Improving indoor thermal comfort by using phase change materials: A review

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Summary
Phase change materials (PCMs) have great potentials to be used in modern building materials to stabilize indoor temperature fluctuations for improving thermal comfort. This paper presents a comprehensive review on the use of PCMs in buildings to improve thermal comfort without increasing energy consumption. Concise discussions of the experimental and computational works reported in literature are presented. A special focus of this review is devoted to discussing different analysis methods and models used to test, characterize, and measure the performance of PCMs in modern building applications under different conditions. This detailed review also highlights the special attention given to organic PCMs, such as paraffin, due to their favorable properties, such as low price, chemical stability, non-corrosiveness, and high latent heat of fusion. The review shows the scarcity of literature reporting the use of eutectic PCMs in building applications, despite their high volumetric storage density.

KEYWORDS
indoor temperature, indoor thermal comfort, PCM, thermal energy storage

1 | INTRODUCTION

The global energy demand is consistently increasing. Such an increase has driven the renewable energy research sector to improve current alternatives to reduce energy consumption, especially in the building energy sector. Solar energy is one of the main renewables with applications to the building energy sector. Unlike other renewables, such as wind or wave energy, solar energy is intermittent along a short time scale and is only available during daytime. One way to improve such a disadvantage of solar energy usage is to use thermal energy storage (TES). TES functions by absorbing and releasing thermal energy in the form of heat using a storage media. TES systems stabilize power generation from solar energy throughout dedicated or combined energy cycles.

Over the years, the use of TES with solar energy systems has been verified to reduce efficiently the excessive usage of fossil fuels in building energy systems. TES plays a necessary role in a wide range of industrial and residential applications to improve the efficiency of

Abbreviations: EPS, expanded polystyrene; GP, glass powder; HVAC, heating ventilation and air conditioning; LA–LWA, lauryl alcohol-lightweight aggregate; LHS, latent heat storage; MPCM, microencapsulated phase change material; PCM, phase change materials; SHS, sensible heat storage; SSPCM, shape-stabilized phase change material; TCM, thermochemical material; TES, thermal energy storage; TESC, thermal energy storage concrete; EAFD, electric-arc furnace dust; TGA, thermo gravimetric analyzer; UHI, urban heat island; VIP, vacuum insulation panels; WPC, wood-plastic composite; xGnP, exfoliated graphite nanoplatelets

Symbols: $Q_{\text{sensible}}$, The sensible heat storage [kJ]; $Q_{\text{latent}}$, The latent heat storage [kJ]; $m$, Mass of storage material [kg]; $\Delta T$, Temperature change of storage material [K]; $C_p$, Storage material specific heat capacity [kJ/kgK]; $\Delta h$, Specific melting enthalpy of storage material [kJ/kg]; $Q$, Amount of heat stored/released [kJ]; $T_e$, the exterior surface temperature [°C]; $T_i$, the interior surface temperature [°C]; $T_a$, the internal air temperature [°C]
the power generation and to stabilize the power supply at a suitable cost. Many techniques can be used in TES systems based on the processing of energy storage to keep it in a certain field with a specific time relevant to each application.8,11-14 A vital purpose of TES can be found in its use to reduce peak loads in HVAC systems.15,16 TES is a practical method which is used to generate cooling or to reduce cost during the period of cooling demand depending on the storage process, so it could be the most suitable method to reduce the mismatch of the gap between the consumption and supply of the energy.17,18 The materials, which apply the principle of TES and absorb or release a specific amount of heat to change from phase into another, are called phase change materials (PCM).19 In recent years, the application of PCMs has increased in different fields, such as solar power plants,20-23 solar dryers24-26 and waste heat recovery27-29; photovoltaic electricity systems,30-32 electronic devices33; electric vehicles,34,35 lithium batteries36,37; and some biomedical applications.38 This review focuses on the use of PCMs in building construction applications, particularly in indoor temperature control for improving thermal comfort. Therefore, the discussions presented in this review primarily focus on the effect of using PCMs, with different applications criteria, on building indoor temperature and thermal comfort.

2 | DIFFERENT TECHNIQUES OF REDUCING THE INDOOR TEMPERATURE OF BUILDINGS

Temperature control strategies can be divided into 2 main groups: active and passive. Active strategies include all HVAC systems which are integrated with the environment to exploit the variable sources of nature for supplying low energy buildings. On the other hand, passive cooling is the system which utilizes the energy available from the natural environment without using any mechanical units in order to reduce the consumption of conventional energy resources.39,40 The different ways of cooling buildings are shown in Figure 1. In the figure, the TES with PCM is considered as a passive system by heat modulation.

3 | THERMAL ENERGY STORAGE MECHANISM

TES methods can be divided according to the storage mechanisms into 3 methods: sensible heat, latent heat, and thermochemical (as shown in Figure 2).

3.1 | Sensible heat

For sensible heat storage (SHS), the amount of absorbed heat depends on 3 characteristics: the mass of the medium, its ability to absorb heat, and temperature changes.4 In sensible heat systems, the energy is stored in the media and the temperature increases according to this process, and this energy can be used when the media releases it during a temperature decrease.5 The disadvantage of sensible heat is the use of large storage mass to store thermal energy which leads to an increase in temperature.15 The sensible heat can be calculated according to Equation 116:

\[ Q_{\text{SENSIBLE}} = m \cdot c_p \cdot \Delta T \]  (1)

3.2 | Latent heat

Latent heat storage (LHS) is one of the most efficient methods of storing thermal energy.53 Latent heat storage functions as the enthalpy of a material change when it changes from 1 phase to another.54 LHS provides higher heat storage capacity with a small change in temperature between charging and discharging.55 LHS could be divided to solid-liquid, solid-gas, solid-solid, and liquid-gas depending on the change of phase during the process.56 The transformations of liquid-gas and solid-gas phase are inappropriate for TES applications because of the complicated large volume alteration through the phase change.57,58 The advantage of an LHS method, which makes it exceed an SHS method, is higher heat storage capacity per volume with a smaller change in temperature between the charging and discharging processes.13,59 The heat storage capacity for latent heat media depends on the specific heat and the latent heat capacity.10,60 The LHS can be expressed as16:

\[ Q_{\text{LATENT}} = m \cdot \Delta h \]  (2)

Equation 3 calculates the total heat stored or released by a media through a phase change is61:

\[ Q = (m \cdot c_p \cdot \Delta T) + (m \cdot \Delta h) \]  (3)

3.3 | Thermochemical

Thermochemical storage relies on the energy which is absorbed and released depending on breaking and reforming molecular bonds.12 In the charging process, the material separates and supplies an amount of heat. In the discharging process, the 2 parts mix at certain pressure and temperature conditions and energy is released. The materials which rely on this principle are termed “thermo-chemical materials” (TCM)s.62
The definition of a phase (thermodynamically) is the state of material which is homogeneous throughout in the chemical composition and the physical state. Therefore, the materials, which follow the LHS principle and capture or release an amount of heat when changing from 1 phase into another at a specific temperature and pressure, are considered PCMs.

4.1 Classification of phase change material

A considerable variety of PCMs is available in any desired temperature range. According to their chemical composition, PCMs can be classified into 3 main groups: organic compounds, inorganic compounds, and eutectic mixtures. This classification is shown in Figure 3 and is explained in the following points:

4.1.1 Organic phase change material

Although organic PCMs occupy a significant space in the list of PCMs, paraffin and fatty acids are the most renowned because of their high LHS. Other organic PCMs used are high density polyethylene, palmitic acid, and capric acid. Organic PCMs have significantly attracted research attention because of their high latent heat capacity, suitable phase-change temperature, and
stable physical and chemical properties.\textsuperscript{40,71} Organic PCMs are also non-toxic, non-corrosive, and have negligible supercooling and segregation properties.\textsuperscript{56,71} On the other hand, organic PCMs have disadvantages, including low thermal conductivity, flammability, and low enthalpy.\textsuperscript{13} A supercooling phenomenon implies that the latent heat cannot be extracted even at much lower temperatures than the phase transition temperature in the heat recovery stage.\textsuperscript{72} A segregation phenomenon occurs with the separation of the components’ materials over successive freeze/melt cycles.\textsuperscript{73}

### 4.1.2 Inorganic phase change materials

Inorganic materials are further classified as salt hydrate and metallic. The most common salt hydrates are $K_2\text{H}_4\text{O}_4\cdot 6\text{H}_2\text{O}$, $K\text{F}\cdot 4\text{H}_2\text{O}$, $K_2\text{H}_4\text{O}_4\cdot 4\text{H}_2\text{O}$, $\text{LiBO}_2\cdot 8\text{H}_2\text{O}$, $\text{FeBr}_3\cdot 6\text{H}_2\text{O}$, and $\text{CaCl}_2\cdot 6\text{H}_2\text{O}$.\textsuperscript{12,61,74} The most common metallics are Gallium and Cerrobend eutectic.\textsuperscript{12} Inorganic PCMs have some attractive properties, including high latent heat, non-flammable, high thermal conductivity, and low vapor pressure.\textsuperscript{12,51,75} However, they suffer from inappropriate properties, including corrosiveness, instability, and supercooling.\textsuperscript{75}

### 4.1.3 Eutectic phase change materials

An eutectic is a combination of 2 or more components, each of which melts and freezes homogenously forming a mixture of the component crystals during crystallization.\textsuperscript{12,76} Eutectic PCMs are mixtures of materials with proportions that provide the lowest possible melting temperature.\textsuperscript{40} The most common eutectic PCMs are Triethylolethane + water + urea, Triethylolthene + urea, $\text{Mg(NO}_3\text{)}_2\cdot 6\text{H}_2\text{O} + \text{NH}_3\text{NO}_3$, $\text{Mg(NO}_3\text{)}_2\cdot 6\text{H}_2\text{O} + \text{MgCl}_2\cdot 6\text{H}_2\text{O}$, and $\text{Mg(NO}_3\text{)}_2\cdot 6\text{H}_2\text{O} + \text{MgBr}_2\cdot 6\text{H}_2\text{O}$.\textsuperscript{12} The eutectic PCMs have advantages, such as melting or freezing without segregation as well as high volumetric energy storage density.\textsuperscript{67} In spite of their high volumetric storage density, their availability is limited.\textsuperscript{64}

### 4.2 Selection criteria

In fact, any substance can be used as a PCM in TES applications, as long as it can go through the phase transitions when the external conditions are satisfied.\textsuperscript{54} However, for employment as a LHS medium, the material must possess certain desirable properties which are mentioned in Table 1.

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**TABLE 1** The selection criteria of phase change materials\textsuperscript{12,13,40,51,54,67,77-90}

<table>
<thead>
<tr>
<th>Thermodynamic properties</th>
<th>1. Suitable phase-change temperature</th>
<th>2. High latent heat of transition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3. High specific heat</td>
<td>4. High thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>5. Homogenous melting</td>
<td></td>
</tr>
<tr>
<td>Kinetic properties</td>
<td>1. No super-cooling</td>
<td>2. High crystallization rate</td>
</tr>
<tr>
<td></td>
<td>3. High nucleation rate</td>
<td></td>
</tr>
<tr>
<td>Physical properties</td>
<td>1. Favorable phase equilibrium</td>
<td>2. High density</td>
</tr>
<tr>
<td></td>
<td>3. Small/no volume change</td>
<td>4. Low vapor pressure</td>
</tr>
<tr>
<td></td>
<td>5. No phase segregation</td>
<td></td>
</tr>
<tr>
<td>Chemical properties</td>
<td>1. Chemical stability</td>
<td>2. Compatible with container</td>
</tr>
<tr>
<td></td>
<td>3. Non-toxic</td>
<td>materials</td>
</tr>
<tr>
<td></td>
<td>4. Non-flammable</td>
<td>5. Non-explosive</td>
</tr>
<tr>
<td></td>
<td>6. Non-corrosiveness</td>
<td>7. No degradation</td>
</tr>
<tr>
<td>Economic properties</td>
<td>1. Available</td>
<td>2. Low price</td>
</tr>
<tr>
<td></td>
<td>3. Easy recycling and treatment</td>
<td>4. Good environmental performance</td>
</tr>
</tbody>
</table>

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### 5 THERMAL ENERGY STORAGE IN BUILDINGS

TES systems are quite relevant to contemporary global warming scenarios and concerns. The use of fossil fuel in power generation, transportation, and industrial plants is the main reason of carbon emissions. Carbon emissions are considered as the main sources for global warming.\textsuperscript{91} The residential energy sector has a significant share in the world’s energy consumption.\textsuperscript{92} It consumes approximately 40% of the available energy in the world. In addition, economic development in the twentieth century has mainly led to improvements in lifestyles in the residential sector. Throughout the past decades, a consistent increase in the use of residential HVAC systems and units across the developing world can be easily noted. This has led to a corresponding increase in the energy consumption of buildings as well as a significant contribution to carbon emissions and global warming. HVAC systems in buildings must provide both thermal comfort and required ventilation for occupants with suitable energy efficiency.\textsuperscript{9,10}

During the past few decades, the development and the optimization of HVAC systems received increasing attention from builders, architects, and engineers to increase
energy efficiency in the construction of modern buildings. One way of achieving such a goal is by incorporating PCMs into the building materials.9,10 TES systems using PCMs have been accepted as one of the most advanced energy technologies in enhancing energy efficiency and the consumption of buildings. The use of PCMs in buildings promises better indoor thermal comfort for occupants by reducing indoor thermal fluctuation, and lowering overall energy consumption due to the load reduction.93 TES systems have the advantage of managing energy through storage, and they are also useful for reducing the usage of fossil fuels which are the main cause of CO₂ production.91 The purpose of implementing PCMs into building is to virtually reduce the maximum thermal load on the building in order to reduce and regulate the electricity demand for heating and cooling.94

### 5.1 | Integration of phase change materials into building components

PCMs, as a LHS technology, integrated in lightweight building components, are considered as an interesting alternative to sensible heat storage in heavyweight constructions, because of their theoretical volumetric storage density which can be up to 15 times higher than that of traditional storage materials.1,2,83,95 The enhancement of thermal performance for a building integrated with PCMs depends on many factors, including design, climate, the orientation of the construction, and the types of PCMs used.93,96 Thermal storage can be part of the building structure, even for light weight buildings, by the addition of PCMs to gypsum board, plaster, concrete, or other building materials.97,98

PCMs can be incorporated into virtually all the components of a building. In spite of that, the major common PCM incorporation into the building is in the walls, floors, ceilings, roofs, and windows, because of their ease of installation and their effective heat transfer.

The most influential studies, based on citations as well as the authors’ viewpoints, were reviewed based on using PCM integrated with buildings’ construction elements (walls, floors, ceilings, roofs, and windows) to evaluate their performance of reducing the indoor temperature of buildings.

### 5.2 | Review of phase change material integration with building components

Athienitis et al.99 carried out experimental and numerical studies on a full scale model room with the dimensions (2.82 m × 2.22 m × 2.24 m) integrated with PCMs. Gypsum board has been immersed into a liquid butyl stearate type PCM, having a phase change range of 16.0°C to 20.8°C and a latent enthalpy of 30.7 kJ/kg. The model was produced and applied in Montreal. PCMs were joined into gypsum wallboards by 25 wt%. The numerical simulation was conducted using an explicit finite difference model to simulate the transient heat transfer procedure in the walls. From the results, the gypsum wall boards were able to reduce the peak temperature by 4°C during daytime. It was also shown that the simulation results were in close agreement with the experimental results.

Kissock et al.100 utilized a test in basic structures treated to 30 wt% using industrially paraffinic PCM (K18) so as to assess the wallboard’s thermal performance. Test cells were led on the experiment with and without paraffinic PCM wallboards. The outcomes acquired demonstrated that, on sunny days, the phase transition test-cell with PCM was lower than that for control test cell without PCM by 10°C. An improved (finite difference simulation) was capable of predicting the temperature of the interior wall within the test cells with considerable accuracy (average error 1.7°C) depending on environmental data and measured characteristics.

Kissock and Hannig et al.101 carried out an experimental and numerical study to investigate the thermal performance of PCM integrated with wallboards. The experiment used 2 test cells with small scale dimensions (1.22 m × 1.22 m × 0.61 m). The cells used basic light-frame construction practices to evaluate the phase change wallboard for exploratory review. The regular wallboard was introduced in one of the test cells, and the wallboard (soaked up to 29% by weight with K18) was introduced in the other test cell. A finite-difference simulation model was adjusted and approved by utilizing experimental information to anticipate inside wall temperatures in the test cells. The outcomes showed that maximum temperatures in the PCM test cell were dependent upon to 10°C not as much as that utilizing the ordinary wallboard during sunny days.

Harald Mehling102 presented his project report at the 8th Expert Meeting and Work Shop, Kizkalesi, Turkey on the (Innovative PCM Technologies) in which it was recommended that windows are introduced with PCM shutters to reduce the room temperature by 2°C and to defer the ideal shading temperature by 3 hours.

Farid and Khudhair13, and Tardieu103 built a variety of symmetric wood-framed test cottages on the Tamaki Campus, University of Auckland, New Zealand. The single-storey building measurements were 2.60 m × 2.60 m × 2.60 m, providing a floor zone of 5.76 m² each. Their wooden casings were made of 9.8 cm × 6.3 cm strong pine wood profiles. Windows were introduced on the north side walls and doors on the east side walls. The 1.25-cm-thick sheets of plywood were
utilized as the outside wall covering. The wall cavities were loaded with fiberglass thermal insulation. Tardieu\textsuperscript{103} lifted the test cabins from the ground. The PCM-upgraded gypsum sheets were subjected to field tests where the seasonal energy performance was identified utilizing entire-building energy simulations. With the end goal of this project, gypsum sheets were incorporated with 27 wt% of PCM with a liquefying range of 18°C to 23°C and a latent heat of melting of 134 kJ/kg. Overall building energy simulations using EnergyPlus package were performed to predict the thermal energy performance. Both the simulation results and field test information have demonstrated that the use of PCM-upgraded gypsum sheets enhances the thermal inertia of buildings (Figure 4). One of the conclusions was that the extra thermal mass of the PCM can decrease the daily indoor temperature vacillation by up to 4°C on an ordinary summer day, as shown in Figure 5.

Schossig et al\textsuperscript{104} carried out a parametric study with a building simulation program to identify promising fields of application. For this purpose, they implemented a model in the open-source building simulation tool ESP-r to calculate the non-linear thermal properties of construction materials. They focused on applications with PCMs in interior wall materials to prevent overheating. To validate the simulation results, they constructed a test facility for wall samples of 50 cm × 50 cm. The simulated results showed that the air temperature of a room with PCMs is less than that of a room without PCMs by 3°C, as shown in Figure 6.

Some interesting field studies exploring the consideration of PCMs into concrete, bricks, insulations, and other building envelope materials were performed by a research group in the University of Lleida, Spain. Cabeza et al\textsuperscript{105} analyzed PCM and its performance by using PCM-enhanced concretes to build one of the 2 symmetric test cottages. The other test cottage was built with ordinary concrete for reference. An entire-building energy model TRNSYS utilizing the PCM subroutine was created by the University of Lleida and was approved based on the laboratory experimental outcomes. Ibanez et al\textsuperscript{96} was utilized for energy performance investigation. The paraffinic PCM with a melting point of 26°C and a latent heat of 110 kJ/kg were utilized as a part of this work. The obtained results demonstrated that hovel PCM incorporation in the concrete decreased the temperature on the test hut containing PCM. The temperature contrast between the reference cabin and the PCM cottage was around 2°C (Figure 7). Additionally, the air in the reference cabin achieved the same day top temperature (36°C) approximately 2 hours prior in contrast with the PCM cottage. For the numerical model, an average maximum room temperature reduction of 3°C was obtained.

Ahmad et al\textsuperscript{106} improved the thermal performance of light envelopes, which are normally being utilized as part of current modern structures by using PCM incorporated in vacuum insulation panels (VIP). Two test cells were designed, and each one was composed of 1 coated face and 5 opaque faces protected with VIPs. The thermal

FIGURE 4 Temperatures inside the cabin with PCM [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Temperatures inside cabin 1 and 2 [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Simulated resultant room temperature profile for a lightweight construction office with and without PCM in the interior plaster [Colour figure can be viewed at wileyonlinelibrary.com]
inertia of one of the cells was expanded by introducing 5 PCM panels. During summer, the effectiveness of the PCM test cell was observed to be striking with a decrease in temperature of 20°C. In winter, the PCM cell avoided negative indoor temperature efficiently as shown in Figure 8.

Shilei et al.\textsuperscript{107} experimentally assessed the thermal performance of incorporating gypsum wallboards with 26 wt\% PCMs, which were a blend of capric and lauric acids. The experiment location was in Shenyang in northeast China, and the test was conducted in winter. The thermal performance of the model room (5 m × 3.3 m × 2.8 m), with and without PCM gypsum wallboards, was observed for 3 sequential days. During the measurement period, the rooms were heated by an electric heating film (2040-W capacity) introduced in the roof. As indicated by the test outcomes, the greatest temperature change in the PCM wall room was 1.15°C, lower than that of the normal wall room (Figure 9). Besides, the thermal stream in the PCM wall room was lower than that of the normal wall room. Along these lines, PCM wallboards can reduce the temperature fluctuations inside buildings as well as the size of heating equipment and hence decrease the related operating cost.

Voelker et al.\textsuperscript{108} applied, experimentally, microencapsulated PCM incorporated in the plaster in Weimar, Germany. The experiment used 2 test rooms developed with lightweight walls. The PCM was incorporated in the plaster and was connected to 1 test room. The outcomes demonstrate that the maximum temperatures can be reduced up to 4°C by the use of PCM consolidated plaster, as shown in Figure 10. Nevertheless, it is observed that if a few consecutive hot days occur, the PCM cannot release the stored heat and this causes loss of their heat storing capacity. To avoid this issue, powerful night ventilation (NV) can be connected.

Kuznik et al.\textsuperscript{109} evaluated, experimentally, the thermal conduction of a light-weight-building-inner-divider wall using a PCM-based wallboard. The experimental study was done in a full-scale test where the surrounding environment (temperature and solar radiation) was controlled to simulate an agent summer day. The installation consists of 2 identical enclosures, called “cell 1” and “cell 2,” which dimensions are 3.10, 3.10, and 2.50 m. The first cell was constituted of 60% microencapsulated PCM, with the melting temperature of 22°C. The final form of the PCM material was flexible sheets of 5-mm thickness with a density of 1019 kg/m\(^3\). It was demonstrated that the vacillation of the inner air temperature and the inside wall surface temperature were decreased by 4.7°C and 3.5°C separately, when a PCM wallboard was utilized.
Furthermore, a pinnacle removal of 40 minutes on the inside wall surface temperature was noted.

Kuznik and Virgone\textsuperscript{110} experimentally tested a comparative light building envelope with a microencapsulated copolymer composite PCM wallboard with 60% paraffin. The test room was composed of 2 symmetric fences in areas called “Test Cells 1 and 2.” The test cell had dimensions of 3.10 m × 3.10 m × 2.50 m and was limited on 5 sides by air volumes controlled at a steady temperature. The sixth face was a coated facade that disconnected the test cell from a climatic room. The experiment used the controlled test cell and assessed the aftereffects of 3 cases, namely: a summer day, a winter day, and a mid-season day. From the test results, it was found that the air temperature in the room with PCMs diminished up to 4.2°C (see Figure 11).

Memon et al\textsuperscript{111} researched the plausibility of utilizing soda-lime squander glass powder (GP) for the application of LHS. n-octadecane was stacked into GP. The thermal execution of a cement bond glue composite PCM was additionally assessed. The most extreme mass percentage of n-octadecane held by GP was observed to be 8. Fourier transformation infrared spectrum analysis (FT-IR 57) demonstrated that the association between the parts of composite PCMs is physical in nature. The melting and solidifying temperatures of the composite PCMs were found to be 26.93°C and 25.03°C, while the corresponding latent heat of melting and freezing were 18.97 and 18.95 J/g, respectively. A thermo-gravimetric analyzer and thermal cycling test results affirmed that the composite PCM is thermally stable. The thermal performance test demonstrated that the cement bond glue board with composite PCMs reduced the indoor temperature by 3°C (Figure 12). It was inferred that the composite PCM can be utilized for TES applications in buildings. Also, its utilization will give manageable solutions for reusing waste glass.

Zhou et al\textsuperscript{112} carried out a numerical study on the thermal performances of shape-stabilized PCM (SSPCM) plates in buildings for free cooling in summer. They also investigated the thermal effects of SSPCM plates as inner linings on the indoor air temperature under NV conditions. A typical south-facing middle room in a multi-layer building in Beijing, China, was considered as the model room for analysis, which has only 1 exterior wall (the south wall) while other walls are all interior envelopes. The dimensions of the room are assumed as 3.9 m (length) × 3.3 m (width) × 2.7 m (height). The south wall is externally insulated with a 60-mm-thick expanded polystyrene (EPS) board. There is a 2.1 m × 1.5 m double-glazed window in the south wall and a 0.9 m × 2 m wood door in the north wall which is adjacent to another room or the corridor. The results obtained showed that the SSPCM plates could diminish the daily maximum temperature by up to 2°C because of the cool stockpiling during the evening.

Ansuini et al\textsuperscript{113} developed radiant floor boards with granulated PCM with consolidated pipes for heating and cooling. The results showed that the PCM boards could be helpful in summer, yet their performance was not useful in winter. The expanded resistance between the pipes and the dissolved granulated PCM is the reason for the awful execution of PCM boards during the warming seasons. With the plan to diminish the thermal resistance of granulated PCM, a special steel framework (acting as a thermal diffuser) was intended to advance the inner structure of the radiant floor. A numerical simulation was done after this advancement in winter, mid-season, and summer season. It was inferred that, in the summer season, the amount of cooling water to keep the temperature within the comfort range was decreased by 25%; however, in the winter season, there was no
impact. In the mid-season, the floor temperature pinnacle was decreased by around 3.5°C (Figure 13). This framework is viably advantageous to keep up the room temperature agreeable with no additional energy source.

Kendrick and Walliman\textsuperscript{114} reviewed different simulations and demonstrated that a phase change temperature of 22°C, which is the mid-purpose of the picked comfortable zone range (20°C–24°C), was the best for the contemplated case. In commercial buildings, peak temperatures can be decreased by around 3°C to 4°C, and day hours when the temperature is over 24°C can be diminished by 80% (Figure 14).

Castell et al\textsuperscript{115} evaluated a full-scale test to study the macro-encapsulated PCM added to the building envelope for field cooling. Five different cubicles were built using different Mediterranean typical constructive solutions to be able to compare the results obtained with the concrete cubicles. The internal dimensions of the new cubicles are (2.4 m × 2.4 m × 2.4 m). The cubicles are located in Puigverd de Lleida.

Three cubicles using different insulating solutions are compared:

1. Reference cubicle (Reference): This cubicle has no insulation.
2. Polyurethane cubicle (PU): The insulation material used is 5 cm of spray foam polyurethane.
3. PCM cubicle (RT27 + PU): The insulation used is again 5 cm of spray foam polyurethane and an additional layer of PCM. CSM panels containing RT27 paraffin are located between the perforated bricks and the polyurethane (in the southern and western walls and the roof).

Their results demonstrated that the interior temperature was lessened by up to 1°C and turned out to be steadier under free-floating conditions (Figure 15). Entrop et al\textsuperscript{116} and Prins et al\textsuperscript{117} examined and evaluated PCM-improved floor systems in 4 plastic holders with the dimensions of 1.0 m × 1.0 m × 0.5 m. These dimensions made the test boxes different from and contrary to reference modern Dutch residential structures. Within each experimental compartment, thermocouples were installed to measure the temperature profiles crosswise with the building shell segments. Two out of the 4 test compartments had the floors containing microencapsulated paraffinic PCM, of a dissolving temperature of approximately 23°C. Two types of thermal insulated envelopes were utilized (heavy and light insulation). The test has demonstrated that indoor maximum space temperatures can be lessened by up to 4.0°C and 3.7°C in the test holders utilizing PCM-improved floors, for heavy and light insulated envelope forms, respectively.

Gowreesunker and Tassou\textsuperscript{118} explored the performance of a PCM-clay composite board put on the walls of a custom constructed test-cell, with wall properties like a timber outline wall. The board contained 21% PCM with a mean enthalpy of fusion 16.5 kJ/kg and a melting temperature range of 12°C to 22°C. A test cell with the inward measurements of 1.3 m × 0.8 m × 1.4 m and
coated veneer measurements of 1.3 m × 0.8 m was developed to give a controlled environment where in the transient conduct of air and PCM could be examined. The wall/ceiling/floor system was made of 48-mm plywood, 90-mm insulation, and 18-mm plywood with skinned PCM mud sheets set within the surface of the walls only. The study comprised the experimental approval of a CFD numerical model of the test-cell, later used to research diverse forms of the PCM sheets’ performance. Initially, applying the PCM sheets brought in 3°C lessening in peak air and surface temperatures, in respect to gypsum plasterboards, avoiding the overheating inclination of the building space.

Shi et al.119 carried out an experimental study on the performance of using macro-encapsulated PCM incorporated into concrete walls in the subtropical climate of Hong Kong. The experiment included a small-scale model of an indoor air temperature level at the focal of the test rooms to highlight the effect of 3 positions of PCM in concrete walls (outside and inside fortified with concrete walls, as well as overlaid inside the concrete walls). The obtained results show that the air temperature level inside the room models was balanced by the macro encapsulated PCM; all things considered, its position in the concrete walls played an important role in its productivity. A thermal performance examination of 3 variables cases exhibited that the best inside temperature control was accomplished by the model with the PCM overlaid inside the concrete walls with a 4°C lessening in the peak temperature.

Royon et al.120 continued their previous experimental study121 and carried out a numerical study to determine the ideal quantity of SSPCM to be brought into the similar floor board to manage the building’s inside temperature. To examine the thermal performance of the PCM floor, a numerical model of the floor with 5 annular setups of PCM (different percentages of PCM concentrations) was developed using Comsol Multiphysics. The simulation outcomes were approved against experimental estimations, and a decent correlation between the 2 methodologies was made. The results showed that the surface temperature varieties in the floor board were diminished by roughly 2°C and the impact of maximum load removal was intensified by the fuse of PCM.

Silva et al.122 led a full-scale experimental model in a Mediterranean climate to analyze the thermal performance of 2 comparative window shutters, present and absent of PCM, in 2 cells’ compositions. The external dimensions of the test cells are 7.00 m × 2.35 m × 2.58 m (length × width × height) and the internal floor areas are 5.17 m². The main cell structure is made of galvanized steel profiles, and the external opaque walls are composed by sandwich panels with 4 cm of insulation material (mineral wool). The roof is composed of sandwich panels with glass fiber and an anti-steam protection layer (total of 8 cm). The internal wall partition that divides both compartments is also a sandwich panel reinforced with 2 layers of 4 cm of insulation (4 cm on each side). The floor, besides of the steel structure, is composed of 18 mm of insulation material with a vinyl finish. The air temperature was measured inside the test cell, which comprised 2 next-to-each-other cubicles. The observed diminish in temperature was found to be 16.6°C in the peak air temperature inside the cell with the PCM shutter in contrast to that of the reference cell (Figure 16).

Cui et al.123 carried out an experimental and numerical study to decide the ideal position of PCM in a room. A macro encapsulated lauryl alcohol-lightweight aggregate (LA-LWA) was prepared for subsequent development of TES concrete (TESC). The macro encapsulated LA-LWA was obtained by encapsulating the surface of LWA with epoxy and modified cement paste. Computer simulations for the room model were then performed using the building energy simulation program EnergyPlus. As indicated by the outcomes, it was observed that PCM incorporated into walls gave the best thermal performance. The best thermal performance of the room model with PCM incorporated into walls was found when the decrease in room temperature was up to 10°C (Figure 17).

Xuming Mi et al.124 showed the inside surface temperature profiles alongside temperature profiles for the southern wall (in the presence and absence of PCM) on a normal 1-day climate in June. The effect of PCM on the energy consumption of a typical multistory office building, located in 5 different cities (Shenyang, Zhengzhou, Changsha, Kunming, and Hong Kong), representing different climate regions of China, was simulated for a whole year using EnergyPlus. The PCM used (PCM27 having a melting temperature of 27°C), was directly selected from the simulation program.

FIGURE 16 Internal air temperature comparison and its decline between cubicles [Colour figure can be viewed at wileyonlinelibrary.com]
DesignBuilder. The office building (with PCM) situated in Changsha decreased the most extreme temperature by 2.1°C, while, in Hong Kong, the peak temperature diminished by 1°C.

Barreneche et al125 directed a current experimental study to assess the thermal and acoustic performance of a shape-settled PCM layer for an intermediate wall of a building in Spain. The new shape balanced out PCM was made out of a polymeric matrix, 12% paraffin PCM, and electric-arc furnace dust (EAFD). The thermal review required in-situ estimations of the surrounding temperatures and wall temperatures for 2 identical cubicles, with and without PCM thick sheets. The aftereffects of the thermal investigation exhibited the capability of the PCM thick sheet to diminish the inside temperature by up to 3°C.

Akeiber et al8 built 2 identical full-scale test models with sizes (3 m × 2.5 m × 2 m) at the University Technology site of Iraq. For the purpose of investigation of the thermal performance of these 2 test rooms, PCM (which is composed of 40% oil and 60% wax) was incorporated into the walls and the roofs to evaluate their effects under the Iraqi climate. The wall and roof of 1 model were integrated with PCM, and those of the other model were integrated without PCM. The thermal behaviors of these models were compared to observe the performance of PCM. The obtained results showed that the incorporation of the PCM in the building reduced the room temperature peak load by 5°C for the same time period (Figure 18).

Navarro Farré et al126 carried an experimental study to analyze the thermal performance of an insulated constructive system and another one with (PCM) located in the envelopes as passive cooling system. The experiments were done in the experimental facility of Puigverd de Lleida, Spain. Three different cubicles, with the same inner dimensions (2.4 m × 2.4 m × 2.4 m) and orientation (N-S, 0°), with no windows, and with an insulated metal door in the north wall, were studied. The 3 cubicles are built based on the traditional brick system which consists of 2 brick layers with an air gap between them. The cubicle, called “Reference cubicle” (REF), has no insulation in its wall constructive system; on the other hand, the Polyurethane cubicle (PU) is insulated between the brick layers with 5 cm of spray foam polyurethane. In the same way as the previous cubicle described, the PCM cubicle (PCM) is insulated with polyurethane, but it also contains a PCM layer on the internal face of the insulation. The PCMs are macro-encapsulated in aluminum panels which are implemented in the southern and western walls, and in the roof. The total amount of PCM for each wall/roof is 33 kg. The results showed that the PCM cubicle managed to decrease more indoor temperature than both the Reference cubicle and the Polyurethane cubicle.

Alam et al127 carried out an experimental study to investigate the potential of (PCM) in reducing the heating/cooling energy consumption of residential houses along with several factors influencing the effectiveness of PCM using EnergyPlus. Simulations were carried out using 5 different phase change temperature ranges at 8 Australian cities which represent 6 climate zones. A single room house was considered for the simulation. The results showed that the daytime zone temperature was reduced by 1.7°C, and the nighttime zone temperature was increased by 1.3°C during April in Melbourne through the incorporation of PCM, as shown in Figure 19.

Kim et al128 prepared shape-stabilized (SSPCM) by impregnating hexadecane, as a PCM, into exfoliated graphite nanoplatelets (xGnP), as a supporting material. In addition, mortar with the prepared SSPCM was investigated in terms of developing advanced building materials.
with TES properties. The heating and cooling behavior test of the SSPCM mortar demonstrated the improvement of the thermal mass and inertia by the mortars containing the SSPCM. Consequently, the thermal behavior of the test buildings made of the hexadecane/xGnP SSPCM mortar was computationally investigated using EnergyPlus. The internal air temperature variations, for 5 days in the test buildings, in winter, spring, and summer time, were simulated. The results showed that the test house temperature was approximately higher than that of the non-treated test house (the control) by 9.1°C, 5.5°C, and 4.8°C, during winter, spring, and summer, respectively.

Nghana et al.\textsuperscript{129} carried out numerical and experimental studies to investigate the potential of PCM. The field experimental study is conducted using twin side-by-side buildings exposed to the same interior and exterior boundary conditions, and EnergyPlus, after being benchmarked with the experimental results, is used for the numerical study. In the experimental study, 2 buildings located side by side each other, with and without PCM, are monitored synchronously for the month of September, 2014. The numerical study was carried out for an existing residential apartment unit with a particular emphasis on the effects of different design parameters, such as orientation and window-to-wall ratio. Preliminary analyses of experimental data show that PCM are effective in stabilizing the indoor air by reversing the heat flow direction. In fact, the indoor air fluctuation was reduced by 2.7°C, respectively.

Ramakrishnan et al.\textsuperscript{130} carried out a numerical study and presented a design optimization related to the application of PCM within buildings, which aims to maximize the utilization of latent heat capacity to improve indoor thermal comfort during summer season. Two performance indicators are developed: efficiency coefficient (a representation of the effective utilization of LHS capacity) and effectiveness coefficient (a representation of improvement of indoor thermal comfort). Results revealed that the PCM incorporation yields a reduction in the peak indoor operative temperature of 1°C and 2.5°C on 2 consecutive days (see Figure 20).

Sage-Lauck and Sailor\textsuperscript{131} built a newly, constructed passive house duplex to monitor indoor environmental quality metrics and building energy use. One unit of the duplex was outfitted with 130 kg of PCM (type BioPCM), while the other unit served as a control. The performance of the PCM was evaluated through an analysis of the observed data and through an additional computer simulation using an EnergyPlus, whole-building energy simulation model validated with observed data. The results showed that the PCM in the west unit could reduce the peak indoor temperature by 0.9°C, more than that of the unit without PCM (east unit) (see Figure 21).

Guichard et al.\textsuperscript{132} focused on the integration of PCM in the roof with a non-ventilated air layer, in order to assess thermal performances of a dedicated test cell, especially for thermal comfort. Experimental equipment was set up at Reunion Island under tropical and humid climatic conditions. A mathematical model, based on the apparent

![FIGURE 19 Zone mean air temperature (Colour figure can be viewed at wileyonlinelibrary.com)](image1)

![FIGURE 20 Effect of PCM application on 2 consecutive days (Colour figure can be viewed at wileyonlinelibrary.com)](image2)

![FIGURE 21 Compares the observed east (without PCM) and west (with PCM) unit air temperatures](image3)
heat capacity method, is used to predict the actual impact of PCM on thermal comfort. On the experimental platform, 4 small-scale cells (called ISOTEST) and a normal-scale building (called LGI) are installed. The ISOTEST cell model is a reduction in size of the LGI building. In order to simulate the dynamic thermal behaviour of a multizone building according to its description and the climate of its location, a prototype of building thermal software, which integrates the hygrothermal and aeraulic phenomena called “ISOLAB,” has been developed. It is observed that the indoor air temperature is higher in the non-PCM building than that in the PCM building by 1.7°C throughout the whole day and by 1.1°C throughout the nighttime.

Kim et al.\textsuperscript{133} developed a PCM model based on the specific heat capacity of the SSPCM sheets measured using a thermostatic chamber, and the simulations' results were obtained using EnergyPlus. The validity of the PCM model was examined by comparing the simulation and experimental results, which showed a similar temperature tendency. The model was then examined to determine the applicability of PCM to the various climates in Japan through annual heating load simulations. Three identical test huts were constructed in the Chiba Prefecture, Japan. The target buildings were classified as Type A (no PCM, reference), Type B (only the floor contained PCM), and Type C (the floor, walls, and ceiling contained PCM) using a standard Japanese house. Types B and C had the same amount of PCM as 2.5 mm SSPCM sheets were installed. The simulation was run for 21 cases, with one being run for each type of building in 7 Japanese climates. The results showed that the peak indoor temperature during the daytime in Hut B decreased by 2.0°C, while it decreased by 2.6°C in Hut C. The averages of the measured indoor temperatures, and the values calculated by EnergyPlus were compared.

Lei et al.\textsuperscript{134} investigated the integration of cool colored coating and PCM for building cooling through experimental and numerical studies. Four types of coating systems were prepared to investigate the cooling performance of combining cool paint and PCM. Type 1 (Control) is a control system where a normal skim coat was coated with normal paint on the surface and type 2 (CP) is the normal skim coat with cool paint coated on the surface. Type 3 (PCM) adopts a PCM-modified skim coat with the normal paint coated on the surface, while type 4 (CP + PCM) is the PCM cool colored coating system where the PCM-modified skim coat was coated with the cool paint on the surface. The sample was fitted in a well-insulated cubic box with the dimension of 70 mm × 200 mm × 130 mm. The top surface of the sample with the paint faced to a halogen tungsten lamp, simulating a natural sunlight condition over the box. Both the exterior and interior surface temperatures ($T_{ex}$ and $T_{in}$) and the internal air temperature ($T_{air}$) were measured. Whole building energy simulations were conducted by using the software EnergyPlus to evaluate the cooling energy savings through the combined use of cool paint and PCM in a tropical climate. A numerical building model was developed based on a single-storey building located in Nanyang Technological University, Singapore. It is a rectangular-shaped building consisting of 2 rooms, ie, a test room and a store room. The incorporation of 20 wt% PCM microcapsules into the skim coat also leads to a reduction in the peak interior air temperature. The peak internal air temperatures of the type 3 (PCM) and type 4 (CP + PCM) were 0.8°C and 3.7°C, respectively, lower than that of the control system (Figure 22).

Yang et al.\textsuperscript{135} presented a study to derive the reduction effect on the urban heat island (UHI) phenomenon by applying PCM in building roofs. In their study, an effect of reduction in surface temperature was verified through a mock-up performance test on a PCM cool roof system, manufactured by combining a PCM and radiation hardened wood (wood-plastic composite WPC), and an analysis of the temperature distribution simulation was conducted by utilizing the mock-up test results to verify the temperature reduction in the canopy layer and roof surface. This study conducted a test with 3 specimens: WPC, WPC + Bio25 (phase change: 25°C), and WPC + n-docosane44 (phase change: 44°C). The study result showed that the temperature was decreased by 6.8°C on average when the PCM cool roof system was applied.

Figueiredo et al.\textsuperscript{136} presented the results of a study on indoor thermal comfort and energy efficiency regarding the PCM's positive role when applied to new constructive solutions, inside a building with a geothermal system linked to the air conditioning system. The PCM study

![FIGURE 22](https://wileyonlinelibrary.com) Temperature profiles of the internal air during the thermal tests of type 1 to 4 [Colour figure can be viewed at wileyonlinelibrary.com]
was based on real and simulated investigations in 2 rooms of a new university department at the Aveiro campus. Higrothermal monitoring (indoor air temperature) of 2 rooms in which one of them has PCM panels incorporated into a gypsum board partition wall and into a suspended ceiling. The scope was driven to investigate the potential of these solutions for overheating mitigation. The numerical study was conducted by using EnergyPlus software. In the scope of this optimization process, constructive solutions with the incorporation of different types of PCMs with different melting temperatures and enthalpy, and different flow rates of natural ventilation were combined to investigate the potential and the payback time of these novel solutions. The results showed that the PCM application in one of the rooms led to a reduction of 2°C in indoor temperature, less than that of the other room.

Siddiqui et al. compared and contrasted the thermal performances of 2 PCM s in the Toronto’s Net-Zero Energy House with commonly available forms of thermal masses using the simulation software (TRNSYS). The roof assembly consists of drywall on 19 mm × 19 mm furring and 0.15-mm polyethylene vapor retarder attached to the bottom of the 294-mm pre-engineered Ijoists. Walls below grade are of the insulating concrete form and have 6.3 cm of a rigid polystyrene board with a waterproof membrane. The results exhibited that the performance of a novel solid-solid phase PCM, recently developed by researchers at Dalhousie University and known as “DalHSM-1,” could be comparable to a commercially available PCM from BASF (Micronal) in the heating mode. The results indicated that DalHSM-1 could reduce the peak indoor temperature by 8.8°C in winter and 0.2°C in summer, while Micronal could reduce it by 9.1°C in winter and 1.7°C in summer.

In order to validate the model developed, several dynamic measurements of an insulated wall, with PCM, were carried out in a laboratory setup, and the experimental data were compared with the simulated data of the same setup by Fateh et al. The test chamber consists of 2, separate plates controllable by the 2 thermostats; one at the top and one at the bottom. As a sample, some XPS insulation with a DuPont Energain board as a PCM layer was used. The PCM was inserted at different positions of wallboards. The PCM proved its effect on reducing the indoor temperature of the model it integrated in.

Akeiber et al. evaluated the thermal performance and economy of a newly developed PCM called “local paraffin.” This PCM, which can be used in potential (TES) systems, was extracted from Iraqi crude petroleum waste products and encapsulated in the building construction. Two identical test rooms were constructed by incorporating such paraffin (40% oil +60% wax) on the roof and walls for determining its effect on the heat transfer over the temperature range of 40°C to 44°C. Two identical test rooms of the same internal dimensions of (3 m × 2.5 m × 2 m) were constructed to examine the energy savings and thermal comfort improvement capacity of the developed PCM. The stable structure is formed by enclosing the PCM (paraffin) inside an aluminum container. Figure 23 shows the effects of the PCM panel (over the concrete slab) on the heat transfer for the month of August (peak summer). It is observed that the room temperature at 1.5-m height without PCM is higher than that of the one with the PCM incorporated panel by 10°C.

Abuelnuor et al. carried out an experimental study to evaluate the performance of using PCM systems in buildings. The PCM used was calcium chloride hexahydrate (CaCl2·6H2O) whose latent heat is 187.8 KJ/kg K and melting point is 30°C. They built 2 small scale models (with and without PCM) with the dimensions (0.36 m × 0.30 m × 0.34 m). The construction material was compressed wood with the thermal conductivity of 0.17 W m⁻¹ K⁻¹. Four thermocouples were attached to the indoor air temperature inside the model, with and without PCM. The results showed that the PCM in the building structure reduced the peak indoor temperature by 3.5°C for the same time period, as shown in Figure 24.

Ramakrishnan et al. carried out a numerical study to investigate the potential applications of PCM to be integrated into buildings to reduce heat stress risks during extreme heatwave periods. A detached single-storey house, without an active air-conditioning system, is refurbished with the installation of macro-encapsulated Bio-PCMTM mats as inner linings of walls and ceilings. Dynamic thermal simulations have been undertaken to reveal the performance of, as well as factors influencing,
the adoption of PCM to reduce heat stress during heatwave periods. A discomfort index has been used as an indicator for measuring the indoor heat stress risks. The results showed that PCM refurbishment, with and without NV, can effectively reduce indoor temperature, indicating a significant advantage in improving the occupant’s health and comfort (see Figure 25).

6 | CONCLUSION

PCM is an effective substitute to traditional cooling systems. PCM, which is a practical application of the LHS concept, can thereby act as a smart material to control the indoor temperature of a building. The significance of PCM is apparent when it is combined with light-weight structures on the ground, that, with its considerable energy storage density, can anticipate high temperature changes in day-time and balance out temperatures in the suitable comfort range.

Different types of PCMs are available and accessible, which can be ordered into 3 distinct categories: organic, inorganic, and eutectic PCMs. To be efficiently combined into the building envelope and to give warm comfortable conditions, the PCM needs to meet certain criteria. These criteria can be classified as: thermodynamic, chemical, physical, and kinetic.

In this review, it was observed that the organic type (paraffin) got the most attention from researchers due to its desirable properties, such as negligible supercooling and segregation, low price, chemical stability, non-corrosiveness, and high latent heat fusion. However, paraffin suffers from flammability and low thermal conductivity. On the other hand, other types of PCMs, such as salt hydrates, showed appropriate characteristics, such as high latent heat, non-flammability, and high thermal conductivity. However, their usage was observed to be limited due to their corrosiveness, instability, and supercooling. Furthermore, the eutectic PCMs were not used in these studies, in spite of their high volumetric storage density. This is due to their low availability and the lack of available data on their properties. This study also evaluated the thermal performance of different integration PCM methods into buildings segments. The numerical studies showed that the effective software to assess the facility of applying PCM in buildings were EnergyPlus, TRNSYS, ANSYS, DesignBuilder, and Esp-r. The experimental studies showed that the available strategies to incorporate PCM into building components were wallboards, Gypsum boards, PCM shutters, PCM improved gypsum sheets, gypsum plasterboards, PCM-enhanced concretes, VIP, GP, SSPCM plates, granulated PCMs with consolidated pipes, plastic holders, floor boards, window shutters, macro encapsulated laurel alcohol-lightweight aggregate (LA-LWA), shape-settled PCMs, exfoliated graphite nanoplatelets (xGnP), cool colored coating, and wood-plastic composite (WPC).

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