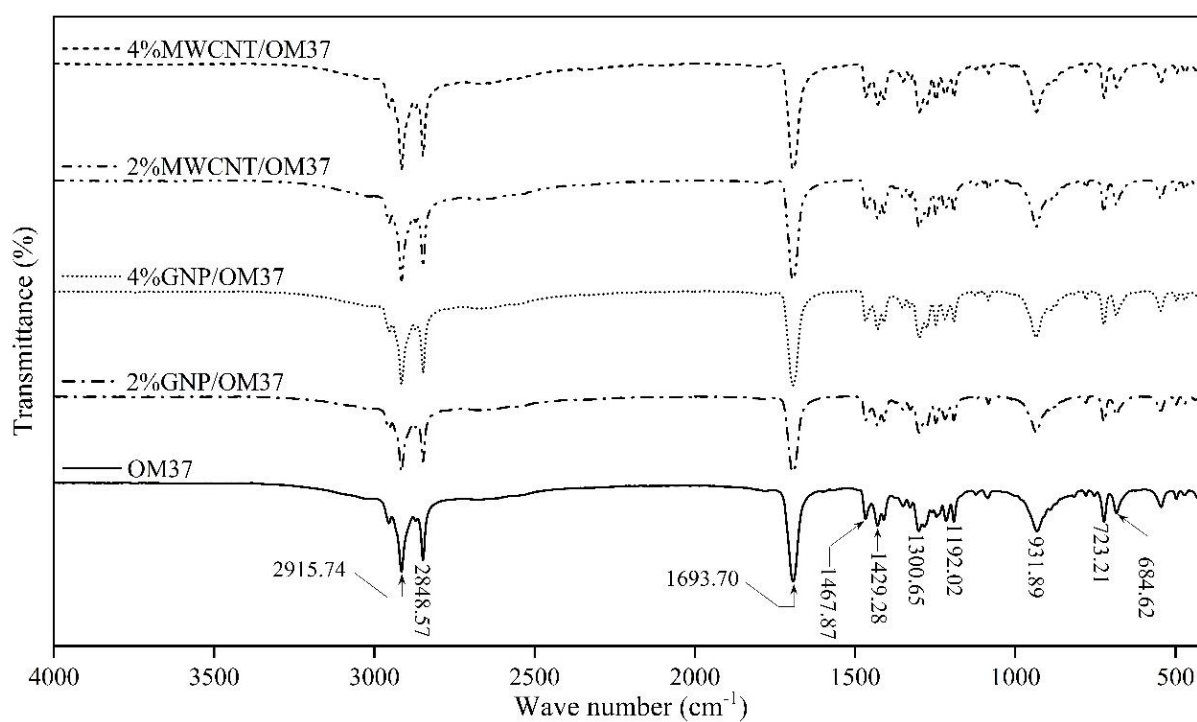


Fig. 6.8 FT-IR spectra of OM37 and OM37-based NePCMs.

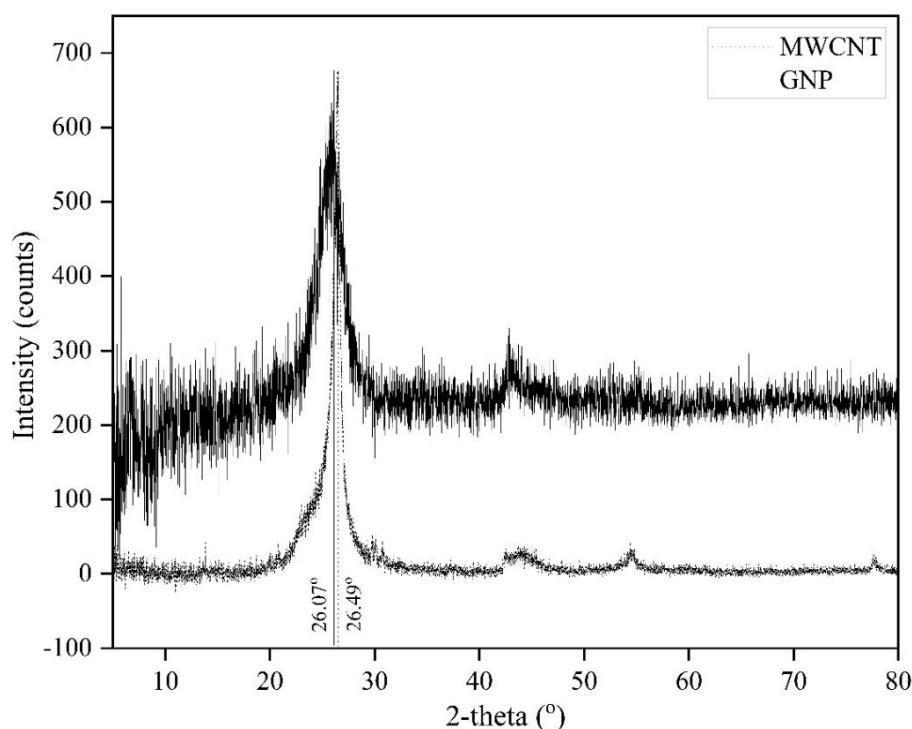


Fig. 6.9 XRD pattern of MWCNT and GNP.

The diffraction pattern of GNP demonstrates poor crystallization capabilities, evidenced by a singular peak at 26.07° . Additionally, the crystallization of MWCNT is discerned through a prominent peak at 26.4° , corresponding to the (002) peaks characteristic of graphite. However, the omission of this peak in MWCNT–NePCM can be ascribed to the relatively low loading of MWCNT. Interestingly, none of the NePCM samples exhibited the diffraction peak of GNP, indicating that GNP/MWCNTs were uniformly dispersed throughout the GNP/MWCNT – NePCMs, possibly due to their intercalation within the NePCM structure. The effect of incorporating GNP and MWCNTs on the crystallization performance of PCMs is illustrated in [Figs. 5.10\(a, b\)](#). The presence of six sharp diffraction peaks observed at 6.05° , 9.04° , 20.2° , 21.447° , and 23.5° in the PCMs are attributed to the diffractions of (004), (012), (110), (200), (020), (002) and other crystal planes, indicating the crystallization of the PCM.

The XRD patterns of the NePCMs exhibit similar peaks to those of the base PCM, suggesting that the crystal structure of the PCM segments remains intact even with nanomaterials. Although there are slight variations in the 2θ values and intensities of the distinguishing peaks in the NePCMs, no new peaks are observed upon the addition of carbon nanoparticles. The intensity of the PCM component's peak in the NePCMs is higher than that of the pure PCM, indicating that the doping of GNP/MWCNTs does not modify the crystal structure of the NePCMs, and no chemical reactions occur between the components. The findings of this XRD analysis are consistent with similar studies conducted by other researchers. For instance, CNS-doped paraffin wax (X. Lu et al., 2020),

expanded graphite-doped olefin block copolymer (OBC)/paraffin blend (W. Wu et al., 2019), CNT doped Myristic acid/Silica fume matrix (Sarı et al., 2019) and GNP @ polyaniline (Quan Wang et al., 2017).

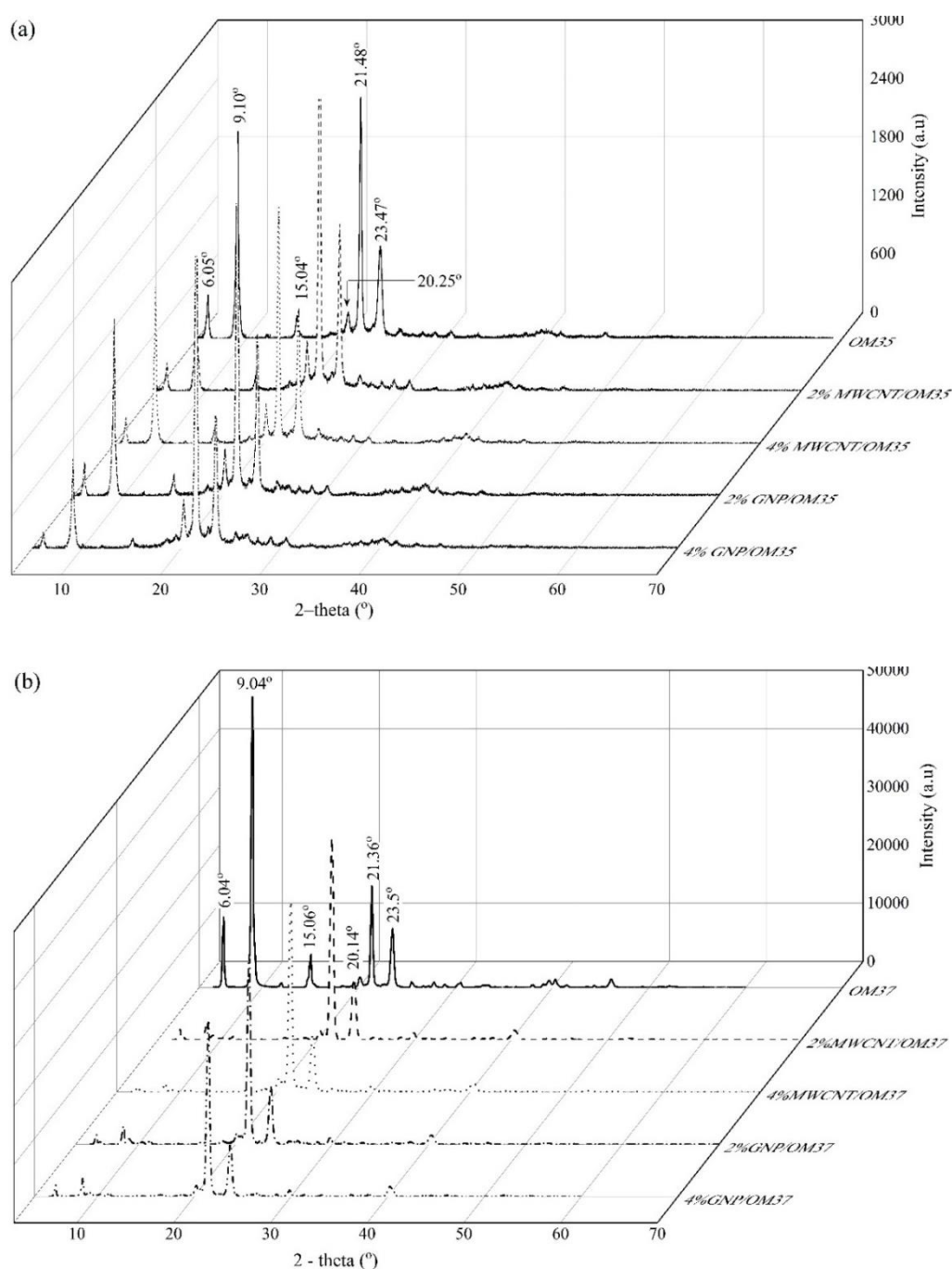


Fig. 6.10 XRD patterns: (a) OM35 based NePCMs; and (b) OM37 based NePCMs.

6.3.3 DSC analysis

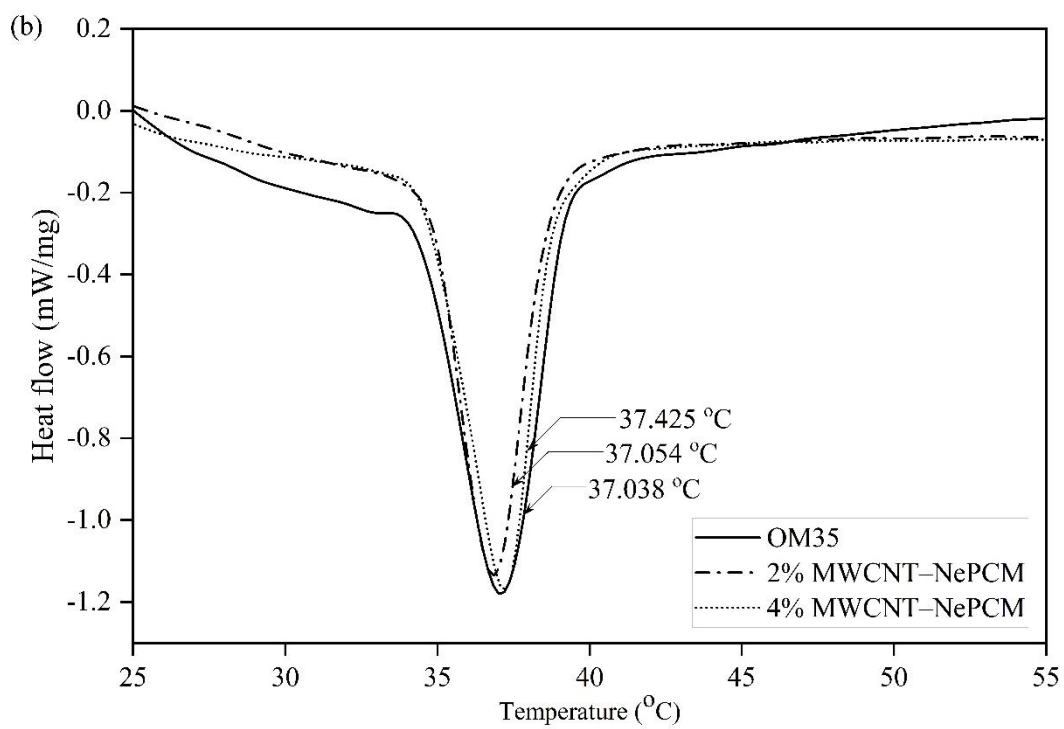
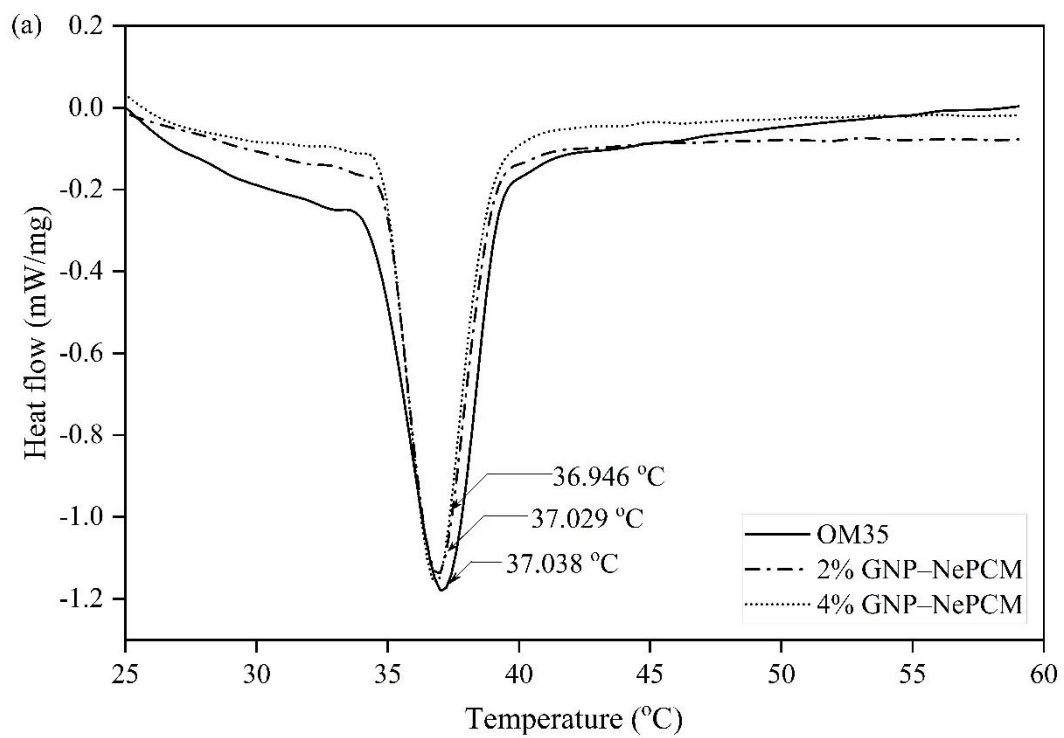
DSC was employed for the thermal analysis of PCMs and NePCMs, encompassing their melting, crystallization, and heat storage characteristics. A DSC apparatus from NETZSCH, which provided

$\pm 2\%$ precision and $0.001\text{ }^{\circ}\text{C}$ temperature resolution, was used for experimentation. The analysis involved three 5mg PCM samples, and the DSC testing was conducted at a ramp rate of $1\text{ }^{\circ}\text{C}/\text{min}$ across a temperature range of $25\text{--}60\text{ }^{\circ}\text{C}$. Determining the phase change temperature involved tracing a line along the steepest slope of the DSC peak and projecting the baseline on the same side as the peak's leading edge. The latent heat of phase transition was calculated by numerically integrating the area beneath the peaks.

6.3.3.1 Phase Transition Temperature

Figs. 6.11(a–d) illustrates the heating and cooling curves for the NePCMs, respectively, at 2% and 4% mass fractions, compared to OM35. Each curve, including NePCMs, exhibits a single peak during the melting phase, indicating the transition from solid to liquid phase. The melting peaks for OM35, 2% GNP–NePCM, and 4% GNP–NePCM manifest at $37.038\text{ }^{\circ}\text{C}$, $37.029\text{ }^{\circ}\text{C}$, and $36.946\text{ }^{\circ}\text{C}$, respectively. In the case of OM35, 2% MWCNT–NePCM, and 4% MWCNT–NePCM, the melting peaks are observed at $37.038\text{ }^{\circ}\text{C}$, $37.054\text{ }^{\circ}\text{C}$, and $37.425\text{ }^{\circ}\text{C}$, respectively. The peak melting temperature values of GNP–NePCM and MWCNT–NePCM exhibit comparability. Similarly, the solidification peaks, reported at $32.397\text{ }^{\circ}\text{C}$, $33.611\text{ }^{\circ}\text{C}$, and $34.171\text{ }^{\circ}\text{C}$, are observed for OM35, 2% GNP–NePCM, and 4% GNP–NePCM, respectively. In contrast, the solidification peaks for OM35, 2% MWCNT–NePCM, and 4% MWCNT–NePCM are found to be $37.038\text{ }^{\circ}\text{C}$, $37.861\text{ }^{\circ}\text{C}$, and $37.460\text{ }^{\circ}\text{C}$, respectively. The peak solidification temperature values of GNP–NePCM and MWCNT–NePCM are comparable. Additionally, it is noteworthy that the solidification curves of NePCMs are shifted rearward compared to OM35. This implies that the temperature parameter associated with the solidification process of NePCMs is lower than that of the solidification process of OM35. Consequently, it can be asserted that introducing MWCNT/GNP into OM35 has a negligible impact on the phase transition temperatures.

Figs. 6.12(a, b) illustrates the phase transition temperatures of the NePCMs. Moreover, the particular carbon nanoparticle variant exerts a negligible influence on phase transition temperatures, all of which cluster around that of the PCM within different NePCMs formulations. Notably, the most pronounced deviations in temperatures during melting and freezing are observed for OM35-based NePCMs, with variations of 0.4°C and 1.9°C , respectively. Conversely, NePCMs based on OM37 exhibit more substantial shifts (2.83°C during heating and 1°C during cooling at 4 wt.% loading) in phase transition temperature. The disparity between the temperatures of melting and freezing, a crucial parameter with implications for hindering energy recovery in thermal cycles, is termed the supercooling degree (Tang et al., 2014). It retards the solidification process that occurs during the transition from a liquid to a solid state. Increased supercooling can detrimentally affect the thermal storage performance to a notable extent.



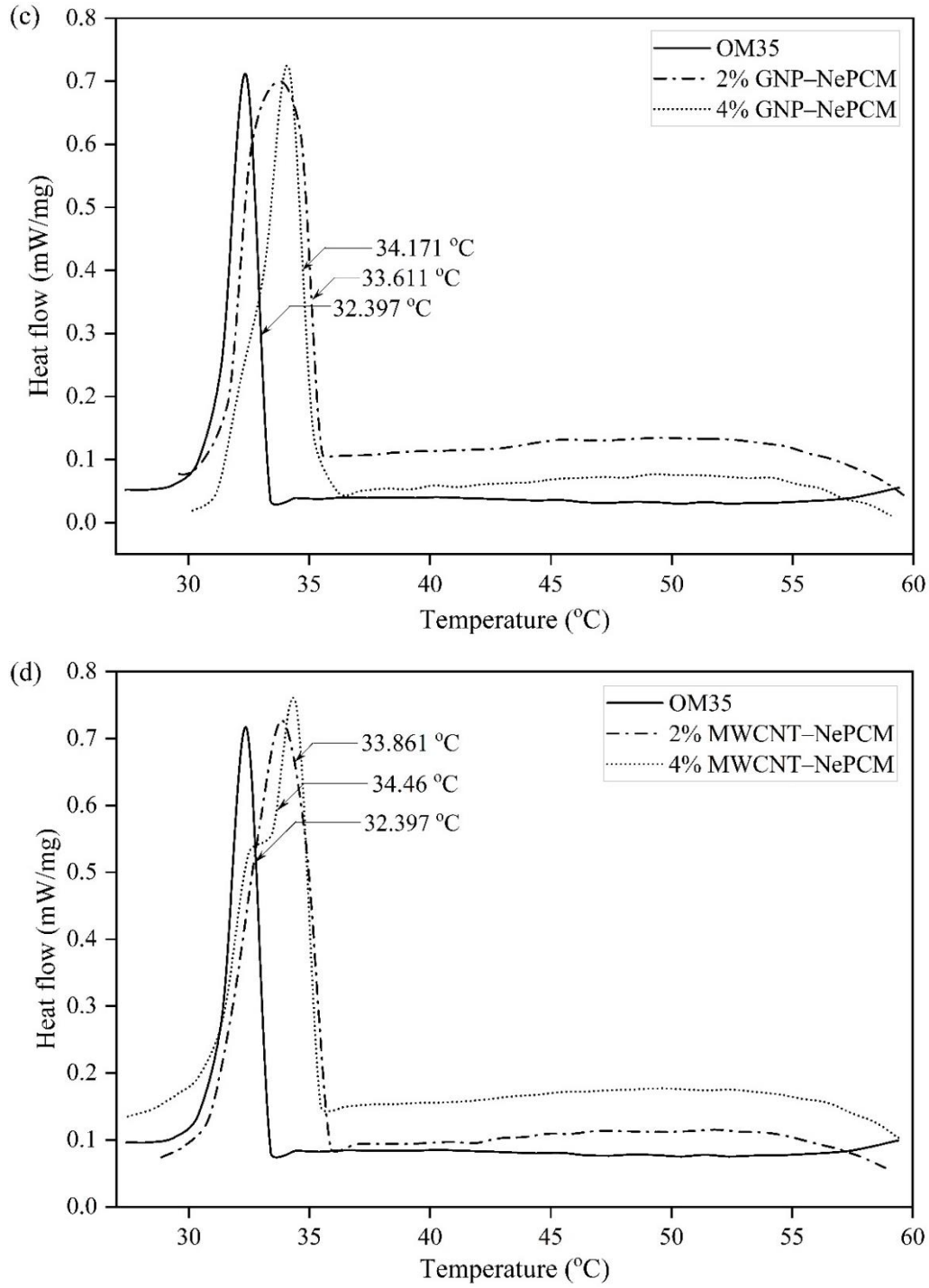


Fig. 6. 11 DSC thermograms: (a–c) GNP–NePCM; and (b–d) MWCNT–NePCM.

The degree of supercooling can be quantified using the following formula:

$$T_{sc} = T_m - T_s \quad (6.1)$$

where T_{sc} represents the degree of supercooling (°C), T_m is the peak melting temperature (°C), and T_s is the peak solidification temperature (°C). It's important to note that T_m and T_s can be

determined from melting and solidification thermograms. All NePCMs, varying in loading levels, exhibit a reduction in supercooling degree.

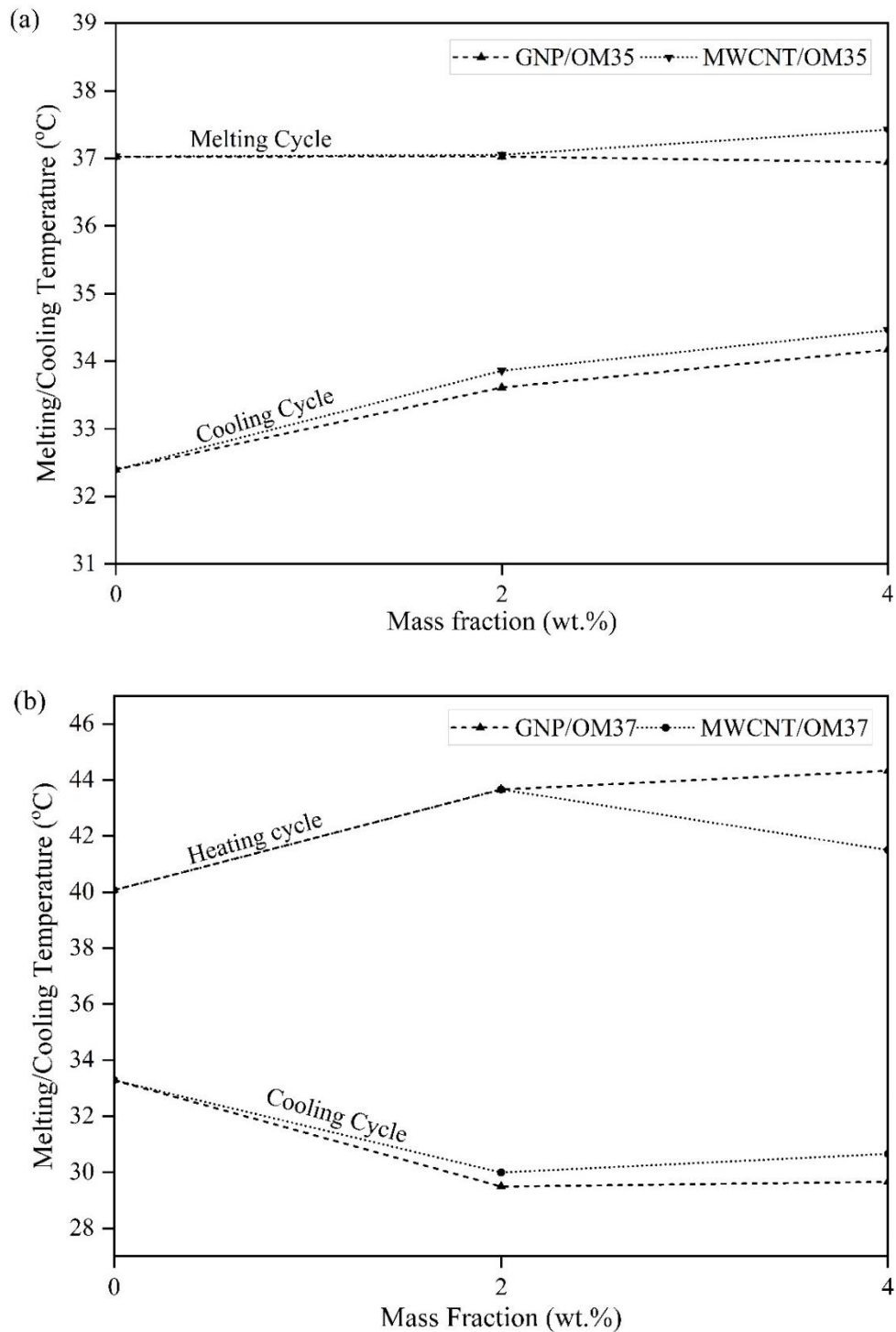


Fig. 6.12 Phase change temperatures: (a) OM35-based NePCM; and (b) OM37-based NePCM.

The reductions in supercooling degree, compared to OM35, are 24% and 29% for a 2% mass fraction of GNP-NePCM and CNT-NePCM, respectively. Additionally, the reductions are 38% and 34% for GNP-NePCM and CNT-NePCM with a mass fraction of 4%, respectively, as outlined in

Table 6.4. Thus doping OM35 with nanomaterials significantly reduces the degree of supercooling. This can be attributed that nanoparticles can act as nucleating agents, promoting the formation of crystal nuclei at lower temperatures. This nucleation effect reduces supercooling by providing sites for PCM crystallization, thereby stabilizing the phase change process closer to the nominal phase change temperature (Eanest Jebasingh & Valan Arasu, 2020b; B. Yang et al., 2021). The literature has documented similar observations (e.g. (Shuo Zhang et al., 2012). Conversely, the OM37-based NePCMs display an increase in supercooling degree, indicating a rise of 116% for GNP–NePCM and 101% for MWCNT–NePCM at loadings of 4 and 2 wt.%, respectively.

Table 6.4 Percentage fluctuation of NePCMs w.r.t base PCMs.

Material	GNP–NePCM				MWCNT–NePCM			
	Melting cycle		Cooling cycle		Melting cycle		Cooling cycle	
	T_m	ΔT_m	T_s	ΔT_s	T_m (°C)	ΔT_m	T_s (°C)	ΔT_s (°C)
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
OM35								
OM35	37.028	n.a.	32.51	n.a.	37.028	n.a.	32.519	n.a.
2% NePCM	37.029	0.001	33.61	3.24	37.054	0.07	33.861	3.96
4% NePCM	36.946	1.02	34.17	4.83	37.425	1.06	34.46	5.63
OM37								
OM37	40.063	n.a.	33.81	n.a.	40.063	n.a.	33.81	n.a.
2% NePCM	43.66	8.23	29.49	12.8	43.66	8.23	29.99	11.29
4% NePCM	44.33	10.65	29.66	12.3	41.50	3.46	30.66	9.31

Conversely, **Fig. 6.13(a, b)** presents the DSC curves for NePCMs, at 2% and 4% mass fractions in comparison to OM37 encompassing heating cycle. The incorporation of both types of nanomaterials marginally elevates the melting point. Across all NePCM formulations, the melting temperatures deviate by a maximum of 4.27 °C and 3.6 °C for GNP–NePCM and MWCNT–NePCM, respectively. Each curve, including those representing NePCMs, displays a singular peak during the melting phase, signifying the shift from the solid to the liquid phase. However, in the case of the 4% MWCNT–NePCM, two distinct melting peaks are observed, exhibiting a 3°C discrepancy. Specifically, the melting peaks for OM37, 2% GNP–NePCM, and 4% GNP–NePCM are identified at 40.06 °C, 43.66 °C, and 44.33 °C, respectively. Similarly, the melting peaks for OM37, 2% MWCNT–NePCM, and 4% MWCNT–NePCM are at 40.06 °C, 43.66 °C, and 41.50 °C,

respectively. The peak melting temperature values of GNP–NePCM and MWCNT–NePCM are almost comparable.

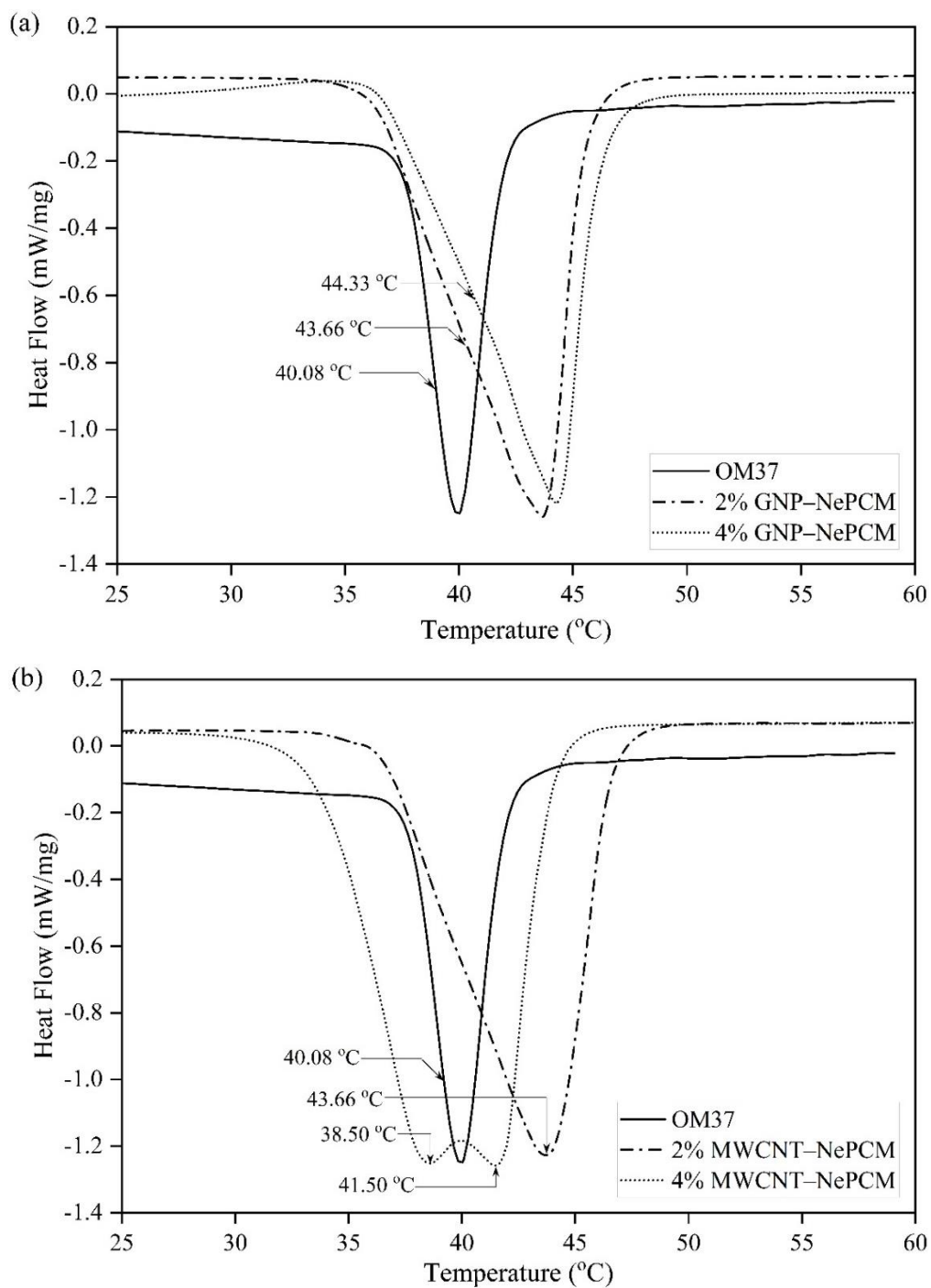


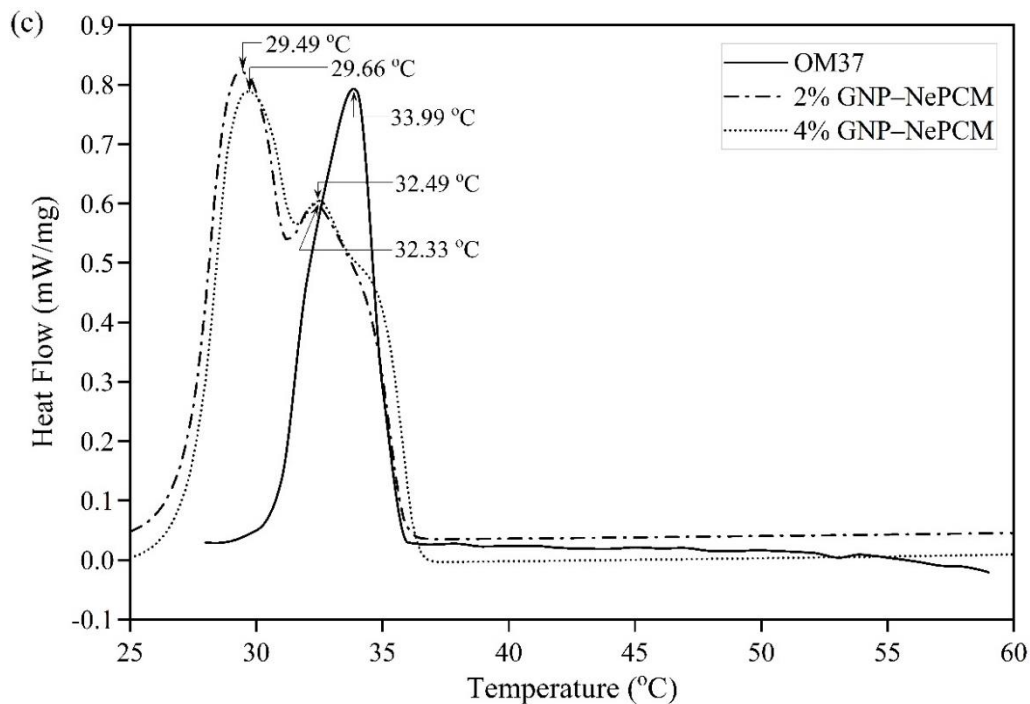
Fig. 6.13 DSC melting thermograms: (a) GNP–NePCM; (b) MWCNT–NePCM.

The solidification temperatures of the two NePCMs display analogous trends. As illustrated in Fig. 6.14 (c, d), the solidification temperatures for NePCMs incorporating GNPs and MWCNTs

are fairly comparable. However, the introduction of 2% GNPs results in a significant alteration of the solidification temperature, leading to a difference of 4.32°C. The presence of the nanoparticle perturbs the arrangement of PCM molecules surrounding the carbon nanoparticles, thereby modifying the surrounding steric hindrance and contributing to the observed variations in phase transition temperatures. During the crystallization process, two distinct peaks representing phase transitions manifest, displaying maximal differences of 3.17°C and 2.84°C for GNP and MWCNT NePCMs, respectively.

6.3.3.2 Phase Change Enthalpy

To optimize the thermal performance of NePCMs, it is advisable to improve their thermal conductivity while minimizing the effect on the phase change enthalpy. The melting and solidification enthalpies (Jg^{-1}) of MWCNT–NePCM and GNP–NePCM, along with PCMs, are given in Table 6.5. The solidification enthalpy of MWCNT–NePCM decreases insignificantly at a 2% mass fraction compared to OM35. However, it reduces by 23.6% at a 4% mass fraction compared to OM35. In contrast, 18.4% and 32.5% reductions were recorded for 2 and 4% mass fractions with OM37. Further, it is observed that the melting enthalpy of MWCNT–NePCM decreases by 6.0% at a 2% mass fraction and by 19.7% at a 4% mass fraction for OM35. However, with OM37, MWCNT–NePCM showed 13.6% and 29.5% reduction in melting enthalpies. Thus, adding MWCNT at 2% and 4% mass fractions to PCMs reduces phase change enthalpy during solidification and melting.



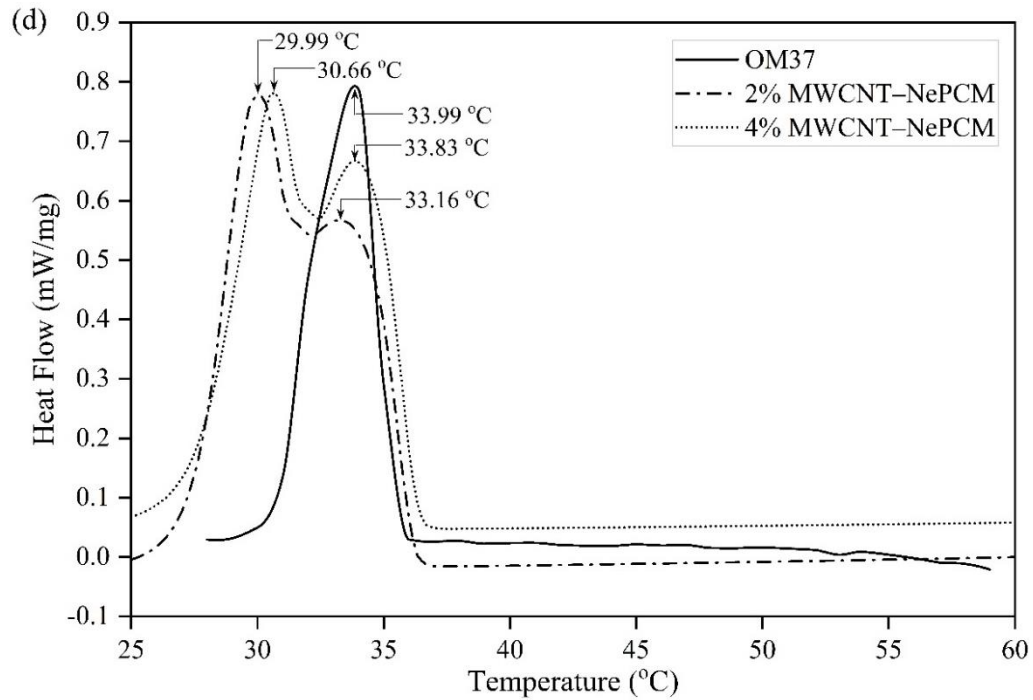


Fig. 6.14 DSC solidification thermograms: (c) GNP-NePCM; (d) MWCNT-NePCM.

However, the reduction is more pronounced during the solidification process and with OM37. The underlying rationale for these alterations can be attributed to the formation of a dense phase, where molecules with higher density surround the nanoparticle, which is caused by the interaction between PCM and MWCNT. As the mass fraction of MWCNT increases, more PCM molecules surround the MWCNT, forming a denser phase. Consequently, there is a decrease in the enthalpy associated with phase change (C. Y. Zhao et al., 2020).

Table 6.5 Enthalpy variation of PCMs and NePCMs.

Material	GNP-NePCM		MWCNT-NePCM	
	Solidification	Melting	Solidification	Melting
	ΔH (Jg ⁻¹)	ΔH (Jg ⁻¹)	ΔH (Jg ⁻¹)	ΔH (Jg ⁻¹)
OM35	269.65	268.00	269.65	268.00
2% loading	216.88	217.41	257.42	251.85
4% loading	178.84	166.74	206.12	215.1
OM37	278.2	280.7	278.2	280.7
2% loading	156.6	178.4	227.0	242.4
4% loading	114	126	187.8	198.0

According to the data presented in Table 6.5, the melting enthalpy of GNP–NePCM decreases by 18.9% and 37.8% at mass fractions of 2% and 4%, respectively, when compared to OM35. However, the solidification enthalpy decreases by 19.6% at a 2% mass fraction and 33.7% at a 4% mass fraction. Conversely, GNP–NePCM showed 36.4% and 55.1% reductions in melting enthalpies and harsh reductions of 43.7% and 59% for 2 and 4% mass fractions with OM37.

To assess the heat storage capacities of NePCMs, the enthalpy efficiency (α) and relative enthalpy efficiency (η) of PCMs and NePCMs were calculated and compared with existing literature. Higher values of α and η indicate lower loss of latent heat. The calculation of α and η values involves the following equations:

$$\alpha = \frac{\Delta H_{m(or)s}^{NePCM}}{\Delta H_{m(or)s}^{PCM}} \times 100\% \quad (5.2)$$

$$\eta = \frac{\Delta H_{m,NePCM}}{\Delta H_{m,PCM} \times W_f} \times 100\% \quad (5.3)$$

where W_f denotes the PCM loading in the NePCMs produced.

The values of α and η for the NePCMs developed in this study and those found in the literature (X. Lu et al., 2020; Sheng et al., 2020; K. Sun et al., 2020; Umair et al., 2020; Yafang Zhang et al., 2020; Zuo et al., 2020) are compared and presented in Table 6.6. According to the data presented in Table 5.5, the values of α and η during the processes of solidification and melting are higher than the majority of values documented in the existing literature.

6.3.4 Thermal Stability Analysis

The thermal stability of PCM and NePCMs was examined using TGA. The TGA curves of the PCMs and NePCMs are displayed in Fig. 6.15, subjecting the samples to a gradual temperature increase from 28 °C to 500 °C at a rate of 5 °C/min. Weight loss percentages were charted against temperature to analyze thermal decomposition.

It can be seen from the TGA peaks that there is no discernible mass loss up to ~ 126 °C for either PCMs or NePCMs. As the temperature increased, the weight loss became more pronounced, reaching its maximum degradation temperature while leaving a constant residue behind. For base PCMs, the weight loss initiates at 126 °C, where the maximum degradation temperature observed was 234 °C, nearly reaching complete degradation (97%). The evaporation of paraffin causes such

decomposition, wherein hydrocarbon chains disintegrate into monomers. Furthermore, it was discovered that the maximum degradation temperature decreased with the inclusion of nanoparticles. The final, residual, initial, and onset temperatures increased with an increase in the weight percentage of nanoparticles. Basically, the nanomaterials form a shielding layer on the surface of paraffin, which impedes vaporization during thermal deprivation. Concerning NePCM samples, weight stability prevailed between 28 °C and 130 °C. Beyond 130 °C, NePCMs underwent complete weight loss until 221 °C, with a recorded weight loss of 95.93% for each GNP/MWCNT–NePCM. No weight loss was observed until ~ 130 °C for all samples, so the developed NePCMs can be employed in building applications.

Table 6.6 The α and η values of NePCMs in the literature and current study.

NePCMs		Freezing		Melting		Refs.
		α				
		α (%)	η (%)	(%)	η (%)	
Paraffin/EG/SR		24.6	91.1	25.3	93.7	(Phase et al., 2020)
Paraffin/HDFS		67.1	95.8	69.1	98.7	(Umair et al., 2020)
Paraffin/HPC		70.9	93.4	70.8	93.3	(K. Sun et al., 2020)
Paraffin/CAN800		53.4	89.0	57.7	96.2	(Zuo et al., 2020)
Paraffin/CNS		93.6	96.3	93.5	96.2	(X. Lu et al., 2020)
OM35	2%GNP	80.43	82.07	81.12	82.77	(Present work)
	4%GNP	66.32	69.08	62.21	64.80	
	2% MWCNT	95.46	97.41	93.97	95.89	
	4% MWCNT	76.43	79.62	80.26	83.60	
	2%GNP	56.29	57.43	64.12	64.85	
OM37	4%GNP	40.97	42.68	45.29	46.75	(Present work)
	2% MWCNT	81.59	83.26	87.13	88.11	
	4% MWCNT	67.50	70.31	70.53	73.47	

6.3.5 Microstructural analysis

The morphology of NePCMs was examined using a Fe-SEM at room temperature. Experimental specimens were created for analysis by employing a two-step approach to produce NePCMs with MWCNTs or GNPs distributed at two different mass fractions (2.0 and 4.0 wt.%). Fig. 6.16(a–f) shows the fractographic images of OM35, MWCNT, and GNP. The MWCNTs exhibited a surface profile characterized by entanglement due to the aggregation of these nano-sized tubes. This significant entanglement issue with MWCNTs can affect their long-term stability when dispersed within the PCM. MWCNTs show the highly convoluted and highly interwoven spaghetti-like

network of MWCNT. The presence of local bends and kinks can be clearly seen in the image (Ref Fig. 6.16(a, b)).

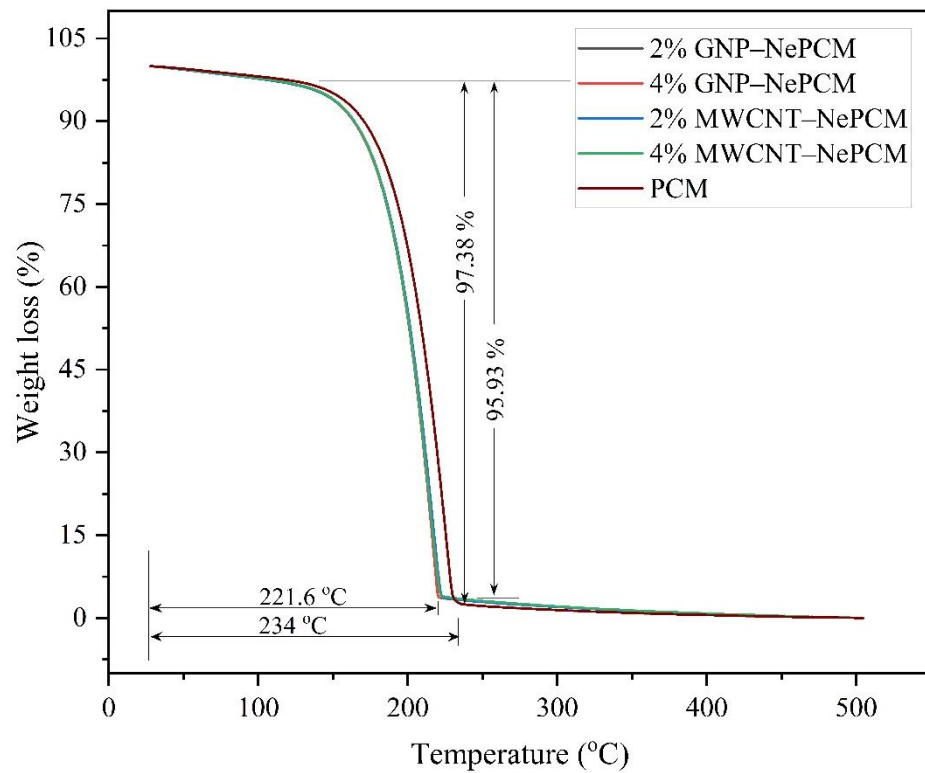
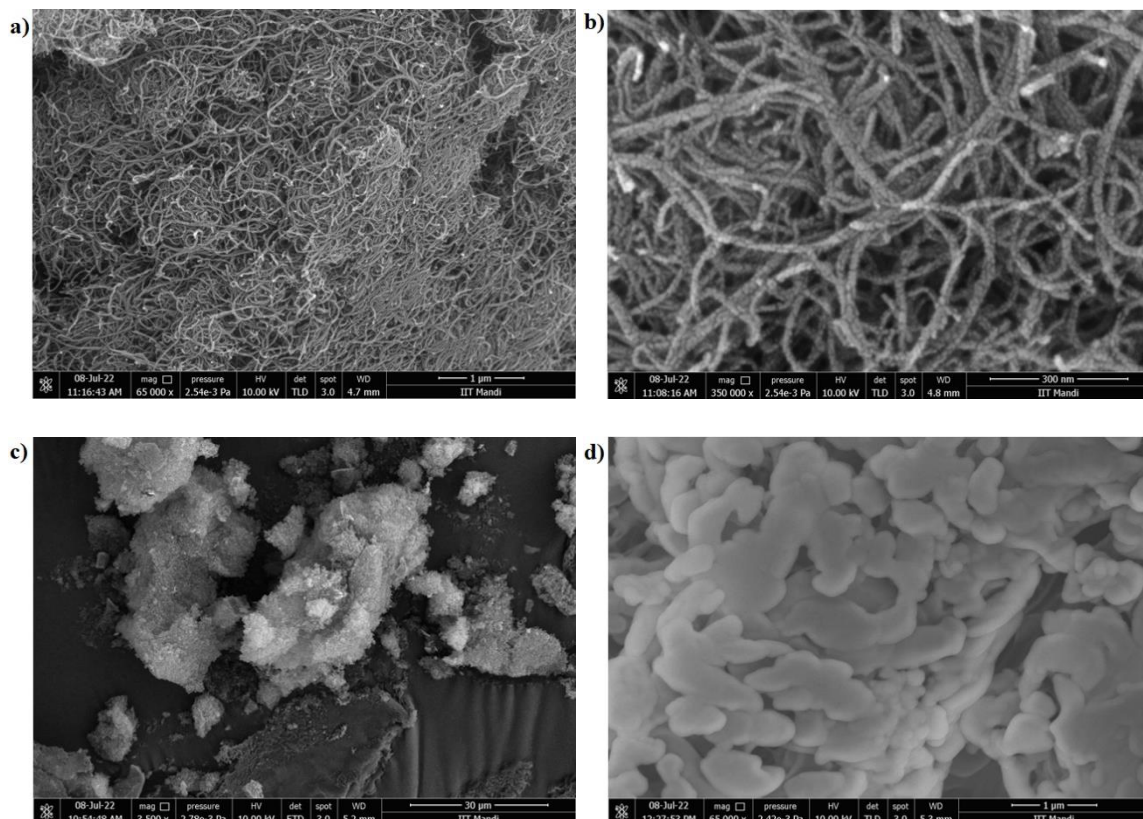


Fig. 6.15 TGA curves of GNP/MWCNT-NePCMs



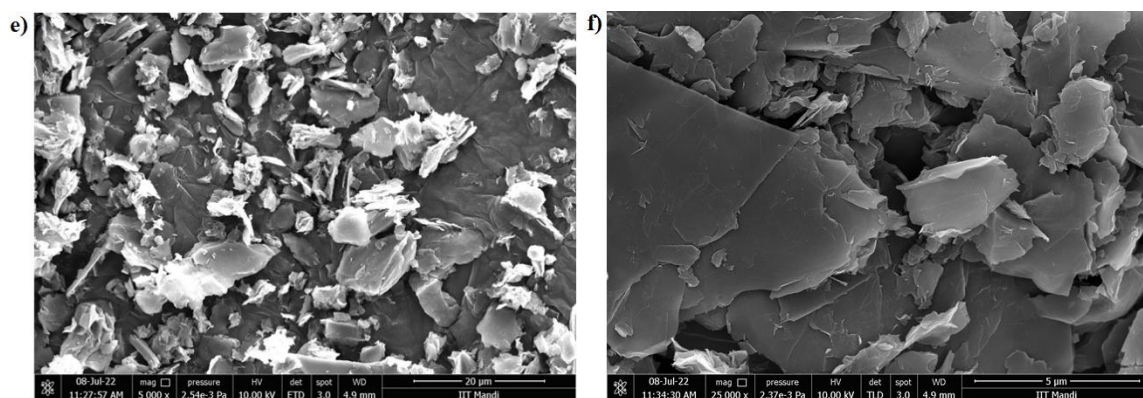


Fig. 6.16 FeSEM images; (a–b) MWCNTs; (c–d) PCM; and (e–f) GNPs at lower and higher magnification.

On the other hand, GNP shows a two-dimensional sheet-like nanoplate structure. It has an uneven arrangement of sheets and crack-like structures of different sizes. The layers in GNPs appeared flaky, and their planarity and high size-to-thickness ratio, as observed in Fig. 6.17(e, f), were confirmed. Moreover, Fig. 6.18(c, d) shows the smooth surface of three-dimensional lamellar structures, indicating the adhesive nature of OM35. Further, it can be seen that OM35 crystallizes, leading to the formation of randomly aligned microplates.

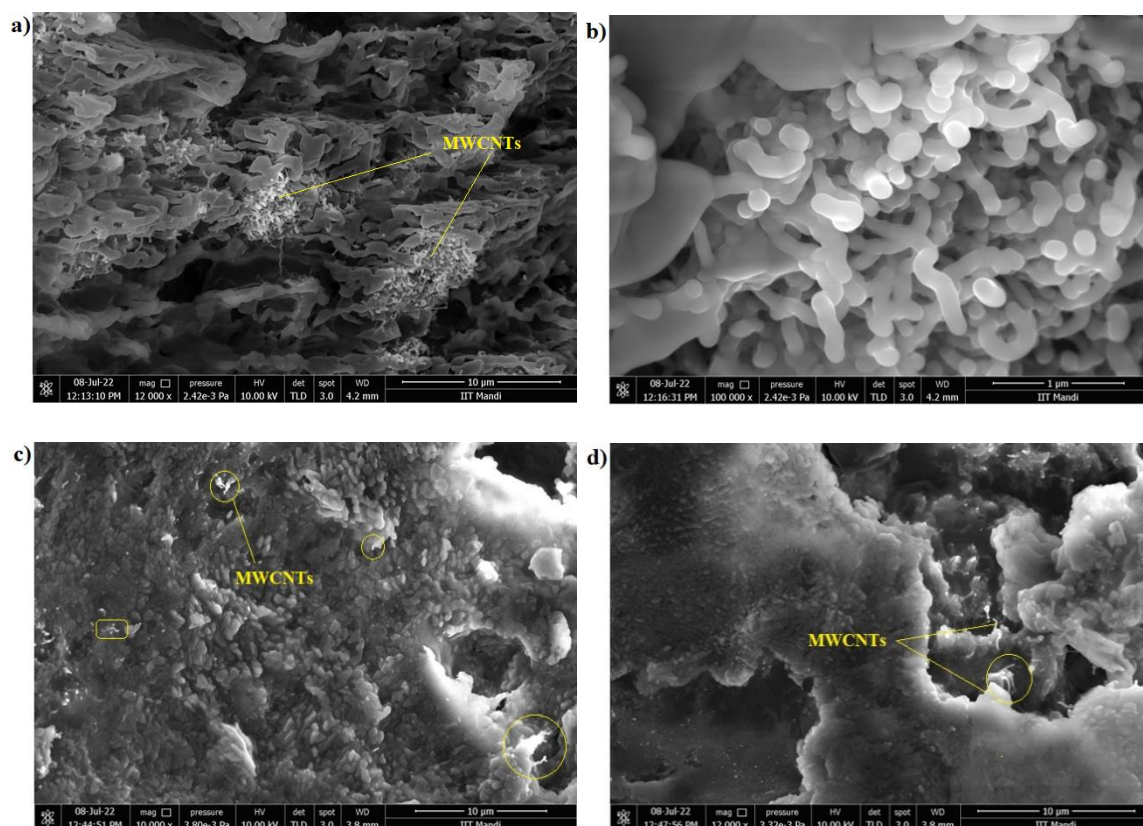


Fig. 6.17 Fe-SEM images: (a–d) MWCNT–NePCM (OM35/37) at lower and higher magnification.

Fig. 5.17(a–d) exhibits fractographic images of MWCNT and GNP NePCMs with a loading of 2%. In MWCNT–NePCMs, the MWCNT additive is represented by the brighter regions, while the darker regions represent the base PCM. The images reveal that the MWCNT additive is uniformly dispersed within the base material. Moreover, the particle sizes of individual MWCNTs are nearly uniform, despite some larger agglomerations. The SEM image of the MWCNT–NePCM samples confirms both the effective impregnation and uniform distribution of MWCNTs within the PCM.

The presence of GNPs is evident due to their consistent shape. The dispersion of GNP in NePCMs is observed to be highly uniform. The relatively low viscosity of the PCM matrix during the mixing process helps prevent significant damage to the GNPs, thereby allowing them to maintain their sheet-like structure. GNPs with a higher contact area enhance heat transfer through multiple pathways. The layer structure of GNP–NePCM can be observed in the FESEM images in Fig. 5.18(a–d). The distinct white plate-like regions indicate the dispersion of GNPs within the NePCMs. The morphology of the NePCMs loaded with 2% and 4% GNPs suggests that they possess electrical conductivity since the SEM employs an electron beam that can only interact with electrically conductive materials.

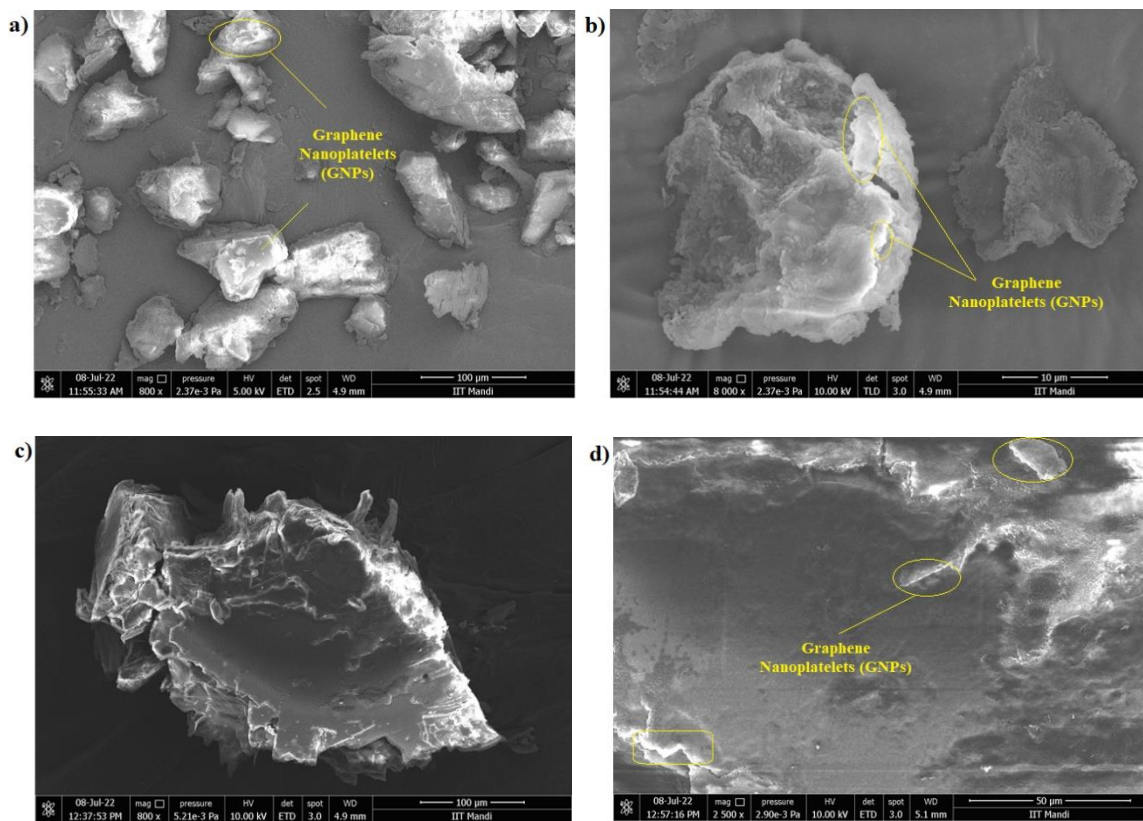


Fig. 6. 18 Fe-SEM images: (a – d) GNP–NePCM (OM35/37) at lower and higher magnification.

6.4 Concluding Remarks

The current study extensively investigated the thermophysical properties of PCMs/NePCMs. Utilizing the experimental data in this study allows for the anticipation and simulation of NePCM behavior within the building applications. Incorporating nanomaterials has been observed to enhance the thermal conductivity of the base PCM. Specifically, the thermal conductivity values of GNP–NePCM were approximately 7% higher than MWCNT–NePCM's. Morphological analysis revealed a uniform and well-dispersed distribution of MWCNT/GNPs within the base PCM. FT–IR analysis indicated significant physicochemical compatibility of NePCMs. XRD spectra demonstrated favorable crystallization behavior of the PCMs. Moreover, the introduction of nanoparticles did not alter the crystal structure of NePCMs or participate in chemical reactions with the constituents. Although nanoparticle doping had an insignificant impact on phase transition temperatures, it decreased the enthalpy associated with phase change. TGA thermograms showed no noticeable mass loss up to approximately 126 °C for both PCMs and NePCMs. Subsequent temperature increases resulted in more pronounced weight loss, reaching maximum degradation temperatures while leaving behind a constant residue. NePCMs experienced complete weight loss up to 221 °C, with a recorded weight loss of 95.93%.

Overall thermal characterization suggests that PCMs hold potential for energy storage applications within building envelopes. The thermal performance characteristics of GNP–NePCM surpass those of MWCNT–NePCM, making GNP–NePCM a more favorable candidate. Therefore, GNP–NePCM was chosen for macroencapsulation and subsequent integration into the biaxial voided roof slab (HRS).

Energo-Economic Evaluation of NePCM-Integrated Concrete Roof Under Ambient Conditions

7.1 Introduction

PCMs are widely used in various industries and buildings because they store latent heat during solid-liquid phase transition at higher temperatures and release it during liquid-solid phase transition at lower temperatures. Phase transition, specifically in buildings, is critical for improving thermal stability and effectively managing peak cooling and heating loads (Baetens et al., 2010). PCM encapsulation can be achieved at nano, micro, and macro scales. The sizes range from 1–1000 nm, 1–1000 μm , and ≥ 1 mm, respectively (Arshad et al., 2019). Among all, macroencapsulated PCM offers improved strength and durability. It provides a practical approach to incorporating PCMs into shell materials of various geometries, such as spheres, rectangles, and tubes (Zayed et al., 2020c). Additionally, it allows for integrating a higher amount of PCM, resulting in an improved encapsulation ratio (Parameshwaran et al., 2012). Numerous studies have integrated macroencapsulated PCMs into building envelopes (Erlbeck et al., 2018; P.-F. Liu et al., 2016; Navarro et al., 2015; Silva et al., 2012).

Developing a two-way BVS that integrates macroencapsulated NePCMs for passive building cooling offers a dual set of significant advantages. Firstly, it capitalizes on the numerous merits of the macroencapsulation technique, which encompasses straightforward preparation, exceptional durability, high encapsulation efficiency, the ability to adapt to varying shapes, robust structural strength, and a guaranteed absence of leakage. The second advantage pertains to the strategic inclusion of nanomaterials within organic PCMs, which has the potential to address the inherent limitation of low thermal conductivity. This study aims to realize the creation of a BVS with macroencapsulated NePCMs, thereby effectively harnessing both of these advantageous elements. Such a roof slab is appealing due to its multifaceted benefits, particularly in space cooling and heating energy requirements, precise temperature regulation, heightened energy efficiency, notable reductions in fossil fuel consumption, and tangible contributions to climate change mitigation. Within this framework, the study's primary focus lies in developing a BVS that combines PCM and NePCM through the macroencapsulation process. It examines latent heat storage attributes within the slab under varying environmental conditions. The selection of materials is a critical aspect of the study. It hinges upon carefully considering historical weather data pertinent to the study area and the thermodynamic properties of the chosen materials. Furthermore, this chapter undertakes an exhaustive examination of the thermal properties of OM35, both in its capacity and when blended with 2% and 4% mass fractions of MWCNT and GNP. This endeavour culminates in the fabrication

of four distinct specimens, including a CRS that remains devoid of any PCM, alongside three BVS specimens, encompassing BVS equipped with PCM and two alternative variations enriched with 2% and 4% GNP–NePCMs. The latent heat storage behavior evaluation comprises an in-depth analysis covering various parameters such as temperature fluctuations, heat flux dynamics, thermal loads, temperature decrement factors, and temperature time lags. Furthermore, the financial feasibility of this technology is scrutinized, incorporating considerations such as electricity cost savings, simple and discounted payback periods, and reductions in CO₂ emissions.

The uniqueness of this chapter lies in two core aspects. Firstly, it encompasses the transformation of containers into macroencapsulations of PCM/NePCMs. Secondly, the study extensively evaluates the latent heat storage potential of a novel Hollow Roof Slab under ambient environmental conditions. Notably, this BVS roof slab, macroencapsulated with PCM/NePCMs, designed to facilitate passive cooling in buildings, represents a pioneering exploration in this domain, heretofore uncharted. The structure of this chapter is thoughtfully organized as follows: Section 7.2, titled 'Material and Methods,' is dedicated to the comprehensive selection of NePCMs, including detailed insights into the experimental setup. Section 7.3, under the heading 'Results and Discussion,' is centered around meticulously examining the substantial findings generated through this study. This section particularly emphasizes the variations observed in many parameters closely linked to latent heat storage behaviour.

7.2 Materials and Methods

7.2.1 Selections of PCM and Nanomaterials

The fluctuating ambient temperatures notably influence the working efficiency of PCMs. In a general operational context, PCMs transition between solid and liquid states to effectively absorb heat during the daytime (charging phase), subsequently releasing the stored heat during night-time as they transit from a liquid to a solid state (discharging phase). This chapter comprises the study conducted in Rupnagar, situated at coordinates 30.9661°N and 76.5231°E, characterized by dry winters and a humid subtropical climate. Given the prevailing climatic conditions, particularly summer temperatures exceeding 32 °C (as depicted in [Fig. 7.1](#)), selecting a PCM with a melting temperature closely aligned with the thermal comfort temperature becomes impractical. Consequently, OM35, a commercially available organic PCM with a transition temperature of 35 °C (Ref. [Table 4.1](#) for properties), is the chosen PCM for this research endeavour.

The selection of nanomaterials plays a pivotal role in moulding the thermophysical characteristics of NePCMs. These characteristics encompass a range of parameters, including but not limited to thermal conductivity, latent heat capacity, supercooling tendencies, phase change duration, phase change temperatures, density, viscosity, and thermophysical properties post-thermal cycling, as expounded in (Leong et al., 2019). It is worth underscoring the remarkable importance of the

thermal conductivity of nanoparticles, which notably surpasses that of the PCM in use. As a tangible example, widely recognized nanomaterials such as MWCNT and GNP exhibit extraordinary thermal conductivities, surpassing 3000 W/m K and 5300 W/m K, respectively (Balandin et al., 2008; P. Kim et al., 2001). The amplification in latent heat within NePCMs can be ascribed to the modifications in the interactions occurring between the PCM and the integrated nanomaterials. However, it is imperative to recognize that an excessive replacement of the PCM with nanomaterials can curtail the latent heat of NePCMs, as explicated in (Bahiraei et al., 2017). In the context of the present investigation, a meticulous choice has been made to employ MWCNT and GNP nanomaterials. A comprehensive exposition of the purity and dimensional specifications of these nanomaterials is adeptly documented in [Table 5.1](#).

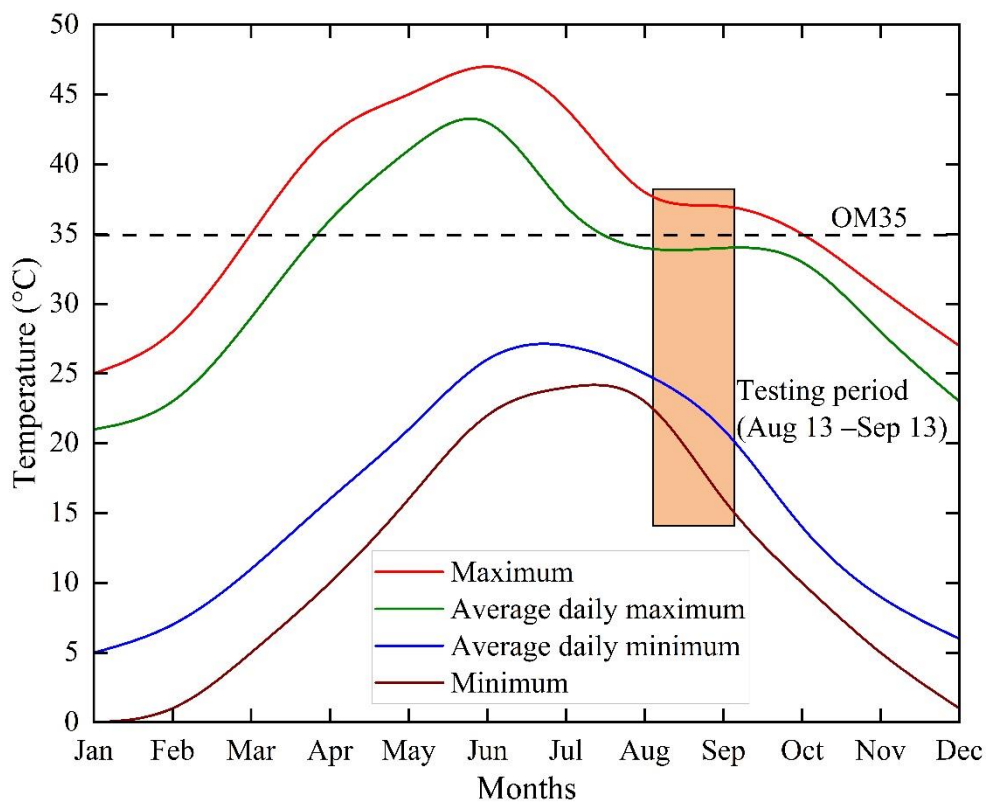


Fig. 7.1 Variation of temperature in the study area.

7.2.2 Macroencapsulation of NePCMs

The initial step in the macroencapsulation of NePCMs involves selecting an appropriate container material capable of effectively storing NePCMs. Given its favourable thermophysical, chemical, and mechanical characteristics, the container utilized in the prior study was retained. Both the material composition and geometric configuration were left unaltered. Depending on the integration method and geometric design, PCMs were macroencapsulated either in their liquid or solid-state (Rathore et al., 2020; Ahmet Sari & Kaygusuz, 2002). In the present work, NePCMs are macroencapsulated within the lower 50% of the container volume in liquid form. The total

thickness of encapsulation in the container is 50 mm, with 20 mm in the bottom truncated spherical portion and 30 mm in the cylindrical portion. Similar PCM thicknesses have also been adopted in the literature. Macroencapsulated NePCMs are encapsulated in the lower section of the container and subsequently adhered to the upper portion. The opening for introducing liquid NePCM into the upper section is then sealed. Consequently, the NePCMs are effectively macroencapsulated within the container and securely stored. Subsequently, the macroencapsulated container will be incorporated into the BVS.

7.2.3 Design procedure of BVS

BVS is a reinforced concrete slab formed by incorporating macroencapsulated containers into the concrete matrix in both directions, longitudinal and transverse. The neutral axis within the slab separates the bottom tension region from the top compression region. Since concrete inherently performs poorly in the tension region, its presence below the neutral axis is ineffective in resisting the imposed load. Thus, macroencapsulated containers can be positioned below the neutral axis replacing the concrete locally, transforming an ordinary slab into a climate-resistant roof slab that can significantly contribute to the passive cooling of the buildings. In addition, by introducing macroencapsulated containers, the dead weight of the roof slab can be reduced by 10% to 26%, based on the density of the NePCM used. In the present study, a dead weight reduction of about 20% was achieved. Reducing dead weight in addition to reducing the stresses on the column and walls of a building results in a substantial reduction in the lateral earthquake forces.

The next step involves designing the BVS, considering the presence and distribution of macroencapsulated NePCM containers within the concrete matrix. The total dead weight of a BVS includes the weights of concrete, reinforcement bars, and macroencapsulated containers. In addition, BVS is subjected to a superimposed dead weight (taken as 1 kN/m^2) and a live load (taken as 2 kN/m^2). Note that the superimposed dead weight is due to the floor finishes, such as tiles. It is important to note that the design of BVS differs from conventional slab design for two reasons: (i) reduction in flexural rigidity and shear resistance due to lower dead weight, and (ii) a shift in the location of shear failure plane in the case of punching shear. A theoretical design of a BVS measuring $2 \text{ m} \times 2 \text{ m} \times 0.15 \text{ m}$ was performed following the guidelines in ACI 318:2019 and IS 456:2000 and the modified equations described in (Yafang Zhang et al., 2020). The concrete grade used in this study is M20, and the steel grade is Fe415. The design exercise considered the dead weights, superimposed dead weights, and the live load. The exercise resulted in two layers of reinforcement mesh. These meshes consist of 10 mm diameter reinforcing bars spaced at 150 mm intervals in both directions. One layer is above the level of the macroencapsulated container, and the other is below. A schematic depicting the topology of the designed BVS is shown in [Fig. 7.2\(a, b\)](#).



Fig. 7.2 Topology of BVS: (a) Perspective 3D view; and (b) Cross-sectional view.

7.2.4 Experimental procedure

The structural topology of a BVS can be perceived as a multi-segment slab, with each segment having a macroencapsulated container. By stacking segments in both the longitudinal and transverse directions, the BVS topology can be recreated. However, a segment of a BVS differs from a full BVS in two distinct aspects. First, a segment lacks continuity of reinforcing bars. Secondly, a segment's structural behaviour and load-carrying capacity differ from a solid slab's. Nevertheless, a segment representation of BVS can help study the non-mechanical behaviour of BVS, such as thermal performance. Recognizing that a segment cannot accurately represent the two-dimensional heat transfer present in the BVS is essential. However, under the assumption of one-dimensional heat transfer, using segment representation is acceptable as it adequately replicates the thermal performance of BVS. A segment of the BVS can be referred to as a unit cell. A unit cell comprises a concrete layer, a macroencapsulated container, and a top and bottom reinforcement mesh. The unit cell concept is widely accepted and has been extensively used by researchers in various applications due to its cost-effectiveness. Given that the main focus of this study is to examine thermal performance rather than the effects of mechanical loading conditions, it is appropriate to use the unit cell approach. A unit cell schematic is shown in [Fig. 7.3](#). The following content briefly explains the casting process of a BVS unit cell.

Fig. 7. 4(a–g) provides a detailed schematic overview of the procedure employed for casting the unit cells. To create four distinct testing specimens, four wooden moulds, each internally measuring 300×300×150 mm, were meticulously constructed. These specimens encompass a conventional RC slab unit cell, denoted as CRS, an OM35 slab unit cell labelled as BVS, a slab unit cell characterized by a 2% GNP mass fraction known as 2% GNP–NePCM, and another with a 4% GNP mass fraction, designated as 4% GNP–NePCM. The production process meticulously adheres to conventional concrete casting methodologies. The composition of the concrete slurry is precisely regulated, comprising cement, fine aggregate, coarse aggregate, and water, meticulously proportioned following M20 specifications (1:1.8:3.1:0.5). The procedure encompasses several sequential stages: (i) Placement of the bottom reinforcement mesh atop the concrete cover blocks. (ii) Pouring of concrete slurry until it attains the uppermost level of the reinforcement mesh. (iii) Positioning of the macroencapsulated PCM/NePCM container. (iv) Pouring of concrete slurry until it reaches the top level of the container. (v) Placement of the top reinforcement mesh. (vi) Filling with concrete slurry until it reaches the uppermost level of the unit cell. Following the concreting phase, a critical 24hr time span is allowed for the concrete to settle and solidify. Subsequently, the wooden moulds are carefully and systematically removed from the unit cells. The specimens are then subjected to an essential period of 28 days of moist curing, ensuring optimal material strength and quality. Upon completing the curing process, the unit cells are meticulously prepared for the subsequent phase of outdoor experimentation, serving as a crucial element in the research study.

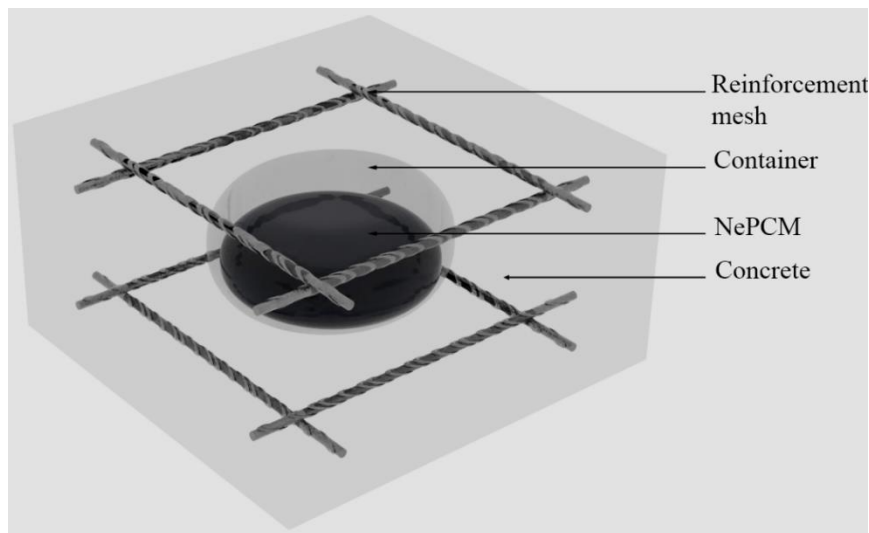


Fig. 7.3 Schematic of a unit cell.

The prepared and cured unit cell specimens are subsequently positioned within three wooden moulds. Among these moulds, one stands out due to its substantial size, boasting internal dimensions measuring 1380×540×175 mm, whereas the other two are comparably smaller, each characterized by internal dimensions of 325×325×175 mm. The larger mould serves the dual purpose of housing both the CRS and BVS unit cells, while the smaller moulds are singularly

designated for the 2% GNP–NePCM and 4% GNP–NePCM unit cells. It's imperative to underscore that the experiments conducted on these unit cells operate under the assumption of one-dimensional heat transfer. In this context, the objective is to restrict heat transfer from all directions except the top surface. This objective can be effectively achieved by incorporating highly insulating materials between the wooden moulds and the surfaces of the specimen. For the purposes of this study, layers of extruded polystyrene sheets measuring 25 mm in thickness are meticulously applied to all surfaces of the specimens except the top surface. Furthermore, any potential gaps between these polystyrene layers are judiciously filled with glass wool fibers to enhance the overall insulation. The strategic combination of extruded polystyrene and glass wool fibers plays a pivotal role in minimizing heat transfer from all other surfaces, thereby facilitating the desired condition of one-dimensional heat transfer.

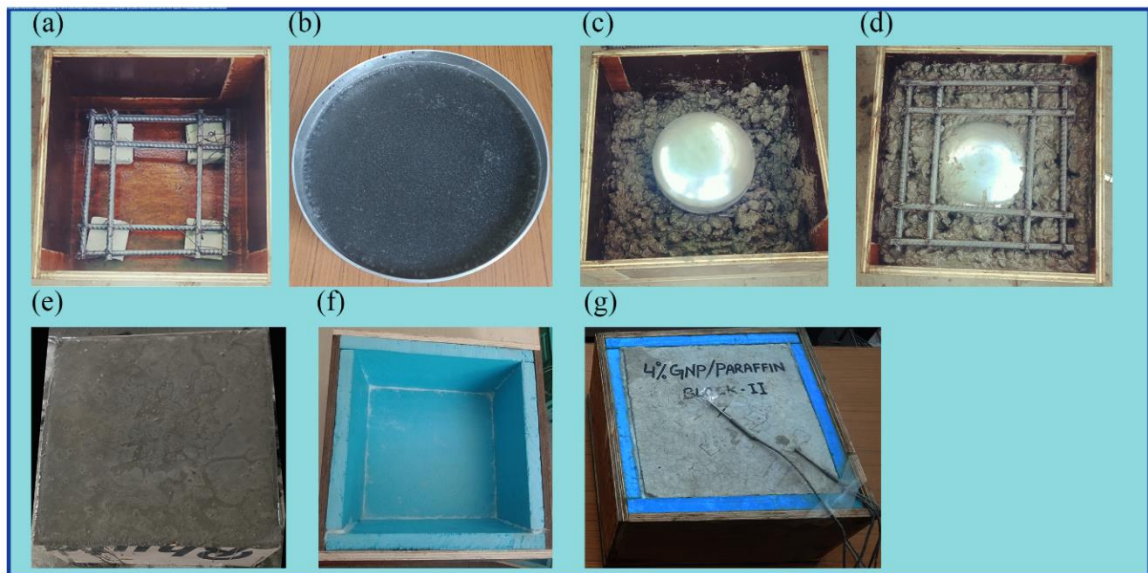


Fig. 7.4 Unit cell casting procedure: (a) Wooden mould; (b) PCM filled container; (c–e) Concrete casting; (f) Insulated mould; and (g) GNP–NePCM specimen.

In this experimental configuration, temperature monitoring is carried out using thermocouples, strategically positioned to measure temperatures externally and internally within the specimens. The CRS is instrumented with a pair of thermocouples, one on the lower and one on the upper surfaces. In contrast, the BVS specimen is equipped with a more complex arrangement, including three thermocouples placed beneath the container region on the lower surface and one each on the lower surface (outside the container region) and the upper surface. For both the 2% GNP–NePCM and 4% GNP–NePCM specimens, a total of three thermocouples are installed. Two thermocouples are affixed to the lower surface; one is positioned outside the container area, and the other within it. The third thermocouple is carefully situated on the upper surface. These thermocouples undergo laboratory calibration procedures, involving precise temperature readings using ice and boiling

water, guaranteeing an exceptional level of temperature accuracy at $\pm 0.1^{\circ}\text{C}$. In the context of these experiments, heat transfer within the specimens occurs in a unidirectional manner, initiating from the upper concrete layer and reinforcement mesh, passing through the container material, air gap, PCM/NePCM, the lower container material, the reinforcement mesh at the base, and ultimately the lower concrete layer. A 16-channel data logger equipped with an automatic recording function consistently records temperature data at one-minute intervals to facilitate data collection. As illustrated in Fig. 7.5, this experimental setup is continually exposed to external environmental conditions.



Fig. 7.5 Outdoor experimental setup.

7.3 Results and Discussion

7.3.1 Variations in T_{es} and T_{is}

The outdoor experiments were carried out over the course of one month, specifically from August 13 to September 13. Throughout this period, temperature variations in all tested specimens were monitored, and the resulting data is visualized in Fig. 7.6, along with corresponding solar radiation variations. The temperature profiles exhibit a predictable gradual increase and decrease trends with some minor deviations. In the case of the CRS, temperature trends primarily follow changes in ambient conditions and the thermophysical properties of the RC. However, in the specimens containing PCM or NePCM, the temperature variations are notably influenced by the thermophysical properties of the PCM or NePCM in addition to the RC. One significant thermal characteristic observed in the temperature profiles is the sustained increase in temperature for the BVS and NePCM specimens compared to the CRS specimens. In Fig. 7.6, it is evident that the temperature in the CRS specimen rises relatively quickly and peaks in the late afternoon. Conversely, the BVS and NePCM specimens display a gradual temperature increase over a more extended period, with their peak temperatures typically occurring in the evening hours. It's

important to note that gradual and sustained changes in thermal energy are generally more favourable for enhancing thermal comfort when compared to rapid temperature fluctuations. In this context, macroencapsulated BVS provides improved interior thermal regulation and insulation.

On multiple days, it is observed that the temperature profiles of $T_{is,BVS}$, $T_{is,2\%GNP-NePCM}$ or $T_{is,4\%GNP-NePCM}$ remain below T_{es} during sunny hours but rise above it during non-sunny hours. This interesting phenomenon can be attributed to the efficient thermal energy storage capabilities of the PCM or NePCM as they store heat as latent energy during sunny periods. Conversely, during non-sunny hours, these materials release the stored latent heat. Consequently, incorporating macroencapsulated PCM or NePCM serves as a valuable mechanism for thermal regulation to the roof by effectively counterbalancing the external thermal flux. This is of paramount importance for upholding the occupants' thermal comfort. Significantly, it's observed that on multiple days, PCM and/or NePCM undergo phase transitions from solid to liquid during sunny hours and from liquid to solid during non-sunny hours. This observation validates the effective functionality of the PCM or NePCM within the specimens. This capacity allows them to release the stored heat at night and recharge the following day. Cyclic charging and discharging are critical functional factors when selecting PCM or NePCM for building applications. The chosen PCM or NePCM is found to satisfactorily fulfill these requirements.

Emphasizing the critical role of heat transfer mechanisms in facilitating phase transitions is imperative. Heat transfer predominantly transpires via diffusion in the initial phases of the melting process of PCM or NePCM. Concurrently, the phenomenon of thermal buoyancy manifests itself in both melting PCMs and NePCMs. This phenomenon induces the upward movement of the liquid phase in close proximity to the container's surface, effectively overcoming the opposing viscous forces and ascending to the container's uppermost region. Heat transfer occurs as the ambient temperature rises through a combination of conduction and natural convection mechanisms. The residual heat ascends along the heated surface until it eventually reaches the upper spherical region of the container, as expounded by previous studies (Huang et al., 2020a; Shokouhmand & Kamkari, 2013b).

In the course of sunny hours, the specimens BVS, 2% GNP–NePCM, and 4% GNP–NePCM undergo a solid-liquid phase transition, a phenomenon that significantly lowers indoor temperatures. The measured reductions in indoor temperature throughout the entire test period are presented in Fig. 7.7. It's important to note that these reductions are assessed by contrasting the temperature differential between the external and internal surfaces. The CRS specimen experiences a maximum temperature reduction of 9.0 °C, a minimum reduction of 0.0 °C, and an average reduction of 3.0 °C. Conversely, the BVS specimen demonstrates more substantial values of 16.5 °C, 2.3 °C, and 8.0 °C, respectively. Consequently, integrating BVS with PCM/NePCMs notably

influences diminishing indoor temperatures. This temperature decline directly results from PCM/NePCMs absorbing thermal energy as latent heat during their phase transition from solid to liquid. It's imperative to recognize that the phase change characteristics of PCM/NePCMs are intricately linked to their latent heat storage capacity. During the melting process, PCM/NePCMs enter a semi-transient state within the regions of the initial phase change. In this state, PCM/NePCMs exhibit a viscoelastic behaviour, devoid of both solid and liquid attributes, displaying a mushy nature. With continued melting, the liquid content within the mushy zone progressively increases until it attains a complete liquid state. The phase change process in PCM/NePCMs is multifaceted, encompassing various phases, such as solid-mushy, liquid-mushy, or combinations thereof (Mirzaei & Haghighat, 2012).

In Fig. 7.7, we can observe the measured indoor temperature reduction values for NePCM specimens. When exposed to sunny conditions, the 2% GNP–NePCM specimen exhibits indoor reductions of 18.0 °C (maximum), 6.0 °C (minimum), and 9.3 °C (average). Similarly, the 4% GNP–NePCM specimen demonstrates reductions of 18.2 °C, 6.9 °C, and 9.7 °C, respectively. Consequently, the difference in indoor temperature reduction values between the 2% GNP–NePCM and 4% GNP–NePCM specimens is minimal. In comparison to the BVS specimen, the NePCM specimens record an increase of 1.7 °C (maximum), 3.7 °C (minimum), and 1.3 °C (average). However, when contrasted with the CRS specimen, the NePCM specimens showcase a maximum temperature reduction of 9.2 °C, a minimum reduction of 6.9 °C, and an average reduction of 9.7 °C. It's crucial to emphasize that these substantial reductions in indoor temperature during daylight hours can significantly alleviate cooling load requirements.

During non-sunny hours, the PCM and NePCMs undergo a transition from a liquid to a solid state, liberating stored heat into the indoor environment. This phenomenon leads to an elevation in indoor temperatures. Fig. 7.7 visually represents the indoor temperature fluctuations observed in all specimens throughout the testing period. The CRS specimen experiences a maximum indoor temperature rise of 6.1 °C, a minimum rise of 0.0 °C, and an average rise of 1.05 °C. The BVS specimen presents significant values of 9.0 °C (maximum), 1.4 °C (minimum), and 3.4 °C (average). Moreover, the specimen containing 2% GNP–NePCM exhibits an indoor temperature increase of 11.0 °C (maximum), 0.2 °C (minimum), and 3.9 °C (average). The 4% GNP–NePCM sample findings are as follows: 10.9 °C, 0.1 °C, and 3.6 °C, respectively. The upsurge in indoor thermal energy contributes positively to the occupants' thermal comfort and concurrently reduces the energy demands for space heating. As shown in Fig. 7.7, the values of $T_{is,BVS}$, $T_{is,2\%GNP-NePCM}$ and $T_{is,4\%GNP-NePCM}$ surpass $T_{is,CRS}$ on various days, signifying the release of latent heat into the interior. It's important to note that discharging latent heat into the indoor environment is less

favorable when temperatures exceed the thermal comfort threshold. In such adverse conditions, it becomes imperative to implement strategies for heat dissipation into the surroundings.

Fig. 7.8 presents a comparative analysis of indoor temperatures among the CRS, PCM, and NePCM specimens. During sunny hours, BVS reduces indoor temperatures by 13.8 °C (at maximum), 0.1 °C (at minimum), and 5.1 °C (on average) in contrast to the CRS specimen. The 2% GNP–NePCM values are 13.8 °C, 4.0 °C, and 6.4 °C. For 4% GNP–NePCM, the values are 14.0 °C, 3.6 °C, and 6.8 °C. Consequently, BVS and NePCM specimens significantly mitigate indoor temperatures in comparison to the CRS specimen during sunny hours. In non-sunny hours, BVS results in an increase in indoor temperatures by 4.7 °C (at maximum), 1.7 °C (at minimum), and 2.8 °C (on average) relative to the CRS specimen. The 2% GNP–NePCM values are 7.7 °C, 1.0 °C, and 3.4 °C. For 4% GNP–NePCM, the values are 7.6 °C, 1.0 °C, and 3.1 °C. These data indicate two key observations: (i) PCM and NePCM specimens exert a notable influence on indoor temperatures, reducing them during sunny hours and elevating them during non-sunny hours in comparison to CRS specimens, and (ii) NePCM specimens lead to a more substantial decrease in indoor temperature during sunny hours and an increase during non-sunny hours compared to PCM specimens.

The thermal characteristics of PCM/NePCM specimens are notably responsive to their ambient surroundings. To illustrate this phenomenon, we have generated temperature profiles for all specimens from August 30 to September 02, as depicted in Fig. 7.9. Over this timeframe, there was a transition in solar radiation patterns, transitioning from cloudy weather with mild rainfall to clearer conditions. This shift is substantiated by the progressively increasing trends in the peak values of both T_{es} and T_{AMB} . It is apparent that PCM/NePCM began its phase transition, shifting from a solid to a liquid state, during the morning hours of August 30, mainly due to rising temperatures. However, the phase transition was not completed, and the material commenced its solidification phase during the afternoon of the same day as temperatures decreased. This solidification phase represented an extended period of heat discharge for PCM/NePCM, a crucial aspect in the cyclic behaviour of these materials, which facilitates full solidification, preparing them for complete recharging on a subsequent sunny day. This phenomenon was particularly noticeable in the temperature profiles for September 01. On this day, indoor temperatures substantially declined, registering reductions of 16.5 °C, 10.3 °C, and 11.3 °C for BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. The temperature drop can be attributed to the favourable weather conditions on August 30 and 31, which were conducive to solidification. In contrast, rainy days promote solidification, enhancing the heat storage capacity of PCM/NePCM for utilization during subsequent sunny periods. The significant peaks observed in Fig. 7.7 and 7.8 are the result of these alternating weather conditions. The interplay of changing weather patterns

promotes both solidification and melting phases. However, persistent rainy conditions can impede the charging capacity of PCM/NePCM, as evidenced by the data presented in Fig. 7.9. On August 20, NePCM specimens experienced the least reduction in indoor temperature, at 7.6 °C, due to unfavourable weather conditions preventing NePCM from reaching its melting point. Therefore, for the effective thermal performance of BVS, which is profoundly influenced by the local climate, it is imperative to ensure the complete cyclic charging and discharging of PCM/NePCM materials.

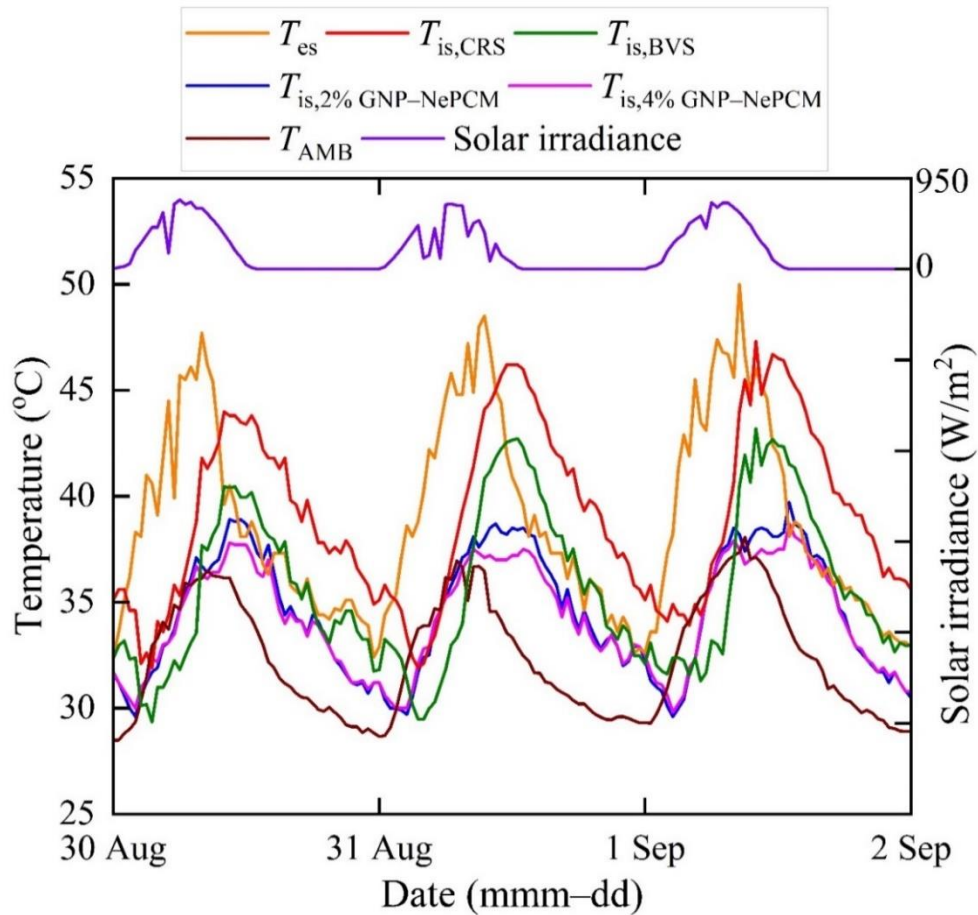


Fig. 7.6 Effect of ambient conditions on temperature profiles.

7.3.2 Variation in H_f

Fig. 7.10 illustrates the temporal distribution of H_f in W/m^2 for all specimens throughout the test duration. Negative H_f values on the graph represent instances where the specimens are releasing heat, while positive H_f values indicate that they are absorbing heat. Notably, in the early morning and late evening hours, all specimens exhibit almost synchronized H_f values. This synchronization implies that the thermal heat flux remains consistent during these specified time intervals within a day. However, when these specimens gain heat, the H_f profiles of BVS and GNP-NePCM deviate

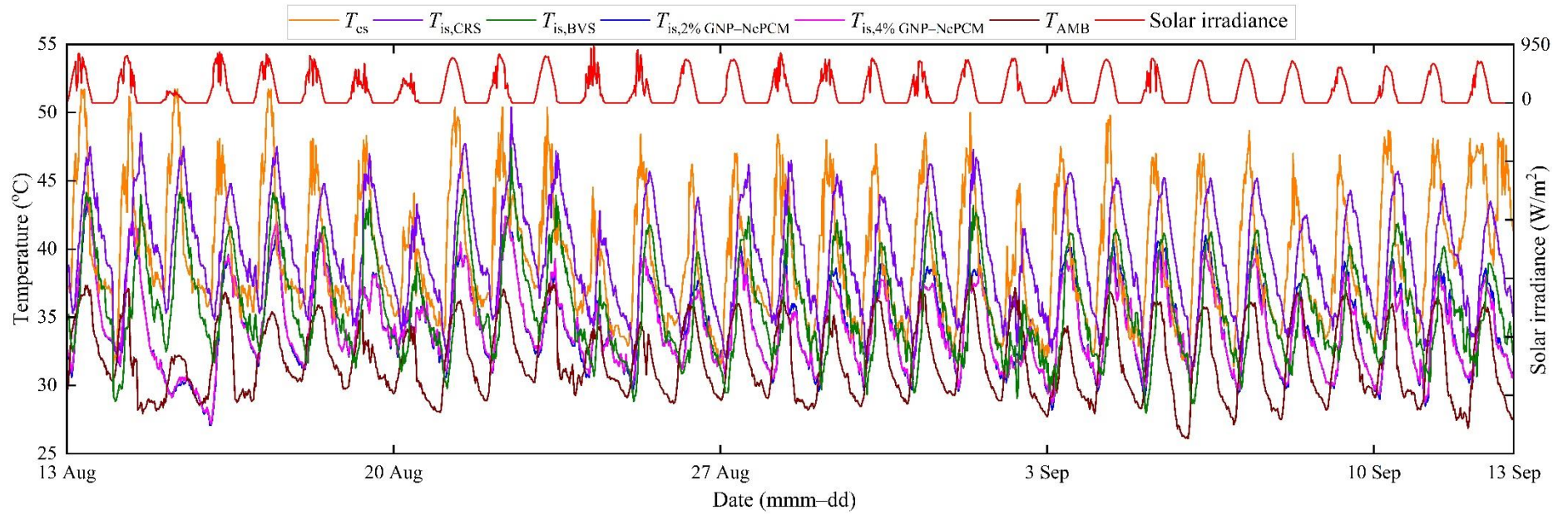


Fig. 7.7 Temperature variations in all specimens.

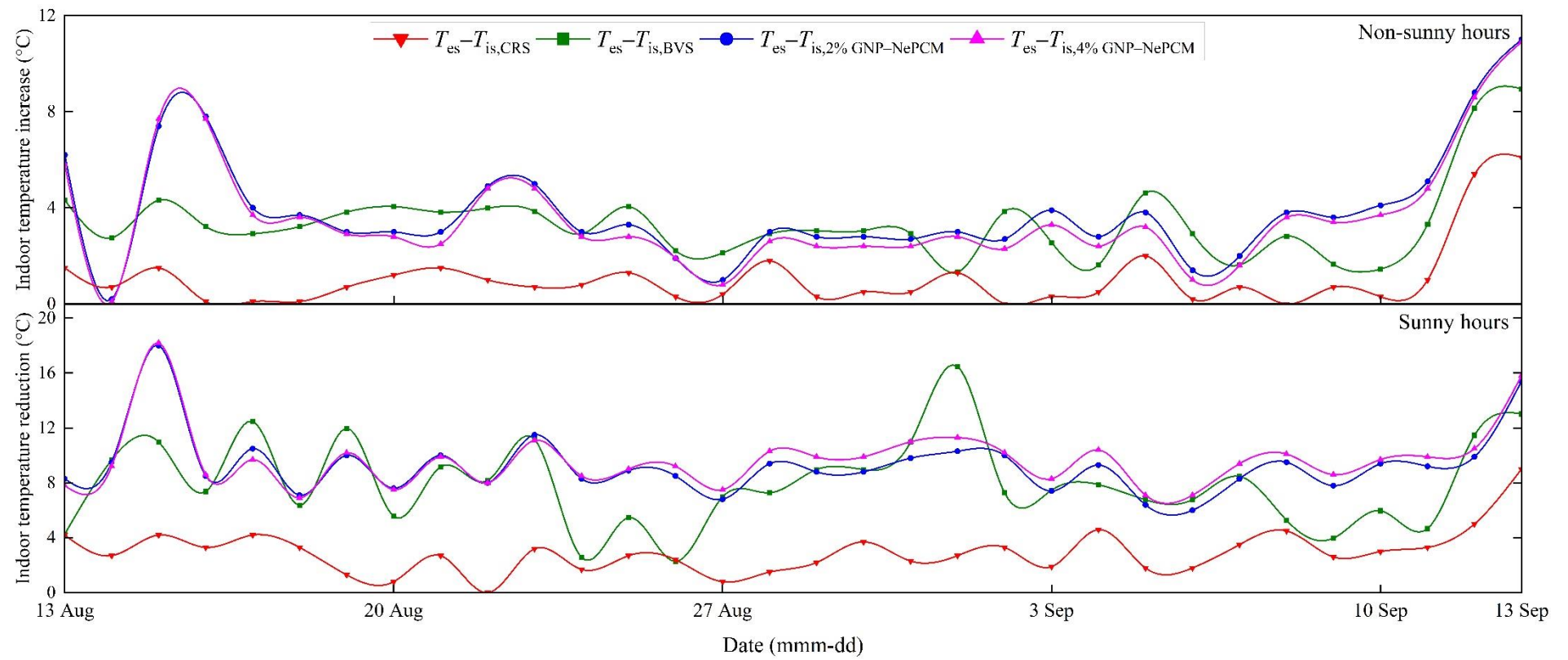


Fig. 7.8 Variation of indoor temperatures in all the specimens.

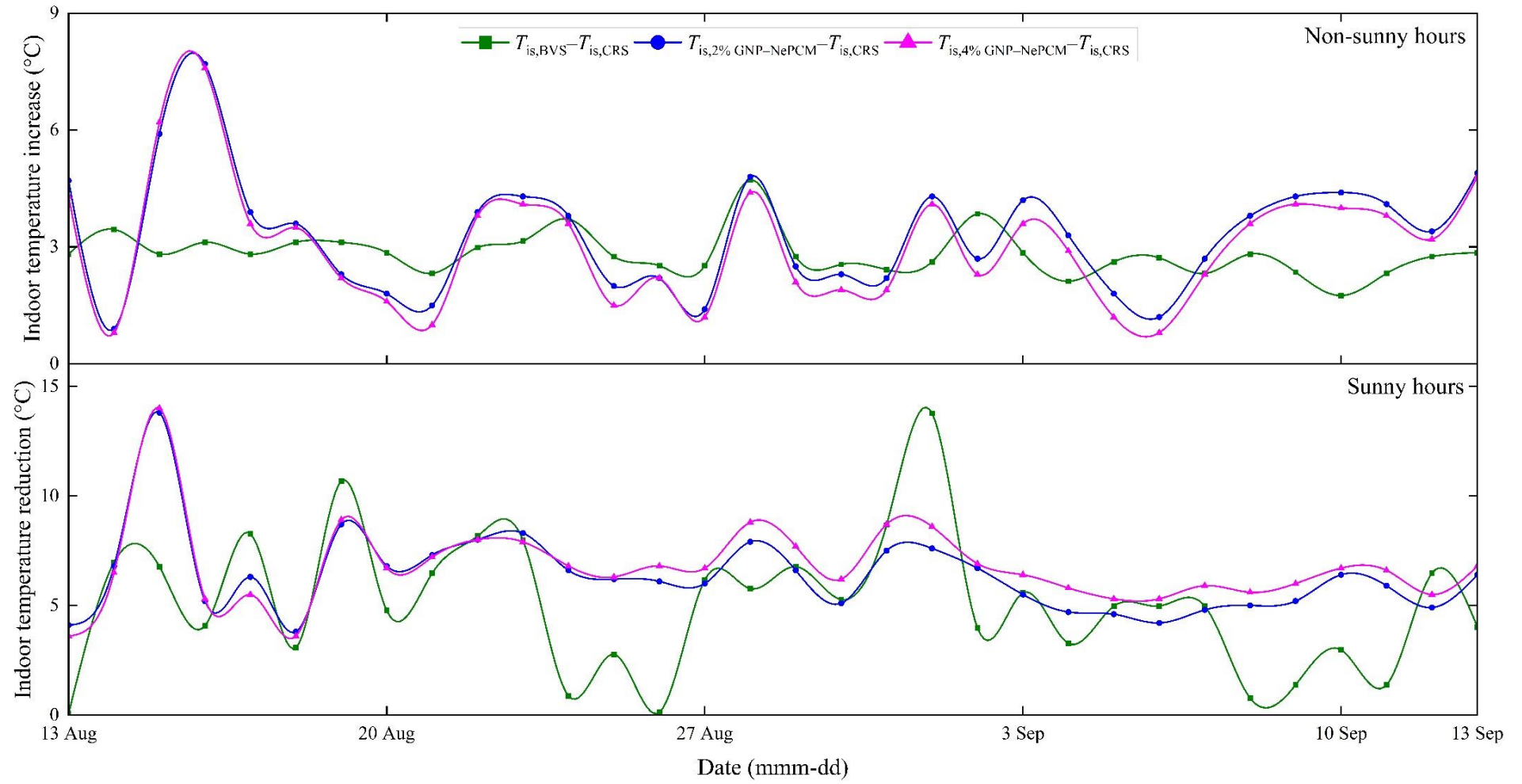


Fig. 7.9 Comparison between NePCM/PCM and CRS specimens.

from those of the CRS specimen. This deviation signifies the improved heat storage capabilities of PCM/NePCM specimens.

To understand the differences in the heat gain and release processes of these specimens, their H_f profiles can be examined in detail. For illustrative purposes, the profiles of all specimens for a single day, specifically September 03, are presented in Fig. 7.11. The daily heat flux profile reveals two distinct sets of transition points. The first set of transition points occurs when the H_f profiles of BVS, 2% GNP–NePCM, or 4% GNP–NePCM ascend from that of CRS during the early morning hours. The associated heat flux values at these transition points typically fall within the range of 1 W/m² to 5 W/m². The second set of transition points is observed when the descending H_f profile of CRS transitions from that of BVS, 2% GNP–NePCM, or 4% GNP–NePCM during the late afternoon hours. Importantly, the second set of transitions occurs within a similar range of H_f values. These transition points are practically significant as they indicate the specific H_f levels at which the phase transition of the PCM/NePCM occurs, whether it's from a solid to a liquid or from a liquid to a solid state. Additionally, it's worth noting that the H_f profile of CRS demonstrates a constant slope at these transition points, indicating a consistent heat flux rate within the CRS specimen under normal weather conditions.

In Fig. 7.12, we present the average percentage reduction H_f among various specimens observed during the test period. During sunny hours, compared to the CRS specimen, the H_f values experience an average reduction of 63%, 79%, and 82% in the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. In non-sunny hours, the H_f values show an average reduction of 33%, 57%, and 53% in the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, compared to the CRS specimen. Consequently, the BVS and NePCM specimens provide a substantial reduction in H_f during both sunny and non-sunny hours. The practical significance of these findings is that macroencapsulated BVS with PCM/NePCM can significantly decrease the energy required for both space heating and cooling. Additionally, Fig. 7.12 provides a comparison of H_f values between the BVS and GNP–NePCM specimens. During sunny hours, compared to the BVS specimen, we observe H_f reductions of 44% and 52% for the 2% GNP–NePCM and 4% GNP–NePCM specimens, respectively. Furthermore, during non-sunny hours, compared to the BVS specimen, H_f reductions of 37% and 32% are seen for the 2% GNP–NePCM and 4% GNP–NePCM specimens, respectively.

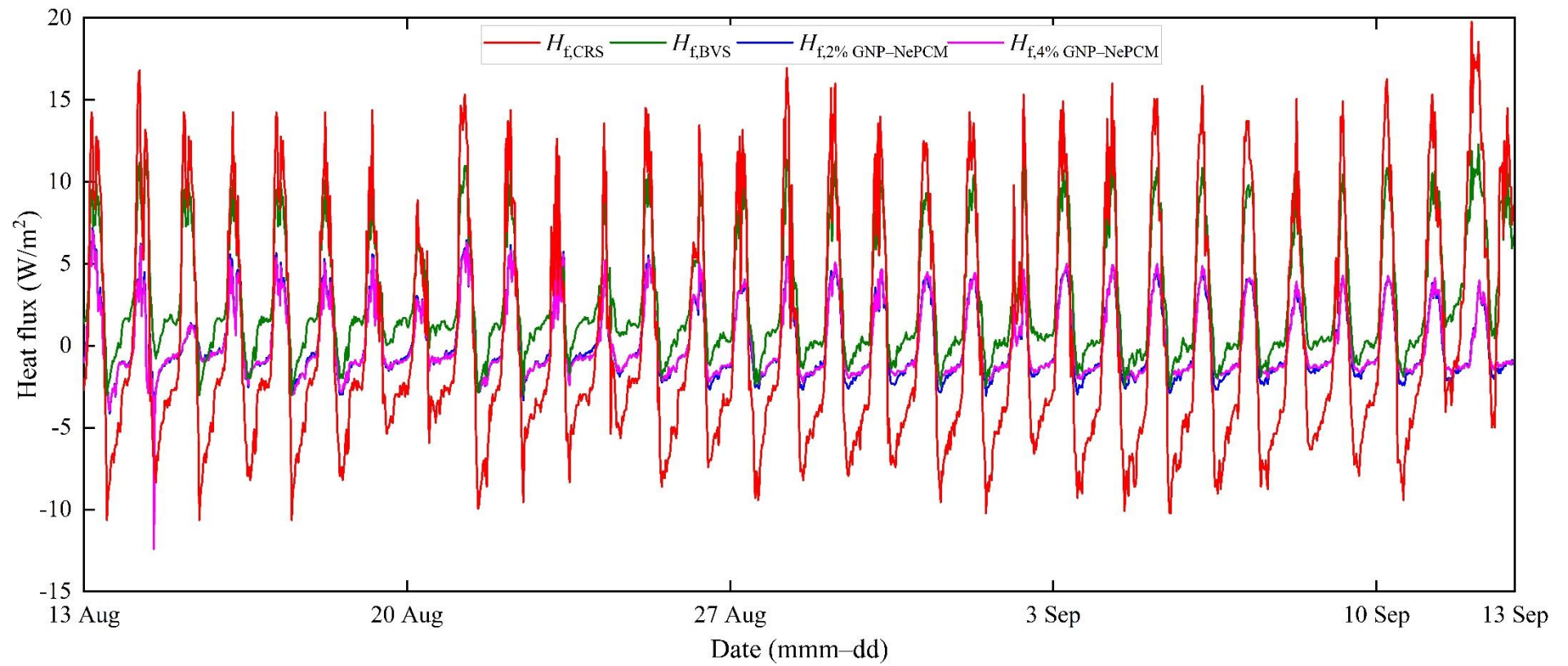


Fig. 7.10 Heat flux variation in all the specimens.

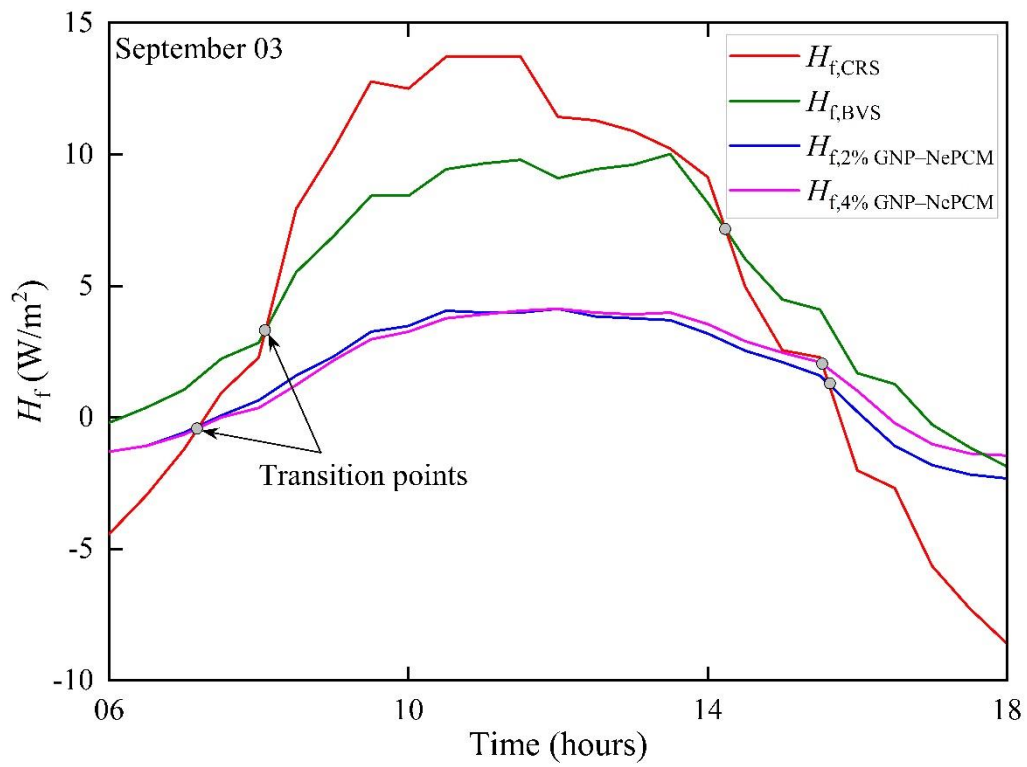


Fig. 7.11 Heat flux transition.

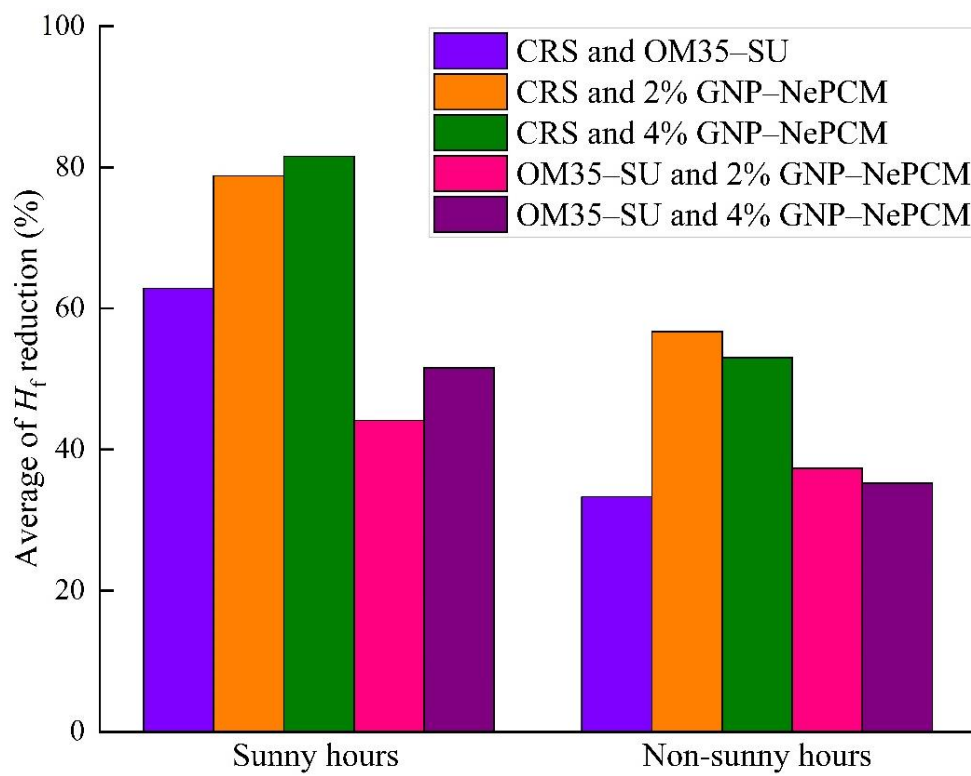


Fig. 7.12 Variation in average heat flux reduction between the specimens.

These results suggest that BVS integrated with NePCM exhibits a more pronounced decrease in H_f compared to integration with a PCM. Additionally, it's worth noting that high negative values of $H_{f,CRS}$ during non-sunny hours are unfavorable, as they indicate a substantial heat release into the interior. In contrast, the negative heat flow observed in BVS and NePCM specimens signifies the discharge of stored latent heat into the indoor environment, which is essential for efficient thermal management.

7.3.3 Heating load H_L

Fig. 7.13 provides an overview of the fluctuations in total H_L for both cooling and heating applications across the various specimens. The data demonstrates that all specimens showcase differing levels of reduction in the transfer of thermal energy originating from solar radiation on the roof's outer surface to the indoor environment. When compared to the CRS specimen, it's observed that the cooling loads for the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens are 33%, 67%, and 68% lower, respectively. Furthermore, the heating loads are reduced by 43%, 69%, and 71% for these specimens, respectively. Additionally, the total H_L values are significantly lower for the PCM/NePCM specimens in comparison to the CRS specimen. The reduction in total H_L is 38% for the BVS, 68% for the 2% GNP–NePCM, and 69% for the 4% GNP–NePCM. These results strongly suggest that macroencapsulated BVS integrated with NePCM can markedly improve thermal comfort by lowering operative temperatures and enhancing the management of thermal loads.

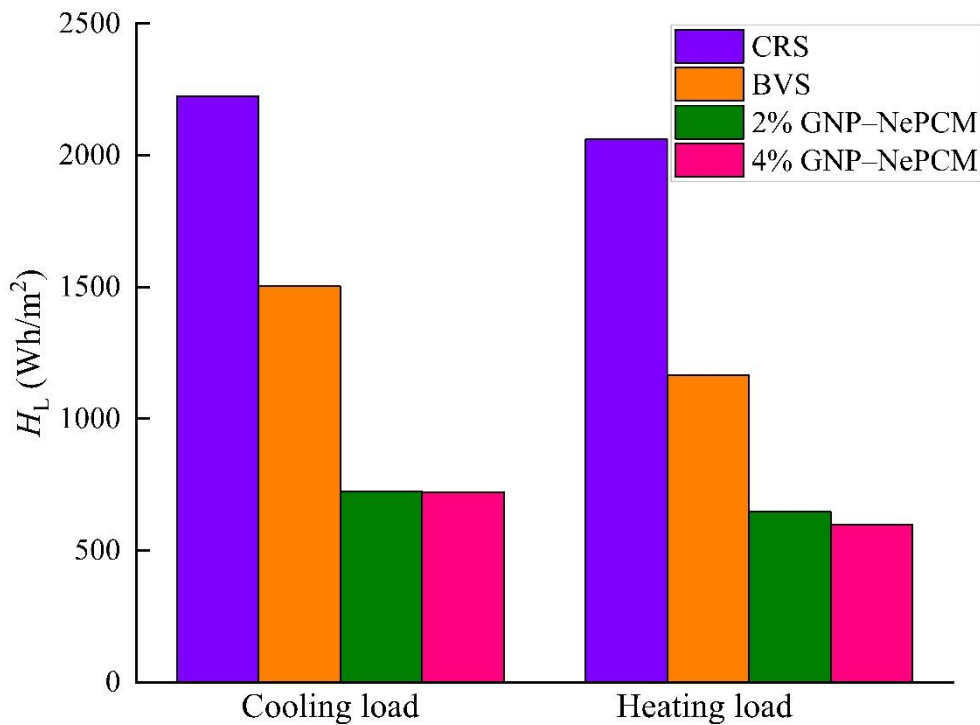


Fig. 7.13 Variation in thermal load.

Fig. 7.13 also facilitates a comparison of H_L for the BVS specimen with that of NePCM specimens. In relation to the BVS specimen, it's observed that the cooling loads for the 2% GNP–NePCM and 4% GNP–NePCM specimens are considerably reduced by 52%. Moreover, the heating loads experience a reduction of 44% and 49%, respectively. These findings clearly indicate that integrating GNP–NePCM within BVS can yield an even more effective approach to managing the indoor thermal environment than integration with BVS. Furthermore, Further, Fig. 7.13 can also be used to compare a specimen's cooling and heating loads. The cooling-to-heating load ratios are estimated to be 1.08, 1.29, 1.12, and 1.20 for the CRS, BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. The results suggest that the CRS specimen contributes approximately equally to heating and cooling loads during the test period. In contrast, the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens exhibit cooling loads of approximately 30%, 12%, and 20% higher, respectively. This observation holds practical significance as it implies that space cooling requirements would decrease during this period, significantly reducing indoor temperature fluctuations.

7.3.4 Variation in E_s

The potential cost savings concerning electricity consumption for both space heating and cooling can be rigorously assessed through the utilization of Eq. 6.8, and the outcomes are meticulously presented in Fig. 7.14. It is imperative to underscore that this computation hinges upon the foundational assumption that electricity consumption for space heating and cooling systems (like air-conditioning or space heating equipment) is approximately equal. The insights gleaned from the data showcased in Fig. 7.14 conspicuously underscore a substantial discrepancy in cost savings between space cooling and heating. This distinction in savings can be justifiably attributed to the notable heat storage capacity rendered by PCM/NePCMs, effectively curtailing the demand for space cooling. Conversely, the prerequisites for space heating are intrinsically tied to the prevailing climatic conditions localized to a specific geographic area. In this context, passive building design paradigms are expressly oriented towards minimizing heating demands, characterized by brief, sporadic heating requirements. Consequently, the need for space heating may arise infrequently. Furthermore, buildings designed with passive principles may exhibit a limited capacity for precise modulation of space heating requirements during transitional phases, instead concentrating their optimization efforts on the coldest periods of the day.

Table 7.1 provides a comprehensive overview of E_s values recorded over the entire duration of the testing. It's crucial to highlight that U_p is consistently maintained at a fixed rate of 7.3 Rupees/kWh or 0.09 USD/kWh. The data analysis indicates that, on average, the E_s value for space cooling is 89% higher in the case of BVS, 42% higher for 2% GNP–NePCM, and 48% higher for 4% GNP–NePCM, as compared to its counterpart space heating. This observation underscores that BVS utilizing PCM

macroencapsulation offers more substantial energy savings, particularly in space cooling, when compared to BVS incorporating GNP–NePCM. Furthermore, the findings suggest that GNP–NePCM makes nearly an equal contribution to both space heating and cooling, achieving a balance in E_s values. Contrasting with the E_s values for BVS, NePCMs exhibit a 22% increase in the maximum value, a 2% increase in the minimum value, and a 31% increase in the average value. These changes correspond to a total E_s increase of 54%, 42%, and 27%, respectively, when considering both heating and cooling. In summary, GNP–NePCM macroencapsulation within BVS demonstrates more significant energy savings than OM35 macroencapsulation. Notably, it's important to recognize that the electricity cost savings achieved with 2% GNP–NePCM are on par with those of 4% GNP–NePCM. This equality underscores that the most substantial savings are realized during favourable weather conditions, emphasizing the importance of efficient PCM/NePCM charging and discharging within BVS for achieving notable reductions in electricity costs.

Table 7.1 Summary of electricity cost savings.

Specimen	Cycle	E_s (Rupees/kWh/m ²)		
		Maximum	Minimum	Average
BVS	Cooling	3.7	2.7	3.1
	Heating	2.1	0.7	1.6
2%GNP–NePCM	Cooling	4.5	2.9	3.9
	Heating	4.4	1.5	2.7
4%GNP–NePCM	Cooling	4.5	2.7	4.0
	Heating	4.4	0.2	2.7

7.3.5 S_p and D_p

In this study, CI entails the financial outlays associated with several components, including the aluminum container, OM35, and GNP. The price of a single container is set at 170₹/2\$. To cover an area of 1 m², nine such containers are required, resulting in a cumulative expenditure of 1530₹/18\$. Furthermore, the cost of 1 kg of OM35 is 450₹/5.4\$, and each container is equipped with 600 g of OM35. Consequently, the cost per square meter for OM35 is 2430₹/29\$. The overall CI for 1 m² of the BVS macroencapsulated with OM35 amounts to 3960₹/47.6\$. Similarly, the cost of 1 g of GNP is 135₹/1.6\$. The weights for GNP with 2% and 4% mass fractions are 12 g and 24 g, respectively. This leads to costs of 1625₹/19.25\$ and 3250₹/38.5\$, respectively. Consequently, the CI for 1 m² of the BVS macroencapsulated with 2% GNP–NePCM and 4% GNP–NePCM are 23,464₹/280\$ and 33,210₹/396\$, respectively. As evidenced, the CI for BVS integrated with 2% GNP–NePCM and 4% GNP–NePCM is approximately 6 and 8.4 times higher than the CI for OM35 integration, respectively.

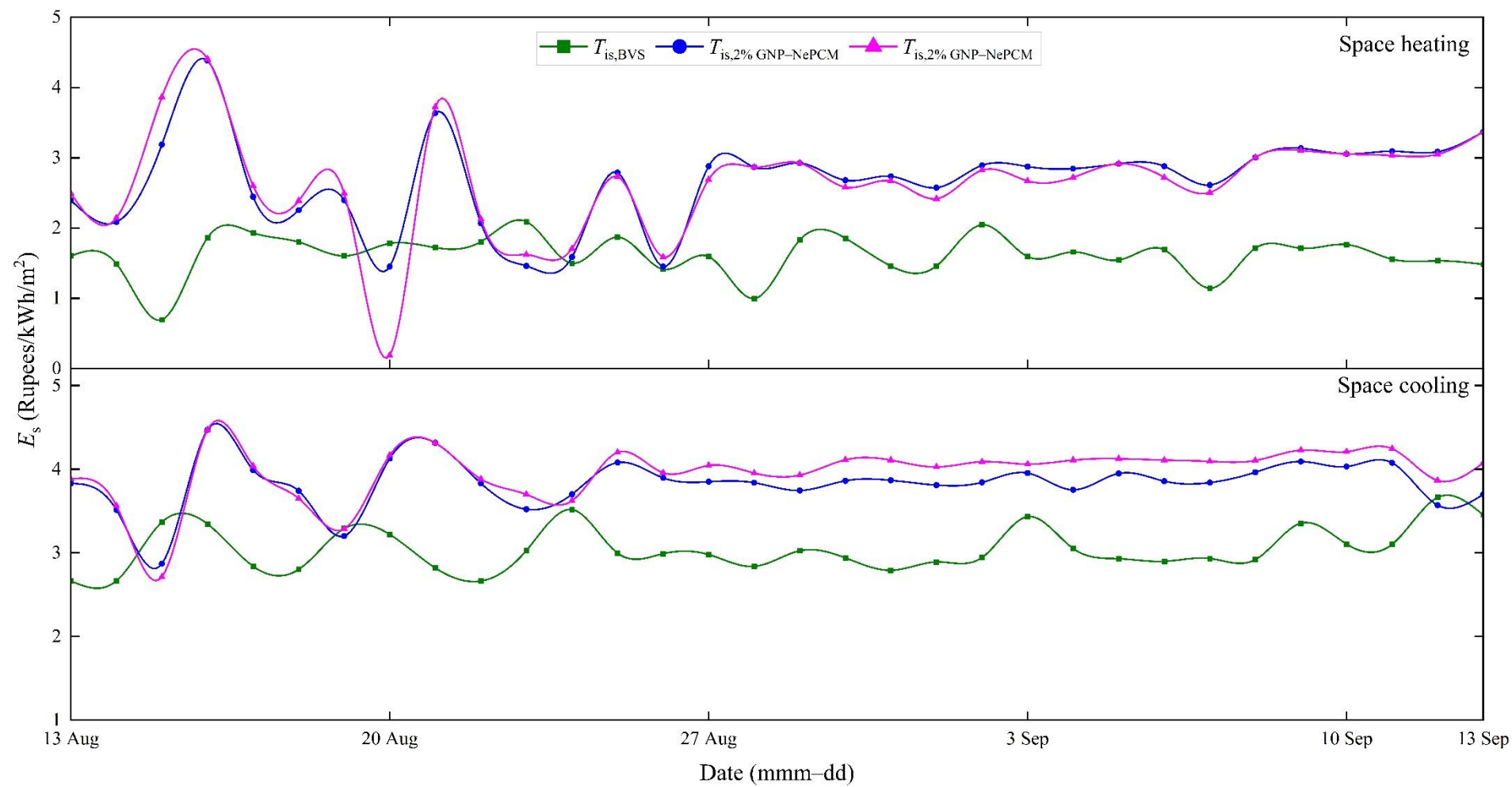


Fig. 7.14 Variation in daily electricity savings.

Furthermore, it's notable that the CI for BVS integrated with 4% GNP–NePCM surpasses that of 2% GNP–NePCM integration by approximately 30%.

The annual cost savings related to electricity are intricately connected to the operational efficacy of PCM/NePCM, a relationship that profoundly influences the yearly return on investment. In this study, the PCM/NePCM material is tailored to activate selectively in response to particular weather conditions. This means its operational time period is not continuous throughout the entire year but is constrained to specific days. An analysis of the region's temperature profile (Ref. Fig. 7.1), reveals that the PCM/NePCM can effectively function for approximately 148 days, distributed across various months. During these 148 days, the ambient temperature exceeds the critical threshold of 35 °C, corresponding to the melting point of PCM/NePCMs. Given the study's focus on the month of September, it is assumed that PCM/NePCM systems operate on all 148 identified days, leading to the calculation of an average E_s , as presented in Table 7.1. Consequently, over the course of these 148 operational days, it's anticipated that the BVS, 2% GNP–NePCM, and 4% GNP–NePCM systems will generate average E_s values of 4.7₹/0.05\$, 6.6₹/0.08\$, and 6.7₹/0.08\$, respectively.

The S_p and D_p metrics for all specimens have been exhaustively detailed in Table 7.2. This tabulated dataset elucidates that the period required for the recovery of CI associated with BVS incorporating OM35, 2% GNP–NePCM, and 4% GNP–NePCM amounts to 5.7, 5.8, and 7.3 years, correspondingly. Despite the considerably elevated (six times) CI for the BVS integrated with 2% GNP–NePCM compared to OM35 integration, it's noteworthy that the S_p values are virtually identical. This paradox can be rationalized by the superior cost savings rendered by the former over the latter. Upon a scrupulous comparative analysis, the recommendation firmly leans toward giving precedence to implementing BVS integrated with 2% GNP–NePCM. This preference primarily stems from its outstanding prowess in managing thermal loads when juxtaposed with BVS constructed using BVS. Notably, it's imperative to underscore that the S_p value of the 4% GNP–NePCM specimen surpasses that of the other two specimens by approximately 30%. This is pertinent, especially considering that the thermal load management attributes of the 4% GNP–NePCM and 2% GNP–NePCM specimens are comparable, accentuating the latter's cost-effectiveness. It's crucial to emphasize that these conclusions are derived based on the specific weather conditions prevalent during the test period. It's imperative to acknowledge that S_p may exhibit variations contingent upon the local weather conditions. Hence, opting for the former may be prudent in scenarios where the 4% GNP–NePCM exhibits the potential to outperform the 2% GNP–NePCM due to altered local weather dynamics.

The values of D_p are likewise documented in Table 7.2, with consistent discount rate (r) and inflation rate (i) values set at 8% and 7.44%, respectively. The D_p values for the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens conspicuously exceed their respective S_p values by margins of 30%, 30%, and 42%, in that order. Notably, there is minimal differentiation between the D_p of the BVS and 2% GNP–NePCM specimens. However, the D_p for the 4% GNP–NePCM specimen surpasses that of the 2% GNP–NePCM specimen by roughly 38%. These findings validate the prior observations regarding S_p . Therefore, the recommendation to employ the 2% GNP–NePCM system over both the BVS and 4% GNP–NePCM systems holds true, given its superior thermal management capabilities and cost-effectiveness under the present climatic conditions.

Table 7.2 Summary of payback periods.

Specimen	S_p (years)	D_p (years)
BVS	5.7	7.4
2 %GNP–NePCM	5.8	7.5
4 %GNP–NePCM	7.3	10.4

7.3.6 Variation in C_s

Fig. 7.15a provides an illustrative representation of the correlation between C_s and space cooling. A discerning analysis of the C_s values reveals the following trends for a given specimen: (i) Lignite-fired power generation tops the chart, exhibiting the most substantial carbon savings, closely followed by coal-fired power generation. (ii) Natural gas power plants exhibit the least carbon savings. (iii) Diesel and naphtha fuel sources depict minimal disparities in their carbon savings. It's noteworthy that the C_s values for 2% GNP–NePCM and 4% GNP–NePCM, across all fuel types, exceed those of BVS by 26% and 30%, respectively. The pragmatic implication stemming from this discernment is that GNP–NePCMs contribute markedly more to the reduction of CO₂ emissions compared to OM35, particularly under the current weather conditions. Furthermore, it's essential to point out that the C_s values linked with 4% GNP–NePCM exhibit a 3.5% increment in relation to the C_s values of 2% GNP–NePCM. This data suggests that both specimens yield comparable CO₂ emissions reductions.

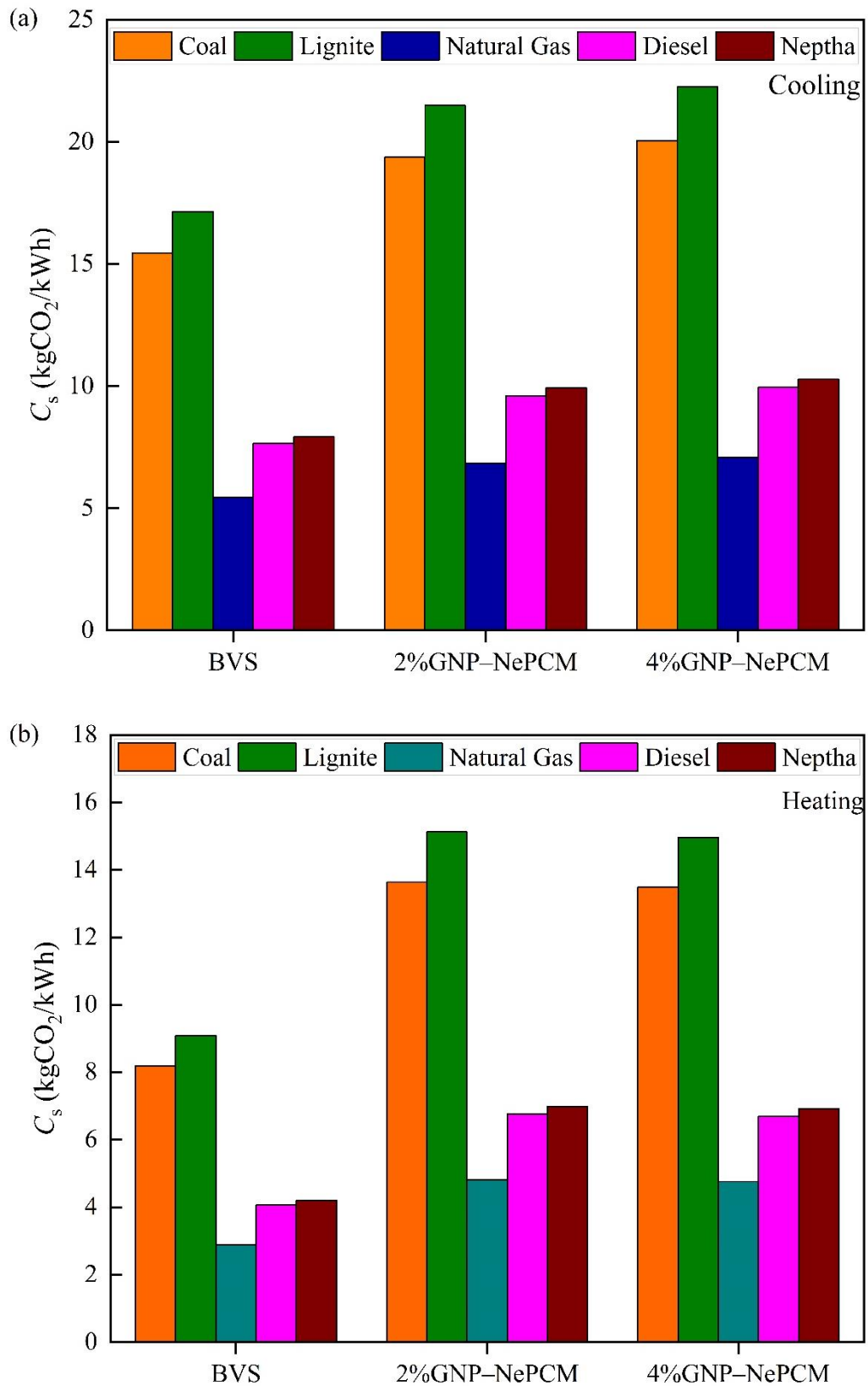


Fig. 7.15 Savings on CO₂ emissions: (a) cooling; (b) heating.

Fig. 7.15b provides a graphical representation of the variations in C_s concerning space heating. The trends and deductions drawn from the C_s values for space heating closely align with those ascertained for space cooling savings. Moreover, it is paramount to accentuate that the C_s values for 2% GNP–NePCM and 4% GNP–NePCM exhibit substantial increments compared to BVS, registering at 67% and 65% higher, correspondingly, across all categories of fuel sources. Notably, the disparities in energy savings percentages for space heating are notably more pronounced than those for space cooling. This pivotal observation underscores the capacity of GNP–NePCM to yield elevated savings in the context of space heating as compared to space cooling. It's also pertinent to note that the C_s values for 4% GNP–NePCM demonstrate only a marginal 1% increment when juxtaposed with the C_s values of 2% GNP–NePCM, signifying that both variants contribute to comparable reductions in CO₂ emissions.

The cumulative C_s values for space cooling employing different fuel sources are calculated to be 53.7, 67.3, and 70.0 kgCO₂/kWh for BVS, 2% GNP–NePCM, and 4% GNP–NePCM, in that order. Concerning space heating, the computed values are 28.4, 47.3, and 46.8 kgCO₂/kWh, respectively. Given the prevailing meteorological conditions, it becomes evident that NePCM specimens substantially outperform the OM35 specimen in terms of overall CO₂ emissions reductions. The strategic management of carbon emissions is a fundamental approach aimed at mitigating global warming and the adverse consequences of climate change, achieved by curbing emissions from fossil fuel combustion and electricity generation. Therefore, implementing BVS incorporating PCM/NePCMs represents a proactive measure to enhance CO₂ emission savings.

7.3.7 Variations in f and ϕ

Fig. 7.16 depicts the distribution of f , denoting the temperature fluctuation factor, across all specimens over the duration of the test. The observations reveal the following trends:

- For the CRS, f varies between 1.15 and 2.55.
- The BVS specimen exhibits f in the range of 0.62 to 1.22.
- The 2% GNP–NePCM specimen demonstrates f values ranging from 0.10 to 0.93.
- The 4% GNP–NePCM specimen has f values spanning from 0.06 to 0.95.

It is evident that the introduction of OM35 leads to a reduction in f compared to CRS, which is further amplified with the integration of NePCMs. The mean value for f_{BVS} , standing at 0.82, is approximately half of that for the f_{CRS} , which is 1.58. In essence, the integration of OM35 effectively reduces temperature fluctuations within the indoor environment by a factor of two when compared to CRS.

Notably, the average f_{BVS} is three times lower than that for GNP–NePCM specimens, measured at 0.50. On average, the incorporation of 2% GNP–NePCM results in a threefold reduction in temperature fluctuations within the indoor environment compared to CRS. Furthermore, the average $f_{2\% \text{GNP-NePCM}}$ and $f_{4\% \text{GNP-NePCM}}$ values are nearly identical, suggesting that there's no substantial reduction in temperature fluctuations with the 4% GNP–NePCM integration. Consequently, it can be affirmed that NePCM macroencapsulated BVS offer superior thermal regulation within the indoor environment when compared to both CRS and OM35 specimens.

Fig. 7.17 visually represents the fluctuations in the ϕ , concerning BVS and NePCM specimens. The ϕ_{BVS} values extend across a range from 0.5 hours to 6.0 hours, while the ϕ_{NePCM} specimens exhibit values spanning from 0.5 hours to 5.0 hours. Furthermore, the computed average ϕ values are determined to be 3.6 hours, 2.5 hours, and 2.4 hours for the BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. Remarkably, the average ϕ values for the 2% GNP–NePCM and 4% GNP–NePCM specimens exhibit significant reductions, amounting to 40% and 46% compared to the BVS. This substantial reduction is attributed to the heightened thermal conductivity observed in NePCMs, as substantiated during the characterization phase. This observation underscores the pragmatic importance of NePCM in minimizing time lag, particularly in contrast to organic PCMs like OM35. Furthermore, the difference in ϕ values between the 2% and 4% GNP–NePCM specimens is merely 1%, indicating their similar behaviour in this context.

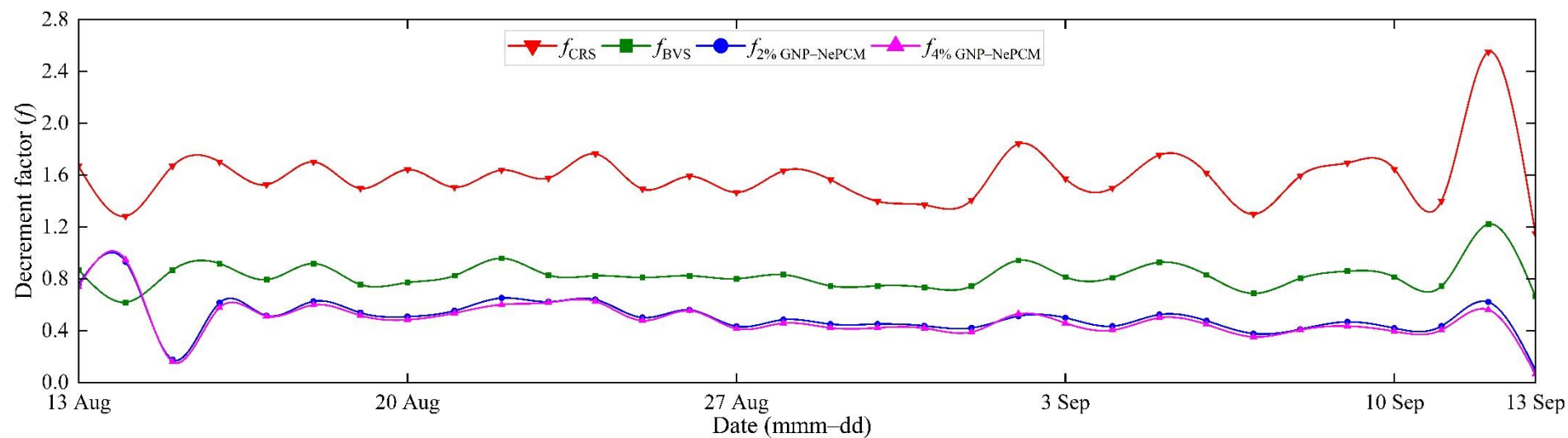


Fig. 7.16 Variation in temperature decrement factor.

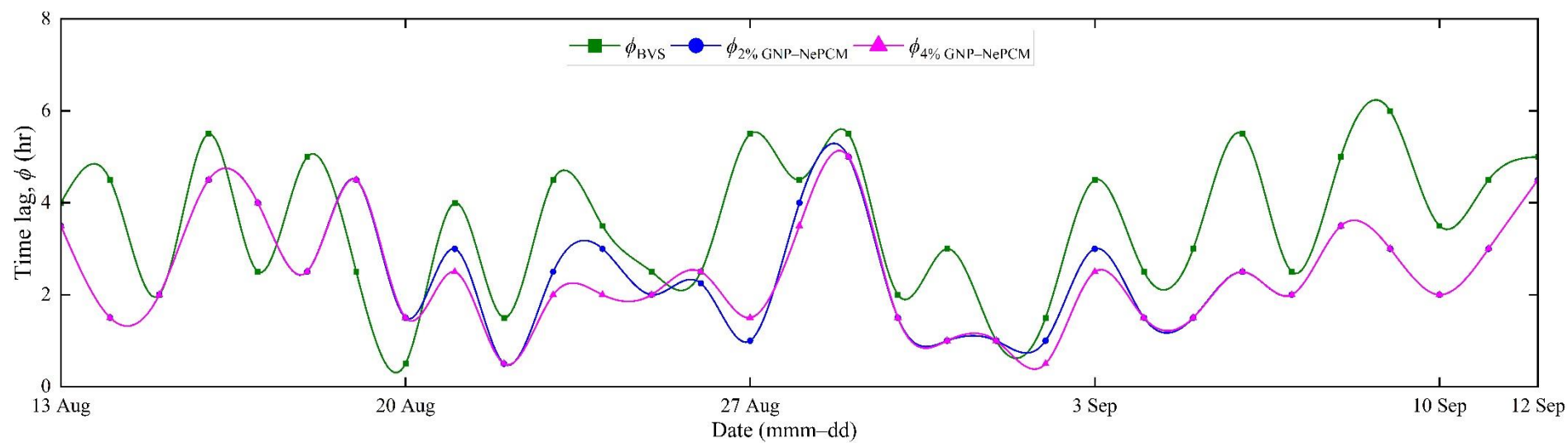


Fig. 7.17 Variation in temperature time lag.

7.4 Concluding Remarks

This experimental study is fundamentally concerned with comprehensively examining latent heat storage characteristics in a series of two-way BVS specimens. These specimens are uniquely integrated with macroencapsulated PCM and NePCM, and they are subjected to an ambient environmental setting. The choice of materials for this study, including the OM35 and the nanomaterials MWCNT and GNP, is informed by careful consideration of local climatic conditions and their respective thermophysical properties. The thermal attributes of OM35 are meticulously examined independently and in tandem with 2% and 4% mass fractions of MWCNT and GNP. Consequently, a set of BVS specimens is methodically crafted, incorporating macroencapsulated OM35 (designated as BVS), 2% GNP (referred to as 2% GNP–NePCM), and 4% GNP (denoted as 4% GNP–NePCM). The evaluation of thermal energy storage performance is carried out through an extensive analysis of parameters, encompassing temperature profiles, heat flux dynamics, thermal load characteristics, time lag, and decrement factor. Additionally, the study extends its scope to financial feasibility considerations, involving calculations of electricity cost savings, payback periods, and reductions in CO₂ emissions. These results are subsequently juxtaposed against those of a conventional reinforced concrete specimen (CRS).

The key findings derived from this study are presented as follows:

- i. In comparison to OM35, the introduction of 2% GNP–NePCM and 4% GNP–NePCM led to substantial enhancements in thermal conductivity by 36.4% and 45.5%, an increase in thermal diffusivity by 16.7% and 21.4%, a reduction in specific heat capacity by 17.8% and 25.6%, a decrease in supercooling by 24% and 29%, and a marked improvement in melting enthalpy efficiency by 94.71% and 92.13%.
- ii. During sunny hours, BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens collectively experienced an average decrease in indoor temperature of 8.0, 9.3, and 9.7 °C. Conversely, in non-sunny hours, the corresponding average interior temperature rise was recorded as 3.4, 3.9, and 3.6 degrees, respectively.
- iii. On average, heat flow values in BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens were substantially lower than in CRS specimens, with reductions of 63%, 79%, and 82% during sunny hours. This reduction in heat flow averaged 33%, 57%, and 53% during non-sunny hours, resulting in overall thermal load reductions of 38%, 68%, and 69%, respectively.
- iv. The daily average power savings for space cooling surpassed those for space heating, with enhancements of 89%, 42%, and 48% for BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. Simple payback periods were estimated at 5.7, 5.8, and 7.3 years,

with discounted payback periods reflecting increases of 30%, 30%, and 42%.

- v. Compared to BVS, 2% GNP–NePCM and 4% GNP–NePCM resulted in notably higher CO₂ emission savings for all types of fuels, registering an increase of 67% and 65%, respectively.
- vi. The mean temperature decrement factor values for BVS were precisely half those of the CRS specimen, and, additionally, the average values for BVS were three times lower than those for GNP–NePCM specimens. Moreover, compared to BVS, the 2% GNP–NePCM and 4% GNP–NePCM exhibited a substantial 40% and 46% reduction in mean time lag.

Conclusions and Future Recommendations

This experimental study is fundamentally concerned with comprehensively examining latent heat storage characteristics in a series of BVS specimens. These specimens are uniquely integrated with macroencapsulated PCM and NePCM and subjected to an ambient environmental setting. The selection of materials for this investigation, comprising phase change materials (PCMs) and nanomaterials such as multi-walled carbon nanotubes (MWCNT) and graphene nanoplatelets (GNP), is guided by meticulous consideration of local climatic conditions and their inherent thermophysical characteristics. The thermal properties of PCMs are scrutinized in isolation as well as in conjunction with 2% and 4% mass fractions of MWCNT and GNP. Subsequently, a series of building envelope specimens (BVS) is systematically fabricated, incorporating macroencapsulated PCM (referred to as BVS), 2% GNP (designated as 2% GNP–NePCM), and 4% GNP (identified as 4% GNP–NePCM). TES performance is evaluated through an extensive analysis of parameters, encompassing temperature profiles, heat flux dynamics, thermal load characteristics, time lag, and decrement factor. Additionally, the study extends its scope to financial feasibility considerations, involving calculations of electricity cost savings, payback periods, and reductions in CO₂ emissions. These results are subsequently juxtaposed against those of a conventional reinforced concrete specimen (CRS).

The study's novelty comprises identifying and characterizing suitable PCM/NePCMs; transforming containers into PCM/NePCM macroencapsulations; and thoroughly assessing roof slab latent heat storage potential under an ambient environment. Such a biaxial voided RCC roof slab that is macroencapsulated with PCM/NePCMs and aimed to assist in the passive cooling of buildings has never been explored before. Few studies have explored the thermal performance of PCM-integrated roofs in the Indian context (Baskar & Chellapandian, 2022; Rathore et al., 2020; Shanmuganathan et al., 2021). However, the current study is unique in the following aspects: PCM leakage has been completely prevented using a metal void former; PCM macroencapsulations are embedded in two directions within the concrete matrix; and a new PCM encapsulation typology has been introduced. The key findings derived from this study are presented as follows:

1. Thermal energy storage using PCMs could significantly reduce the HVAC energy consumption in buildings because of the significant latent heat of PCMs. The use of PCM in buildings seems to be very beneficial; PCM can increase energy savings, shift the peak loads of cooling energy demand, decrease temperature fluctuations, provide a thermally

comfortable environment, and reduce electricity consumption.

2. The study demonstrated that using PCMs in building roofs (i) improves indoor thermal comfort (ii) while reducing or eliminating the need for active heating or cooling systems, thus (iii) limiting the overall energy consumption of the building. Furthermore, PCM reproduces high-inertia buildings' behavior by reducing the transmitted temperature's amplitude.
3. The choice of a PCM predominantly relies on its thermo-physical characteristics. This study prioritized the latent heat as the primary criterion, followed by thermal conductivity, specific heat capacity, density, and phase change temperature. These parameters are crucial in assessing PCM performance. The outcomes of the AHP analysis revealed that latent heat garnered a global weight of 50.28%, while the phase change temperature obtained the least weight (3.48%). The TOPSIS and VIKOR results indicated that OM35 and OM37 emerged as the optimal options, considering factors such as availability, pricing, desired temperature range, and thermophysical properties. The findings underscore the efficacy and applicability of MCDM tools in ranking and selecting PCMs in building applications.
4. The study focused into the comprehensive thermophysical properties of PCMs. The outcomes revealed that the thermal conductivity of the PCMs was 0.22 and 0.20 W/mK, respectively. Morphological examinations revealed the presence of smooth surfaces within 3D lamellar structures, suggesting the adhesive nature of the PCM. Analysis of FT-IR spectra indicated significant physicochemical compatibility of the PCMs. XRD spectra exhibited favorable crystallization behavior of the PCMs. Furthermore, PCMs demonstrated minimal alterations in their melting and solidification behavior and associated enthalpies even after undergoing 1000 cycles. TGA thermograms indicated that the PCMs nearly completed their weight loss (97%) by 234 °C. Overall thermal characterization suggests that the PCMs hold promise for applications in energy storage within building envelopes.
5. In comparison to OM35, the introduction of 2% GNP-NePCM and 4% GNP-NePCM led to substantial enhancements in thermal conductivity by 36.4% and 45.5%, an increase in thermal diffusivity by 16.7% and 21.4%, a reduction in specific heat capacity by 17.8% and 25.6%, a decrease in supercooling by 24% and 29%, and a marked improvement in melting enthalpy efficiency by 94.71% and 92.13%.
6. During sunny hours, BVS, 2% GNP-NePCM, and 4% GNP-NePCM specimens collectively experienced an average decrease in indoor temperature of 8.0, 9.3, and 9.7 °C. Conversely, in non-sunny hours, the corresponding average interior temperature rise was recorded as 3.4, 3.9, and 3.6 °C respectively. Throughout the entire testing period from 14th

August to 14th September, OM37 showed substantial improvement in sunny and non-sunny hours compared to OM35. The improvements calculated were 36.58 to 66.75% and 26.94 to 50.19% for $T_{is,BVS}/T_{is,CRS}$ and $T_{es}/T_{is,BVS}$ during sunny and non-sunny hours.

7. On average, heat flow values in BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens were substantially lower than in CRS specimens, with reductions of 63%, 79%, and 82% during sunny hours. This reduction in heat flow averaged 33%, 57%, and 53% during non-sunny hours, resulting in overall thermal load reductions of 38%, 68%, and 69%, respectively. Moreover, the utilization of OM37 for heat transfer into the BVS showed a noteworthy improvement of 13% to 59% compared to OM35, specifically during sunny hours. However, during non-sunny hours, the heat flux values for OM37 to OM35 increased by a factor of 0.3 to 1.7.
8. During sunny and non-sunny hours throughout the testing period, the electricity cost savings per day achieved with OM37 were almost 1.5 times higher than those obtained with OM35. The daily average power savings for space cooling surpassed those for space heating, with enhancements of 89%, 42%, and 48% for BVS, 2% GNP–NePCM, and 4% GNP–NePCM specimens, respectively. Simple payback periods were estimated at 5.7, 5.8, and 7.3 years, with discounted payback periods reflecting increases of 30%, 30%, and 42%.
9. Integration of OM37 PCM leads to an almost 20% greater reduction in carbon emissions than OM35. During the testing period, a substantial portion of total emissions, exceeding 65%, is attributed to the cooling load, and heating loads make 40%. Compared to BVS, 2% GNP–NePCM and 4% GNP–NePCM resulted in notably higher CO₂ emission savings for all types of fuels, registering an increase of 67% and 65%, respectively. Given that the cooling load represents a significant share of overall energy consumption during this stage, any reduction in the cooling load can substantially decrease life cycle carbon emissions.
10. The mean temperature decrement factor values for BVS were precisely half those of the CRS specimen. Additionally, the average values for BVS were three times lower than those for GNP–NePCM specimens. Additionally, the average number of f_{CRS} is about 23.77% higher than that of f_{BVS} , suggesting that a biaxially voided slab unit integrated with OM37 is more effective than OM35 in reducing interior overheating. Compared to BVS, the 2% GNP–NePCM and 4% GNP–NePCM exhibited a substantial 40% and 46% reduction in mean time lag. Moreover, the average time lag of OM37 is 4.58 hrs while that of OM5 is 3.9 hrs, a rise of a 1.17 factor.
11. Compared to CRS, the maximum operative temperature difference reaches 3.76 °C, 7.25 °C, and 7.15 °C for BVS, 2%GNP–NePCM, and 4%GNP–NePCMs. Moreover, the

maximum DHR of 10.73%, 13.66%, and 13.73% for OM35SU, 2%GNP–NePCM, and 4%GNP–NePCMs was attained. Compared to BVS, the average DHR values of 2%GNP–NePCM and 4%GNP–NePCMs are 17.39% and 18.88% higher.

The results from this study suggest that the developed PCM integrated BVS can significantly reduce temperature and heat transfer to the interior environment. It is anticipated that forthcoming global warming will lead to increased occurrences of extreme weather phenomena, particularly characterized by elevated temperatures. Consequently, the advancement and manufacturing of PCMs are expected to pivot towards higher temperature ranges and greater latent heat capacities. Failure to adapt PCM development accordingly may necessitate adjustments to our comfort standards, potentially resulting in an upward shift in the comfort temperature zone.

Several avenues for further exploration in this realm include:

1. PCM stands as a proficient method for passive cooling. Nevertheless, a need exists to study its integration with diverse passive cooling methodologies, like natural ventilation, to augment its efficacy. Such amalgamation holds promising potential for delivering both cooling and ventilation within a sustainable framework.
2. Despite the extensive recognition of PCM's efficacy in cooling applications within numerous studies, limited attention has been directed towards the economic dimensions. Convincing the market of the financial returns associated with the initial investment is crucial to fostering broader adoption.
3. Organic PCMs are encumbered by the drawback of flammability, significantly impeding their practical utility. To address this issue, future investigations should explore the utilization of composite PCMs.
4. In tropical climates, where high humidity levels often accompany elevated temperatures, managing thermal comfort becomes a multifaceted challenge. While conventional cooling systems primarily focus on temperature control, addressing humidity is equally crucial for ensuring occupant comfort and well-being. By leveraging the humidity-regulating properties of PCMs, researchers can develop innovative building solutions that offer comprehensive thermal comfort in tropical climates, addressing both temperature and humidity concerns to create healthier and more livable indoor environments.
5. Passive cooling techniques offer sustainable and energy-efficient solutions for maintaining comfortable indoor environments, particularly in buildings. However, their effectiveness is often contingent upon external climatic conditions, such as temperature and humidity levels. This reliance on ambient factors can sometimes limit their efficacy, especially during extreme weather conditions or in regions with highly variable climates. Thus,

exploring the integration of these techniques with active conventional cooling systems could emerge as a crucial area for future research endeavors.

6. Comprehensive investigations are warranted to explore a range of configurations involving void formers and varying thicknesses of PCM. These studies would entail conducting experiments or simulations on a larger scale, encompassing a broader spectrum of parameters such as different types and arrangements of void formers, as well as varying thicknesses of the PCM layer itself. This approach would enable a more thorough understanding of how different configurations influence the behavior and efficiency of PCM integration within various applications, facilitating the development of optimized designs tailored to specific practical requirements and constraints.
7. Considering that the thermophysical properties of PCM alter with temperature and that heat transfer within the specimen encompasses both conduction and convection, it becomes essential to incorporate these factors into analyses of heat transfer phenomena. This entails evaluating the temperature-dependent properties of the PCM, such as its specific heat capacity, thermal conductivity, and density, across the entire range of operating temperatures. Additionally, accounting for convective heat transfer involves understanding the fluid dynamics within the PCM, particularly how buoyancy-driven convection affects heat transfer rates.
8. The high values of time lag factors observed in the experiment are due to the low thermal conductivity of the PCM; hence, extensive research on the integration of nanomaterials to improve the thermal conductivity of PCMs is recommended. Nanomaterials possess unique thermal properties and can significantly enhance the thermal conductivity of PCM matrices. This approach has the potential to revolutionize the design and implementation of TES systems, leading to more efficient and sustainable building technologies.
9. Thermal performance of the PCM integrated biaxial voided slab is evaluated for roof purposes, but it can also be assessed for ceiling applications. Ceilings play a crucial role in the thermal comfort and energy efficiency of buildings by insulating the indoor space from external temperature fluctuations. By integrating PCM into ceiling structures, similar benefits to those achieved in roofs can be realized.

List of Publications from Thesis

Journal

1. P.J. Abass, S. Muthulingam, Selection and thermophysical assessment of phase change materials (PCMs) for space cooling applications in buildings, Numer. Heat Transf. Part A Appl. (n.d.) 1–23. <https://doi.org/10.1080/10407782.2023.2292183>.
2. P.J. Abass, S. Muthulingam, Thermal energy storage performance of biaxial voided RCC roof slab integrated with macroencapsulated PCM for passive cooling of buildings, J. Energy Storage 88 (2024) 111478. <https://doi.org/https://doi.org/10.1016/j.est.2024.111478>.
3. P. Jaffar Abass, S. Muthulingam, Comprehensive assessment of PCM integrated roof for passive building design: A study in energo-economics, Energy Build. 317 (2024) 114387. <https://doi.org/https://doi.org/10.1016/j.enbuild.2024.114387>.
4. P.J. Abass, S. Muthulingam, Optimizing energy Efficiency of a novel roof slab with Phase Change Materials in severe Hot Climates: An experimental study, Journal of Thermal Science – Revision submitted.
5. P.J. Abass, S. Muthulingam, Thermal Performance of Concrete Roof Integrated with Macroencapsulated Nano-Enhanced PCM: An Experimental Study Under Hot Climate, Energy and Buildings – under review.
6. P.J. Abass, S. Muthulingam, Evaluation of Melting Front Kinetics in cylindrical Phase Change Materials Module Using Infrared Thermography and Digital Imaging, Material Letters- under review.
7. P.J. Abass, S. Muthulingam, Incorporation of Phase Change Materials into Building Materials and Envelopes for Thermal Comfort and Energy Optimization: A Comprehensive Review, Building and Environment– Submitted.

Conference Proceeding

1. P.J. Abass, S. Muthulingam, Experimental Investigation of a PCM-Enhanced Building Envelope Towards Energy Savings and Mitigation of Carbon Emissions During Hot Climates, International Conference on Applied Mathematics and Mechanics (ICAMM 2023), IIT Indore, 18 – 20 October, 2023.
2. P.J. Abass, S. Muthulingam, “Experimental Evaluation of the Energy and Economic Performance of PCM-Integrated Hollow Slabs in A Severely Hot Climate”, the International Conference on Condition Assessment, Rehabilitation & Retrofitting of Structures (CARRS 2023), Hyderabad, India, IIT Hyderabad, 10th – 13th December 2023.
3. P.J. Abass, S. Muthulingam, “Prioritizing phase change materials for thermal energy storage in building applications”, International Conference on Recent Trends in Energy Science and Engineering (ICRTESE 2021), Rajiv Gandhi Institute of Petroleum Technology (RGIT),

Amethi, 26 – 28 October 2021.

Awards

1. YOUNG SCIENTIST AWARD: The paper (Prioritizing phase change materials for thermal energy storage in building applications), was nominated for Young Scientist Award (YSA), by the International Academy of Physical Sciences (IAPS). It was presented at the International Conference on Recent Trends in Energy Science and Engineering (ICRTESE 2021) as a part of CONIAPS XXVII, held at Rajiv Gandhi Institute of Petroleum Technology (RGIPT), Amethi, from October 26 to 28, 2021.

Chapter 9

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- 2021 *Global Status Report for Buildings and Construction* | Globalabc. (n.d.-b). Retrieved May 11, 2024, from <https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction>
- 2022 *Global Status Report for Buildings and Construction* | UNEP - UN Environment Programme. (n.d.). Retrieved July 2, 2023, from <https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction>
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