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Review

A Review of Recent Improvements, Developments, and Effects of Using Phase-Change Materials in Buildings to Store Thermal Energy

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Abstract: When it comes to guaranteeing appropriate performance for buildings in terms of energy efficiency, the building envelope is a crucial component that must be presented. When a substance goes through a phase transition and either gives out or absorbs an amount of energy to provide useful heat or cooling, it is called a phase-change material, or PCM for short. Transitions often take place between the matter's solid and liquid states. Buildings use PCMs for a variety of purposes, including thermal comfort, energy conservation, managing the temperature of building materials, reducing cooling/heating loads, efficiency, and thermal load shifting. Improved solutions are applied using new method and approach investigations. Undoubtedly, researching and applying PCM use in building applications can help create buildings that are more energy-efficient and environmentally friendly, while also increasing thermal comfort and consuming less energy. It provides a possible answer to the problems posed by climate change, rising energy demand in the built environment, and energy use optimisation. However, it is true that no particular research has yet been conducted to thoroughly analyse the linked PCM applications in the building industry. Thus, the principal tactics are addressed in this paper to determine current and efficient methods for employing PCMs in buildings to store thermal energy. By gathering around 50 instances from the open literature, this study conducts a thorough assessment of the up-to-date studies between 2016 and 2023 that used PCMs as thermal energy storage in building applications. As a result, this review aims to critically evaluate the PCM integration in buildings for thermal energy storage, identify a number of issues that require more research, and draw some important conclusions from the body of literature. Specifically, the building envelope roof and external wall uses of PCMs are highlighted in this research. Applications, general and desired characteristics, and PCM types and their thermal behaviour are described. In comparison to a traditional heat storage tank that simply contains water, this review indicates that a water storage tank containing 15% PCM improves heat storage by 70%. Also, less than 7 °C of internal air temperature was reduced by the PCMs in the walls, which avoided summer warming. Finally, using PCM for space cooling resulted in substantial energy savings across the various seasons.

Keywords: PCMs; thermal comfort; energy savings; cooling/heating load reduction; thermal load shaving and shifting

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1. Introduction

About 40% of the world's annual total energy consumption, of which more than 27% is attributed to household energy consumption, is accounted for by the construction and building industry [1–4]. Moreover, a significant contributor to global carbon emissions is the construction industry [5,6]. Due to the rising demand for thermal comfort in buildings, space heating and cooling account for more than 38% of the energy used in residential structures [7]. Particularly high-rise residences frequently have significant problems with energy efficiency. Indoor thermal discomfort brought on by everyday temperature changes and vertical temperature gradients is one of the most frequent reasons. In order to maintain comfortable living conditions, thermal discomfort raises the energy requirements for air conditioning and indicates a greater dependence on mechanical systems [8]. Also, because of its height and orientation, has apartments have a considerable exterior effect. With regard to the heat gain brought on by solar radiation entering the structure, the building's tilt is particularly important [9]. As a result of the apartment's different heat-acquisition elements from the outside climate, which vary depending on the building's height and orientation, attempts at achieving energy savings for apartments are necessary to lower the energy consumption for heating and cooling.

Due to their ability to store significant amounts of heating or cooling during the phase-change process through the use of latent heat storage, PCMs have emerged as a crucial component of the solution to the energy problem facing buildings [10–12]. Specifically, PCMs are a type of thermal energy storage material that can be used in buildings to store and release heat. PCMs can absorb and release large amounts of thermal energy during a phase change from solid to liquid or liquid to gas. Thus, PCMs with high latent heat and great thermal conductivity are needed for thermal energy storage. They need to have a melting temperature that is within a suitable operating range, and be inexpensive, non-toxic, and non-corrosive. Scientists have concentrated on a wide range of materials during the past 40 years, including salt hydrates, paraffin waxes, fatty acids, and eutectics mixtures of organic and inorganic compounds. Specifically, those are the most well-known types of PCMs [13]. For instance, paraffin-based PCMs are characterised by their low toxicity, non-corrosiveness, and chemical stability. They exhibit a narrow melting temperature range, which allows for precise thermal energy storage and release. Paraffin-based PCMs find applications in building materials, thermal energy storage systems, textiles, and electronics cooling [14]. Furthermore, salt hydrates have a high latent heat storage capacity and a wide range of melting temperatures, and therefore offer high thermal conductivity and chemical stability. Salt hydrate PCMs are used in applications such as solar energy storage, building climate control, and thermal management in electronics [15]. In this aspect, organic and inorganic PCMs are widely used in several applications such as building insulation, refrigeration systems, textile fabrics for thermal regulation, and thermal storage for concentrated solar power, waste heat recovery, and high-temperature thermal management, respectively [16].

In buildings, PCMs can be integrated into walls, ceilings, or floors to regulate indoor temperature and reduce heating and cooling loads. The three most popular methods for adding PCMs to building materials today are impregnation, direct addition, and encapsulation. When used as construction materials with a microporous structure, the impregnation technology stores molten PCMs via the capillary force of micro-pores and prevents the liquid phase-change material from exhibiting fluidity during the solid–liquid phase transition processes (such as porous concrete, gypsum board, expanded clay, and brick) [17]. During the day, when outdoor temperatures are high, PCMs can absorb heat and store it as latent heat. At night, when temperatures are cooler, PCMs can release the stored heat to maintain comfortable indoor temperatures. In other words, the use of PCMs in building construction could successfully minimise summertime overheating, lower interior air temperatures, and decrease roof heat flux [18].

PCMs have a number of benefits over conventional heating and cooling systems. These could lessen the need for power-hungry air conditioning and heating systems, resulting in lower energy costs and a reduction in carbon emissions. Additionally, PCMs can provide a more stable indoor temperature and reduce temperature fluctuations, improving thermal comfort for building occupants. PCMs come in a variety of forms, including those made of organic, inorganic, and eutectic materials. Each variety has special characteristics and uses of its own. The location, climate, and energy requirements of the structure all play a role in the choice of PCM [19].

Researchers have looked into PCMs as an energy-saving material for buildings and the method of incorporating PCMs into building materials over the past 20 years [20,21]. The insertion of PCMs into building materials is an intriguing technique to address the concern of energy consumption; the optimum approach is to include PCMs in blocks made of concrete, stone, or wood [22,23]. Investigations were also conducted on the alteration of thermal performance and the alteration of PCM shapes that were applied to concrete blocks. A room made using PCMs had a thermal conductivity (K-value) drop of around 17% and used less energy than an air-conditioned room [24]. Because of their uniform distribution, spherical PCMs melted in the quickest amount of time. Considerable experience in providing building services, or large rectangular concrete hollow bricks (CHBs), are used in construction. Indeed, services provided by buildings are impacted by the usage of hollow bricks in construction. Hollow bricks have holes or cavities that can be used to install HVAC (heating, ventilation, and air conditioning) systems, plumbing lines, and electrical cabling. The insulating qualities of hollow bricks also enhance the energy efficiency, which influences the layout and functionality of HVAC systems. The integration of these services into the structural components of the structure is what ultimately connects building services to hollow brick construction [25].

Concrete is used in the CHBs' construction. Such CHBs have low thermal, acoustic, and electrical resistivity qualities, together with high-density blocks. Due to these drawbacks, developers dislike CHBs as a building material [26]. In this regard, PCMs also have some potential disadvantages that need to be considered, despite their potential for thermal energy storage in buildings. Cost is one concern related to employing PCMs. In addition to being more expensive than conventional insulating materials, PCMs may also require more engineering and construction work to integrate into building structures. The low heat conductivity of PCMs presents another difficulty. Despite their large thermal storage capacity, PCMs might not be able to transmit heat as efficiently as other materials, which could have an impact on the system's overall performance [27]. In terms of their compliance with other building materials, PCMs could also have restrictions. For instance, some PCMs might not work with specific adhesives, sealants, or insulation materials, which could have an impact on the building envelope's overall performance and longevity [28]. Moreover, PCMs could need unique handling and maintenance techniques, especially if they are included in construction materials that need routine upkeep or repair. In extreme temperatures, such as those that are extremely hot or cold, PCMs may not be able to offer sufficient thermal regulation, which could restrict their usefulness [29].

The latest review studies were carried out by Ikutegbe and Farid (2020) [30] and Junaid et al. (2021) [31] who reviewed the perspectives of PCMs in building applications such as thermal energy storage. Ikutegbe and Farid (2020) [30] discussed several interventions in the manufacturing of PCM foam composites, conventional and cutting-edge insulations, and their application concerns are explored in this research along with their potential for use. Junaid et al. (2021) [31] approved the importance of PCMs for the enhancement of energy efficiency and sustainability. The authors focused on inorganic PCMs and discussed challenges in the thermos-physical aspects, including the super-cooling, encapsulation, phase separation, and corrosion issues. Tyagi et al. (2022) [32] concentrated on discussing the thermal stability and dependability of various PCMs, including organic, inorganic, eutectic, and composite materials for heat storage applications. Also, they concentrated on resolving the impact of heat cycle testing on the characteristics of various PCMs. Due to its low values of thermal conductivity, Hassan et al. (2022) [33] discussed the possibility of adding nanoparticles to PCMs in addition to porous metal foams and encapsulation to resolve this concern. Furthermore, the authors stated the importance of realizing the most important parameters of the phase transition temperature, phase transition enthalpy and thermal conductivity before the selection of PCM into a specific field. Thus, it can be said that the associated aspects of utilising PCMs in the building sector, including thermal comfort, energy conservation, and thermal load shifting, have not been evaluated yet in a specific study. Therefore, this review intends to critically assess the PCM integration in buildings to store thermal energy, highlight a number of challenges that need more study, and make some significant conclusions from the existing literature. Specifically, the examination of PCMs in buildings considering thermal comfort, energy conservation, controlling the temperature of building materials, reducing cooling/heating loads, efficiency, and thermal load shifting are outlined. A number of technological, research, and development methodologies related to PCMs are covered in great detail. Future research may be guided by the present study's results since they will make it easier for researchers to comprehend the multiple improvements made to PCM that still need to be made.

2. PCM Studies Utilised in Buildings for Thermal Comfort

The psychological state of satisfaction with a building's thermal environment is referred to as thermal comfort. The degree of comfort felt by inhabitants in connection with the ambient temperature, humidity, air movement, and other environmental elements is a crucial component of building design. For a building to encourage resident contentment, productivity, and general well-being, thermal comfort must be attained. Air temperature, relative humidity, air velocity, and radiant temperature are examples of environmental variables that affect thermal comfort.

PCMs have been widely used to increase the occupancy temperature of the building. The use of mechanical cooling and heating can be decreased by introducing PCMs into building envelopes, which can help control interior temperature variations and create a more stable and comfortable indoor environment. Also, by collecting or releasing body heat as needed, PCMs used in clothing and bedding can improve thermal comfort, boost sleep quality, and use less energy for heating and cooling. Consequently, the incorporation of PCMs into structures can aid in the creation of hygienic, cozy, and energy-efficient indoor environments. This section entails elaborating the specific studies that discussed the utilisation of PCMs in building for thermal comfort. This in turn would include a detailed description of the configuration, studied parameters, and the associated performance indicators.

In a home in Melbourne, Australia, Jamil et al. (2016) [34] studied the potential of PCM as a retrofitting solution to enhance occupant thermal comfort and lower the zone air temperature. In this investigation, both the tests and numerical approaches were used. In the experiment, PCM was put in one of the room's ceilings, and the interior air temperatures of two different rooms—with and without PCM—were measured. Utilising the collected temperature data, a simulation model was created using the building modelling program EnergyPlus. The findings explored that the inactive installation of PCM on the ceilings reduced thermal discomfort hours by 34% and the indoor air temperature in BED 2 by up to 1.1 °C throughout the day (Figure 1). It was shown that the inclusion of PCM reduces thermal discomfort hours more effectively if windows are left open during the night for night purging and interior doors are continually shut to prevent any mixing with nearby zones without PCM.

Figueiredo et al. (2017) [35] reported the results of an investigation on interior thermal comfort and energy effectiveness that focused on the positive impact of PCMs when utilised for innovative, new options. The study was conducted in a building with a geothermal system connected to the air conditioning system (Figure 2). The PCM investigation was considered in a number of studies that were conducted in two rooms of a brand-new academic division on the campus of Aveiro, both real and simulated. An evolutionary algorithm and the simulation-based program EnergyPlus® were employed to carry out the numerical analysis. In order to study the prospective and payback time of these unique solutions, constructive solutions were paired with diverse kinds of PCMs with various enthalpies and melting temperatures, as well as different natural ventilation flow rates. The results of the measurements show that persistent discomfort is brought on by the rooms' interior thermal comfort, specifically overheating. Yet, it was demonstrated that the PCM implication in one of the rooms caused a decrease in overheating by 7.23%, which is equivalent to 35.49% PCM efficiency. Following optimisation, the usage of PCM in one of the rooms resulted in a 34% decrease in overheating, as shown in Figure 3.

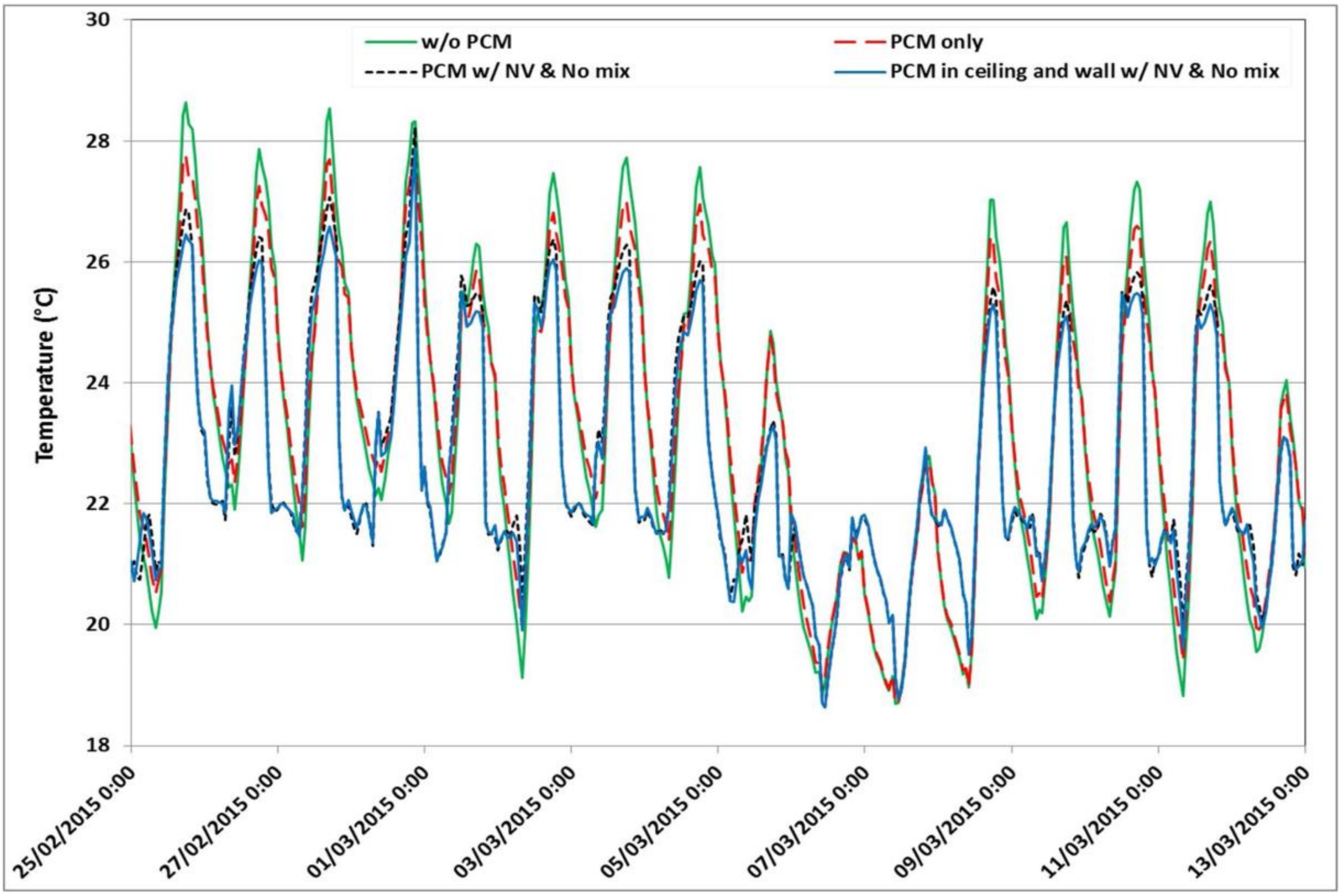


Figure 1. Temperatures in the BED 2 Zone with comparisons between spreading with and without PCM [34].

Table 1. A summary of research on PCMs used in construction for various applications.

1: Associated Studies on PCMs Utilised in Buildings for Thermal Comfort					
Authors (year) [reference]	Configuration	Type of study	Type of PCM	Studied parameters	Findings
Jamil et al. (2016) [34]	PCM was put in one room's ceiling and two rooms with specific indoor air temperatures (one with PCM and the other without PCM).	Experimental and numerical	BioPCM™ of polyfilm-encapsulated fatty-acid-based organic PCM.	Effect of installing PCM in the ceiling.	If windows are left open at night for night purging and interior doors are maintained closed at all times to prevent any mixing with nearby zones without PCM, integrating PCM will be more successful at lowering thermal discomfort hours.

Table 1. *Cont.*

1: Associated Studies on PCMs Utilised in Buildings for Thermal Comfort					
Figueiredo et al. (2017) [35]	Focused on the PCM's beneficial function, indoor thermal comfort and energy efficiency.	Experimental and numerical	BioPCM® M51/Q23.	Impact of PCM in one room.	One of the rooms' overheating was reduced by 7.23% as a result of the PCM application, for a PCM efficiency of 35.49%.
Derradji et al. (2017) [36]	Comparing an office with traditional walls to an office with walls made of phase-change materials (PCMs).	Numerical	PCMs of type 204.	Impact of the presence of the PCM in the walls.	PCMs in the walls prevented summertime overheating and lowered the internal air temperature by 7 °C.
Alizadeh and Sadrameli (2019) [37]	In a building with a ceiling fan-assisted ventilation system, PCM helps provide innovative solutions.	Experimental and numerical	Commercial available PCM S27.	Effect of applying PCM inside a building.	The trials revealed that the suggested hybrid system may, on average, lower discomfort level by around 2.61% over the course of two months of winter, which corresponds to a PCM efficiency of about 35.49%.
Adilkhanova et al. (2020) [38]	PCM and natural ventilation may improve thermal comfort in lightweight relocatable buildings.	Experimental and numerical	PCM 26, 28, 30, and 32.	The potential of PCM.	The greatest performance was shown by PCM 26 + NV, which had a storage efficiency of more than 39.1% and TDC values up to 1818.
Qu et al. (2021) [39]	PCM-integrated building envelopes.	Numerical	BioPCMTM23.	Integrating the PCM into the envelope.	The variation in interior temperature may be efficiently decreased by integrating the PCM into the envelope.
Zhu et al. (2021) [40]	MPCMs with n-octadecane.	Experimental	N-octadecane, MPCM.	Impact of using MPCMs with n-octadecane.	Only 13 min may be spent maintaining this temperature in the chamber without PCM covering.
Rangel et al. (2022) [41]	Roofs in semi-arid climates when paired with natural ventilation and phase-change material (PCM).	Experimental	Not defined.	Impact of PCM and natural ventilation.	The PCM setup with a 30 cm air gap and no natural ventilation had the greatest results, lowering the interior air's maximum temperature of 2.5 °C, decreasing the cooling load by 6.85%, and extending thermal comfort by 50 min.

Table 1. *Cont.*

1: Associated Studies on PCMs Utilised in Buildings for Thermal Comfort					
Ye et al. (2022) [42]	Combined effect of PCM and ventilation.	Experimental and numerical	Composite phase-change materials.	Important aspects such as thickness, phase-change temperature, ventilation, building orientation, and climatic region influence the thermal properties of PTHs.	The 1st level of thermal comfort hours of the PCM rooms were more than those of the reference room when the overall thickness of the wall remained unchanged. The PTH in Guangzhou had a substantial upgrading in thermal comfort hours and a decrease in energy consumption. However, the PTH in Kunming showed a decrease in thermal comfort hours with higher ventilation rates.
Al-Yasiri and Szabó (2022) [43]	PCM-enhanced thermally poor building envelope.	Experimental	Not defined.	The benefit of using PCM.	In comparison to the reference room, the PCM room exhibits thermal comfort improvements of 11.2% and 34.8%, based on the DHR and MHGR, respectively.
Nateghi and Jahangir (2022) [44]	Three versions of a home in EnergyPlus: one without SC, one with SC, and one with SC plus a layer of phase-change material (PCM).	Numerical	Not defined.	Impact of PCM in SC in a house of three different modes.	In hot-arid climates, incorporation of PCM into solar chimneys leads to displeasure in both SC operating modes (ventilation and heating).
Li et al. (2022) [45]	A PCM-integrated Trombe wall system.	Numerical	Not defined.	Impact of PCM in Trombe wall.	The PCMs were successful in completing the phase transition procedure thanks to the Trombe wall.
Hu et al. (2023) [46]	Healthcare professionals may wear clothing made of phase-change material (PCM-CC).	Experimental	PCM-CC.	Effect of PCM_CC.	In the 26 °C thermal condition, wearing PCM-CC decreased discomfort in the head and face by 25% and 41%, respectively.
Christen et al. (2023) [47]	Concrete that was 3D printed uses reclaimed brick aggregate with PCM included in it (3DPC).	Experimental	Not defined.	Effect of using PCM.	The efficacy of the PCM in the PCM-3DPC façade portion after five months of exposure to outside ambient spring and summer circumstances shows that there has been little PCM leakage.

Table 1. *Cont.*

1: Associated Studies on PCMs Utilised in Buildings for Thermal Comfort					
Sawadogo et al. (2023) [48]	Natural fibers are used as PCM support materials for shape-stabilised applications in structures.	Experimental	PCM of economic shape-stabilised composites.	Impact of using composite in a building application.	Latent heat greater than 50 J g^{-1} was found in almost all of the developed composites, which is extremely encouraging for applications that involve energy storage in buildings.
2: Associated Studies on PCMs Utilised in Buildings for Energy Storage					
Authors (year) [reference]	Configuration	Type of study	Type of PCM	Studied parameters	Findings
Stropnik et al. (2019) [49]	PCM-filled thermal energy storage device with integrated modules.	Experimental	PCM RT 28 HC.	Impact of using PCM in the thermal energy storage unit.	Longer-lasting water temperature may be provided using a thermal energy storage device with joined modules loaded with PCM.
Park et al. (2021) [50]	Retrofit systems with phase-change materials.	Experimental and numerical	n-octadecane and n-heptadecane in a ratio of 7:3.	Impact of using PCMs.	The flat-type flats with a southerly orientation and a westward orientation, respectively, seemed to be adequate for PCMs of 20 °C and 26 °C.
Heniegal et al. (2021) [51]	Using concrete hollow blocks (CHBs) and paraffin wax as PCMs and pumice fine aggregates (PUs), the walls and ceilings are constructed (CILs).	Experimental	Paraffin wax.	Impact of using paraffin wax and pumice fine aggregates (PUs) with concrete hollow blocks (CHBs).	The findings for the room indicate a 5.75 °C drop in the room's interior temperature.
Yousefi et al. (2021) [52]	To create a form-stable PCM composite, recycled expanded glass aggregate (EGA) was used as the PCM carrier.	Experimental	(PCM) composite using recycled expanded glass.	Using EGA-PCM composite.	According to the thermal performance evaluations, utilizing EGA-PCM composites may drastically lower the cement mortar's heat transfer rate by up to 47%.
Cruz-Elvira et al. (2022) [53]	Thermophysical characteristics of a new composite PCM manufactured by vacuum impregnation and constructed from dodecanol/ tepexil.	Numerical	Dodecanol/tepexil PCM composite.	Impact of PCM composite dodecanol/ tepexil.	The PCM composite dodecanol/tepexil material might be regarded as an effective prospective material with the possibility of energy storage in building facilities owing to its great energy storage performance and thermal/chemical stability.

Table 1. *Cont.*

2: Associated Studies on PCMs Utilised in Buildings for Energy Storage					
Wang et al. (2022) [54]	A three-story office building has a solar energy and electric heat storage system installed.	Experimental and numerical	PCM tepexil/dodecanol composite.	Grouping of electric heat storage and solar energy.	Based on solar energy forecasting, there is a large application potential for combining solar energy with electric heat storage for distributed building heating.
Cárdenas-Ramírez et al. (2022) [55]	SS-PCM is based on capric-myristic (CA/MA), lauric–myristic (LA/MA), and palmitic–stearic (PA/SA) eutectic fatty acid combinations.	Experimental	SS-PCM based on eutectic fatty acid mixes of capric–myristic, palmitic–stearic and lauric–myristic.	Impact of SS-PCM-based acrylic plaster in building envelopes.	Thermal lag was enhanced by 67.26%, the deterioration factor was dropped by 9%, and the interior temperature was reduced by 20.8% in building envelopes with fiber cement siding and an acrylic plaster covering created with SS-PCM.
Hekimoğlu et al. (2022) [56]	The attapulgite clay (ATC) was then added to the eutectic mixture to create the shape-stabilised composite.	Experimental	Attapulgite/myristic-palmitic acid composite PCM.	Impact of ATC/MPEM composite.	The created ATC/MPEM composite has great potential as a revolutionary admixture material with TES capacity that may be used to enhance interior thermal comfort in buildings while minimising energy consumption.
Halder et al. (2022) [57]	A new PCM microcapsule with a dopamine coating derived from biological sources and the cenosphere serving as its protective shell.	Experimental	PCM microcapsule uses the cenosphere.	Impact of a novel PCM microcapsule.	A brand-new PCM microcapsule that not only increases the mortar's compressive strength but also combines latent heat storage capacity, something that no previous PCM microcapsules have been able to do.
Sun et al. (2022) [58]	Cation exchange and layer-by-layer self-assembly were used to construct the novel shell-core PCM (E-shell PCM).	Experimental	Core–shell structural expanded perlite/polyethylene glycol composite PCM.	Impact of using a shell-core PCM (E-shell PCM).	The crystallisation and melting enthalpies reach and 74.61 J/g and 76.06 J/g, respectively, when the latent heat of the TES WPC phase transition constantly increases with the rising E-Shell PCM.
3: Associated Studies on PCMs Utilised in Buildings for Material Temperature Management					
Authors (year) [reference]	Configuration	Type of Study	Type of PCM	Studied parameters	Findings
Pandey et al. (2020) [59]	PCM-integrated built environment.	Experimental	Not defined.	Impact of using PCM.	In comparison to PCM used passively, PCM with active usage and induced convection are more effective.

Table 1. *Cont.*

3: Associated Studies on PCMs Utilised in Buildings for Material Temperature Management					
Kishore et al. (2021) [60]	PCM-integrated lightweight building walls.	Analytical	PCM 10, 25, 50, and 100.	Impact of optimised PCM.	The adjusted PCM may entirely reverse the wall's transient heat gain curve, reducing wall-related heat gain by up to 70% during peak hours without significantly increasing cumulative heat gain.
Rai (2021) [61]	PCM-integrated brick masonry walls.	Experimental	PCM (RT from Rubirherm).	The benefit of PCM integrated with brick masonry walls.	The PCM must be installed on the inside of the wall with enough insulation to protect it from the elements, and its melting temperature must be near to the set-point temperature within the building.
Koželj et al. (2021) [62]	PCMs as thermal storage in traditional water tank storage.	Experimental	Not defined.	Effect of using PCM inside the water storage tank.	In comparison to traditional heat storage tanks with just water within, 15% of the PCM inside the water storage tank enhances heat storage by 70%.
Guo and Zhang (2021) [63]	PCM wallboard is subjected to realistic sessional weather conditions and solar radiation while accounting for various melting point values (22, 24 and 26 °C).	Analytical	Not defined.	The benefit of PCM wallboard under realistic sessional weather.	More than 5% of energy loss is reported with the detrimental influence of the PCM layer.
Boobalakrishnan et al. (2021) [64]	The first example (plain roof) included no PCM in the roof at all, and the next case (PCM with encapsulated paraffin in the roof) (PCM roof).	Experimental	Paraffin wax.	Using PCM in the roof.	PCM lowered peak interior temperature by 9.5 °C and average indoor temperature by 5 °C.
Mahdi et al. (2021) [65]	Multiple PCMs of different melting temperatures.	Numerical	PCM (RT-26, RT-35, RT-42).	The use of multiple PCMs.	Several PCMs in the suggested design may increase PCM melting time by 18% and PV thermal-management duration by 33%.
Zhu et al. (2021) [66]	Optimised PCM Trombe.	Numerical	PCM Trombe.	The benefit of optimised PCM Trombe.	Optimised PCM Trombe lowered yearly building load by 13.52% compared to the reference Trombe wall.

Table 1. *Cont.*

3: Associated Studies on PCMs Utilised in Buildings for Material Temperature Management					
Yang et al. (2021) [67]	PCMs with integrated passive radiative cooling and energy storage.	Experimental	Flexible composite PCM.	Impact of PCMs.	Buildings' and electrical devices' temperatures may be lowered by 5.5 and 9.3 °C, respectively.
Alghamdi et al. (2022) [68]	PCM in a building.	Experimental	Not defined.	The PCM is inside the wall.	The PCM within the wall reduced power use from January to June but slightly increased it in the following months.
4: Associated Studies on PCMs Utilised in Buildings for Cooling and Heating Load Reduction					
Authors (year) [reference]	Configuration	Type of Study	Type of PCM	Studied parameters	Findings
Gholamibozanjani and Farid (2020) [69]	Active PCM storage system in buildings.	Experimental	Commercial macroencapsulated PCM–RT25HC.	Impact of using PCM.	Also, the adoption of PCM for space cooling resulted in total energy savings of 10% in January and 30% in March/April.
Cao et al. (2022) [70]	Building heating and cooling PCMB-PHC energy storage.	Experimental	PCMB-PHC energy pile.	The effects of different PCMB properties on heat extraction and injection performances of PCMB-PHC energy pile.	The PCMB thermal conductivity represents the largest element affecting the heat extraction and injection abilities of the PCMB-PHC energy pile during heating and cooling modes, followed by the PCMB melting temperature and latent heat.
Kitagawa et al. (2022) [71]	Structures with natural ventilation and phase-change materials installed (PCMs).	Numerical	Not defined.	Impact of PCM and ventilation.	With the existing hot and humid circumstances, a PCM thickness of 6 mm and overnight ventilation are the ideal parameters for the radiant floor cooling system.
Hai et al. (2022) [72]	In two different situations, PCMs of Pure Temp 23, 25, 27, and 29 were incorporated into the structure.	Numerical	PCMs of Pure Temp 23, 25, 27, and 29.	Impact of using PCMs.	The MASS portion underwent heat recovery, and it has been shown that this scheme, with a decrease of 2.77 kWh/m^2, may be helpful for this area of the structure.
5: Associated Studies on PCMs Utilised in Buildings for Enhanced Thermal and Energy Efficiency					
Authors (year) [reference]	Configuration	Type of Study	Type of PCM	Studied parameters	Findings
Sovetova at al. (2019) [73]	Residential buildings with PCM integration may be found in eight different cities.	Experimental	PCM 20–32.	Effect of using PCM in the residual building.	The max. temperature decreased by up to 2.04 °C because of the best PCMs' ability to lessen temperature swings.

Table 1. *Cont.*

5: Associated Studies on PCMs Utilised in Buildings for Enhanced Thermal and Energy Efficiency					
Bolteya et al. (2020) [74]	Phase-change material (RT28HC) glazed unit.	Experimental and numerical	PCM (RT28HC).	The effect of PCM thicknesses.	Raising the PCM thickness may successfully enhance thermal performance characteristics until a thickness of 30 mm, and greater thickness can inverse the variance trend.
Jangeldinov et al. (2020) [75]	Phase transition materials that work well for eight different cities.	Numerical	PCM 24–26.	The benefit of applying PCM.	As the surface area of the ideal PCM was increased and the thickness was decreased, the efficiency of the PCM improved for a constant volume.
Kumar et al. (2020) [76]	With and without PCM wall integration.	Numerical	PCM (HS 29).	Impact of integrating PCM into building walls.	The positioning of the PCM layer is one of the most important factors in lowering heat build-up in the building wall before it enters the space.
Frigione et al. (2019) [77]	Using a PCM that is environmentally friendly and based on aerial lime.	Experimental	PCM (PEG 1000).	Impact of the addition of aggregates.	These aggregates cause an inappropriate drop in mechanical characteristics when added to mortar formulations.
Mohseni and Tang (2021) [78]	Concrete containing PCM.	Numerical	PCM 19–29.	Impact of using PCM.	According to the environmental study, installing 10 mm thick PCM on a structure with a 50-year lifespan would result in a total CO_2 emission reduction of around 264 tone.
Kalbasi et al. (2023) [79]	Three cases: the first (no PCM), the second (phase transition but no PCM), and the third building (with phase transition).	Experimental	Not defined.	Impact of using PCM.	It was discovered that the installation of the PCM close to the topmost layer increased energy savings by 3.72 kWh/m^2.
6: Associated Studies on PCMs Utilised in Thermal Load Shaving and Shifting					
Authors (year) [reference]	Configuration	Type of Study	Type of PCM	Studied parameters	Findings
Mohammed et al. (2020) [80]	Compare the performance of identical materials after amalgamation to that of unamalgamated materials.	Experimental	Paraffin wax.	Benefits of using amalgam and amalgamated materials.	Wood shavings are substantially less expensive than PCMs; therefore, there might be a cost decrease.
Gholamibozanjani and Farid (2020) [81]	Peak load shifting using active PCM storage and a price-based control.	Experimental	PCM-RT25HC.	Impact of applying PCM.	A PCM with a melting point of 23 °C might be used for cooling and heating purposes.

Table 1. *Cont.*

6: Associated Studies on PCMs Utilised in Thermal Load Shaving and Shifting					
Riahi et al. (2021) [82]	PCM-based vapour-compression cooling system.	Experimental and numerical	Oleic acid PCM.	Impact of using PCM.	Peak shaving rises from 12.7% to 68.7% for the same increment in PCM volume.

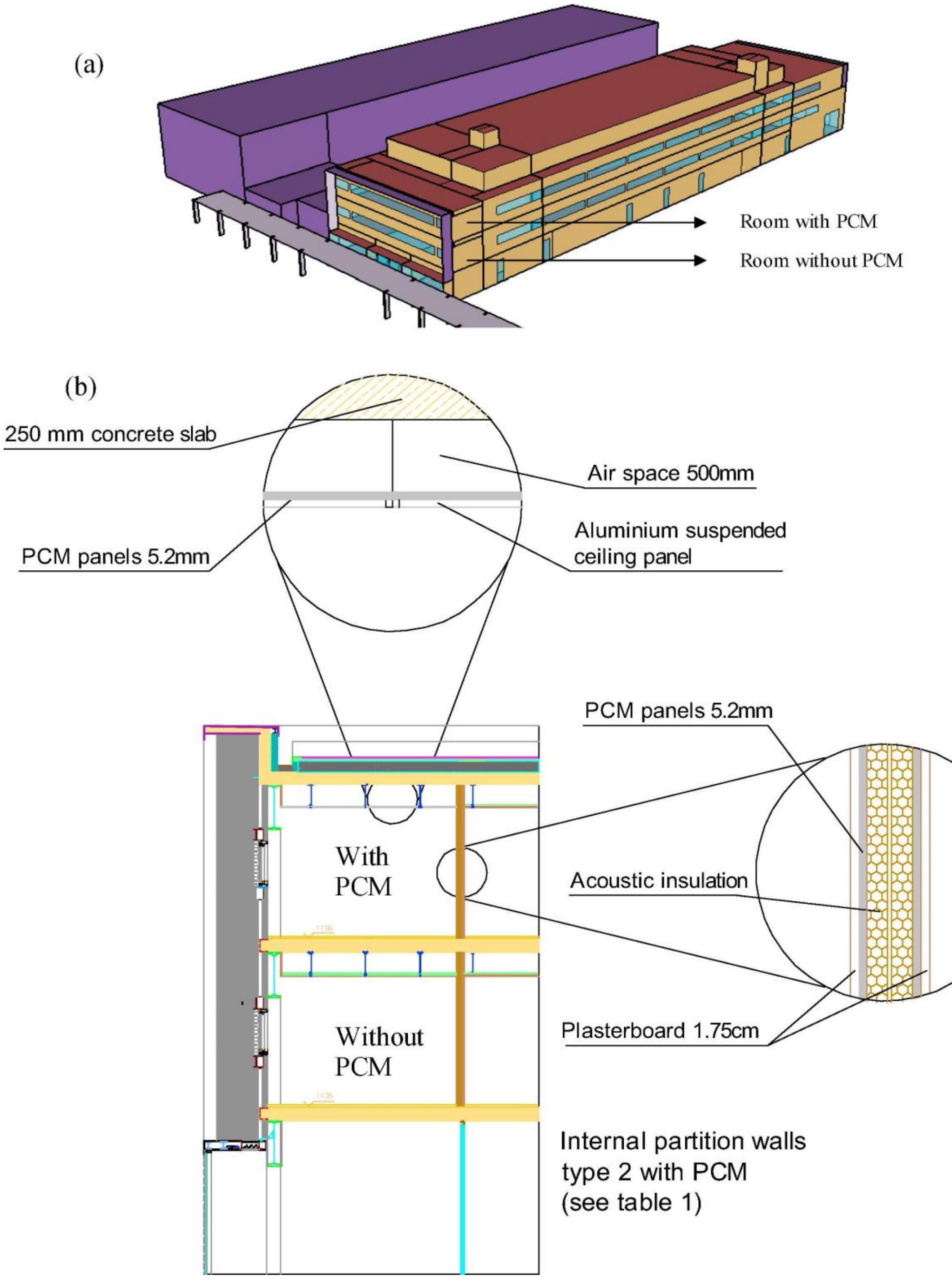


Figure 2. Presentation of the observed rooms and suggestions for improvement: (**a**) a room with and without and PCM; (**b**) an example of a suspended ceiling solution and a representative piece of the partition wall [35] (see Table 1).

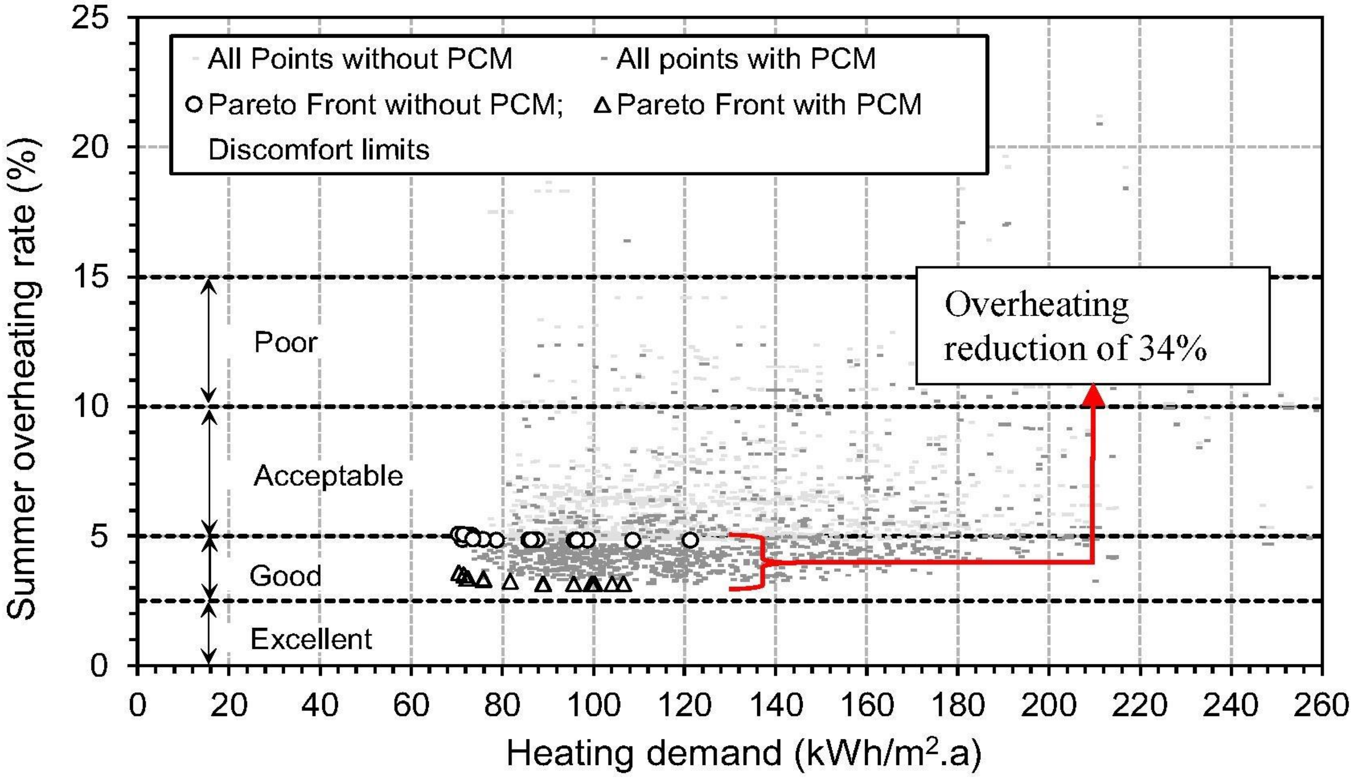


Figure 3. Results that are optimised (distinct overheating for each room and reduced heating requests) [35].

Derradji et al. (2017) [36] used the TRNSYS 17 application to generate a thermal dynamic simulation utilizing type 204 to examine the thermal properties of an office with traditional walls and another office with walls made of PCMs. An Algiers climate simulation was performed on the top floor of an office that was 3.5 m long, 3 m wide, and 3 m high (Algeria). The results showed that the temperature of the office rose between 3 and 4 °C during the winter as a consequence of the installation of PCMs in the concrete ceiling and hollow brick walls. The results also showed that by reducing the interior air temperature to 7 °C, the PCMs in the walls minimised summertime overheating. The office with PCM needs 18 kWh to heat in January as compared to the 33 kWh requirement of the office without PCM, as depicted in Figure 4.

In a building with a ventilation system aided by ceiling fans, Alizadeh and Sadrameli (2019) [37] presented research on indoor energy efficiency and thermal comfort by discussing the PCM's beneficial impact when used in new creative ideas. The goal of the investigation was to assess the probable remedy for preventing overcooling and overheating. Investigations based on the five-level RSM CCD technique were conducted in order to evaluate the prospective impacts of utilising PCM panels and to define the individual effects of factors on the thermal discomfort index, PPD. The findings demonstrate that the lowest rate of discomfort could be attained when the PCM slab height and thickness, humidity and intake air temperature, and fan rotational speed were calibrated to 31 cm, and 2.6 cm, 48%, 29 °C, and 115 rpm, respectively. PPD was at 4.1% under optimal conditions. Then, actual daily temperature profiles for winter and summer were applied to optimised test rooms. In the summer, the trials indicated that the PCM usage in one of the rooms resulted in a 13.83% decrease in overheating, or a 56% PCM efficiency. Figure 5 shows that the peak temperature in Room B is 1.9 °C lower than in Room A. On the other hand, the lowest temperature of the PCM rooms is 0.9 °C greater than the case without a PCM.

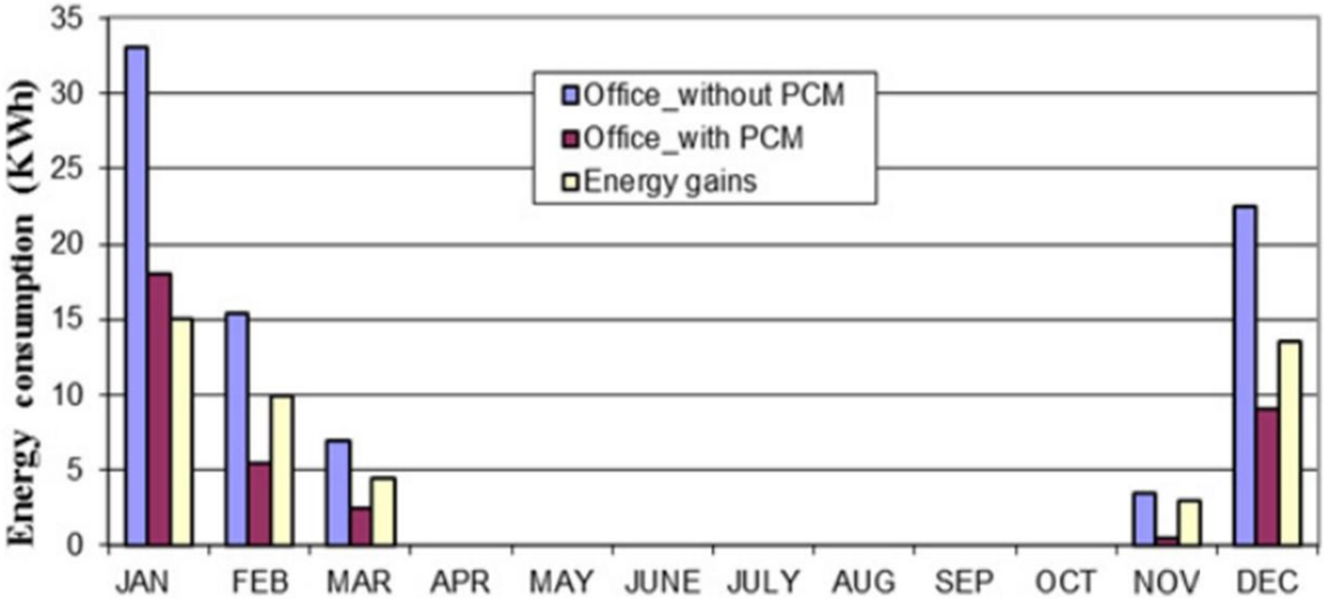


Figure 4. Monthly heating use assessment of the conventional offices and the office using PCMs [36].

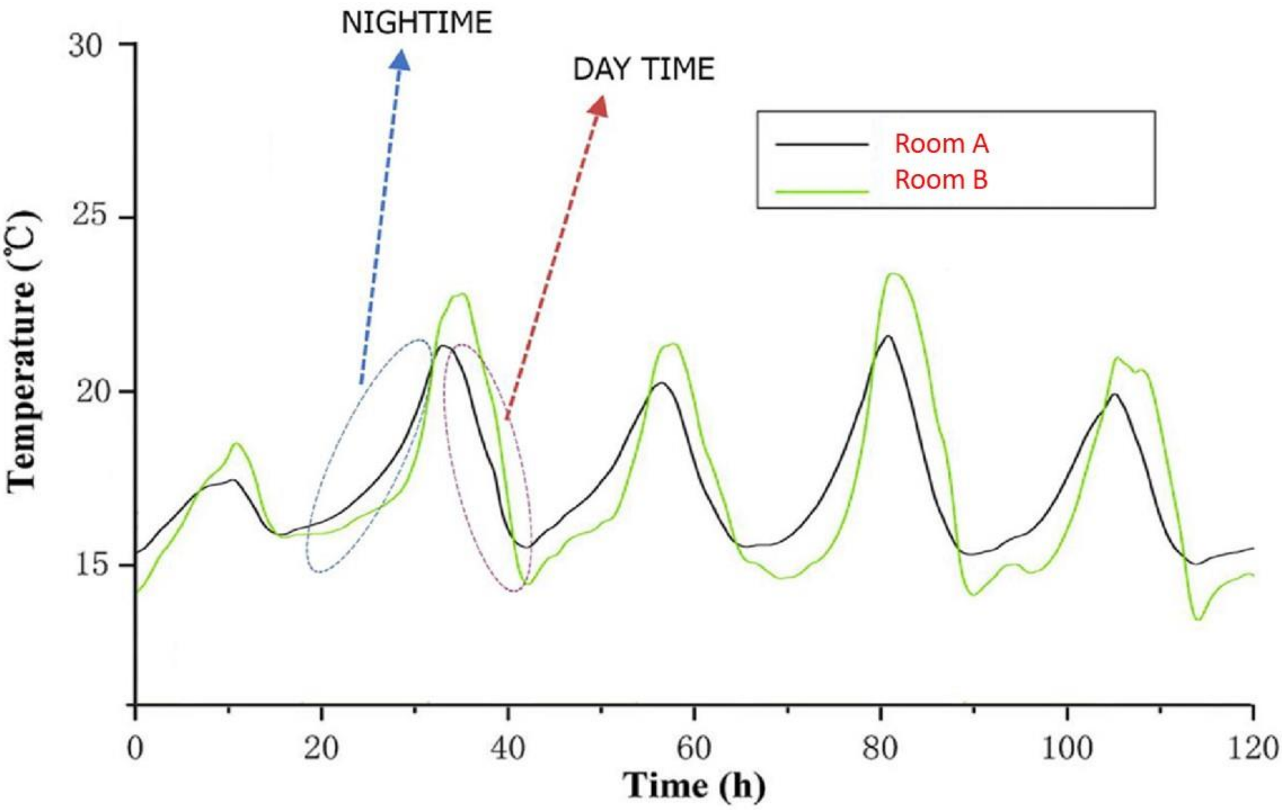


Figure 5. Winter case and temperature comparison between Room A (without PCM) and Room B (with PCM) inside [37].

During the summer, the idea of utilizing natural ventilation and PCM to maintain thermal comfort within a light-weight mobile private residence in Kazakhstan was investigated by Adilkhanova et al. (2020) [38]. The influence of the PCM on thermal comfort was measured by employing the ideas of the greatest operational temperature lessening and discomfort metric. Total Discomfort Change (TDC), a new metric that can be used to select the optimum PCM, was created. Next, the behaviour of the improved PCM was completely assessed via PCM storage performance and activation of the PCM. PCM 26 + NV demonstrated the greatest efficiency across all cities, achieving TDC values up to 1818 and 39.1% of storage performance. The examination of how genuine PCMs affected the thermal comfort conditions was then conducted. According to the analysis, RT 26 + NV was the most effective in all cities, attaining more than the 1977 TDC value. The impacts of climate change under the RCP 8.5 emission case (2095) were also evaluated, and the optimal combinations were found to be RT 28 + NV and RT 26 + NV.

Qu et al. (2021) [39] started a multi-factor orthogonal simulation study to look into the degree to which four important building envelope factors that are combined with PCM affect energy use and interior thermal comfort in the Chinese environment. Four important characteristics related to energy conservation and interior temperature were examined, along with their sensitivity and interactions. The findings revealed the following:

- The four essential components of the PCM envelope may be listed in decreasing order as determined by the degree to which they impact energy use and the period of interior thermal comfort as follows: envelope type is tailed by the PCM layer pattern, kind, and thickness.
- Out of all the options considered, using BioPCMTM23 (PCM2) on the interior side of the wall and the roof with a thickness of °m is the best choice.
- Incorporating the PCM into the envelope may successfully minimise the interior temperature variation. By carefully choosing the PCMs in accordance with the local climatic conditions, a significant energy-saving rate between 4.8 and 34.8% can be obtained. As shown in Figure 6, the effect of a number of parameters on the duration of interior thermal comfort is quite similar to that of the use of power.

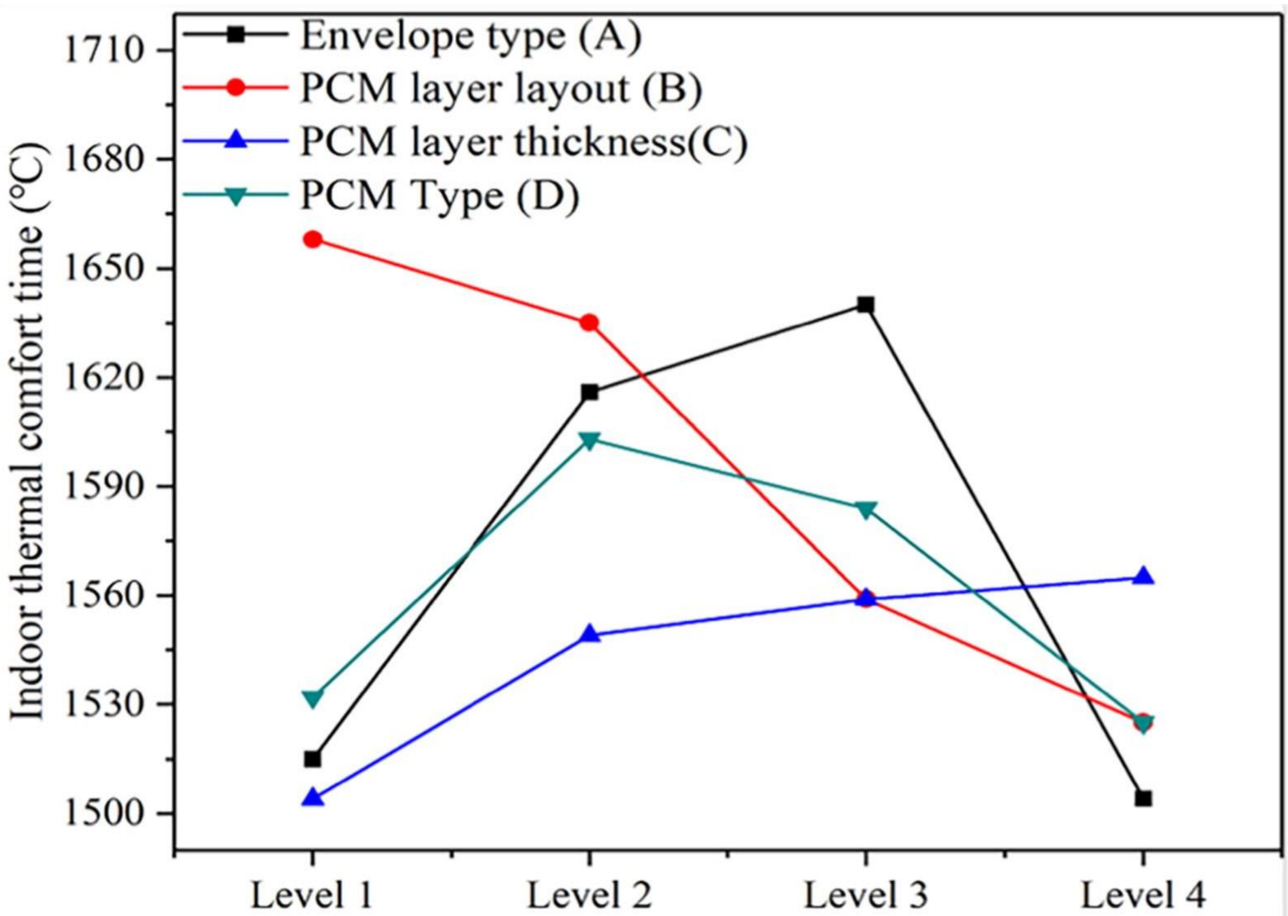


Figure 6. Effects of many parameters on the duration of indoor thermal comfort [39].

Zhu et al. (2021) [40] established a novel heat-storage composite coating employing micro-encapsulated phase-change material (MPCM) to improve the thermal energy storage of the interior walls of an indoor environment. Interface polymerisation was used to create MPCMs using n-octadecane as the core and polyurea as the shell. The latent heat capacities and heat-storage coatings of MPCM were 151.89 J/g, and 45.5 J/g, respectively. Also, the associated parameters of temperature time lag, film-forming and thermal stability performed well. After 200 heating–cooling cycles, MPCM and the heat-storage coatings continued to display remarkable thermal stability. The identical testing procedures were applied to two reduced-scale test chambers that were surrounded by wall boards painted with and without MPCM coatings. When the heating load was 80 W/m^2, the MPCM-coated chamber could preserve a constant temperature of 26 to 28 °C for around 77 min. Nevertheless, the PCM-coated chamber can only sustain this temperature for 13 min.

Rangel et al. (2022) [41] attempted to enhance the thermal efficiency of roofs in semi-arid climatic environments when natural ventilation and PCM are combined. The outcomes included an adaptable assessment of thermal comfort. The effectiveness of the two modules was described as a correlation to the lag time at peak temperature, interior air temperature, heat flow and surface temperature. The authors also evaluated two design cases of a continuous roof and a roof with an air gap, with and without natural ventilation. The findings demonstrated 10 and 70 min as the peak lag time and the greatest reduction in interior air temperature between 3.94% and 7.02%. Similarly, with natural ventilation, a 19–41% increase in PCM's solidification time was observed.

Ye et al. (2022) [42] explored the effects of a number of significant factors on the thermal performance of PTHs, comprising phase-change temperature, thickness, climate area ventilation, and building orientation. The impact of PCMs on the dynamic thermal efficiency of PTHs was measured using the thermal comfort hours and energy use as gauges. the PCM rooms' I-level thermal comfort hours were higher than those of the reference room when the thickness of the wall was left unaltered. The interior I-level thermal comfort hours for walls made of 100 mm insulation boards in the Beijing region were 803 h, whereas those hours increased to 1511 h for walls built of 10 mm PCM panels and 90 mm insulation boards. The best PCMs were nearly the same for each building orientation, but it was important to note that they were distinct for the PTH while considering the two cases with and without air conditioning.

At Al Amarah, an extremely hot city in Iraq, two similar rooms—one filled with PCM and the reference room without PCM—were constructed and evaluated by Al-Yasiri and Szabó (2022) [43]. When constructing the PCM room, the best-performing PCM capsules combined with concrete bricks were taken into account together with previously determined parameters, such as the appropriate location and thickness of the PCM layer in the roof. To demonstrate the potential of PCM, a number of energetic and thermal comfort metrics were ascertained and acknowledged, including the decrement factor, time lag, highest temperature reduction, mean temperature fluctuation reduction, operative temperature difference, maximum heat gain reduction and discomfort hours reduction. Based on the test findings, adding PCM could greatly improve the thermal efficiency of a building envelope that is subjected to elevated outside temperatures.

With SC, without SC, and with SC plus a layer of PCM, Nateghi and Jahangir (2022) [44] built a computer model of a home in three distinct ways. The parameters of thermal comfort for these scenarios have been found for three distinct climates in three cities of Iran: hot and dry, hot and humid, and cold and semi-arid. The findings showed that incorporating PCM in solar chimneys resulted in climatic displeasure in both modes of SC operation (heating and ventilation). Yet, PCM works with SC to provide interior thermal comfort in the selected three distinct climates. The mean thermal comfort metrics for the hot and humid city increase from "0.75" to "0.67" (summer-SC) and from "−0.07" to "0.04" (winter-SC). Also, after adopting PCM, the semi-arid city's PMV index changed from "−1.1" to "−0.85" (winter-SC) and from "1.24" to "1.16" (summer-SC). In all situations, PCM was favourable in the cold semi-arid climate's cooling mode.

The incorporation of PCMs with the Trombe wall system was recommended by Li et al. (2022) [45], which resulted in ten different configurations while considering PCMs and a range of 18 and 28 °C of melting temperature to test the thermal comfort. In this regard, the combined integrated indoor discomfort degree-hour (IDH), indoor discomfort duration (ID), PCM liquid percentage, indoor air temperature, and heat flux across wall indicators were used to estimate the interior thermal comfort in both cold winter and hot summer locations. According to the data, the integration of the Trombe wall has effectively aided the PCMs to attain the phase transition process. With a yearly IDH and ID of 12,974 and 2877 h, respectively, the Trombe wall has the lowest values.

Hu et al. (2023) [46] recommend that healthcare practitioners take nucleic acid samples outside while wearing cooling clothing combined with PCM-CC. Human tests and particular surveys were deployed to analyse the impact of wearing PCM-CC on the thermal sensations of healthcare workers in order to assess the efficacy of PCM-CC in refining thermal comfort due to lowering thermal stress. The outcomes indicated that wearing PCM-CC was helpful in reducing numerous heat feelings connected to wearing PPE in a hot environment. Wearing PCM-CC affected head and facial discomfort by 25% and 41% under the 26 °C thermal environment while enhancing the mean thermal sensation vote (TSV) values by 1.85 and 0.71 under the 32 °C and 26 °C thermal environments, respectively, and putting the mean TSV value near to the acceptable value. The chest experienced the most extreme cooling when wearing PCM-CC, which decreased the mean skin temperatures by 0.65 °C.

Christen et al. (2023) [47] used PCM incorporation in 3D-printed concrete by impregnating aggregate with recovered brick. Two cavity façade sections were 3D printed with two different concrete mix designs as follows:

- Replacing 64% of the natural cumulative in the mix with recycled brick aggregate, and
- Modifying the first design by vacuum-impregnating PCM into the pores of the recycled brick aggregate to create concrete with an overall average latent heat capacity of 7360 J/kg.

These façade components are utilised in four different thermal testing series in Stellenbosch, South Africa. The maximum internal ambient temperatures are decreased by up to 3.9 °C, and it is determined that latent heat storage causes PCM to delay heat transfer through the passive design façade section of PCM and 3D-printed concrete, markedly prolonging the period of time that internal ambient temperatures are within standardised thermal comfort ranges. After five months of exposure to ambient spring and summer conditions outside, the effectiveness of the PCM in the PCM-3DPC façade piece demonstrates that there has been negligible PCM leakage.

Sawadogo et al. (2023) [48] investigated the prospective of natural fibers to support the PCMs for architectural applications utilizing stabilised shapes. Four natural fibers have been chosen as a tentative choice by the material selection algorithm Ansys Granta based on physical, thermal, geographic, and economic characteristics (fir fibers, hemp shives, hemp fibers, and flax mulch). After being soaked with capric and lauric acids, the prospective fibers' contributions are assessed, which allows the selection of the most favourable fiber with the greatest impregnation rate. The hemp shingles that had a strong thermal stability below 150 °C and a maximal LA impregnation rate of about 50% were selected as the support material because they produced the best performance. It was then saturated with five various pure fatty acids and seven eutectic combinations to find the most acceptable composite. Due to their excellent performance, lauric acid hemp shives composites have been chosen as possible future building materials. This is due to considering the thermal demands of elevated latent heat, low under-cooling, and temperature of fusion ranging from 15 to 45 °C.

3. PCM Studies Utilised in Buildings for Energy Storage

Buildings have also used PCMs for energy storage. Buildings can store excess thermal energy during off-peak times and deliver it during peak times when there is a strong demand for heating or cooling by integrating PCMs into thermal energy storage systems. This can lead to substantial energy savings and enhanced building efficiency by lowering energy consumption and peak loads in heating, ventilation, and air conditioning systems. This section explains particular research that covered the use of PCMs for energy storage in buildings. This would then include a detailed explanation of the configuration, the parameters that were examined, and the most important findings.

In order to better integrate the PCM into storage tanks, Stropnik et al. (2019) [49] introduced nearly zero energy buildings (nZEB) and thermal energy storage. The HEART project (HORIZON 2020) developed an energy toolkit to carry out a comprehensive retrofit of residential constructions. This project takes a step toward the self-sufficient cooling and heating of buildings after utilising a wide set of aspects such as thermal energy storage. The residential sector's energy demand may be reduced by constructing structures that require nearly no energy. Experimental research was conducted on PCM-filled cylindrical modules that improve sensible thermal energy storage. The findings of the experiment demonstrate that a thermal energy storage unit with built-in modules loaded with PCM can maintain the correct water temperature for a longer amount of time. Implications that need a restricted temperature range for the delivery and storage of thermal energy benefit from PCM's thermal energy storage capabilities.

Park et al. (2021) [50] looked at the energy efficiency of apartment buildings utilising retrofit systems using PCMs. The installation of a state-of-the-art PCM system is evaluated while considering the kind of apartment, building orientation, and height. The two apartment building designs selected were flat-style and tower-style apartments. The findings reveal a complex relationship between building orientation, height floor, and climatic parameters. For energy-saving objectives, building orientation and height vary based on solar altitude, solar features, solar time, wind speed and direction. The most energy-efficient PCM technology depends on these factors as well. As a result, it was determined that PCMs of 20 °C and 26 °C were appropriate for flat-type flats that faced south and west, respectively. At 23 °C, it has been concluded that these units with a westward and northward direction have elucidated the greatest reduction in energy consumption. However, tower-type apartments with an eastward and southern orientation have exhibited the greatest energy savings at 24 °C with a PCM.

By utilising pumice fine aggregates with concrete hollow blocks (CHBs) and paraffin wax as PCMs with CHBs, Heniegal et al. (2021) [51] investigated ways to reduce the energy consumption of sustainable buildings (CILs). Eight concrete hollow block CHB examples were made using cement mortars. The first category includes four samples, including CHBs, and three mixtures with varied PCM percentages (0%, 50%, and 75%) by volume of sand (Standard; without mortar). The second category, which was made up of three CHB samples with 0%, 50%, and 75% of PCMs by volume of pumice fine aggregates, was made using PU aggregate to identify the influences of pumice fine cumulative and PCM replacement on the thermal characteristics. Pure PCMs were included inside the seventh CHB specimen. The test specimens' thermal characteristics have improved, according to the results. The findings for the room indicate a 5.75 °C drop in the room's interior temperature. According to Figure 7, the peak periods measured for the walls with composite PCMs were typically 2 h earlier than the 6:00 P.M. time period for the typical room with PCMs.

Recycled expanded glass aggregate (EGA) was used by Yousefi et al. (2021) [52] to manufacture form-stable PCM composites (Figure 8). The leakage information from the diffusion-oozing circle test and the EGA's high absorption ratio of 80% both validated the sustainability of the synthesised composite. The results of the thermogravimetric analysis indicated that the composite had a high degree of thermal stability. Moreover, thermal performance analyses revealed that using EGA-PCM could meaningfully decrease the heat transfer rate of the cement mortar by as much as 47%. The EGA-PCM composites are eventually more advantageous from an environmental aspect despite their high cost of production and initial installation.

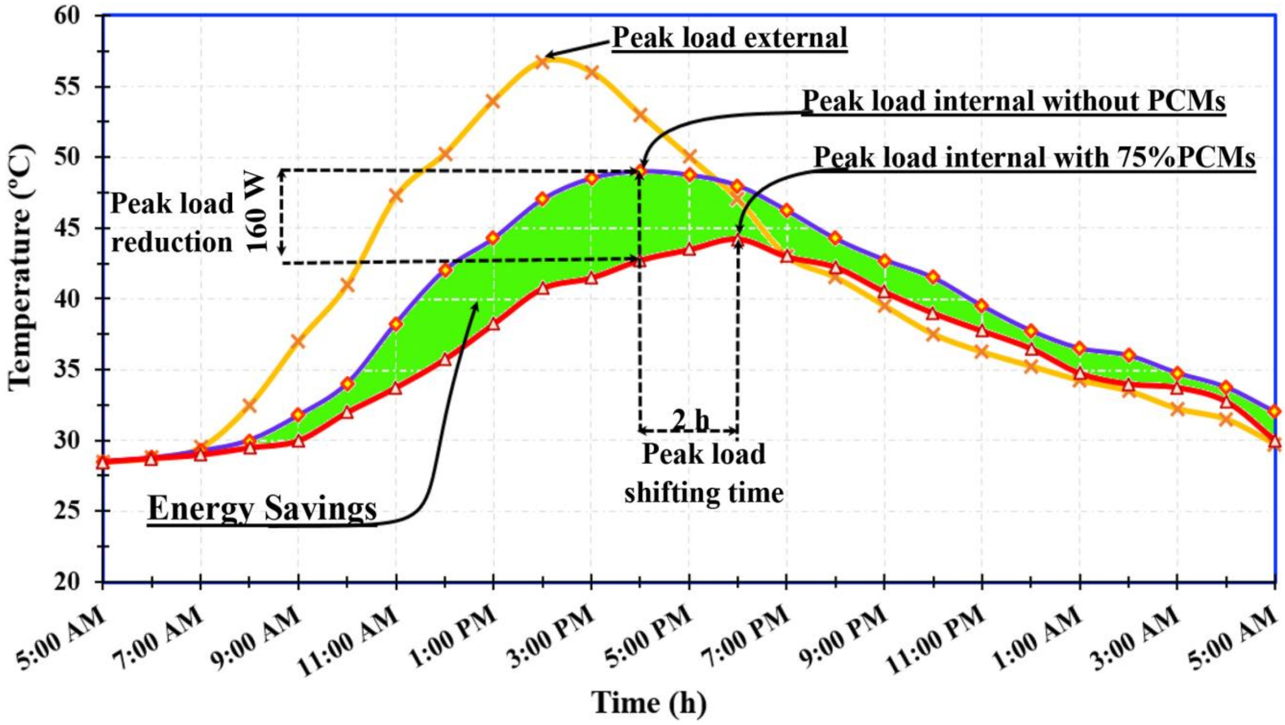


Figure 7. Peak-load alterations and reductions in the room with and without PCMs [51].

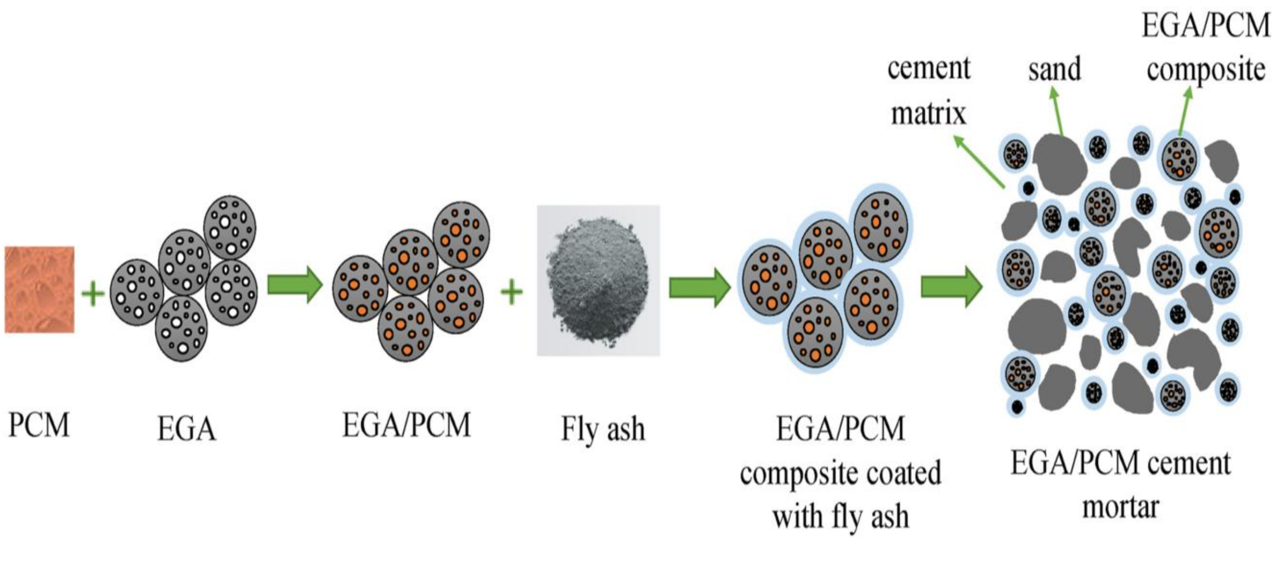


Figure 8. Conceptual picture of the EGA-PCM manufacturing process [52].

Cruz-Elvira et al. (2022) [53] demonstrated the thermophysical characteristics of a new vacuum-impregnated composite PCM consisting of tepexil and dodecanol. Although some earlier research on the use of dodecanol to create PCM composites has been conducted, its enthalpy values have not met expectations. The PCM tepexil/dodecanol composite has fusion and solidification temperatures of 24.13 °C, and 20.41 °C, respectively, and 108.35 J g^{-1} of fusion enthalpy, based on dynamic T-History measurements. The authors claim that these findings reflect the greatest values to date for the 21–26 °C thermal comfort range for a temperate region with strong annual thermal oscillations employing impregnation procedures. At 30 °C, the final thermal conductivity of the synthesised composite was 0.308 W m^{-1} K^{-1}. Tepexil particles smaller than 250 nm had typical pore sizes of 9.5, 36, and 250 nm. Leakage studies on the composite demonstrated a maximal dodecanol retaining rate of 40%.

Wang et al. (2022) [54] analysed the techno-economic aspects of the electric heat storage system integrated into solar energy constructed in a three-story office building in Tianjin, China (2000 m^2 heating area). An electric heat storage system with a 1274.8 MJ heat storage capacity was constructed on the first level of the building. The solar collector system, which has a 160 m^2 total area for heat collection, was installed on the building's roof. The long short-term memory was utilised to gauge the heat gain from the solar collector to control heat stored in the storage system. According to the findings, the produced storage medium had a total heat storage capacity of 448.8 kJ/kg between 50 and 150 °C, which was a good thermal characteristic. The vacuum tube solar collectors had an average thermal efficiency of 51.3% and daily heat gains of 6.5 MJ per square meter. The thermal efficiency of the heat storage system was maintained at 95.8%. This system has a specified operating cost of 15.6 renminbi/m^2/season for the whole heating season. As compared to centralised heating, a distributed clean building heating (DCBH) system may reduce heating costs by as much as 61%.

Using a testing method that allows for the evaluation of samples in steady state and dynamic cases, Cárdenas-Ramrez et al. (2022) [55] assessed three SS-PCMs based on eutectic fatty acid mixes of capric–myristic, palmitic–stearic and lauric–myristic. An SS-PCM-based acrylic plaster's potential for usage as a fiber cement siding finish was also examined. Using the collected data, it was easy to determine the parameters for heat storage capacity, thermal transmittance (U-value), and thermal inertia throughout a simulated diurnal cycle. The outcomes indicated that using phase transition materials in powder form causes a decrement factor of 0.2 besides increasing the thermal latency between 148% and 180%. Moreover, the decrement factor was decreased by 9%, the thermal lag was extended by 67.26%, and the interior temperature was decreased by 20.8% in building envelopes with fiber cement siding and an acrylic plaster coating manufactured from SS-PCM.

Hekimoğlu and Sarı (2022) [56] created a shape-stabilised composite that prevents liquid PCM leakage by blending a eutectic mixture with attapulgite clay (ATC). The results of FT-IR and SEM analyses indicated that the MPEM and ATC had a high degree of physicochemical agreement. According to the DSC study, the composite had a latent heat of fusion of roughly 74 J/g and a phase-change temperature between 44 and 45 °C. The outcomes of the TGA test show that the produced composite has a high degree of thermal stability and durability. The results support the hypothesis that the created composite exhibits promising prospective as a new material with TES competence that can be deployed to enhance interior thermal comfort in buildings besides energy conservation.

Halder et al. (2022) [57] created a unique PCM microcapsule that uses the cenosphere as a protective shell and a dopamine coating that is bio-inspired. Cenosphere shells, which are hollow fly ash particles, are tougher and more durable than typical polymer-based protective shells. The PCM microcapsule and the surrounding cement paste are better bonded thanks to dopamine's potent capacity to connect to various surfaces via covalent and non-covalent interactions. For these reasons, this microcapsule has the potential to significantly increase the strength of the cement mortar that is created. According to an experimental investigation, including 10 weight percent of the new PCM microcapsule in the cement mortar caused an improvement in compressive strength of 35%. According to a microstructure study and hydration products examination, the dopamine coating improves the cement's hydration and generates a tighter and more robust contact between the cement paste and microcapsule.

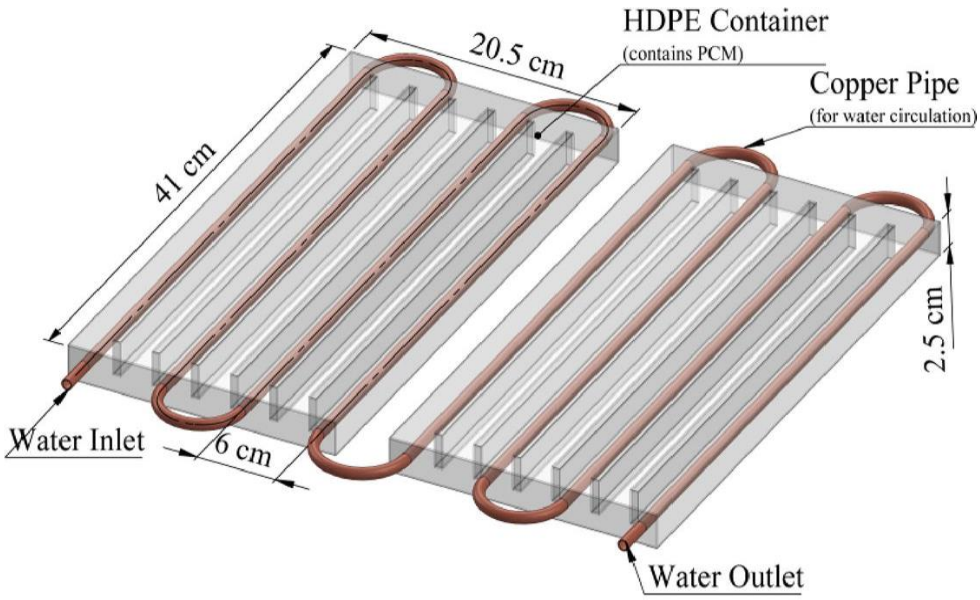
Sun et al. (2022) [58] developed a peculiar type of shell-core PCM, which was distinguished by its super thin shell and ultra-high number of active core materials. A high latent heat potential (136.40 J/g), outstanding high integrity, and a wide range of sustainable energy application possibilities were all provided by the PCM's distinctive protective shell. The TES WPC has great morphological stability, remarkable mechanical robustness, significant thermal stability, high phase transition heat, and strong heat storage capacity.

The latent heat of the TES WPC phase transition progressively upsurges with the constant growth in E-Shell PCM, and as a result, the crystallisation enthalpy and melting enthalpy reach 74.61 Jg^{-1}, and 76.06 Jg^{-1}, respectively. The development of EP simultaneously pushed the idea of using a construction material with composite heat and smoke suppression capabilities to regulate temperature.

4. PCM Studies Utilised in Buildings for Material Temperature Management

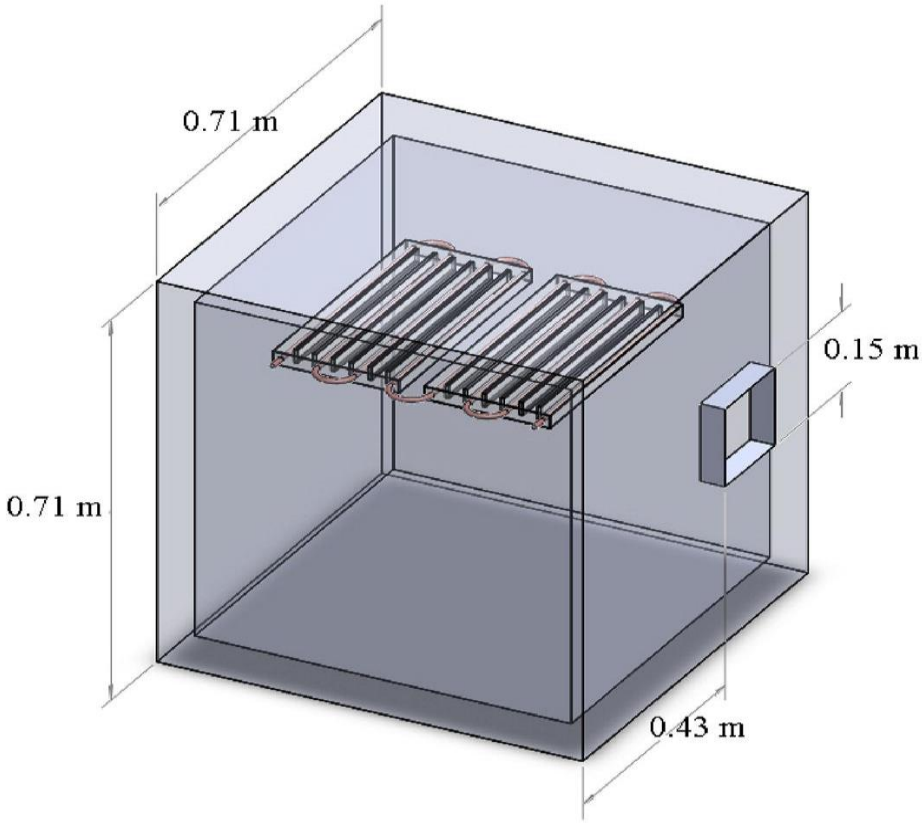
This section focuses on addressing the associated studies that discussed the use of PCMs to regulate material temperature. By introducing PCMs into building materials such as concrete, asphalt, and roofing materials, they can aid in temperature regulation, extending the lifespan and efficiency of these materials. For instance, PCMs in concrete can lower temperature swings, avoid cracking, and boost toughness. PCMs in roofing materials can lower heat gain and increase roof longevity. PCMs in asphalt can improve skid resistance, lessen rutting and cracking, and enhance pavement stability. As a result, the incorporation of PCMs into building materials can improve their use, save maintenance costs, and promote sustainable building techniques. This section explains the specific research that covered the use of PCMs in buildings for controlling material temperature. To assess the configuration, researched parameters, and related performance indicators, critical criticism is used.

Ansys Fluent and EnergyPlus, two of the most popular BES tools, were used in a co-simulation framework developed by Pandey et al. (2020) [59] to simulate the PCM interconnected built environment and assess the validity of its forecasts (Figure 9). Active, passive, and forced convection PCM consumption have all been modeled as three experiments for the assessment of forecast accuracy. The findings show that the anticipated co-simulation is more effective at prediction than the BES tool for active and passive PCM consumption under forced convection. BES is suggested for passive PCM modeling during natural convection. This research could aid in simulating the built environment with PCM at the earliest steps of building design for adverse climatic circumstances because active PCM with induced convection is more efficient than passive PCM.



(a)

Figure 9. *Cont.*



(b)

Figure 9. (**a**) PCM-based heat exchanger that is encased, as well as (**b**) how it is set up in the test chamber [59].

Kishore et al. (2021) [60] conducted a sensitivity analysis on PCM-integrated lightweight building walls (Figure 10). Using numerical simulations, the study covered eight PCM factors including the PCM position in the wall, thickness, transition temperature, density, specific heat, latent heat, thermal conductivity and transition range. The findings demonstrated that the improved PCM suggested in their research may entirely reverse the wall's transient heat gain profile and reduce wall-related heat gain by up to 70% during peak hours without significantly increasing cumulative heat gain. When the PCM settings are 50% lower than their common values, as shown in Figure 11a, the peak period heat gain is shown. When the PCM settings are 50% higher than their common values, the peak period heat gain is shown in Figure 11b.

Rai (2021) [61] examined the energy efficiency of PCM-incorporated brick masonry walls for cooling load management in inhabited structures in intervallic steady-state situations in order to classify the factors that affect its actions and improve simple design strategies. The outcomes are displayed in Figure 12. The study found that cooling loads and daily heat gains were the same for wall designs with matching thermal resistances and identical boundary circumstances, independent of the amount of latent heat stored by the PCM. Likewise, even when night ventilation was used, adding a PCM layer to a wall that was sufficiently insulated did not reduce its cooling demand. As a result, the PCM incorporation was useless in lowering the cooling load. Nonetheless, the hourly heat gains and fluctuations in cooling demands were diminished by the PCM's latent heat storage, making PCM integration appropriate for peak load control. For optimum PCM performance, the PCM should be installed inside a wall with adequate insulation to shield it from the outdoors and a melting temperature that is almost the same as the interior set-point temperature.

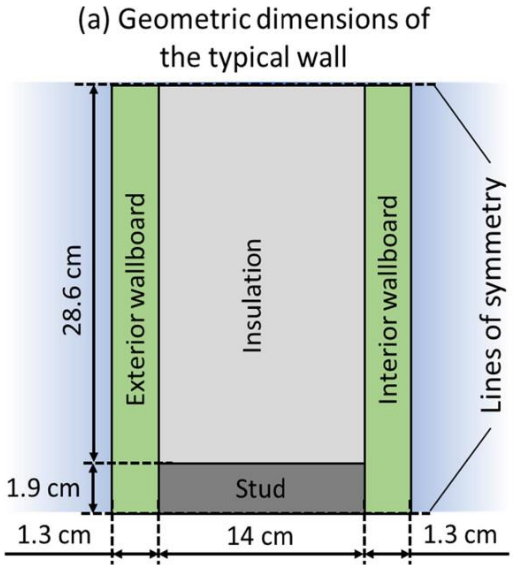


Figure 10. The main dimensions of the (**a**) normal building wall and the (**b**) PCM-integrated wall are shown in the two-dimensional geometries of the lightweight building walls [60]. (*X* is the thickness of the insulation from the interior side.)

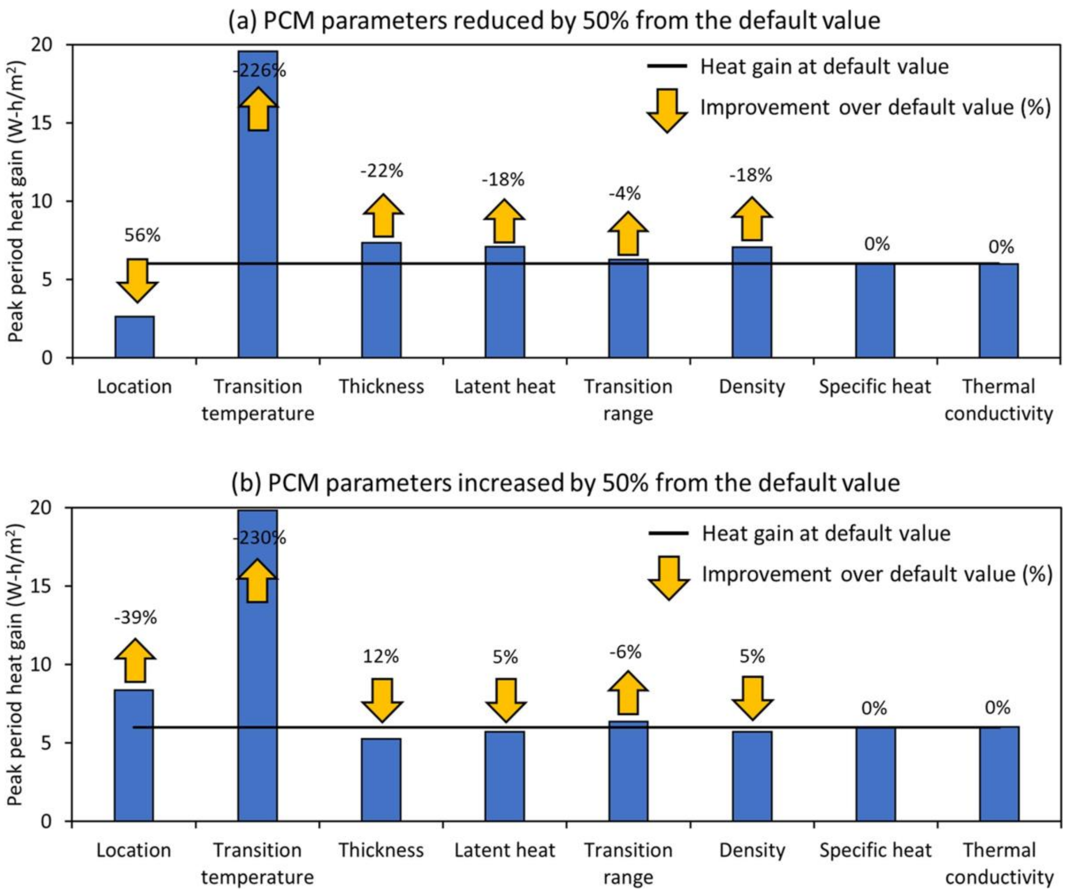


Figure 11. Analysis of the sensitivity of several PCM settings as corresponding to the peak period heat gain in Las Vegas and impacts on peak heat gain owing to (**a**) a 50% drop in default PCM parameter values and (**b**) a 50% increase in default PCM parameter values [60].

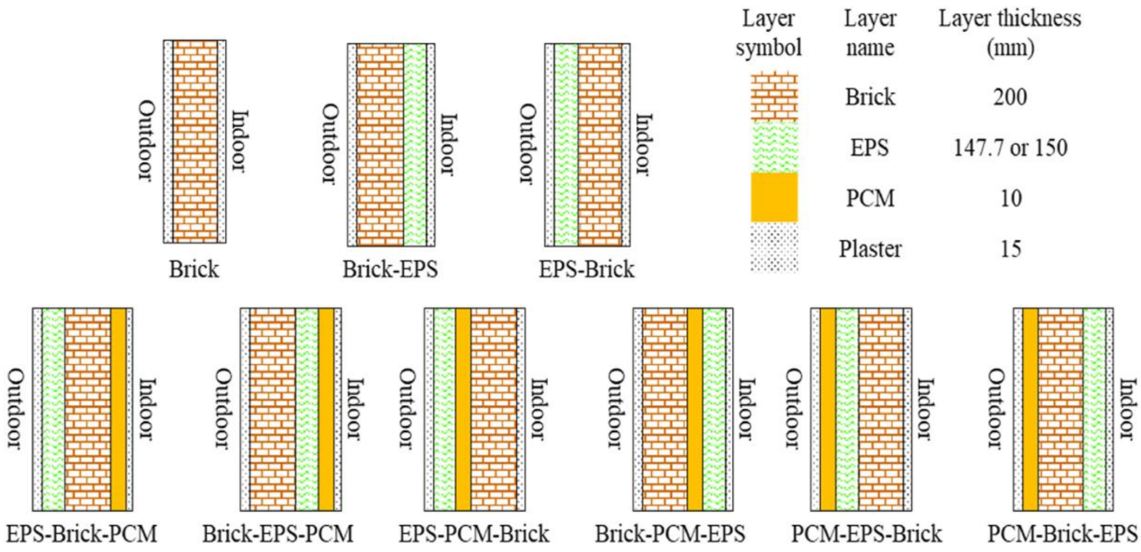


Figure 12. Schematics for various wall designs. The layers (Brick, EPS, and PCM) are arranged from outside to inside [61].

Koželj et al. 2021 [62] investigated PCMs as a thermal storage alternative to conservative water tank storage. The PCM was contained in cylindrical nodules and combined with the water tank to enhance the energy density of the conventional water heat storage tank. This in turn would introduce a contrast between a hybrid latent heat storage tank and a standard sensible thermal energy storage tank. The findings (shown in Figure 13) ascertain that the inclusion of 15% PCM in a conservative heat storage tank that contains just water boosts heat storage by 70%. The observed experimental data and the simulation consequences were contrasted to aid future research and development of the heat storage tank incorporated into the PCM.

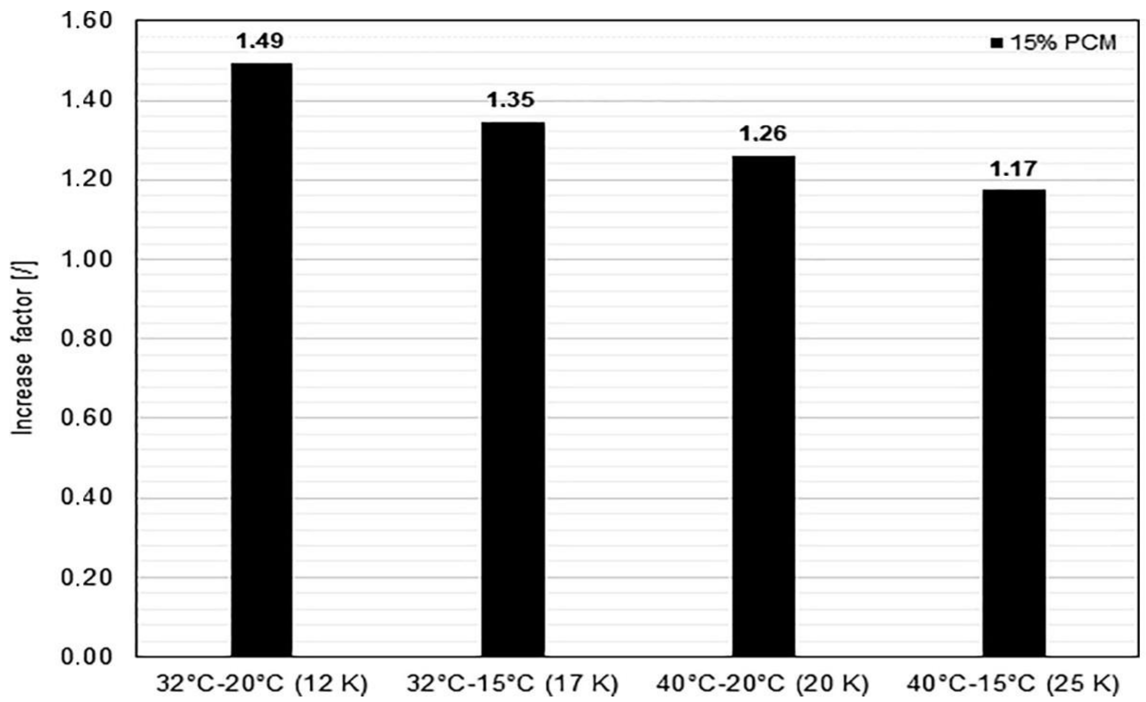


Figure 13. Increase in the water thermal storage tank's internal heat storage capacity using 15% PCM [62].

Guo and Zhang (2021) [63] tested the efficiency of a PCM wallboard (Figure 14) under actual solar radiation and sessional weather by taking into consideration three alternative values for the melting point: 22, 24, and 26 °C. The accurate enthalpy-porous model and the real heat transfer chain were utilised in order to determine the solid–liquid interface and the liquid fraction. According to the findings, the PCM layer does not always have a beneficial effect, and a negative impact on energy loss of more than 5% was recorded. Therefore, the performance is very dependent on a variety of other important aspects, such as the circumstances of the environment and the volumetric quantity.

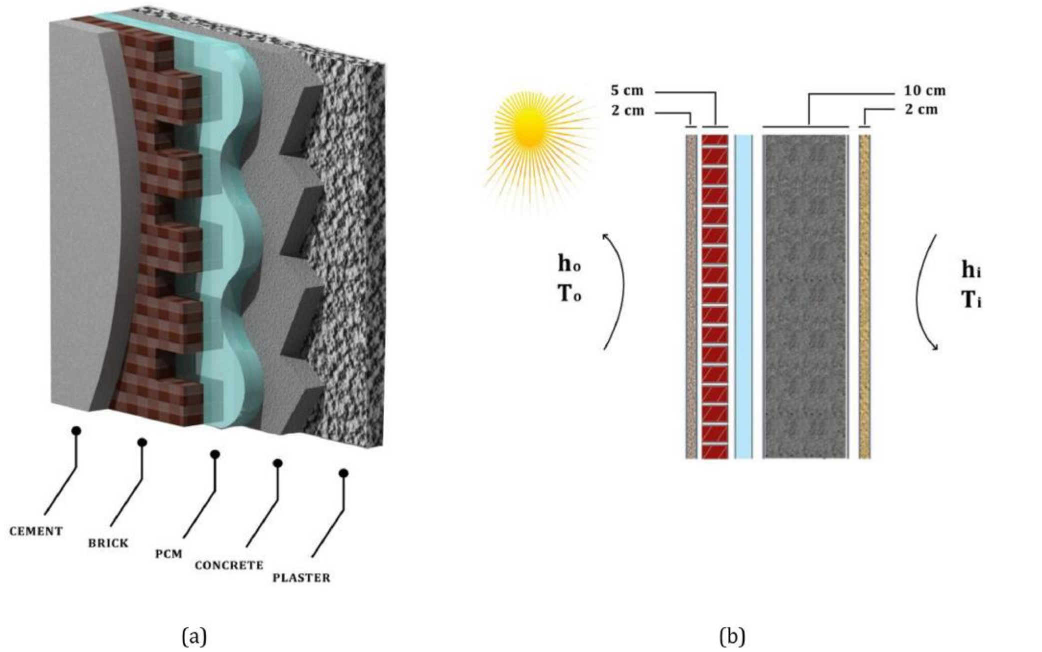


Figure 14. The building envelope's planned structure, (**a**) layer kinds, and (**b**) 2D configuration with dimensions [63].

Boobalakrishnan et al. (2021) [64] made an effort to lessen the entire cooling load of a building, which may alleviate a significant amount of the demand for conventional electricity. In order to conduct the study, a scale model of the projected structure was constructed and evaluated. The studies were carried out in two different ways: in the first instance, there was no PCM in the roof (also known as a "Plain Roof"), and in the second case, there was encapsulated paraffin serving as the PCM inside the roof. The outcomes of the tests stated that the incorporation of PCM into the metal roof of the one-story structure triggered a significant lessening in the temperatures of the building's inner roof and outer roof, and thus in the interior space of the building. Figure 15 shows that the deployment of PCM has resulted in a reduction of 9.5 °C in the highest temperature that could be reached inside and a daily average decrease of 5 °C in the lowest temperature.

Several PCMs with various melting temperatures have been used to dramatically extend the thermal management periods in PVs, according to Mahdi et al. (2021) [65]. The goal is to organise the various PCMs such that their melting points reduce along the direction of heat flow, resulting in a PV module with a more uniform temperature and a slower rate of PCM melting. This encourages PCMs to maintain temperature control for longer, resulting in a PV module that produces more electricity. According to the numerical simulation findings, the usage of multiple PCMs based on the recommended configuration can extend the PV thermal-management duration by more than 33% and increase the PCM melting time by more than 18%, based on the PV inclination and the quantity of multiple PCMs being utilised. Additionally, combining additional PCMs with adequate thermo-physical characteristics considerably boosts the thermal capacity of the PCM component and lengthens the thermal regulation time of PV.

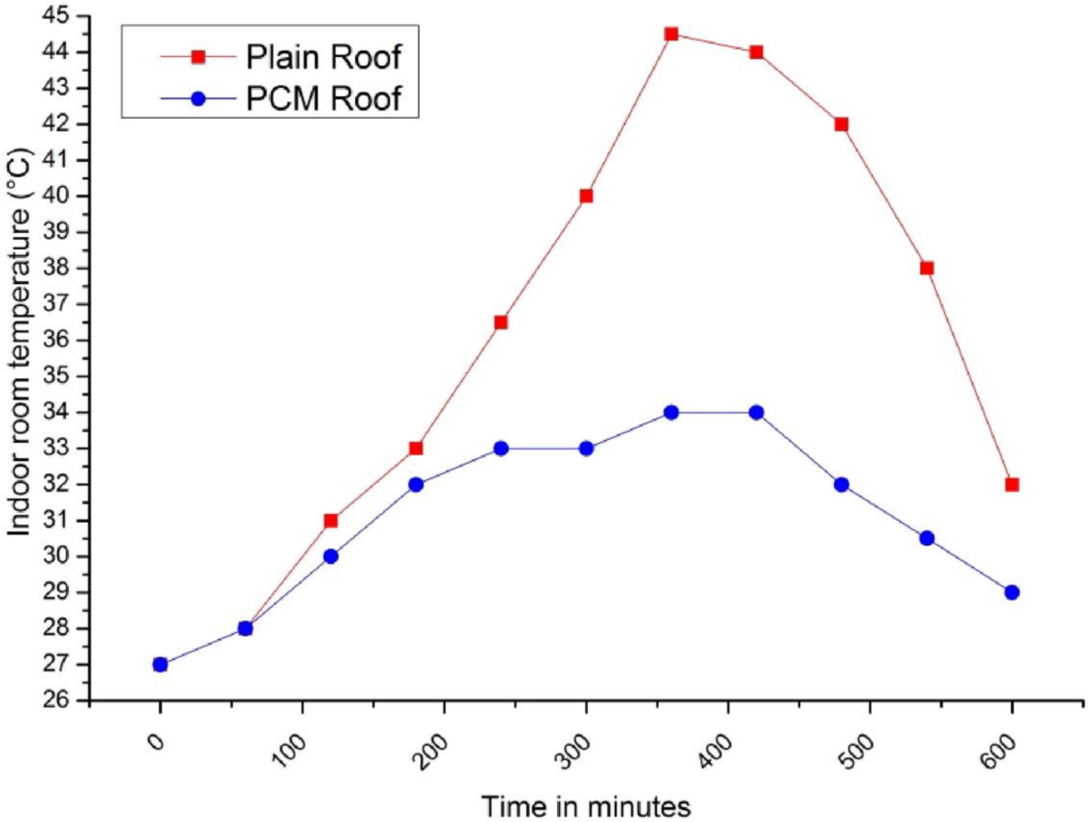


Figure 15. The inside room temperature during the testing days [64].

Zhu et al. (2021) [66] constructed a dynamic heat transfer model of the PCM Trombe room while considering six significant settings that had an influence on the thermal efficiency of the studied system. Using the TRNSYS heat transfer model and GenOpt optimisation tool, the energy consumption and the ideal values of the main determinant parameters of the system were investigated and discovered. The ideal vents area was 0.6 m^2, the ideal air gap thickness was 0.05 m, and the ideal thermal storage wall thickness was 0.68 m. The ideal melting temperatures for the higher temperature PCM layer and lower temperature PCM layer were 27.75 °C, and 16.5 °C, respectively. When comparing the optimised PCM Trombe to the reference Trombe wall and optimised reference Trombe room to the conventional Trombe wall, the yearly total building load was lessened by 13.52% and 7.56%, respectively.

A novel cross-linked polymer swelling method was utilised by Yang et al. (2021) [67] to synthesise flexible shape-stabilised PCMs with primitive thermal ability. This was accomplished by adjusting its energy storage capability and passive radiative cooling capacity, and also by combining these two capabilities. The large-scale generated PCMs displayed excellent temperature control capacity when employed as thermal management materials for electronics and buildings. This was due to the fact that the PCMs had both the role of passive radiative cooling and the role of phase-change energy storage. The temperature of electronic devices and buildings can be lowered by 5.5 °C and 9.3 °C, respectively, with the assistance of the composite PCM film, which reveals a significant amount of untapped potential in the field of practical applications relating to thermal management.

Alghamdi et al. (2022) [68] employed PCM to delay the peak heat transfer in a structure until a low load was achieved. This led to the creation of a brand-new proportional–integral–derivative (PID) controller system. This system had the capability of adjusting the temperature based on six different set points. In order to conduct an accurate evaluation of PCM performance, a layer of PCM measuring 5 cm was added to the wall. In order to keep the same overall wall thickness, Thermalite Turbo, which had the greatest heat resistance, had its thickness decreased by 5 cm. The energy equation for an interior area was validated, and the temperature distribution inside the wall was conducted by taking into account both the PCM phase shift and the effects of radiation. Yet, the yearly review reveals that PCM was successful in cutting demand for power by 15.3%. In order to make up for the poor performance of the PCM during the warm summer months, a PID control system will turn off the primary chiller and attach an additional chiller to the circuit. Utilising the new PID has resulted in a 2.2% reduction in the required amount of power. The schedule showed that there was a 2.3% drop in the amount of power used.

5. PCM Studies Utilised in Buildings for Cooling and Heating Load Reduction

Buildings have employed PCMs extensively to reduce cooling and heating loads. The related studies that were conducted between 2020 and 2022 are mentioned in this section and thoroughly examined. A critical discussion is carried out to evaluate the configuration, investigated parameters, and associated performance indicators.

Gholamibozanjani and Farid (2020) [69] evaluated the system's energy efficiency over the course of several seasons and demonstrated the deployment of an active PCM storage system in buildings. Two test huts were employed to carry out the study in order to achieve this goal. Each hut was furnished with solar and electric heaters in the winter and an air conditioner in the summer. Furthermore, one of the huts had PCM storage units added. In this regard, the results from the data from that hut were contrasted with those from the reference hut. Transferring data for the purposes of processing, analysis, and interacting with the host computer was accomplished with the help of a data collection device called CompactRIO. This system was driven by real-time software called LabVIEW. According to their findings, the active PCM storage units have the potential to store solar energy during the winter months or free night cooling during the summer months for future use. Thus, the amount of heating or cooling loads was reduced. The authors were able to save a total of 40% in the month of May and 10.3% in the months of June and July 2019 on energy used for heating. Also, using PCM for space cooling causes cumulative energy savings of 10% in January and 30% over the course of the months of March and April.

In order to assess the thermal response of a PCMB-PHC energy pile when it was exposed to the heating and cooling modes of a building, Cao et al. (2022) [70] developed a 3D heat transfer model of a PHC energy pile with PCMB. It has been concluded that raising the PCMB thermal conductivity would improve the heat transfer of the PCMB-PHC energy pile. Furthermore, the overall amount of energy exchanged is able to increase by 256.8% (during the cooling mode) and 258.8% (during the heating mode) for every one-watt per meter increase in the PCMB thermal conductivity (W/m.K). When the PCMB melting temperature of 4 °C is raised or lowered, the heat transmission capacity of the PCMB-PHC energy pile increases by 19.3 and 14.2%, respectively, depending on whether it is being heated or cooled. An increase of 200 kJ/kg in the PCMB latent heat may boost the heat transfer capacity of a PCMB-PHC energy pile by 17.7% (when operating in the heating mode) and 12.6% (when operating in the cooling mode). Additionally, a higher melting temperature while the PCMB-PHC energy pile is in the heating mode, a lower melting temperature when it is in the cooling mode, and higher PCMB latent heat all have the potential to lessen the amplitude of temperature fluctuations in the soil around it, using the Taguchi-GRA method as a foundation.

Using a heat balance simulation model, Kitagawa et al. (2022) [71] estimated the thermal storage impact of PCMs in naturally ventilated buildings with installed PCMs. Field measurements obtained in Indonesia's hot and muggy climate corroborated the simulation results, which were run for the target building where the radiant floor cooling system was installed. The outcomes showed that the utilised model of heat balance analysis has a proper capacity to estimate the heat balance and temperature of PCMs in naturally ventilated buildings with uneven distributions of air temperature and air flow. For instance, the simulation accuracy in terms of the floor surface and PCM temperatures increased by

0.3 °C when linked with radiative heat transfer computation and taking into account the surface temperature difference between the floor and the other surfaces.

Hai et al. (2022) [72] evaluated the energy balance of a building, the energy in the mechanical air supply system (MASS), and the energy in the temperature regulation section. In two different situations, PCMs of Pure Temp 23, 25, 27, and 29 were incorporated into the structure. The temperature within the building in the first scenario remained steady at 23, 24, and 25 °C. When Pure Temp 29 was introduced into the structure, which experiences phase change at 29 °C, less energy was used, with consumption rates of 17.39 kWh/m^2 at 23 °C, 17 kWh/m^2 at 24 °C, and 16.92 kWh/m^2 at the setpoint of 25 °C. In the next situation, when the interior temperature fluctuated between 23 and 25 °C, Pure Temp 29 again performed best, with energy savings of 15.52 kWh/m^2. An economiser was added to reduce energy consumption in the MASS portion, and when it was activated, 1.92 kWh/m^2 less energy was used. The MASS portion then underwent heat recovery, and it was found that this device, with a decrease of 2.77 kWh/m^2, may be helpful for this area of the structure.

6. PCM Studies Utilised in Buildings for Enhanced Thermal and Energy Efficiency

Buildings are using PCMs more frequently to improve their thermal and energy efficiency. During peak or off-peak hours, PCMs have the ability to absorb or release heat, which lowers the peak demand on cooling or heating equipment and shifts energy use to off-peak hours. Compared to conventional storage materials such as water or concrete, PCMs offer a higher energy storage density due to having high latent heat of fusion (the amount of energy absorbed or released during the phase transition). They are useful for compact and space-constrained applications in buildings because they can hold a significant amount of energy in a relatively small volume. PCMs can therefore assist in the control of indoor temperature changes, save energy usage for heating and cooling, and enhance thermal comfort for inhabitants by being integrated into building envelopes including roofs, walls, and floors. Specifically, PCMs can absorb excess heat during the day and release it at night and therefore can stabilise indoor temperature. Also, by reducing the usage of fossil fuels and decreasing emissions of greenhouse gases, PCMs can assist buildings in meeting energy efficiency goals and minimising their negative environmental effects. An in-depth discussion of the related studies conducted between 2019 and 2023 was collected in this section. An evaluation of the configuration, researched parameters, and associated performance indicators are carried out below.

With EnergyPlus, Sovetova et al. (2019) [73] appraised the thermal and energy efficiencies of PCM-combined inhabited buildings situated in several cities from a hot desert climate zone. The PCMs used were of thirteen different types. The best PCMs lessened the temperature swings, and the greatest temperature was lowered by up to 2.04 °C, according to the test data. The best PCMs, with the exception of Cairo and Biskra, were around the cooling set point, indicating that in hot climates, PCM with high melting points works well. Energy efficiency was improved as the surface area and PCM layer thickness fell for a given volume of PCM, and for a selection of cities, the energy consumption drop ranged from 17.97 to 34.26%. Statistical analysis was used to create an equation that demonstrates the correlation between energy conservation and weather conditions.

Bolteya et al. (2020) [74] concentrated on employing different media in glazing cavities to reduce heat transmission via transparent building components. They experimentally tested a glazed unit made of a PCM (RT28HC) against one that was filled with air in a dry, arid environment to determine which had the better thermal efficiency. After that, using the Fluent program, the impact of PCM thicknesses on the thermal efficiency of double-glazing units was examined, taking into account temperature time lag, internal temperature, total transmitted energy, and liquid percentage. The outcomes showed that PCM has a considerable influence on room temperature. In comparison to the standard double-glazing unit, the interior layer’s peak temperature time lag in the PCM-filled double-glazing unit was around 5 h. Moreover, increasing PCM thickness up to 30 mm may substantially enhance thermal performance characteristics and reverse the trend in variance.

Jangeldinov et al. (2020) [75] assessed the thermal and energy efficiencies of buildings in different eight cities with warm, humid summers. It has been shown how the pattern of heating and cooling energy savings influences the choice of the best PCM for the selected cities. Also, the influence of PCM volume, specifically the impact of variable and constant volume, on energy savings for the lightweight steel-framed structure was evaluated. Using eleven PCM melting temperature ranges, simulations were run in EnergyPlus. According to the test findings, the energy savings were the greatest during the swing season, when temperatures were decreased by a maximum of 3.3 °C. Energy savings from heating and cooling were shown to have a significant impact on choosing the best PCM. The best PCMs were determined to be PCMs 24–26 for cities with the greatest cooling energy savings, and PCM 21 for towns with the greatest heating energy savings.

A numerical simulation with and without the incorporation of PCM in building walls was conducted by Kumar et al. (2020) [76]. To assess the effects of various configurations of exterior building walls, PCM building walls were integrated. In the PCM and non-PCM structures, the internal temperature was examined during the winter and summer seasons in Chennai, India. Clay bricks filled with PCM make up the building wall. The outcome demonstrates that a PCM filled with clay brick walls considerably increases thermal inertia. Also, the placement of the PCM layer is one of the chief elements in reducing heat gain in the building wall before it enters the room.

Aerial lime-based mortar that included an eco-sustainable PCM was studied by Frigione et al. (2019) [77] with the aim of enhancing building energy efficiency. Poly-ethylene glycol, a thermoplastic polymer that is non-toxic, has been chosen as PCM (PEG 1000). This substance was used in inert support that was a result of quarry stone extraction. PEG/stone, the finished product, is a composite that may be used as mortar aggregate. The sustainable aggregates PEG/stone have acceptable Latent Heat Thermal Energy Storage values. These aggregates cause an inappropriate drop in mechanical characteristics when added to mortar formulations.

PCMs were assessed by Mohseni and Tang (2021) [78] for their effectiveness in enhancing the thermal efficiency and thermal comfort of an inhabited structure. In their work, numerical modeling and validation were conducted for the experimentally investigated heat transfer of concrete containing PCM. Several construction components used PCMs with thicknesses of 5 and 10 mm and melting temperatures of 19 to 29 °C. The effects of the climatic conditions and the heating and cooling loads were assessed after determining the best PCM for the energy analysis. The EnergyPlus PCM module in the computational model and the experimental findings were in good agreement. The findings showed that models with PCM integration may lessen temperature swings, increase interior comfort, and minimise cooling and heating loads. The PCM used in the roof and wall, with a 21 °C melting temperature and 10 mm thickness, performed best in terms of energy consumption and shifting loads away from peak demand periods. Figure 16 demonstrates that the temperature of the component with PCM is lesser than that of the component without PCM, improving interior comfort.

Kalbasi et al. (2023) [79] evaluated the relevance of the sensible storage characteristic to the latent characteristic defined for a building (no PCM), a second building (PCM without phase transition), and a third building (phase transition). It was discovered that the thermal resistance of the envelopes and set point affect the sensible/latent importance. At set point 22 °C, it was observed that the PCM-enhanced building utilised less electricity by 32.4 kWh/m^2. In such circumstances, the latent storage as well as the percentage of sensible storage are 46%, and 54%, respectively. It was discovered that installing PCM close to the topmost layer increased energy savings by 3.72 kWh/m^2 and increased PCM efficacy. The phase change in PCM was present; however, this is not necessarily a negative observation. In one instance, it was found that PCM without phase transition reduced energy consumption by 9.4 kWh/m^2, but PCM with phase transition reduced energy consumption by 7.1 kWh/m^2.

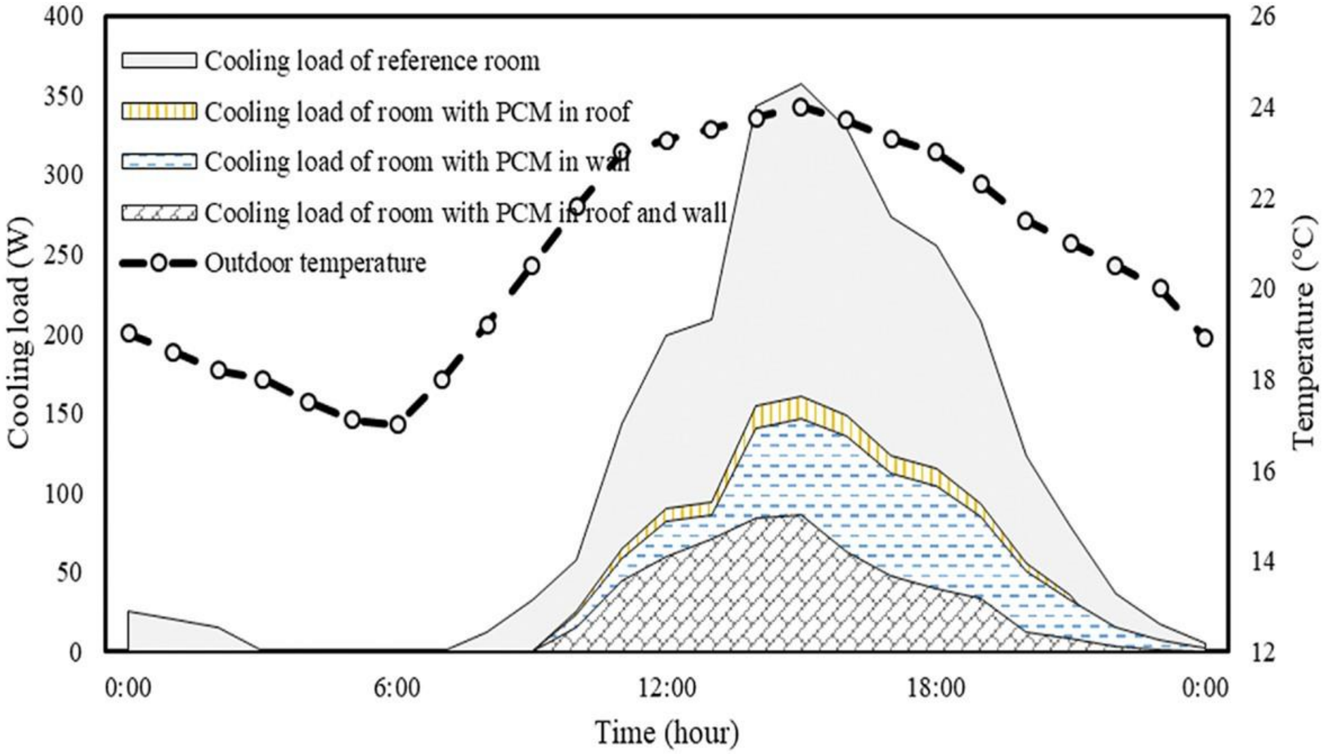


Figure 16. Average cooling demand per hour on December 1st [78].

7. PCM Studies Utilised in Thermal Load Shaving and Shifting

The use of PCMs in thermal load shifting and shaving applications has increased, particularly in the building and energy industries. By going through a phase shift, usually, from solid to liquid or vice versa, which can happen at a certain temperature known as the melting or solidification point, these materials are able to store thermal energy. This section discusses the related studies in detail.

Mohammed et al. (2020) [80] came up with an experimental approach to examine amalgam's thermal performance and contrast it with the performance of identical materials made without amalgam. A comparative investigation showed that merging would not be likely to result in any substantial thermal improvements. The overall weight of the insulating system would, however, be significantly reduced, in this example by up to 20.94%. Thus, potential stresses on structural components caused by the application of insulation to buildings are further reduced. When it comes to traditional architecture methods, when substantial volumes and thicknesses of insulation are employed, this may be extremely advantageous. Also, because wood shavings are much less expensive than PCMs, a cost decrease might be achieved.

Gholamibozanjani and Farid (2020) [81] experimentally studied the impact of an active PCM storage system in conjunction with price-based control on peak load shifting. Two matching experiment huts that were furnished with an air conditioner in the summer and an electric and solar heater in the winter were used for the trials. However, one of the shelters also included an active PCM storage system that was powered by a solar heater. Data transmission and host computer communication were conducted using a CompactRio data capture system with a LabView interface. The suggested system was effective in moving the demand for both heating and cooling to off-peak times, according to the results. In winter, a relevant 65% of cost savings and more than 47% of daily energy savings (0.83 kWh) were realised. In summer, a relevant 42% of cost savings and more than 23% of daily energy savings (0.27 kWh) were achieved.

A vapour-compression cooling system employing PCM that shifts the peak load of power consumption was examined by Riahi et al. (2021) [82]. More particularly, the dynamic behaviour of the cooling system with and without PCM was appraised and was demonstrated in detail on the warmest day of the year in Tehran, Iran. A number of characteristics, including the system performance coefficient, compressor power consumption, the cooling load that is readily available, and PCM melting percentage, were assessed. The findings indicated that PCM enhances the available cooling load during peak load hours while reducing power usage. On the warmest day of the year, the daily energy consumption, daily accessible cooling energy, and electrical peak load, respectively, are reduced by 0.9%, 2.9%, and 47%, respectively, for 154 L of PCM. The PCM melting percentage decreases when the PCM volume is increased, yet the peak load hours' melting time increases. Also, there is a 6.9% drop in the daily accessible cooling load and a 4.5% decrease in energy usage, which results in a 2.7% decrease in the coefficient of performance (COP). Figure 17 summarises the lowest, mean, and maximum values of the available cooling capacity.

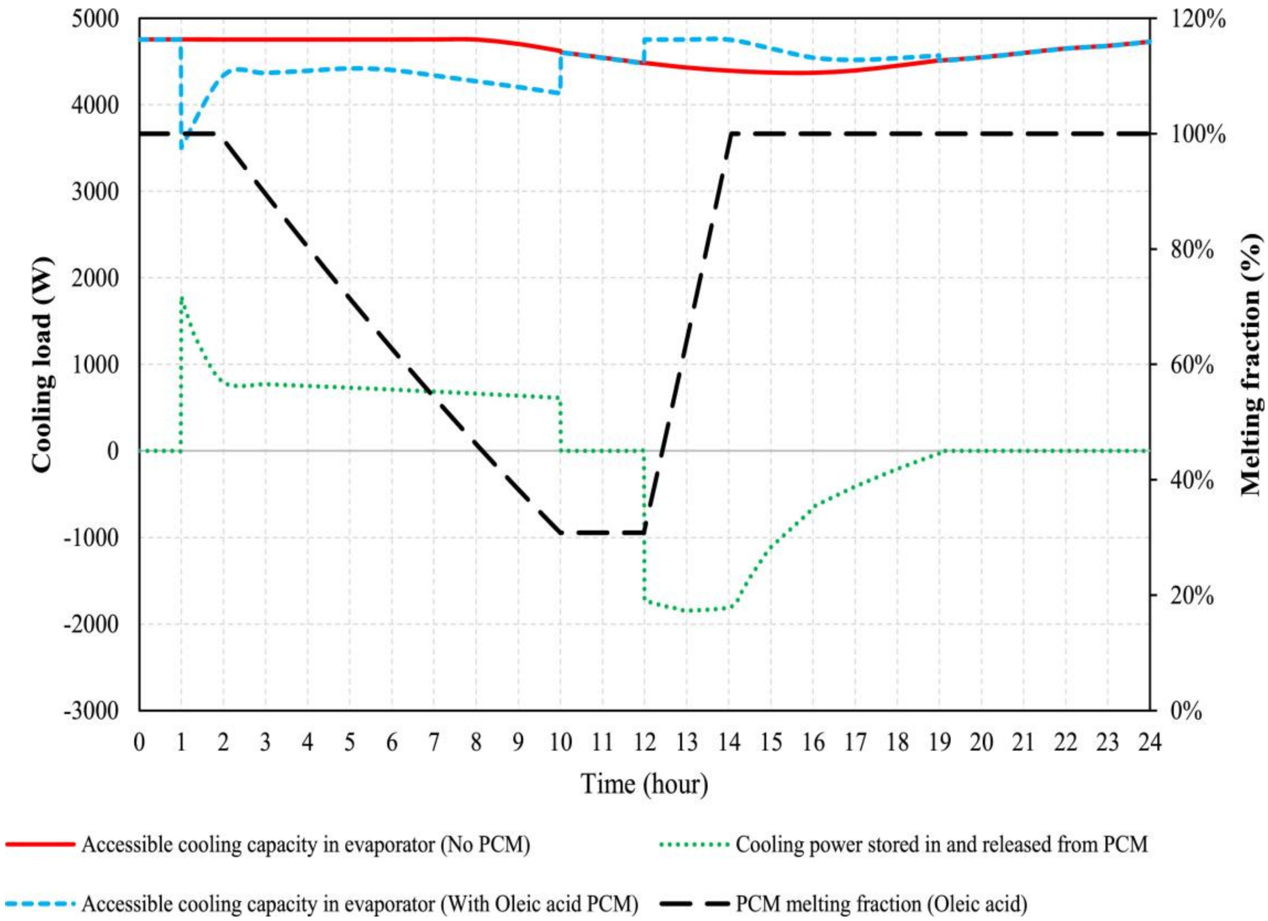


Figure 17. The available cooling capacity with and without PCM is compared [82].

Table 1 shows an outline of the studies on phase-change material utilised in buildings for different purposes presented in this review paper.

8. Conclusions

The use of PCMs in buildings is a promising technology for reducing energy consumption, improving thermal comfort, and promoting sustainable building practices. This article provides a survey of the current research literature on phase transition materials used in creating thermal energy storage techniques for latent heat. The discussion began with thermal comfort ideas, selection criteria, and property testing. Energy storage elements were then discussed. The control of material temperature is explored. Reducing the building's cooling and heating burden is discussed. The use of PCM studies for building efficiency is then explored. By examining the results shown in Table 1 and the thermal performance analyses offered in each of the associated studies that have been evaluated, it is fair to admit that there are many advantages to using PCMs in construction applications. One prominent application entailed adding PCM to a room, which dramatically increased PCM efficiency and successfully decreased overheating. Likewise, summertime warming was avoided by incorporating PCMs into the walls, leading to a notable decrease in the interior air temperature of up to 7 °C.

Specific factors must be taken into account to maximise PCM integration's effectiveness. For instance, maintaining interior doors locked to prevent mixing with neighboring zones without PCM and making sure windows are open at night for night purging both significantly improve the success of thermal comfort optimisation. An early rise in PCM efficiency was observed in tests of a proposed hybrid system, which showed an average decline in discomfort levels throughout two months of winter.

Wall heat gain can change dramatically as a result of PCM modifications. A skilled modification of the PCM allows for a complete reversal of the wall's transient heat gain profile, which can reduce peak wall-related heat gain by up to 70% without greatly impacting cumulative heat gain. It is advised to install PCM on the inner side of the wall with enough insulation to protect it from the environment for the best performance. The ideal interior set-point temperature ought to line up with the PCM's melting temperature.

Passive PCM use has not been found to be as effective as active PCM use, especially induced convection. Only 15% of PCM can be added to conventional water-based heat storage tanks to increase heat storage by a remarkable 70%. Particularly, when PCM was used for space cooling, significant energy savings were observed across the seasons.

The thermal performance of PCM is greatly influenced by its thickness. Significant increases in thermal properties can be obtained up to a PCM thickness of 30 mm; however, going beyond this thickness may reduce the reported advantages. Furthermore, according to environmental research, adding a 10 mm thick PCM layer to a structure with a 50-year lifespan might significantly lower CO_2 emissions, which are thought to be roughly 264 tons.

Cost is an issue to be taken into account while deploying PCMs. As a less expensive option to PCMs, wood shavings can help cut costs while still offering some advantages. To ensure the practicality and financial feasibility of the overall building application, thorough assessment and cost analysis are essential when choosing PCM materials.

9. Limitations of PCMs and Recommendations for Future Studies

This overview on the use of PCM in the building industry shows the possibilities for PCM addition in building materials, envelops, facades, walls, roofs, floors, and associated components such as windows and shading equipment to minimise thermal impacts, energy consumption, and the overall greenhouse gases emissions. The current paper covered a considerable amount of associated studies using simulation-based models developed for different configurations and experimental settings. The key findings of this review's study may be useful in illuminating potential developments, impending trends in energy storage materials research and development, and potential new applications in the construction sector.

Based on the current study, it can be stated that the PCMs have a number of limitations that should be addressed in the upcoming research. These are as follows:

1. Some PCMs may only function within a limited temperature range, making them ideal for particular climates or seasons but less useful in areas with large temperature changes.
2. Careful thought must go into selecting the best PCM for a given application. A number of elements need to be considered, including the ideal melting temperature

range, thermal conductivity, compatibility with construction materials, and long-term stability. When PCMs interact with other parts or building materials, compatibility problems may occur that could result in leakage or poor performance.
3. The efficient transport of heat during the energy absorption (charging) and energy release (discharging) cycles is essential for the optimal operation of PCMs. Some PCMs' low thermal conductivity might cause heat transfer limits, which can slow down charging and discharging speeds.
4. To successfully use PCMs in construction applications, it is essential to guarantee their long-term stability and endurance. The efficiency and reliability of PCMs can be impacted over time by elements such as heat cycling, age, and probable chemical deterioration.
5. A major obstacle to PCMs' broad use in construction applications may be their price. Some PCMs can be quite costly, especially ones with outstanding features.

The following is an example of a collection of suggestions that can improve the utilisation of PCMs in building applications:

1. Future research should consider the optimisation of PCMs' quantity and temperature according to the intended use and local weather conditions.
2. In order to guarantee PCMs can be used in a variety of climate zones, their nominal temperature range must be expanded.
3. It would be interesting to know what are the most accepted properties of PCMs that would satisfy the current circumstances of the climate.
4. To ensure optimum PCM selection and compatibility with diverse building materials, extensive research and testing are required.
5. To tackle the low thermal conductivity and boost system efficiency, PCMs' heat transfer properties can be improved, or heat transfer enhancement methods such as fins or heat pipes can be used.
6. New PCM technology research is also crucial, such as the potential for a dynamically modifiable and even programmable phase-change temperature.
7. The goal of future research is to create PCMs with improved robustness, long-term stability, and minimal deterioration after repeated temperature cycling.
8. Utility incentives may be available for PCM technology if upcoming parametric studies confirm their potential for energy savings and demand reduction.
9. There are not enough real-world trials to evaluate how PCMs relate to energy performance in building enclosures in various climatic conditions.
10. With PCMs or without PCMs, it is necessary to analyse and evaluate latent heat storage and real temperature distributions in the building enclosure systems.
11. Since designers will ultimately need to assess the thermal performance of enclosure systems using PCMs, further study is needed to analyse the usability of these systems for existing modelling tools and to evaluate performance indicators to quantify and evaluate actual heat transfer across diverse wall systems.
12. Durability and cost-effective production methods are crucial for making PCM-based solutions economically feasible for a variety of building projects.

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Abbreviation

PCMs	Phase-change materials
CBHS	Considerable experience in providing building services
TDC	Total Discomfort Change
MPCM	Microencapsulated phase-change material
MTR	Maximum temperature reduction
ATFR	Average temperature fluctuation reduction
OTD	Operative temperature difference
MHGR	Maximum heat gain reduction
TSV	Thermal sensation vote
3DPC	3D-printed concrete
CHBs	Concrete hollow blocks
TGA	Thermo-gravimetric analysis
CFD	Computational fluid dynamics
DGU	Double-glazing unit
PEG	Poly-ethylene glycol

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