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Review article

An in-depth review of phase change materials in concrete for enhancing building energy-efficient temperature control systems

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ABSTRACT

To address the environmental and energy challenges in modern construction, integrating phase change materials (PCMs) into concrete has emerged as a sustainable solution. This literature review critically examines the incorporation of PCMs in concrete, highlighting its potential to transform building energy efficiency and thermal management. The study categorizes PCMs into four main types: organic, inorganic, eutectic, and bio-based, each with distinctive properties and applications. Additionally, this review explores the thermal energy regulation of PCMs in concrete, focusing on integration methods like microencapsulation and vacuum impregnation while maintaining structural integrity. Practical applications demonstrate that PCMs help mitigate temperature fluctuations, enhancing indoor comfort and reducing energy demand. However, despite their energy-saving benefits, the integration of PCMs can negatively affect the mechanical properties of concrete. Empirical evidence from multiple case studies under various climatic conditions further validates the effectiveness of PCM-enhanced concrete in real-world scenarios. In summary, while PCMs can significantly improve thermal efficiency in buildings and reduce energy consumption, it is crucial to balance thermal management performance with mechanical properties through appropriate PCM selection and advanced integration techniques. Future research should focus on enhancing the dispersion, stability, and long-term durability of PCMs in concrete to ensure they maintain their effectiveness without compromising structural integrity. In addition, addressing the fire resistance and environmental stability of PCMs under various conditions will be essential for broader adoption in construction.

1. Introduction

Portland cement concrete has long been the most widely used material in construction due to its durability, mechanical properties, and cost-effectiveness. However, traditional concrete materials are increasingly unable to meet the demands for energy-efficient and sustainable building solutions, especially in climates with significant temperature fluctuations. The lack of inherent thermal management in these materials results in higher energy consumption for heating and cooling [1]. In response to global challenges such as climate change and energy crises, PCMIC have emerged as a promising innovation, gaining significant attention from researchers and industry professionals for their potential to transform modern building technologies. The core concept of PCMIC is to integrate PCMs into traditional concrete, endowing it with unique thermal management properties. Recent research has focused on enhancing the thermal performance of concrete through various methods of PCM incorporation, including direct mixing into the concrete matrix, microencapsulation to prevent leakage, and vacuum impregnation, all of which aim to optimize energy storage and release within the building envelope [2]. PCMs undergo a solid-to-liquid transformation at designated temperatures, during which they absorb or discharge considerable latent heat. The attributes of heat acquisition and dissipation allow PCMIC to effectively mitigate the temperature fluctuations, providing buildings with a more stable internal thermal environment. During the day, PCMs within the concrete absorb heat from the sun, preventing indoor temperatures from rising too sharply and at night, these materials release the stored heat, helping to maintain a warmer indoor environment [3,4] (as depicted in Fig. 1). PCMIC is particularly well-suited for application in buildings with high energy demands for temperature regulation, such as residential homes, office buildings, and industrial structures in regions with extreme or

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Nomenclature

PCM	Phase change material
PCMIC	Phase change material integrated concrete
HVAC	Heating, ventilation, and air conditioning
PEGs	Polyethylene glycols
PTFE	Polytetrafluoroethylene
DSC	Differential scanning calorimetry
TGA	Thermogravimetric analysis

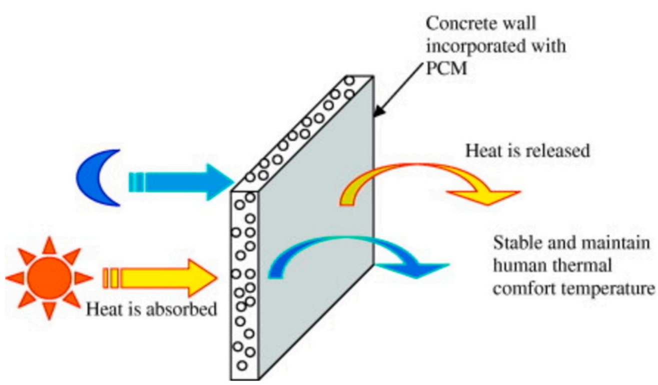

Fig. 1. The working principle of concrete walls incorporating PCMs. During the day, the concrete wall absorbs and stores heat, which is subsequently released during cooler periods, thereby maintaining stable indoor thermal comfort [4].

fluctuating climates. By stabilizing indoor temperatures, PCMIC reduces reliance on external heating and cooling systems, making it an ideal solution for energy-efficient construction. The primary advantage of PCMIC lies in its ability to regulate temperature through phase change, providing efficient thermal management. Compared to traditional insulation materials and reflective coatings, PCMs not only reduce heat transfer but also store and release heat as needed across seasons. In contrast to thermal mass materials like brick or stone, PCMIC offers greater latent heat storage and more flexible temperature control capacity. Additionally, it is compatible with various building types and can be integrated with other energy-efficient strategies, such as passive house designs, for enhanced energy savings.

With the increasing emissions of greenhouse gases worldwide, climate change has become an imminent issue [5]. According to data from recent studies (2022), buildings account for approximately 40 % of global energy consumption [6]. The construction and operation of buildings are responsible for about 28 % of global energy-related CO_2 emissions [7]. These figures highlight the urgent need to improve energy efficiency in the building sector to mitigate the effects of climate change and reduce the carbon footprint of construction activities. Fig. 2 provides insights into the energy expenditure and the production of greenhouse gases in building construction. Fig. 2(a) exhibits that steel rolling dominates energy consumption at 58.9 %, followed by cement production at 27.8 %, and Fig. 2(b) indicates that steel rolling is the primary source of greenhouse gas emissions at 57.6 %, with cement products also significant at 30.0 % [8]. These data highlight the substantial environmental impact of building construction, particularly in energy use and emissions. Traditional building materials like ordinary concrete can offer good insulation but often fail to provide comfort under extreme temperature conditions, leading to increased energy use for heating or cooling. In contrast, PCMIC effectively addresses the energy challenges associated with traditional concrete. Meng et al. [9] executed a study on the performance of PCMIC panels in China during summer and winter seasons. They observed a temperature decrease of 4.3–7.7 °C in the summertime and an increase of 6.9–9.5 °C in the winter. The outstanding thermal management capabilities of PCMIC can lead to lower energy consumption in buildings, thus greatly contributing to worldwide energy savings and emission mitigation.

Moreover, with the accelerating process of urbanization, the "urban heat island effect" has also become an issue that cannot be ignored [10]. In hot summers, urban concrete and asphalt absorb large amounts of solar radiation and cause night-time temperatures in city to be significantly higher than those in surrounding rural areas [11]. This temperature difference leads to increased air conditioning use and worsens urban air pollution. The use of PCMIC can absorb and store daytime solar heat and subsequently release it during the night, offering a solution to mitigate the "urban heat island effect" and enhance city livability.

Over the past few years, with the rising demand for energy efficiency and sustainability in the construction industry has increased, the application of PCMs as energy-saving materials has received widespread attention. Despite numerous related research findings, a comprehensive introduction to the systematic integration of PCMs into building materials is still lacking. This study aims to fill that gap by exploring the selection of suitable PCMs and focusing on key integration techniques such as microencapsulation and vacuum impregnation, which address the issue of PCM leakage during thermal cycling while maintaining the durability and stability of PCMIC. Moreover, a critical aspect of this study is balancing the thermal performance with the mechanical properties of PCMIC, as PCMs negatively affects compressive strength and workability. Through the empirical analysis of case studies, this research validates the effectiveness of PCM-enhanced concrete in reducing indoor temperature fluctuations and energy demands, particularly in buildings exposed to extreme climates. By focusing on the integration methods and addressing these challenges, this research provides a comprehensive foundation for future innovations in sustainable construction, offering practical insights into optimizing thermal management.

2. Different types of PCMs

PCMs, which transition between physical states at certain temperatures or pressures to absorb and release heat, are embedded in building components. This integration helps stabilize indoor thermal fluctuations and minimize energy demands for climate control [12]. Researchers classify the PCMs into organic, inorganic, and eutectic categories, with recent developments including the bio-based PCMs sourced from natural elements like agricultural products and animal fats [13].

2.1. Organic petroleum-based PCMs

Organic petroleum-based PCMs are derived from petroleum and consist of carbon-based compounds, including hydrocarbons and their derivatives. They are valued for their excellent chemical stability, moderate phase change temperatures, high latent heat capacities, and environmentally benign characteristics. The molecular structure of these PCMs typically features high symmetry and regularity, which facilitates the stable energy absorption and release during phase transitions. Additionally, these structures include long carbon chains, such as those found in paraffins and certain fatty acids, which enable substantial energy storage during phase changes [14]. Specific chemical functional groups, such as carboxylic acids and esters, significantly influence their melting points and latent heat characteristics. The intermolecular interactions, particularly hydrogen bonding and van der Waals forces, are crucial in determining the transition dynamics between the solid and liquid states of these PCMs.

2.1.1. Paraffinic

Paraffin waxes represent the most prevalent class of organic petroleum-based PCMs which are characterized by their saturated

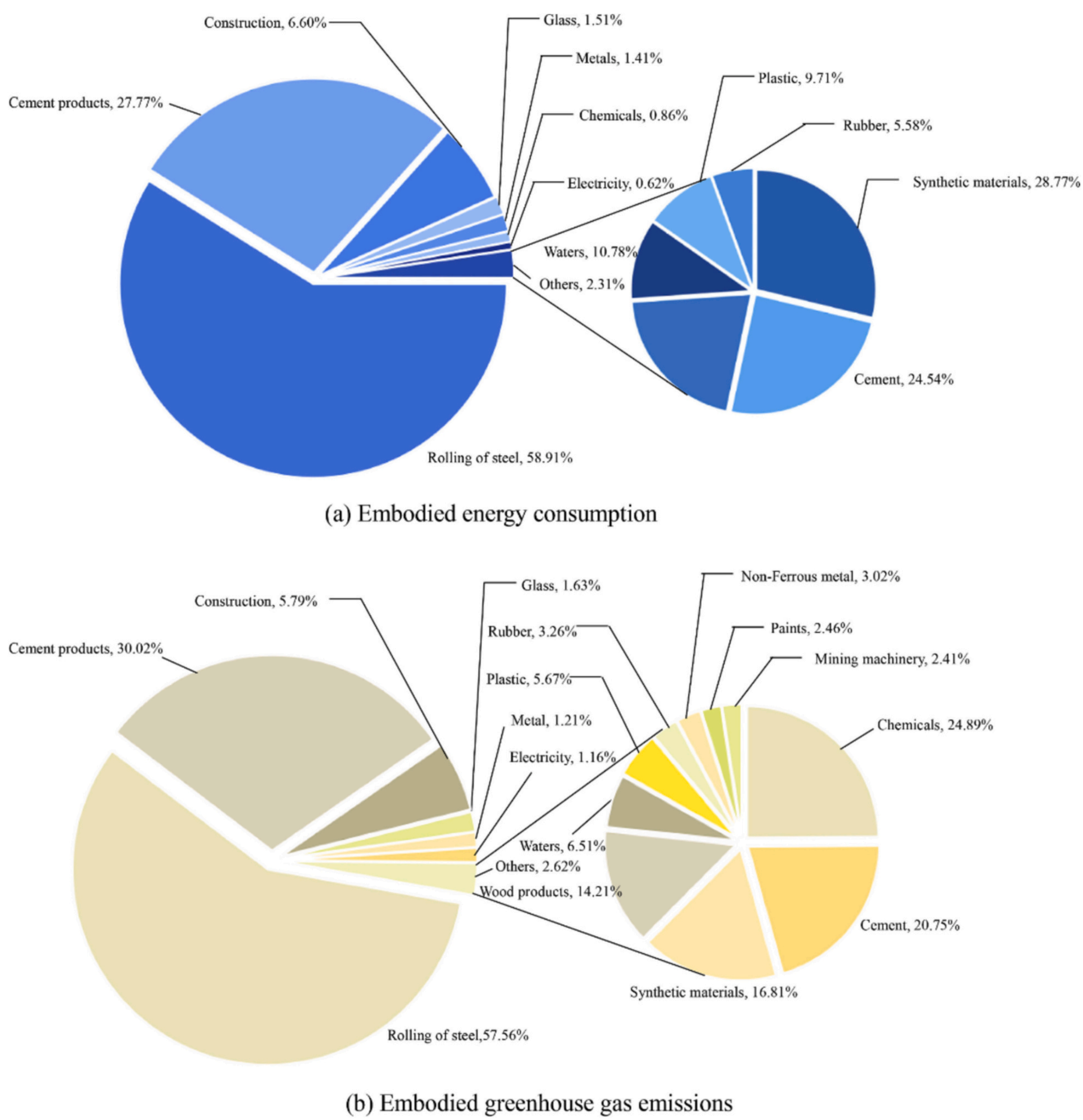

Fig. 2. Energy expenditure and greenhouse gas production in the construction industry [8].

hydrocarbon composition, featuring straight or branched alkane structures. These paraffin waxes adhere to a general molecular formula, $C_nH_{2n} + 2$, where the value of 'n' typically falls within the range of 20 to 40. In their solid state, these long-chain hydrocarbon molecules demonstrate a densely packed structure [15], requiring a substantial input of energy for the phase change. This attribute accounts for the notably high latent heat capacity associated with paraffin waxes [16]. Common paraffin waxes are visibly milky white solid at room temperature. Fig. 3(a) presents a specimen of polyethylene-paraffin, while Fig. 3(b) illustrates a specimen of paraffin wax.

The phase change temperature, also known as the melting point, of paraffin waxes is directly determined by the molecular structure, particularly the length of the carbon backbone and the degree of branching. Longer carbon chains result in higher phase transition temperatures, while increased branching lowers these temperatures. Commercial paraffin products are customized to specific the melting point ranges by adjusting the proportions of various chain length alkanes. Sharma et al. [18] demonstrated this correlation in Table 1, indicating that a paraffin wax with a 14-carbon chain melted at 5.5 °C, a 15-carbon chain at 10 °C, and a significant rise to a 33-carbon chain increased the melting point to 73.9 °C, illustrating the impact of chain length on thermal properties.

Paraffin features long molecular chains that enhance the van der Waals forces, requiring more energy for phase changes, leading to higher melting points and increased latent heat due to greater molecular participation in the phase change process. Its high latent heat capacity allows for an effective temperature regulation by efficiently absorbing and releasing heat. Paraffin is also chemically stable, non-toxic, and prevents interactions with other materials, which can enhance its durability and cycle stability. The fusion point of paraffin can be customized for specific purposes by modifying its molecular structure. Moreover, the cost-effectiveness and wide availability make paraffin ideal for thermal energy storage in construction materials, improving temperature control across various applications.

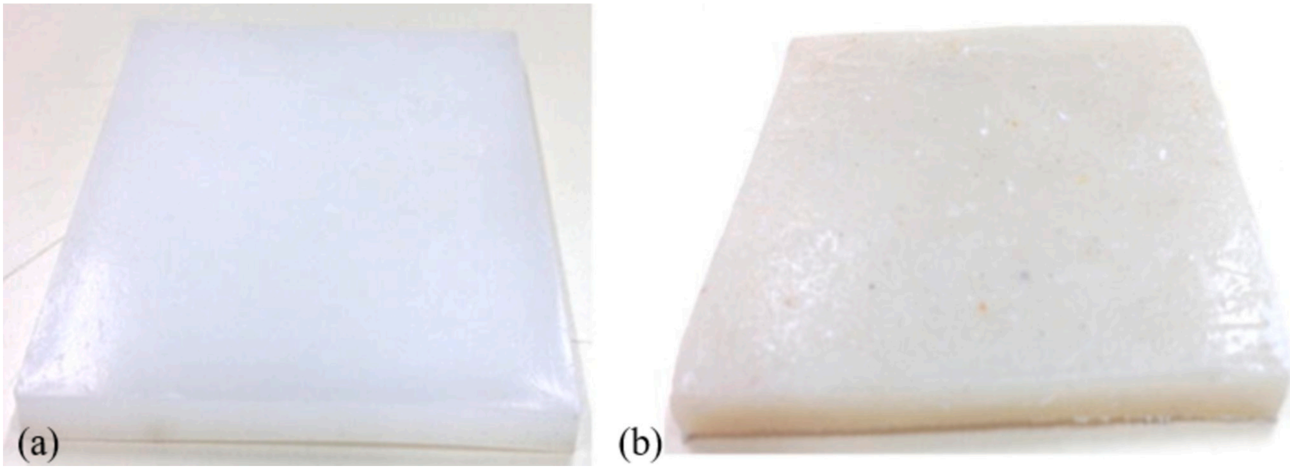

Fig. 3. Samples of (a) polyethylene-paraffin and (b) paraffin wax [17].

Table 1
Phase transition temperatures and latent heats corresponding to different carbon atoms [18].

Carbon atoms	Phase transition temperature (°C)	Latent heat (kJ/kg)	Carbon atoms	Phase transition temperature (°C)	Latent heat (kJ/kg)
14	5.5	228	24	50.6	255
15	10.0	205	25	49.4	238
16	16.7	237	26	56.3	256
17	21.7	213	27	58.8	236
18	28.0	244	28	61.6	253
19	32.0	222	29	63.4	240
20	36.7	246	30	65.4	251
21	40.2	200	31	68.0	242
22	44.0	249	32	69.5	170
23	47.5	232	33	73.9	268

To maximize the effectiveness of PCMs, selecting the appropriate phase change temperature is crucial. Ye et al. [19] pointed out that PCMs with lower phase change temperatures were more effective in winter, while those with higher temperatures were more effective in summer. Hence, choosing materials with suitable phase change temperatures is particularly important for enhancing thermal comfort for occupants, generally considered to be within the temperature range of 20 °C to 30 °C [20]. Table 2 summarizes several paraffin-based PCMs that meet these conditions.

2.1.2. Non-paraffinic

The family of organic PCMs also includes diverse non-paraffinic substances - fatty acids, alcohols, ethers, and esters, which are derived from petroleum or bio-based resources. Fatty acids are sourced through petrochemical processes or from natural oils. Alcohols can be produced via petroleum processing or crop fermentation. Ethers are generally made from petroleum-derived alcohols, and esters are created from reactions involving petroleum-derived alcohols and acids or from plant oils and alcohol. Each class offers unique characteristics and properties suitable for specific thermal energy storage and management applications. The bio-based PCMs will be detailed in Section 2.4.

2.1.2.1. Fatty acids. Fatty acids are a class of organic PCMs that stand out for their excellent latent heat retention capacity and favorable thermal stability. The molecular structure of fatty acids is primarily composed of long-chain carboxylic acids, with the carbon backbone providing substantial latent heat during phase transition [29]. The carboxyl groups (-COOH) allow for the formation of intermolecular hydrogen bonds, which is why fatty acids can maintain relatively high latent heat even at lower temperatures [30]. The melting points of fatty acids and their derivatives vary widely, allowing for the adjustment of phase change temperatures by selecting fatty acids with different chain lengths to meet various application requirements. Table 3 summarizes various fatty acids and their derivatives, including fatty acid methyl esters, detailing their melting points and latent heat capacities to highlight their distinct thermal performance characteristics for temperature regulation in buildings.

2.1.2.2. Alcohols. Alcohols, characterized by molecular structures with hydroxyl groups (-OH) that form intermolecular hydrogen bonds, significantly influence their phase change temperatures and latent heat properties. Adjusting the carbon chain length and hydroxyl group count allows for modulation of these temperatures. For instance, long-chain

Table 2
Phase transition temperature and latent heat of suitable paraffin-based PCMs.

Reference	Paraffin	Phase transition temperature (°C)	Latent heat (kJ/kg)
Koschenz et al. [21]	Heptadecane	22	214
Kousksou et al. [22]	Hexadecane	18.1	236
Hong [23]	Polyethylene–paraffin	30.8	157
Eddhahak-Ouni et al. [24]	Micronal DS 5001	23	110
Ramakrishnan et al. [25]	Paraffin RT-21	24.5	133
Castell et al. [26]	Paraffin RT-27	27	179
Xamán et al. [27]	Paraffin MG29	27–29	205
Sun et al. [28]	Paraffin ZDJN-28	26–28	231

Table 3
Fusion point and latent heat of fusion of fatty acid for building.

Reference	PCM	Fusion point (°C)	Latent heat (kJ/kg)
Zhang et al. [31]	Capric acid	31.5	150.8
Natalia et al. [32]	Capric acid-lauric acid (50:50)	20.5	129.0
Natalia et al. [32]	Capric acid-lauric acid (60:40)	19.4	117.9
Kong et al. [33]	Capric acid and 1-dodecanol (CADE)	26.5	126.9
Sayyar et al. [34]	Capric acid-palmitic acid	26.2	177.0
Feldman et al. [35]	Methyl Palmitate and Methyl Stearate	25.0	185.0
Karaipekli et al. [36]	Eutectic capric acid-myristic acid	22.0	160.0

alcohols like hexadecanol exhibit higher phase transition temperatures and latent heats. Veerakumar et al. [37] researched the thermal performance and compatibility of lauryl alcohol with other building materials, confirming its non-corrosive nature. Additionally, Huang et al. [38] explored myristyl alcohol combined with metal foams such as nickel and copper through vacuum melting infiltration, achieving enhanced heat conductivity and efficiency in storing and releasing thermal energy.

2.1.2.3. Ethers. Ethers like diethyl ether, with a boiling point of 34.6 °C and a low latent heat of vaporization around 26.4 kJ/mol, typically lack suitable latent heat for building applications, limiting their thermal storage capacity. Consequently, focus shifts to PEGs, a type of polyether. PEGs, with their repeating -CH_2-CH_2-O- units, have higher melting points and greater latent heat capacities due to their molecular structure and weight. These properties make PEGs ideal for construction uses, where efficient thermal energy storage and release are essential for maintaining consistent indoor temperatures.

Zhang et al. [39] conducted a study on shape-stabilized PCMs using polyethylene glycol alkyl ethers and porous silica, aiming to enhance the energy storage. These materials demonstrated a latent heat capacity of 81.7 kJ/kg. Fig. 4 illustrates the microstructure of these PCMs, in which Fig. 4(a) shows the polyethylene glycol alkyl ethers and Fig. 4(b) depicts these ethers encapsulated within porous silica, which improves thermal energy storage and maintains structural integrity.

2.1.2.4. Esters. Esters are a compelling category of organic PCMs, characterized by their molecular structure featuring extended carbon chains linked by ester bonds (-COO-). These materials are noted for their chemical stability and high latent heat storage capacities. The phase change characteristics of esters can be finely tuned by varying their compositions, making them highly suitable for thermal management systems. Wi et al. [40] investigated the fatty acid esters combined with graphite nanoplatelets for shape-stabilized PCMs, concluding that the incorporation of nanomaterials significantly boosted thermal energy storage rates. This enhancement is particularly beneficial for passive solar climate control systems in buildings, underscoring the potential of ester-PCMs to improve energy efficiency and sustainability in building applications.

2.2. Inorganic PCMs

Inorganic PCMs are generally categorized into crystalline or amorphous forms and encompass single substances like metals or salts, as well as multi-component systems such as saltwater solutions. According to the research performed by Memon [41], these materials exhibited melting points twice as high as the organic PCMs, making them ideal for high-temperature thermal energy storage by virtue of their superior thermal conductivity. However, their corrosive nature posed challenges for metal containment. Inorganic PCMs are divided into salts, metallics, salt hydrates, and metal oxides [42]. Pielichowska et al. [43] highlighted that both salts and metals possessed high melting points in the range of several hundred degrees Celsius, rendering them less suitable for the building applications. Current research is thus directed towards developing salt hydrates and metal oxides.

2.2.1. Salt hydrates

Salt hydrates are crystalline materials that incorporate water molecules into the lattice structure of a salt, typically expressed as Salt·xH_2O, where ‘x’ is the molar ratio of water to salt [44]. These materials undergo specific phase transitions while maintaining a stable structure, making them ideal for precise temperature control applications. However, Tan et al. [45] noted significant drawbacks: their corrosiveness towards metals required careful container and heat exchanger material selection, they often exhibited supercooling which reduced the energy available during phase transitions, and they can undergo phase separation during thermal cycles, diminishing their thermal storage capacity. Ryu et al. [46] suggested adding 3–5 % thickener to counteract phase separation by increasing viscosity. Despite these challenges, salt hydrates are highlighted in Table 4 for their high latent heat capacities, up to 296 kJ/kg, underscoring their utilizable energy storage potential in building systems for temperature regulation and energy conservation.

2.2.2. Metal oxides

Metal oxides typically exhibit melting points higher than those of

Table 4
Melting temperature and latent heat for suitable salt hydrate.

Reference	Salt hydrate	Melting temperature (°C)	Latent heat (kJ/kg)
Abhat [47]	$KF·4H_2O$	18.5	231
Cabeza et al. [48]	$FeBr_3·6H_2O$	21	105
Dinçer et al. [49]	$CaCl_2·6H_2O$	29–30	171–192
Naumann et al. [50]	$Na_2SO_4·10H_2O$	31–32.4	251–254
Mehling et al. [51]	$Na_2SO_4·3H_2O$	32	251
Zalba et al. [52]	$LiNO_3·3H_2O$	30	296

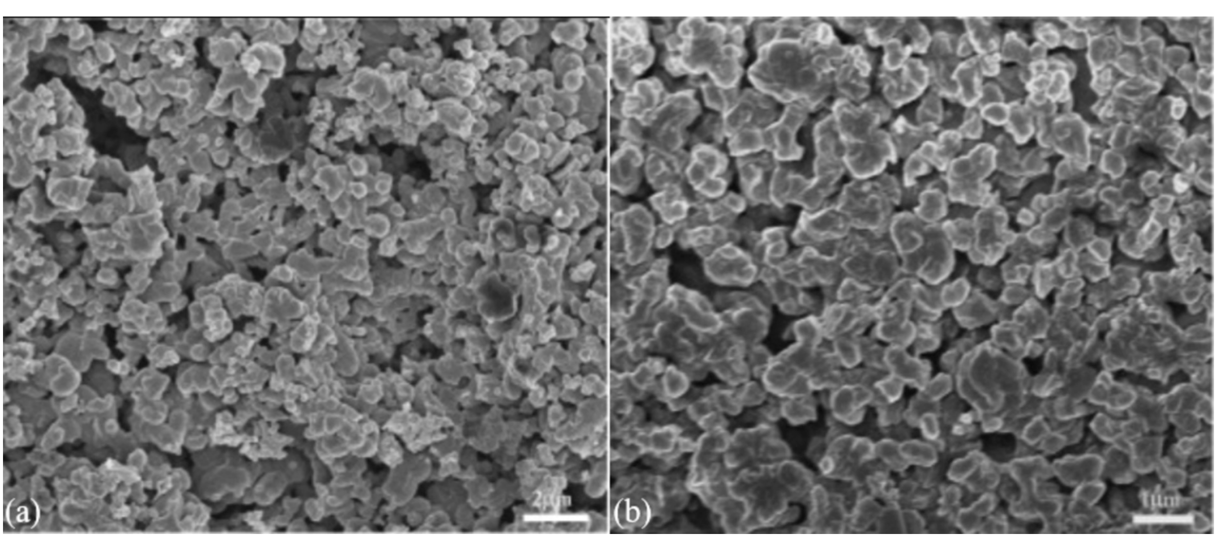

Fig. 4. Microstructure of shape-stabilized PCMs of (a) polyethylene glycol alkyl ethers and (b) polyethylene glycol alkyl ethers with porous silica composite [39].

conventional PCMs. This characteristic renders them suitable for high-temperature applications. Moreover, their robust thermal properties make them valuable for being incorporated into composite materials that enhance the performance of lower melting point of PCMs by increasing their overall thermal stability and conductivity.

Gupta et al. [53] focused on the effects of metal oxide nanomaterials-TiO_2, ZnO, Fe_2O_3, and SiO_2 on the thermophysical properties of $Mg(NO_3)_2{\cdot}6H_2O$, an inorganic salt hydrate PCM. They found that a 0.5 % addition of these nanoparticles significantly enhanced thermal conductivity by 148 %, 63 %, 55 %, and 45 %, respectively. TiO_2 nanoparticles significantly improved thermal conductivity and reduced the solar thermal charging time from 27 min to 17 min, indicating a 37 % increase in heat energy storage efficiency (as illustrated in Fig. 5). This consequently underscores the significant potential of nano metal oxide materials in enhancing thermal conductivity and regulating phase change characteristics.

2.3. Eutectic PCMs

Eutectic PCMs are composed of multiple components that melt and solidify at a unified temperature known as the eutectic point. This characteristic can ensure the consistent thermal energy storage and release under constant thermal conditions, which is highly advantageous in building applications for stabilizing indoor environments. This can lead to significant energy savings, especially in regions with large temperature variations.

2.3.1. Organic eutectics

Organic eutectic PCMs consist of a blend of two or more organic compounds combined in precise proportions to create a eutectic mixture. This mixture undergoes phase transitions at a temperature generally lower than that of each individual compound. These materials have lower melting points, good chemical stability, and minimal volume change during phase transitions, making them environmentally friendly and biodegradable. As expected, their lower thermal conductivity can be enhanced by adding conductive fillers or designing composite materials.

Zhao et al. [54] and Singh et al. [55] explored the synthesis and characterization of eutectic mixtures of fatty acids for use as PCMs. Four common fatty acids were used to create binary and ternary eutectic mixtures, and their thermal properties and effectiveness for energy conservation in building climate control were investigated. It was discovered that specific proportions of different fatty acids in eutectic mixtures resulted in lower melting points as compared to individual fatty acids or simpler binary mixtures. This characteristic of eutectic mixtures, where components collectively exhibit lower melting points, is essential for developing effective organic PCMs for temperature regulation applications.

2.3.2. Organic-inorganic eutectics

Organic-inorganic eutectic PCMs blend the organic substances with inorganic salts or metallic compounds, formulating mixtures with superior thermal capacity and chemical stability. These PCMs have specific melting points, a wide range of phase transition temperatures, good thermal stability, and improved thermal conductivity, making them ideal for complex thermal management systems. Tayeb [56] investigated these mixtures in solar energy systems, leveraging the high energy release of organic compounds and the stable temperature control of inorganic materials. The study revealed that the optimal proportions of organic-inorganic blends were crucial for maximizing energy retention and release, utilizing the high thermal conductivity of inorganic materials and the lower phase transition points of organic components.

2.3.3. Inorganic eutectics

Inorganic eutectic PCMs, formed by mixing two or more inorganic compounds in specific ratios, undergo phase changes at fixed temperatures, efficiently absorbing and releasing heat during transitions within the solid-liquid states. At the eutectic point, the constituents crystallize together to form a homogeneous phase with a crystalline structure. These PCMs can provide excellent thermal conductivity and substantial latent heat capacity, enhancing their effectiveness in high-temperature thermal storage applications. However, some challenges such as high costs and phase separation are noted, requiring precise control of the composition and manufacturing processes. Pichandi et al. [57] synthesized a binary eutectic PCM composed of magnesium sulfate heptahydrate and sodium carbonate decahydrate, demonstrating that this PCM could reduce the temperature by up to 7 °C and increase the daily average efficiency by 1.21 %, highlighting its practical effectiveness in solar technology.

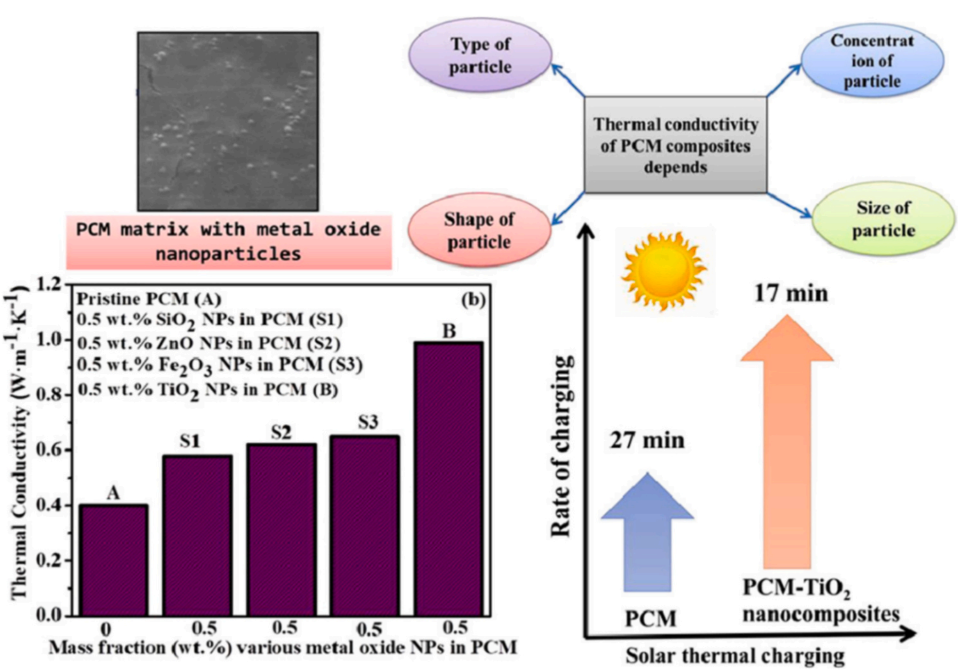

Fig. 5. Impact of nano-sized metal oxides on thermal conductivity and charging time of PCMs [53].

2.4. Bio-based PCMs

Bio-based PCMs are a category of materials made from renewable biological resources, primarily derived from natural plant oils or animal fats [13]. The materials can be pure single substances or mixtures containing multiple substances. Due to their origin from renewable resources, the bio-based PCMs are considered as an environmentally friendly solution for thermal energy storage, and they can be continuously renewed via sustainable agricultural activities [58]. Fig. 6 illustrates the sustainable lifecycle of the bio-based PCMs. It can be observed that the bio-based PCMs are valued for their sustainability, biodegradability, and reduced environmental impact, making them an attractive choice for green building designs and thermal energy storage systems.

Although the bio-based PCMs are eco-friendly, they typically have lower thermal conductivity, reducing their heat storage capacity. In general, their thermal performance can be enhanced through chemical modification or synthesizing new bio-based PCM types. This involves altering the chemical structures of organic substances or developing new bio-based composites. Additionally, improving performance may require combining bio-based PCMs with base materials that possess superior thermo-conductivity. Jeong et al. [60] addressed bio-based PCM leakage and low thermal conductivity issues by integrating boron nitride, creating a high-performance material suitable for building applications. Some typical bio-based PCMs suitable for buildings are stated in Table 5.

2.5. Comparison of different kinds of PCMs

The environmental impact and disadvantages of PCMs in building applications vary significantly by type. Organic PCMs, while stable and non-toxic, rely on non-renewable petroleum-based resources, thus affecting sustainability. Additionally, they present flammability risks, necessitating the implementation of stringent fire safety measures in large-scale construction projects, which can substantially increase costs. Despite their initial cost-effectiveness, these additional safety requirements limit their overall economic advantages. Inorganic PCMs offer excellent thermal performance but are often toxic and corrosive, particularly under certain conditions, posing risks to both worker safety during installation and long-term handling over the life cycle of the building. Moreover, inorganic PCMs are susceptible to phase separation and super-cooling, which negatively affect their long-term efficiency and can detract from the aesthetics of the exposed or transparent architectural elements, where visual clarity and material stability are crucial. Eutectic PCMs, combining organic and inorganic materials, present challenges in recycling and disposal since separating their components at the end of the serviceability is both complex and costly. Additionally, the aesthetic application of eutectic PCMs may be constrained by their opacity or the potential for discoloration over time, which can interfere with the modern architectural design aesthetics. Lastly, Bio-based PCMs, though eco-friendly due to their renewable nature, tend to have higher upfront costs and lower thermal efficiency, which may require larger quantities, affecting both cost-effectiveness and design compactness in building applications.

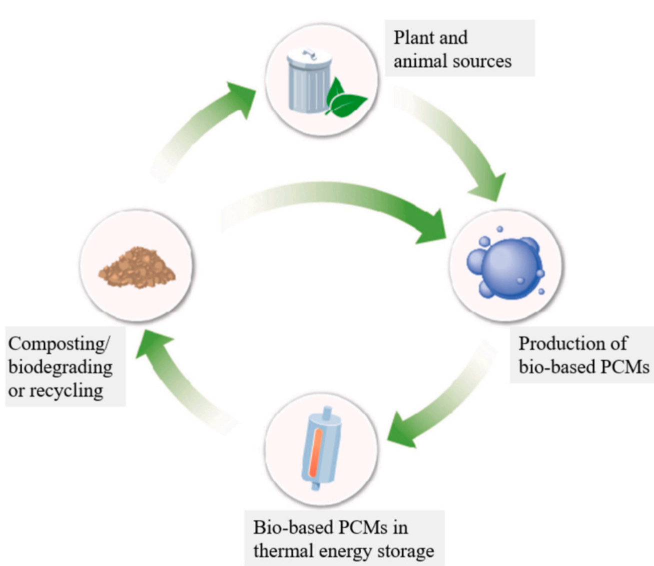

Fig. 6. Lifecycle of bio-based PCMs - from production to use in thermal energy storage and recycling [59].

Table 5
Melting point and latent heat for bio-based PCMs.

Reference	PCM	Melting temperature (°C)	Latent heat (kJ/kg)
He et al. [62]	Bio-based PEGs	33.2–34.5	74.3
Duan et al. [63]	Coconut oil	23–25	103
Boussaba et al. [64]	Coconut fat	17.4–22.6	106.2
Kang et al. [65]	Soybean oil	29.2	147.2
Boussaba et al. [66]	Hydrogenated palm kernel vegetable fat	26.5	75.2
Fabiani et al. [67]	Animal fat	25.2	23.3

3. Selection criteria and methods for PCMs in concrete

3.1. Selection criteria of PCMs

The selection of PCMs for various applications, particularly in thermal energy is governed by several key criteria. These criteria help in determining the suitable PCMs for a specific application, ensuring efficient and effective energy management. Khan et al. [68] provided a summary of the melting temperatures and enthalpies for existing PCMs, as shown in Fig. 7. From this figure, it is evident that for applications in buildings (20–40 °C), the potential PCMs that can be selected include paraffins, fatty acids, salt hydrates, gas hydrates, and polyethylene glycol. Khare et al. [69] categorized the selection criteria for PCMs into five distinct aspects: thermal, physical, kinetic, chemical, and economical. These categories encompass a broad range of properties and considerations crucial for the effective application of PCMs in various fields.

While this section outlines the criteria for selecting PCMs in concrete, including thermal, physical, kinetic, chemical, and economical, a more critical view is necessary to fully capture the scope and limitations. The

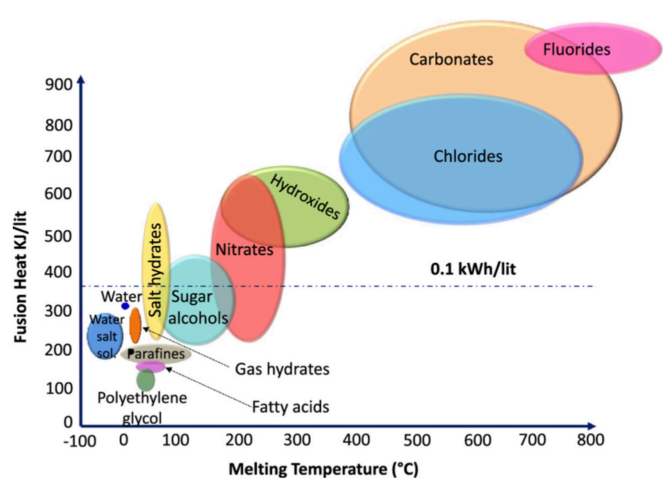

Fig. 7. Melting temperature and fusion heat for existing PCMs [68].

selection of PCMs is highly context-dependent, and the ideal characteristics often vary depending on the specific application and environmental conditions. For instance, PCMs with high latent heat and suitable phase change temperatures may perform well in moderate climates but prove ineffective in extreme environments where temperature fluctuations exceed the PCMs operational range. Moreover, the chemical stability of PCMs, particularly organic and bio-based types, can degrade over time due to exposure to alkaline environments in concrete, limiting their long-term effectiveness. Cost considerations also present a major limitation, as more advanced PCMs with optimal thermal properties, such as microencapsulated or bio-based PCMs, are often cost-prohibitive for large-scale projects. Additionally, the integration of PCMs into concrete can lead to challenges in workability and mechanical performance, particularly in high-load structures. These limitations highlight the need for more comprehensive studies on PCM performance in various environmental and structural contexts, as well as the development of cost-effective solutions that do not compromise on safety, durability, or performance.

3.1.1. Thermal properties

i. Suitable phase transition temperature: The efficacy of a PCM in thermal regulation depends on its phase transition temperature aligning with actual temperatures of the operational environment. For architectural applications, a PCM that transitions at indoor temperatures enhances ambient temperature stability [69].
ii. High latent heat capacity: A desirable PCM should possess a high latent heat capacity to store or release significant energy per unit mass during phase changes. This feature is vital for maximizing thermal storage in limited spaces, such as in concrete structures [70].
iii. Superior thermal conductivity: A PCM with high thermal conductivity facilitates rapid heat transfer, enabling quick responses to temperature fluctuations. This behavior is especially valuable in residential buildings where the fast temperature adjustments are necessary. Utilizing materials like metal fillers or graphite can enhance this attribute [71].
iv. Stable thermal stability: PCMs should maintain consistent thermophysical characteristics, including phase change temperature and thermal storage capacity, across multiple thermal cycles. Stability ensures the long-term performance and minimizes the need for replacements and maintenance, making it crucial to select PCMs that are robust against numerous thermal cycles.

3.1.2. Physical properties

i. Favorable phase equilibrium: This ensures the PCM performs consistently during its phase change process, converting between solid and liquid forms without degrading, which is necessary for sustained use [72].
ii. High density: A higher density PCM can store more energy per unit volume, offering efficiency and space-saving benefits, especially in space-constrained applications.
iii. Small volume change: PCMs with minimal volume change during phase transitions are desirable as they prevent structural stress or damage to the containment system. This behavior is crucial when the PCM is encapsulated or integrated into solid structures to avoid leaks [73].
iv. Congruent melting: Congruent melting allows a PCM to melt or solidify at a uniform temperature, ensuring predictable and effective latent heat delivery. This property is vital for efficient heat transfer and storage in applications requiring precise temperature management [74].

3.1.3. Kinetic properties

i. No super-cooling: Super-cooling can cause a liquid to remain unfrozen below its freezing point, leading to sudden and uneven thermal energy release which impacts system performance [75]. Ideally, a PCM should solidify predictably at its designated temperature for consistent thermal response.
ii. Effective crystallization and nucleation rates: Crystallization signifies the transformation of a PCM from a liquid to a solid state, with nucleation representing the initial phase of this process involving the formation of a stable solid structure [76]. These rates are crucial as they determine how quickly and uniformly a PCM solidifies upon reaching its solidification temperature. This ability is essential for the rapid response and efficient thermal management.

3.1.4. Chemical properties

i. Chemical stability: Chemical stability in PCMs is essential for ensuring longevity and reliability through repeated thermal cycles [77]. A stable PCM maintains its composition and properties over time, preventing alterations in melting point and latent heat capacity which are crucial for consistent performance.
ii. No toxicity or fire hazard: Safety is important for PCMs, particularly in residential settings. PCMs should be non-toxic, producing no health risks through inhalation, ingestion, or skin contact [78]. Png et al. [79] suggested that reducing the combustibility of organic paraffins through flame retardants or surface coatings was costly. Therefore, using inherently non-flammable materials is a more effective solution, ensuring they do not pose a fire hazard, especially when used in buildings.
iii. Compatibility with container materials: The PCM must be chemically compatible with its container and surrounding materials to prevent reactions that could damage the container or degrade performance [80]. In concrete structures, the PCM should not react with substances in the concrete. It is important to evaluate PCM compatibility to avoid adverse chemical reactions, such as those between paraffin and fatty acids in highly alkaline environments.

3.1.5. Economic properties

i. Cost-effectiveness: Cost is an important consideration in practical applications. The ideal PCM should have a reasonable cost to ensure the economic feasibility of its widespread application [81].

3.2. Mixing methods with concrete

The addition of PCMs to concrete can generally be categorized into two approaches: direct and indirect methods.

3.2.1. Direct methods

In direct mixing method, PCM is directly incorporated into the concrete mix. This may involve blending PCM powders or granules directly with the concrete materials. This approach is straightforward but may lead to PCM leakage during the concrete curing process. Navarro et al. [82] highlighted that the direct mixing approach for integrating PCMs into concrete was prone to leakage, leading to void formation and significantly impairing the mechanical properties. This observation underscored the critical challenge of maintaining the structural integrity of PCM-enhanced concrete, emphasizing the need for advanced encapsulation techniques or alternative methods to prevent PCM leakage and preserve the mechanical strength of concrete. In addition to this, Bentz et al. [83] and Schossig et al. [84] identified a major limitation of the direct mixing method for integrating PCMs into concrete, noting that unencapsulated PCMs can adversely interact with the concrete matrix and alter its properties. This can negatively affect the structural and thermal performance of the concrete. As a result, recent research focuses on advanced methods to prevent direct contact between PCMs and concrete matrix, keeping the materials intact and efficient while preserving strength and durability.

3.2.2. Indirect methods

3.2.2.1. Microencapsulation. In microencapsulation technology, PCM is encapsulated within tiny capsules, which are then incorporated into the concrete. Microencapsulation prevents PCM leakage and improves its distribution within the concrete. Fig. 8 shows the microstructure of the prepared microcapsules with PCMs. It can be observed that the encapsulated PCM microcapsules possess a stable structure, which is crucial for maintaining the effectiveness and durability of PCM integration in concrete applications. This stability is crucial not only for preventing leakage but also for ensuring consistent thermal performance and mechanical integrity over the lifetime of the concrete.

Jamekhorshid et al. [86] explored microencapsulation, a process that encased particles or droplets within a film to form microcapsules, ranging from micrometers to millimeters in size. The microcapsules consisted of a PCM core encased within a shell composed of either polymer or inorganic material, as illustrated in Fig. 9. The shell functioned as a protective barrier for the PCM. When integrating microcapsules into concrete, selecting a hard-shell material is vital for preventing rupture and subsequent leakage of PCMs during the mixing process [4]. The chosen shell must withstand the mechanical stresses encountered during concrete mixing to maintain the integrity of the microcapsules. A robust shell material ensures the microcapsules can effectively store energy and regulate temperature without compromising the concrete properties.

The following elaborates on three primary methods for producing microcapsules encapsulating PCMs: physical, physicochemical, and chemical methods, each offering distinct advantages for specific applications.

i. Physical methods: Techniques like spray drying and fluidized bed drying use physical forces to create fine droplets from active substances, which are then dried and solidified within a shell [88,89]. These methods are simple but may not suit heat-sensitive substances due to limited control over shell uniformity.
ii. Chemical methods: Based on chemical reactions including polymerization or crosslinking, these methods develop a robust shell around the core material [90,91]. They provide high customization and enhanced shell integrity but may increase costs due to special chemicals and equipment [92].
iii. Physicochemical methods: Merging physical and chemical processes, these methods include techniques such as co-precipitation, solvent evaporation, and phase separation [93,94]. The physicochemical methods produce microparticles by altering the solvent conditions to encapsulate the core material, offering precise control over microcapsule size and shape. These methods accommodate a wide range of materials but need careful parameter management.

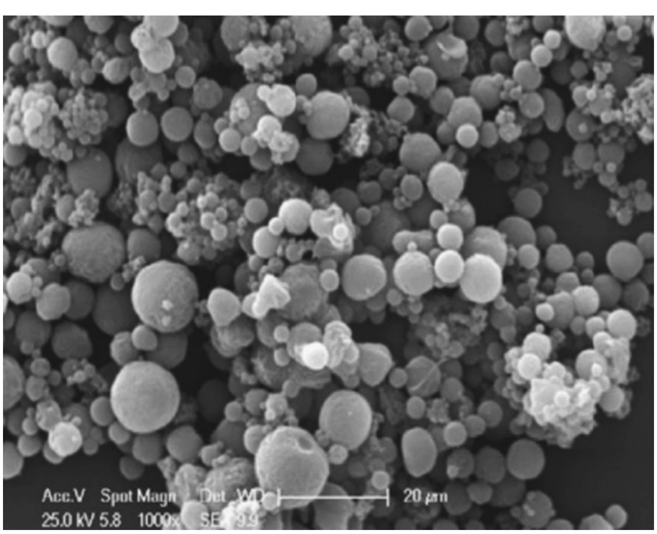

Fig. 8. Microstructure of PCM-encapsulated microcapsules. The shapes of the microcapsules are highly stable, indicating effective encapsulation and uniform particle size distribution [85].

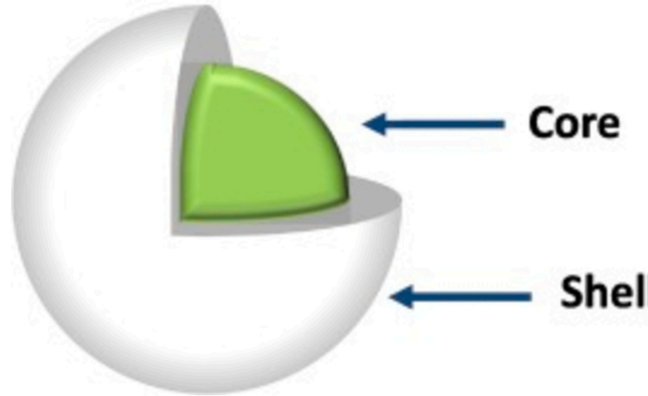

Fig. 9. Schematic diagram of a microcapsule encapsulating PCMs [87].

For PCMs, physicochemical and chemical methods are generally more suitable. Physicochemical methods offer precise control over microcapsule dimensions, which is crucial for the effective performance of PCMs. Chemical methods ensure specific functionalities and durability, important for the long-term effectiveness and efficiency of PCMs in temperature control and thermal energy storage [95]. Parameshwaran et al. [96] applied the in-situ polymerization method to produce the bio-based phase change microcapsules, achieving a latent heat of 47.3 J/g and a compressive strength of 38.8 MPa in concrete mixtures. Fig. 10 shows the microencapsulation process of PCMs starting with an oil-in-water emulsion and progressing through micelle formation, synthetic intermediate development, and finally the formation of microcapsules using catalysts. Moreover, Alehosseini [97] developed nanoencapsulation technology, a notable advancement in microencapsulation that enhanced the PCM thermal performance by encapsulating substances at the nanoscale, providing superior thermal properties over traditional methods.

3.2.2.2. Immersion. The immersion method for integrating PCMs into concrete is an innovative approach that involves a meticulous process. In this technique, porous materials, such as expanded clay or shale, are immersed in liquid PCM (as shown in Fig. 11(a)). This immersion allows the PCM to be absorbed into the aggregates through capillary effects, which ensures that the PCM is evenly distributed within the aggregates. Once these aggregates are fully saturated with the PCM, they are then incorporated into the concrete mix (as depicted in Fig. 11(b)).

This method offers several advantages. For example, by integrating the PCM-treated aggregates into the concrete, the thermal properties of the concrete can be enhanced. The PCM provides a thermal buffer by sequestering and discharging heat during phase changes, thereby helping to regulate the temperature within the concrete. This uniform dispersion of PCM within the mix is more effective than direct mixing methods, as it minimizes the risk of PCM leakage during phase transitions. However, the immersion method also presents certain challenges. One of the primary concerns is the potential for PCM leakage over time. Despite the initial containment within the aggregates, the PCM can still

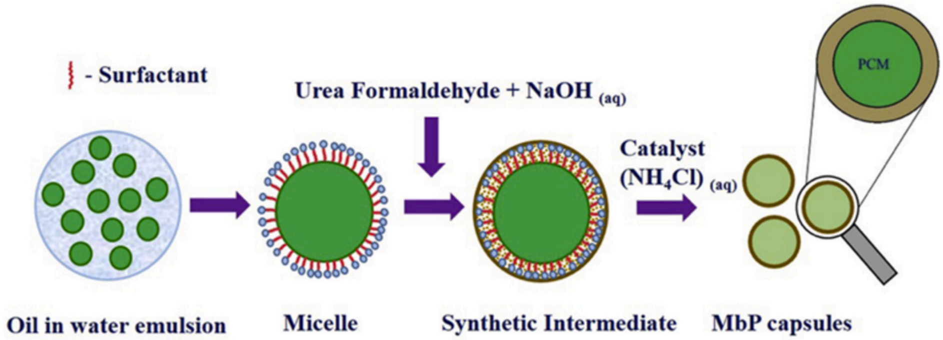

Fig. 10. Stages of microencapsulation process for PCMs via in-situ polymerization method [96].

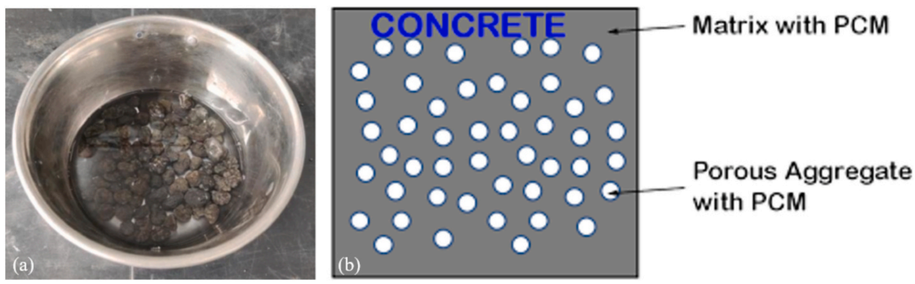

Fig. 11. (a) Porous aggregates are soaked in liquid PCMs and left to allow PCMs to infiltrate the pores, forming PCM-immersed porous aggregates [98] and (b) the PCM-immersed porous aggregates are evenly mixed into the concrete matrix, ensuring a uniform distribution within the composite material [99].

seep out, especially under fluctuating temperatures and pressures. This leakage not only diminishes the thermal efficiency of the concrete but also poses a risk of chemical compatibility issues with other construction materials. Additionally, the presence of the PCM in the concrete mix can lead to accelerated corrosion of reinforced steel. This is due to the potential chemical interactions between the PCM and the steel, which can weaken the structural integrity of the concrete over time.

3.2.2.3. Vacuum impregnation. In the vacuum impregnation method, PCMs are introduced into porous aggregates via a vacuum process [100]. Initially, porous aggregates are placed in a vacuum-capable flask, and PCMs are stored in a connected container, typically a funnel. A vacuum pump creates a vacuum within the flask, removing air from the pores of aggregates. The vacuum pump connects to the flask via tubes and valves, including a valve controlling PCM flow. When opened, the PCMs substitute the removed air due to the pressure differential created by the vacuum, ensuring effective filling of the voids. A heater may be employed to maintain the PCM in a liquid state, facilitating better penetration. Once impregnated, these aggregates are mixed into concrete, enhancing its thermal storage capacity by absorbing and releasing thermal energy, aiding in temperature regulations. Fig. 12 displays the experimental setup for the vacuum impregnation method of introducing PCMs into porous aggregates.

This method offers advantages over the immersion method, where aggregates are soaked in the PCM, relying on capillary action, which may leave some pores partially filled. The vacuum method ensures complete penetration by removing air before introducing PCM, resulting in a higher impregnation ratio and better thermal performance. Aggregates impregnated using this method have a greater capacity for thermal storage, as fully filled pores allow the maximum absorption and release of thermal energy, improving thermal inertia. This is particularly beneficial in environments with significant temperature fluctuations, helping regulate temperatures within structures. Besides, the vacuum impregnation guarantees more consistent outcomes by ensuring uniform

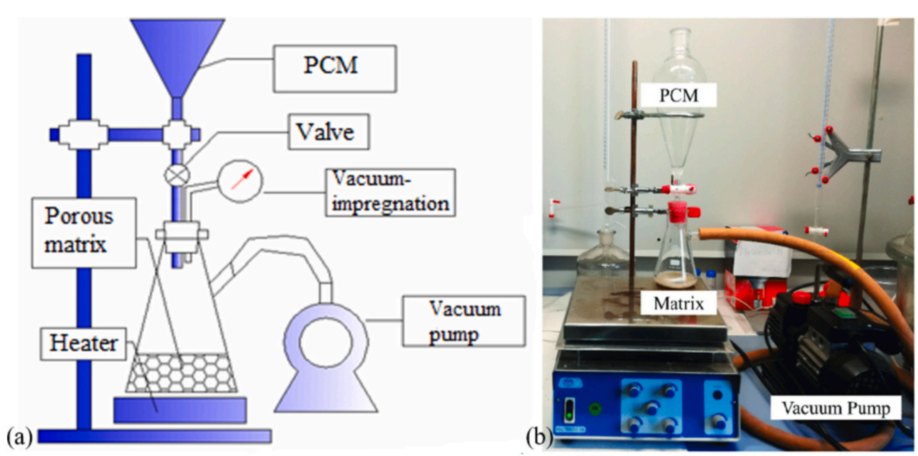

Fig. 12. (a) Schematic and (b) actual experimental setup of vacuum impregnation [101].

thermal properties across the concrete mix. Fig. 13 compares the impregnation ratios of various porous materials, indicating that recycled expanded glass achieves the highest impregnation ratio at 80 %, followed by ceramsite with 63.1 %, and the shale ceramsite at the lowest with 25.8 %.

4. Impact of PCMs integration into concrete

4.1. Thermal properties

Wang et al. [102] presented a comprehensive diagram in Fig. 14 that outlined the methodologies for assessing distinct thermal characteristics of the materials. The schematic categorized the thermal properties such as phase transition temperatures, latent heats, thermal stability and conductivity, and correlated them with corresponding analytical techniques. For instance, DSC and DSC-TGA were used for phase transitions and latent heats, TGA for thermal stability, as well as thermal conductivity analyzers, thermal constant analyzers, and the laser flash technique for thermal conductivity. This overview can serve as an academic resource for selecting appropriate techniques for the rigorous thermal property assessment.

4.1.1. Thermal energy storage

PCMs can store and discharge significant latent heat within its phase transition temperature range, substantially increasing the capacity of concrete to retain thermal energy [103]. This allows concrete to store and release more heat during temperature fluctuations, contributing to temperature regulation. Thermal energy storage capacity depends on the type and properties of the PCMs, such as transition temperature and heat storage capacity, and their alignment with environmental temperatures [3]. The concentration and uniform distribution of PCMs are crucial, as higher PCM addition improves thermal energy storage but may affect mechanical properties [104]. To address this, encapsulation methods can prevent leakage and ensure uniform distribution [105]. Additionally, the thermal conductivity of the PCMIC matrix likewise enhances heat transfer and PCM efficiency. For instance, introducing thermally conductive materials like graphite or carbon nanotubes can further boost thermal energy storage efficiency [71]. Moreover, the manufacturing and construction technics, including mixing and curing, also influence PCM distribution and performance. Hence, optimizing these factors can notably enhance thermal energy capabilities of PCMs, ultimately improving their thermal regulation and energy efficiency [102].

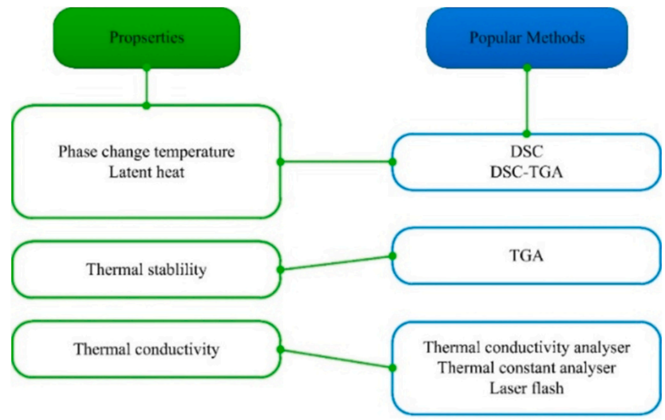

Fig. 14. Thermal properties and testing methods [102].

Zhang et al. [106] used an organic phase change material (Butyl Stearate), porous aggregates, and conventional concrete materials to improve the thermal energy retention. They employed a vacuum impregnation method to improve the PCM absorption into aggregates, significantly boosting the thermal retention capacity. Berardi et al. [107] and Bahrar et al. [108] found that integrating PCMs into concrete increased the thermal storage, mass, and passive regulation, reducing energy usage and peak thermal loads for temperature regulation, and improving indoor climate stability and comfort. The collective findings of these studies emphasize the significant benefits of PCMs in enhancing thermal energy storage abilities of concrete.

4.1.2. Thermal conductivity

The thermal conductivity of PCM-enhanced concrete is influenced by the type of PCM, its encapsulation method, and its distribution within the concrete matrix. Berardi et al. [107] noted that while PCMs can lower the overall heat conductivity of concrete, this reduction varied with the PCM state-higher in solid state than liquid. Fig. 15 shows that increasing microencapsulated PCM content in the concrete mixture leads to a noticeable reduction in thermal conductivity, significantly impacting its heat transmission efficiency. When the PCM content reaches 5 %, the thermal conductivity can decrease by about 45 %. Ramakrishnan et al. [109] found that replacing 20 %, 40 %, 60 %, and 80 % of sand with PCMs reduced thermal conductivity by approximately 15.8 %, 31.6 %, 52.6 %, and 65.8 %, respectively. Similarly, Xu et al. [110]

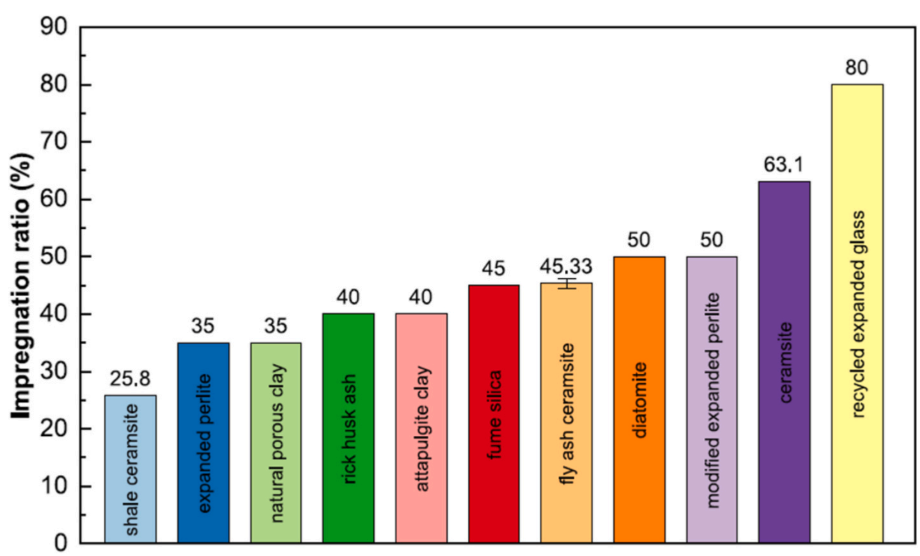

Fig. 13. Impregnation ratio of different porous materials with PCMs [98].

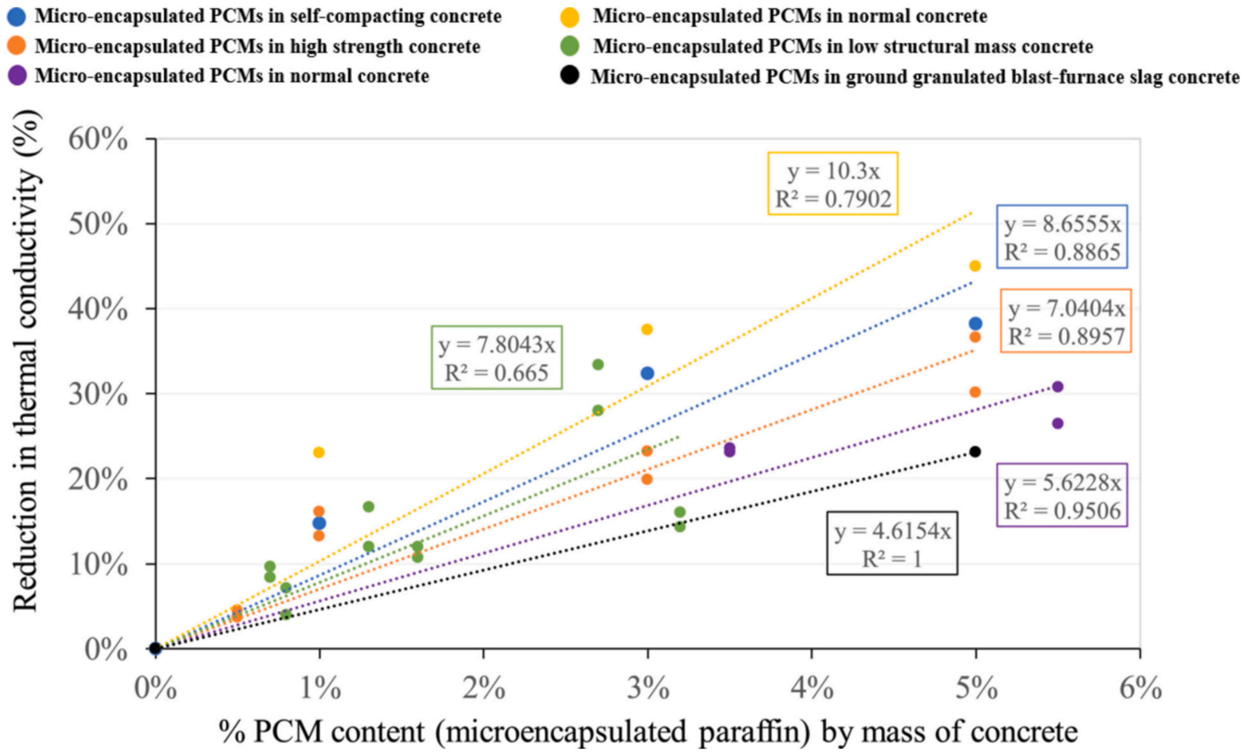

Fig. 15. The thermal conductivity of concrete is adversely impacted by the incorporation of PCMs [107].

reported that substituting 10 %, 15 %, 20 %, and 30 % of cement with PCMs led to reductions in thermal conductivity of 13.8 %, 21.0 %, 26.2 %, and 33.6 %, respectively. These findings underscore the essential need for balancing thermal energy storage with reduced thermal conductivity when designing PCM-enhanced concrete for specific applications.

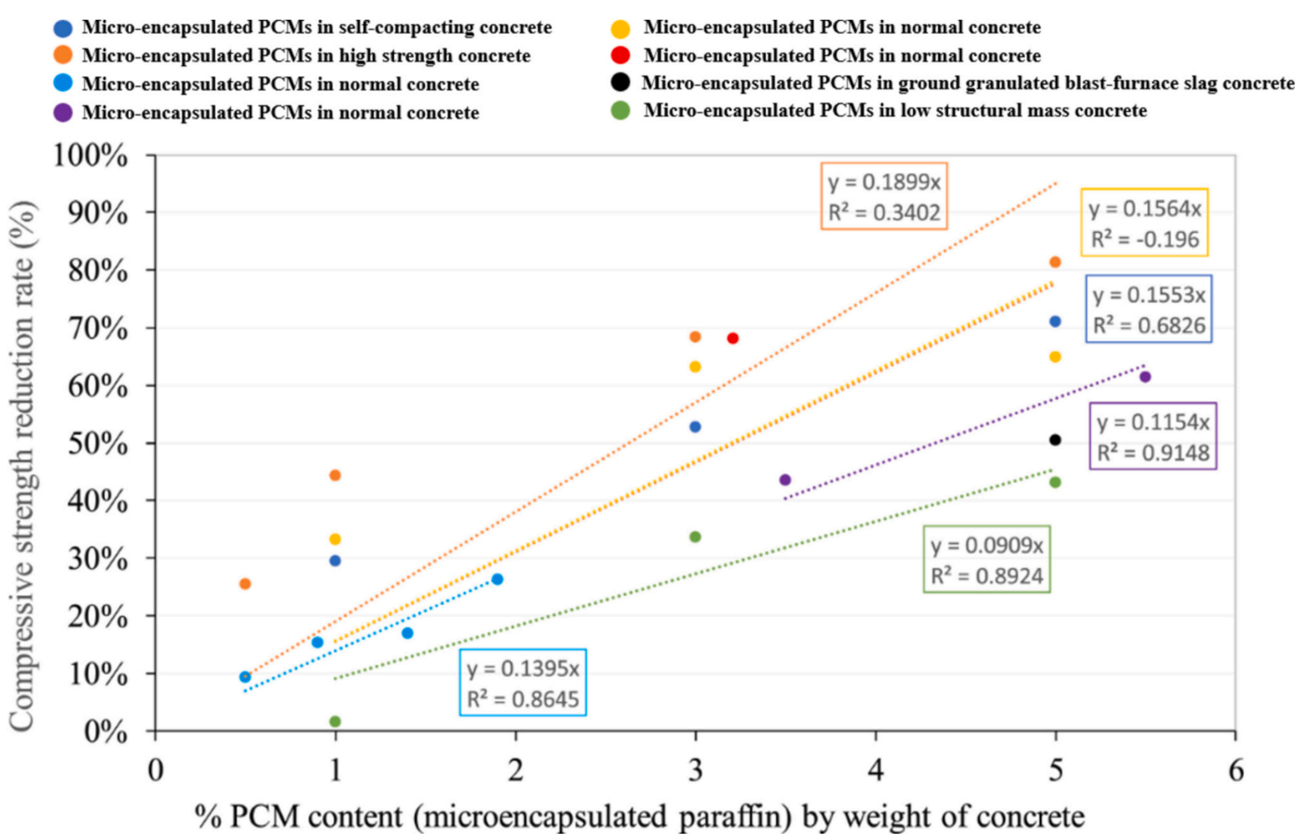

Fig. 16. The compressive strength of concrete is adversely impacted by the incorporation of PCMs [107].

4.2. Mechanical properties

Studies have consistently revealed that adding PCMs to concrete generally leads to a decrease in its compressive strength. This reduction is mainly due to the leakage of PCMs and thereby compromising the structural integrity of the concrete. Moreover, inadequate compatibility between the PCMs and the concrete matrix can increase porosity, which subsequently weakens the concrete overall strength.

The study carried out by Hunger et al. [111], Cao et al. [112], and Ling et al. [4] collectively concluded that the integration of PCMs into concrete had a noteworthy impact on its compressive properties. Importantly, these studies consistently illustrated a pattern where a higher content of PCMs was associated with a more substantial reduction in strength. Specifically, Hunger et al. [111] explored the impact of incorporating varying proportions of PCMs (1 %, 3 %, and 5 %) into self-compacting concrete. Their findings indicated that the addition of 5 % PCM led to a decrease in compressive strength by approximately 50–60 %. Cao et al. [112] reported that concrete with 3.2 % microencapsulated PCM demonstrated a 25–30 % reduction in compressive strength as compared to the control concrete without PCM. Ling et al. [4] examined the effect of varying contents (5 %, 10 %, and 20 %) of micro-encapsulated PCM on PCMIC and a gradual decline in compressive strength with increasing PCM addition was observed, reaching up to 45 % when the PCM content was 20 %. Fig. 16 summarizes the influence of incorporating micro-encapsulated PCMs into concrete on its compressive strength. When the addition amount reaches 5 %, the strength of the concrete can be reduced by up to 80 %. Furthermore, Meshgin et al. [113] found that utilizing PCMs to substitute 10 % of cement reduced the flexural strength of concrete by approximately 6 %. Lecompte et al. [114] found that the bending strength exhibited a similar trend to compressive strength when PCMs were added, with values ranging from 1.7 MPa in mixtures with high PCM content to 6.1 MPa in cases with the lowest PCM content. These results highlight the notable impact of PCMs inclusion on the mechanical properties of concrete, with higher proportions correlating with greater reductions in strength. This correlation necessitates careful consideration in the design and utilization of the PCM-enhanced concrete to ensure structural safety and functionality.

4.3. Workability

The incorporation of PCMs into concrete can impact the workability of the mixture, influencing its flowability and ease of handling. Addressing these effects may require adjustments in the mixing ratio of cement and water or the introduction of other modifying agents [115]. Asadi et al. [116] have proposed a solution to enhance the workability of mortar and PCMIC by incorporating superplasticizers, particularly those based on Naphthalene. This approach demonstrates an effective strategy for mitigating potential workability challenges associated with the addition of PCMs into mortar and concrete mixtures.

4.4. Durability and fire performance

Hawes et al. [117] emphasized the potential impact of high alkalinity environments on the stability of PCM. In concrete specimens containing high alkalinity volcanic ash aggregates, the latent heat performance of the PCM, particularly dodecanol, exhibited an evident decline phenomenon. This may be attributed to the effect of alkaline environments on the chemical stability of PCM. This implies that when designing PCMIC, it is necessary to consider the potential impact of aggregate alkalinity on PCM performance and to take measures to maintain the required performance.

Preliminary fire-resistant tests found that PCM-impregnated concrete maintained good performance under high temperature flames. Even after 10 min of exposure to a 700 °C flame, only minor cracking appeared on the exterior of the concrete samples without significant damage. This result suggests that although PCM is generally considered to be a flammable material, it may not significantly affect the fire resistance of concrete [117]. This is an important finding as it indicates that PCMIC can maintain its structural integrity in high temperatures or fire situations.

The stability of PCMIC under freeze-thaw cycling is an important aspect to consider, especially in environments that experience extreme temperature fluctuations. Pilehvar et al. [118] focused on evaluating the performance of concrete containing microencapsulated PCMs under freeze-thaw conditions. It was indicated that the addition of micro-encapsulated PCM can affect the freeze-thaw durability of concrete. While some reduction in mechanical properties was observed after freeze-thaw cycling, the overall performance of PCMIC remained within acceptable limits for certain applications.

Compared to conventional concrete, PCMIC may present certain technical challenges regarding durability and long-term stability. While PCMs significantly improve the thermal regulation performance of concrete by absorbing and releasing latent heat, the repeated phase change processes can adversely affect the microstructural performance of the concrete, leading to attenuated mechanical properties such as reduced compressive strength and the potential for crack formation [119]. This structural degradation caused by the thermal cycling is particularly evident when the encapsulation is inadequate, or the material distribution is poor. In contrast, conventional concrete offers more stable and predictable mechanical strength and long-term performance with broader adaptability. However, by employing appropriate encapsulation techniques and optimizing the integration with the concrete matrix, the potential issues of PCM-enhanced concrete can be effectively mitigated, ensuring that it achieves efficient thermal management while maintaining good structural integrity and durability [120].

5. Real-world application in building

PCMIC, a novel composite material with phase change substances, has become increasingly integrated into various domains of architectural engineering, particularly in residential and commercial constructions. This integration aims to enhance the thermal comfort within built environments while reducing overall energy expenditures. The application of PCMIC in buildings effectively stabilizes the indoor temperature fluctuations under extreme climatic conditions, thereby augmenting occupant comfort and diminishing reliance on conventional HVAC systems [122]. PCM technology, increasingly employed in modern architecture, therefore mitigates energy consumption in HVAC systems. By leveraging the latent heat properties of PCMs, buildings efficiently absorb excess heat during peak hours and release it when the temperature drops, maintaining a more consistent indoor environment. This thermal buffering effect enhances occupant comfort and reduces the strain on HVAC systems, leading to significant energy savings [123].

One of the most notable instances of PCM application is in office buildings with large facades, where temperature fluctuations are significant. Zhong et al. [124] employed paraffin MG29 to fill windows, resulting in an 18.3 % reduction in heat influx during summer. Arkar et al. [125] studied the inclusion of PCMs into wall structures to extend the time lag of the heat wave in buildings by up to 12 h. By integrating PCMs into building structures like walls or ceiling panels, they can counteract rapid temperature changes caused by solar gains. The PCM takes in heat during the day to avert overheating and releases it at night, maintaining the indoor climate consistent. In residential buildings, building materials enhanced with PCMs level out daily temperature fluctuations, especially in regions with large day-to-night temperature differences, thereby minimizing the reliance on external heating or cooling. Moreover, PCMs are being adopted more frequently in sustainable building designs, such as green roofs and walls, enhancing thermal insulation and mitigating urban heat islands. Roman et al. [126] found that PCM-incorporated roofs reduced the thermal transmittance by 54 % in comparison with conventional roofs. Chowdhury et al. [127] emphasized that ambient temperature, average radiative temperature, and thermal variations were critical for thermal comfort, and all of which were essential for developing efficient and energy-saving temperature control systems. Nicol [128] reported the importance of maintaining a stable human body temperature, as even a one-degree Celsius change would cause discomfort, highlighting the need for precise temperature settings in practical applications.

5.1. Floor systems

The implementation of PCMIC within floor systems serves as a pivotal method for indoor temperature regulation [129]. Given the large surface area of flooring, this application becomes a significant expanse for the absorption and dissipation of thermal energy, which is particularly advantageous in conjunction with radiant floor heating systems. Mazo et al. [130] introduced the concept of a radiant floor system, predominantly heated by either conventional heating methods or heat pumps. Nevertheless, the integration of PCMs as efficient thermal energy storage mediums enabled the storage of heat within the floor system, therefore circumventing periods of peak electricity usage. Through numerical simulations, this approach has been estimated to yield approximately 18 % savings in energy loss. Fig. 17(a) exhibits a standard concrete floor panel, while Fig. 17(b) illustrates a concrete floor panel incorporating PCMs. Rashid et al. [131] demonstrated that using 10 mm of PCM in radiant heating systems can reduce annual heating energy by 2.4 %, while 20–50 mm can save 7.3 % to 15.3 %. The radiant floor system reduced energy consumption by up to 8 % for heating and 4 % for cooling compared to others.

5.2. Wall systems

The incorporation of PCMs into both internal and external wall assemblies holds the potential to effectively mitigate diurnal overheating and nocturnal cooling irregularities. This application is instrumental in enhancing the thermal inertia of wall systems, ultimately improving indoor thermal comfort and lessening the operational burden on climate control systems. Peippo et al. [133] pioneered the integration of PCMs into wall systems for passive solar heating, identifying the capacity of PCMs for high volumetric storage density and nearly isothermal phase change processes, making them suitable for temperature control. By integrating PCMs into traditional wall materials like plasterboard and cement, a significantly improved thermal performance of passive solar buildings can be achieved (as shown in Fig. 18). These walls gather solar energy in the daytime and release stored heat at night, ensuring efficient solar energy utilization. Numerical simulations in Helsinki (Finland) and Madison (USA) revealed ideal daily heat retention when the temperature of phase transition was configured to be 1–3 °C above the ambient temperature, highlighting the need for location-specific considerations in PCM applications [133]. In addition, a study conducted by Hichem et al. [134] in Algeria found significant enhancements in the thermal performance of inner walls through the implementation of specific measures. Notably, there was a substantial reduction in the inner wall temperature, approximately by 3.8 °C. Moreover, the heat flux, representing the rate of heat transfer through the inner walls, exhibited a remarkable reduction of approximately 82.1 %.

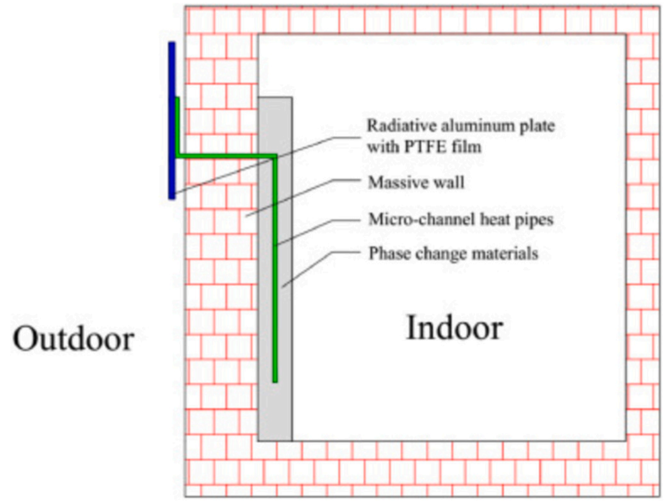

Fig. 18. The basic wall structure integrated with PCMs. The structure includes A PTFE film-covered radiative aluminum plate, a thick wall, micro-channel heat pipes, and PCMs. These elements work synergistically to achieve efficient thermal energy transfer and storage between indoor and outdoor environments [135].

5.3. Roofing and ceiling systems

The utilization of PCMIC in roofing and ceiling systems is a strategic approach to harness the solar energy. During daylight hours, these systems absorb solar radiation and subsequently releasing the stored thermal energy during nocturnal periods, which contributes to a reduction in the building's overall energy demand. Belmonte et al. [136] conducted a study on an innovative cooling ceiling system integrated with PCMs. This system, incorporating a water circulation finned tube heat exchanger and PCM, worked in conjunction with a floor system incorporating PCM likewise. The combination of these elements formed a comprehensive approach to notably reduce cooling requirements during summer months (as illustrated in Fig. 19). The integration of PCM within the ceiling system allowed for effective storage and release of thermal energy, leveraging the latent heat properties of the PCM to ensure a consistent indoor climate. Additionally, the use of a water circulation system enhanced the efficiency of heat transfer, thus optimizing the cooling process. Moreover, the integration of a PCM-enhanced floor system complemented the existing ceiling setup, resulting in a synergistic impact that amplified the cooling efficiency. This dual incorporation of PCM technology, both in the ceiling and the floor, facilitates a more harmonized and efficient utilization of the building's thermal mass. Consequently, this approach leads to a substantial decrease in the demand for active cooling systems, particularly during peak heat periods.

Fig. 17. (a) Standard concrete floor panels and (b) PCM-enhanced concrete floor panels [132].

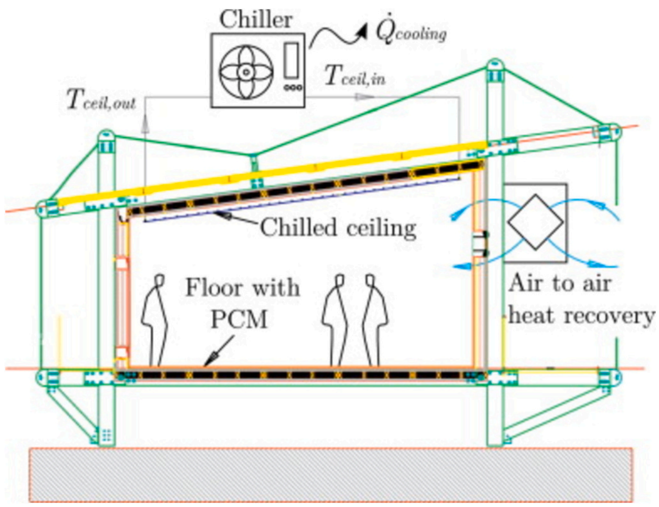

Fig. 19. The operational mechanism of an indoor temperature control system with a PCM-integrated floor and a chilled ceiling. Efficient temperature regulation is achieved through an air-to-air heat recovery system and a chiller, enabling thermal energy storage and release via the PCM floor [136].

5.4. Case studies

PCMIC can be employed within the core of various structural elements such as beams and columns, leveraging the thermoregulatory capabilities of the PCMs to enhance the thermal efficiency of the entire structure [137]. This comprehensive incorporation of PCMIC in building construction underscores its potential in energy conservation and thermal management, reflecting an evolving paradigm in sustainable architectural design [138]. In a study conducted by Kuznik et al. [139] in Lyon, the effectiveness of fatty acids and paraffin (melting point of 13.6 °C) in regulating indoor air temperatures was demonstrated. Their research focused on the implementation of PCMs within a room setting and measured the resulting temperature variations. The findings demonstrated a significant reduction in room air temperature, with PCM application leading to a temperature drop of up to 4.2 °C. Also, a study conducted by Ahmed et al. [140] employed PCMs with a melting point of 7 °C and determined that the highest room temperature was lowered by up to 2.2 °C. Both of these cases, studied in the same season in France, underline the significance of selecting a suitable phase change temperature for practical applications.

The initial cost of PCMIC is generally higher than conventional concrete due to the additional cost of incorporating PCMs and the encapsulation process. However, these higher upfront costs are offset by long-term savings through reduced energy consumption in buildings, particularly in climates with significant temperature variations. A detailed life-cycle cost analysis should be conducted to fully assess the economic benefits, regarding both the material costs and the operational savings over the lifespan of the building.

This study summarizes several real-world applications of PCMs in building structures across different countries, highlighting their use in various climates and building types, as detailed in Table 6. Case studies from the United States, China, Turkey, Portugal, and other nations illustrate the global application of PCMs in diverse architectural contexts. In warmer climates, such as those in Turkey and China, PCMs effectively mitigate heat gain, reduce indoor temperature fluctuations, and lower energy consumption, particularly in lightweight structures and high-temperature regions. In contrast, in cooler climates like the United States and Portugal, PCMs contribute to energy savings by enhancing thermal retention during colder periods, particularly in residential and office buildings. Across all regions, PCMs consistently improve indoor comfort by delaying the onset of peak heat flux, making them vital for energy-efficient and sustainable building designs, regardless of the local climate or building type.

Table 6
Case studies of PCMs application in building.

Researcher	Country	Building type	Thermal regulation and energy efficiency improvement
Kuznik et al. [139]	France	Light weight building envelops	Air temperature decreases 4.2 °C
Evers et al. [141]	USA	Frame walls	Temperature reduces 9.2 °C
Lai et al. [142]	China	Boards walls	Peak heat transfer reduces 29.1 % and total reduce 16.3 %
Kara et al. [143]	Turkey	Frame walls	14 % of annual heat load is provided by PCM
Kong et al. [144]	China	Perforated brick rooms	Room temperature reduces 2 °C
Banu et al. [145]	Canada	Wallboard	Energy saving about 79 %
Mandilaras et al. [146]	Greece	Board walls	Room temperature decreases by 30–40 %
Shi et al. [147]	China	Walls	Temperature reduces 4 °C
Silva et al. [148]	Portugal	Walls	Thermal amplitude reduces 5 °C and time delays 3 h
Heim et al. [149]	Poland	Passive solar building	Heating energy demand reduces by up to 90 %
Principi et al. [150]	Italy	Hollow bricks	Delay of 6 h in heat flux peak
Diaconu [151]	Portugal	Building envelope	Saving about 10 kWh energy
Acuña-Díaz et al. [152]	Australia	Residential envelopes	Reduction of 7 % greenhouse gas

6. Research gaps and future directions

While PCMIC has shown promise, several critical research gaps remain. One major gap is the need for comprehensive long-term durability studies, particularly under extreme conditions like repeated thermal cycling, where issues like PCM leakage, microstructural degradation, and mechanical property loss persist. Moreover, the integration of natural carbonized materials as cost-effective and eco-friendly alternatives to traditional PCMs requires more exploration. These materials offer potential for improved thermal conductivity and sustainability, but their interaction with concrete matrices, particularly in high-alkaline environments, is not well understood. Another crucial area of concern is the fire resistance and high-temperature performance of PCMIC. The behavior of these materials in fire or under extreme heat remains largely unstudied, posing safety concerns for real-world applications in buildings exposed to fire hazards.

Furthermore, scaling up the use of PCMIC from small-scale experiments to large construction projects faces special challenges. Research is needed on cost-effective production methods, ensuring consistent PCM distribution within concrete matrices, and minimizing potential issues such as segregation during mixing. A lack of comprehensive life-cycle cost analyses also hampers the assessment of economic feasibility, as studies typically focus on energy savings without considering the balance between initial investment and long-term benefits. Additionally, there is a need for studies assessing the performance of PCMIC in different building types, such as high-rise, commercial, and industrial structures, and across various climate zones, especially in extreme environments where temperature regulation is critical. Such research would help determine whether PCMIC is suitable for a wider range of applications beyond the lightweight and temperate-focused studies currently available. Finally, the absence of standardized testing protocols for PCMIC limits comparability across studies, making it difficult to evaluate performance consistently in terms of both thermal and mechanical properties. Developing universally accepted standards for testing would facilitate more reliable assessments and help drive broader adoption of PCMIC technologies in the construction industry.

Future research on PCMIC should prioritize the innovations that improve material efficiency and stability, with a strong focus on bio-based PCM formulations to align with global sustainability goals. Enhancing the dispersion and stability of these PCMs in concrete is critical for effective integration, ensuring their performance without compromising the structural integrity of the material. Moreover, research should aim to develop cost-effective manufacturing processes that enable large-scale adoption, particularly by customizing PCM formulations for various climatic conditions, with an emphasis on under-researched tropical regions. The mechanical performance of PCMIC must be systematically investigated, optimizing mix designs through microstructural analysis and mechanical testing to balance thermal benefits with structural strength. In addition, fire resistance and high-temperature behavior of PCMIC also demand more attention, as safety concerns in extreme heat or fire scenarios remain unresolved. To further advance PCM applications in building energy conservation, numerical simulations combined with real-world engineering validation play a crucial role in establishing practical design standards and construction guidelines. Such efforts should not only address energy efficiency but also ensure long-term durability and cost-effectiveness, thus encouraging the wider use of PCMIC in the construction industry. Addressing these research gaps will bridge current limitations and drive innovation towards more sustainable, efficient, and resilient building materials.

7. Conclusions

This review delves into the potential of integrating PCMs into concrete matrix to enhance energy efficiency and temperature control systems, highlighting their significance in energy-saving architectural design. The utilization of PCMs facilitates the moderation and stabilization of internal temperatures, reducing dependence on traditional heating and cooling systems, thereby achieving substantial energy savings and sustainable development. Despite challenges such as reduced concrete strength and workability, these can be overcome with optimized integration methods and the development of more efficient PCMs. In summary, the main conclusions include:

1) Energy efficiency enhancement: Energy-saving and eco-friendly PCMs significantly improve thermal efficiency in concrete construction, reducing energy demand and dependency on traditional heating and cooling systems. They also reduce greenhouse gas emissions, contributing to environmental protection.
2) Combination of PCMs: Different types of PCMs possess distinct functions and combining them can leverage each material's advantages for optimal results. This approach enhances temperature control and energy storage, improving system performance and adaptability to various building and industrial needs.
3) Technological innovations: Integration methods like microencapsulation and vacuum impregnation have improved the effectiveness of PCMs in concrete. Advances in integration technique are extremely crucial to prevent PCM leakage and enhance the durability and stability of PCM-enhanced concrete.
4) Importance of PCM selection: Choosing the suitable PCMs, suitable phase change temperatures and latent heat capacities, is vital for meeting specific thermal regulation needs of buildings.
5) Structural and service longevity considerations: The integration of PCMs into concrete requires careful consideration of both structural and service life aspects. PCMs can affect the mechanical behaviors of concrete necessitating meticulous design and material selection. Additionally, the prolonged stability of PCMs under various environmental conditions, including high alkalinity, fire, and freeze-thaw cycles, is critical to ensure the durability and effectiveness of concrete structures.
6) Application and safety: Case studies from around the world confirm the effectiveness and adaptability of PCMs in various climatic conditions, indicating that their large-scale commercial use in buildings is theoretically viable. However, for safety and health compliance, it is preferable to utilize non-toxic and non-flammable PCMs.
7) Suitability of PCMIC: PCMIC suits many building types focused on energy efficiency, such as residential and office buildings. However, it may not be ideal for cold storage or high-load-bearing structures due to reduced mechanical strength. PCMs are most effective in hot climates with significant temperature variations, supporting passive design strategies to stabilize indoor temperatures and reduce energy consumption.

CRediT authorship contribution statement

Zizheng Yu: Writing – original draft, Methodology, Investigation, Formal analysis. **Ruizhe Shao:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jun Li:** Writing – review & editing, Supervision, Conceptualization. **Chengqing Wu:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] R. Obringer, R. Nateghi, What makes a city 'smart'in the Anthropocene? A critical review of smart cities under climate change, Sustain. Cities Soc. 75 (2021) 103278.
[2] R. Zhang, Phase Change Materials and Phase Change Energy Storage Technology 8, Science Press, Beijing, China, 2009, pp. 32–34.
[3] P.K.S. Rathore, N.K. Gupta, D. Yadav, S.K. Shukla, S. Kaul, Thermal performance of the building envelope integrated with phase change material for thermal energy storage: an updated review, Sustain. Cities Soc. 79 (2022) 103690.
[4] T.-C. Ling, C.-S. Poon, Use of phase change materials for thermal energy storage in concrete: an overview, Construct. Build Mater. 46 (2013) 55–62.
[5] M. Santamouris, Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change, Solar Energy 128 (2016) 61–94.
[6] P.K.S. Rathore, S.K. Shukla, Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review, Construct. Build Mater. 225 (2019) 723–744.
[7] Ú. Cárdenas-Mamani, R. Kahhat, I. Vázquez-Rowe, District-level analysis for household-related energy consumption and greenhouse gas emissions: A case study in Lima, Peru, Sustain. Cities Soc. 77 (2022) 103572.
[8] Y. Li, M. Han, S. Liu, G. Chen, Energy consumption and greenhouse gas emissions by buildings: A multi-scale perspective, Build. Environ. 151 (2019) 240–250.
[9] E. Meng, H. Yu, B. Zhou, Study of the thermal behavior of the composite phase change material (PCM) room in summer and winter, Appl. Therm. Eng. 126 (2017) 212–225.
[10] H. Zhang, M.-y. Kang, R.Z-r Guan, A.-l. Zhao Zhou, W.-j. Wu, H.-r. Yang, Assessing the role of urban green infrastructure in mitigating summertime urban heat island (UHI) effect in Metropolitan Shanghai, China, Sustain. Cities Soc. 112 (2024) 105605.
[11] N.H. Gapski, D.L. Marinoski, A.P. Melo, S. Guths, Impact of urban surfaces' solar reflectance on air temperature and radiation flux, Sustain. Cities Soc. 96 (2023) 104645.
[12] D. Lencer, M. Salinga, B. Grabowski, T. Hickel, J. Neugebauer, M. Wuttig, A map for phase-change materials, Nat. Mater. 7 (12) (2008) 972–977.
[13] A.A. Mehrizi, H. Karimi-Maleh, M. Naddafi, F. Karimi, Application of bio-based phase change materials for effective heat management, J. Energy Storage 61 (2023) 106859.
[14] P.K.S. Rathore, S.K. Shukla, Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review, Energ. Buildings 236 (2021) 110799.

[15] S. Himran, A. Suwono, G.A. Mansoori, Characterization of alkanes and paraffin waxes for application as phase change energy storage medium, Energy Source. 16 (1) (1994) 117–128.
[16] P. Bose, V.A. Amirtham, A review on thermal conductivity enhancement of paraffinwax as latent heat energy storage material, Renew. Sustain. Energy Rev. 65 (2016) 81–100.
[17] P. Sobolčiak, H. Abdelrazeq, N.G. Özerkan, M. Ouederni, Z. Nógellová, M. A. AlMaadeed, M. Karkri, I. Krupa, Heat transfer performance of paraffin wax based phase change materials applicable in building industry, Appl. Therm. Eng. 107 (2016) 1313–1323.
[18] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2) (2009) 318–345.
[19] R. Ye, R. Huang, X. Fang, Z. Zhang, Simulative optimization on energy saving performance of phase change panels with different phase transition temperatures, Sustain. Cities Soc. 52 (2020) 101833.
[20] A.K. Mishra, M. Ramgopal, Field studies on human thermal comfort—an overview, Build. Environ. 64 (2013) 94–106.
[21] M. Koschenz, B. Lehmann, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, Energ. Buildings 36 (6) (2004) 567–578.
[22] T. Kousksou, A. Jamil, T. El Rhafiki, Y. Zeraouli, Paraffin wax mixtures as phase change materials, Solar Energy Materials and Solar Cells 94 (12) (2010) 2158–2165.
[23] Y. Hong, G. Xin-Shi, Preparation of polyethylene–paraffin compound as a form-stable solid-liquid phase change material, Sol. Energy Mater. Sol. Cells 64 (1) (2000) 37–44.
[24] A. Eddhahak-Ouni, S. Drissi, J. Colin, J. Neji, S. Care, Experimental and multi-scale analysis of the thermal properties of Portland cement concretes embedded with microencapsulated Phase Change Materials (PCMs), Appl. Therm. Eng. 64 (1–2) (2014) 32–39.
[25] S. Ramakrishnan, J. Sanjayan, X. Wang, M. Alam, J. Wilson, A novel paraffin/expanded perlite composite phase change material for prevention of PCM leakage in cementitious composites, Appl. Energy 157 (2015) 85–94.
[26] A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza, Experimental study of using PCM in brick constructive solutions for passive cooling, Energ. Buildings 42 (4) (2010) 534–540.
[27] J. Xamán, A. Rodriguez-Ake, I. Zavala-Guillén, I. Hernández-Pérez, J. Arce, D. Sauceda, Thermal performance analysis of a roof with a PCM-layer under Mexican weather conditions, Renew. Energy 149 (2020) 773–785.
[28] X. Sun, L. Liu, Y. Mo, J. Li, C. Li, Enhanced thermal energy storage of a paraffin-based phase change material (PCM) using nano carbons, Appl. Therm. Eng. 181 (2020) 115992.
[29] G. Puchkovska, S. Makarekno, V. Danchuk, A. Kravchuk, Temperature study of resonance intermolecular interaction in normal long-chain carboxylic acid crystals using IR absorption spectra, J. Mol. Struct. 744 (2005) 53–58.
[30] Y. Yuan, Y. Yuan, N. Zhang, Y. Du, X. Cao, Preparation and thermal characterization of capric–myristic–palmitic acid/expanded graphite composite as phase change material for energy storage, Mater. Lett. 125 (2014) 154–157.
[31] Z. Zhang, Y. Yuan, N. Zhang, X. Cao, Experimental investigation on thermophysical properties of capric acid–lauric acid phase change slurries for thermal storage system, Energy 90 (2015) 359–368.
[32] M.N.R. Dimaano, A.D. Escoto, Preliminary assessment of a mixture of capric and lauric acids for low-temperature thermal energy storage, Energy 23 (5) (1998) 421–427.
[33] X. Kong, S. Lu, Y. Li, J. Huang, S. Liu, Numerical study on the thermal performance of building wall and roof incorporating phase change material panel for passive cooling application, Energ. Buildings 81 (2014) 404–415.
[34] M. Sayyar, R.R. Weerasiri, P. Soroushian, J. Lu, Experimental and numerical study of shape-stable phase-change nanocomposite toward energy-efficient building constructions, Energ. Buildings 75 (2014) 249–255.
[35] D. Feldman, D. Banu, D. Hawes, Development and application of organic phase change mixtures in thermal storage gypsum wallboard, Solar Energy Materials and Solar Cells 36 (2) (1995) 147–157.
[36] A. Karaipekli, A. Sarı, Capric–myristic acid/expanded perlite composite as form-stable phase change material for latent heat thermal energy storage, Renew. Energy 33 (12) (2008) 2599–2605.
[37] C. Veerakumar, A. Sreekumar, Thermo-physical investigation and experimental discharge characteristics of lauryl alcohol as a potential phase change material for thermal management in buildings, Renew. Energy 148 (2020) 492–503.
[38] X. Huang, Y. Lin, G. Alva, G. Fang, Thermal properties and thermal conductivity enhancement of composite phase change materials using myristyl alcohol/metal foam for solar thermal storage, Solar Energy Materials and Solar Cells 170 (2017) 68–76.
[39] L. Zhang, H. Shi, W. Li, X. Han, X. Zhang, Structure and thermal performance of poly (ethylene glycol) alkyl ether (Brij)/porous silica (MCM-41) composites as shape-stabilized phase change materials, Thermochim. Acta 570 (2013) 1–7.
[40] S. Wi, J. Seo, S.-G. Jeong, S.J. Chang, Y. Kang, S. Kim, Thermal properties of shape-stabilized phase change materials using fatty acid ester and exfoliated graphite nanoplatelets for saving energy in buildings, Solar Energy Materials and Solar Cells 143 (2015) 168–173.
[41] S.A. Memon, Phase change materials integrated in building walls: A state of the art review, Renew. Sustain. Energy Rev. 31 (2014) 870–906.
[42] M.F. Junaid, Z. ur Rehman, M. Čekon, J. Čurpek, R. Farooq, H. Cui, I. Khan, Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications, Energ. Buildings 252 (2021) 111443.
[43] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, Prog. Mater. Sci. 65 (2014) 67–123.
[44] N. Kumar, J. Hirschey, T.J. LaClair, K.R. Gluesenkamp, S. Graham, Review of stability and thermal conductivity enhancements for salt hydrates, J. Energy Storage 24 (2019) 100794.
[45] P. Tan, P. Lindberg, K. Eichler, P. Löveryd, P. Johansson, A.S. Kalagasidis, Effect of phase separation and supercooling on the storage capacity in a commercial latent heat thermal energy storage: experimental cycling of a salt hydrate PCM, J. Energy Storage 29 (2020) 101266.
[46] H.W. Ryu, S.W. Woo, B.C. Shin, S.D. Kim, Prevention of supercooling and stabilization of inorganic salt hydrates as latent heat storage materials, Solar Energy Materials and Solar Cells 27 (2) (1992) 161–172.
[47] A. Abhat, Low temperature latent heat thermal energy storage: heat storage materials, Solar Energy 30 (4) (1983) 313–332.
[48] L.F. Cabeza, A. Castell, C. d Barreneche, A. De Gracia, A. Fernández, Materials used as PCM in thermal energy storage in buildings: A review, Renew. Sustain. Energy Rev. 15 (3) (2011) 1675–1695.
[49] I. Dincer, M.A. Rosen, Thermal Energy Storage: Systems and Applications, John Wiley & Sons, 2021.
[50] R. Naumann, H.-H. Emons, Results of thermal analysis for investigation of salt hydrates as latent heat-storage materials, J. Thermal Anal. 35 (1989) 1009–1031.
[51] H. Mehling, L.F. Cabeza, Heat and cold storage with PCM, Heat Mass Transf. (2008) 11–55.
[52] B. Zalba, J.M. Marín, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Appl. Therm. Eng. 23 (3) (2003) 251–283.
[53] N. Gupta, A. Kumar, H. Dhasmana, V. Kumar, A. Kumar, P. Shukla, A. Verma, G. V. Nutan, S. Dhawan, V. Jain, Enhanced thermophysical properties of metal oxide nanoparticles embedded magnesium nitrate hexahydrate based nanocomposite for thermal energy storage applications, J. Energy Storage 32 (2020) 101773.
[54] P. Zhao, Q. Yue, H. He, B. Gao, Y. Wang, Q. Li, Study on phase diagram of fatty acids mixtures to determine eutectic temperatures and the corresponding mixing proportions, Appl. Energy 115 (2014) 483–490.
[55] P. Singh, R. Sharma, A. Ansu, R. Goyal, A. Sarı, V. Tyagi, A comprehensive review on development of eutectic organic phase change materials and their composites for low and medium range thermal energy storage applications, Solar Energy Materials and Solar Cells 223 (2021) 110955.
[56] A.M. Tayeb, Organic-inorganic mixtures for solar energy storage systems, Energ. Conver. Manage. 36 (10) (1995) 969–974.
[57] R. Pichandi, K. Murugavel Kulandaivelu, K. Alagar, H.K. Dhevaguru, S. Ganesamoorthy, Performance enhancement of photovoltaic module by integrating eutectic inorganic phase change material, Energy Sources, Part A (2020) 1–18.
[58] F.L. Rashid, M.A. Al-Obaidi, N.S. Dhaidan, A.K. Hussein, B. Ali, M.B.B. Hamida, O. Younis, Bio-based phase change materials for thermal energy storage and release: A review, J. Energy Storage 73 (2023) 109219.
[59] G. Simonsen, R. Ravotti, P. O'Neill, A. Stamatiou, Biobased phase change materials in energy storage and thermal management technologies, Renew. Sustain. Energy Rev. 184 (2023) 113546.
[60] S.-G. Jeong, J.-H. Lee, J. Seo, S. Kim, Thermal performance evaluation of bio-based shape stabilized PCM with boron nitride for energy saving, Int. J. Heat Mass Transf. 71 (2014) 245–250.
[62] Y. He, H. Li, F. Luo, Y. Jin, B. Huang, Q. Qian, Bio-based flexible phase change composite film with high thermal conductivity for thermal energy storage, Compos. A: Appl. Sci. Manuf. 151 (2021) 106638.
[63] J. Duan, F. Li, Transient heat transfer analysis of phase change material melting in metal foam by experimental study and artificial neural network, J. Energy Storage 33 (2021) 102160.
[64] L. Boussaba, A. Foufa, S. Makhlouf, G. Lefebvre, L. Royon, Elaboration and properties of a composite bio-based PCM for an application in building envelopes, Construct. Build Mater. 185 (2018) 156–165.
[65] Y. Kang, S.-G. Jeong, S. Wi, S. Kim, Energy efficient bio-based PCM with silica fume composites to apply in concrete for energy saving in buildings, Solar Energy Materials and Solar Cells 143 (2015) 430–434.
[66] L. Boussaba, S. Makhlouf, A. Foufa, G. Lefebvre, L. Royon, Vegetable fat: A low-cost bio-based phase change material for thermal energy storage in buildings, J. Build. Eng. 21 (2019) 222–229.
[67] C. Fabiani, A.L. Pisello, M. Barbanera, L.F. Cabeza, F. Cotana, Assessing the potentiality of animal fat based-bio phase change materials (PCM) for building applications: an innovative multipurpose thermal investigation, Energies 12 (6) (2019) 1111.
[68] M.I. Khan, F. Asfand, S.G. Al-Ghamdi, Progress in research and development of phase change materials for thermal energy storage in concentrated solar power, Appl. Therm. Eng. 219 (2023) 119546.
[69] S. Khare, M. Dell'Amico, C. Knight, S. McGarry, Selection of materials for high temperature latent heat energy storage, Solar Energy Materials and Solar Cells 107 (2012) 20–27.
[70] M. Kenisarin, K. Mahkamov, Solar energy storage using phase change materials, Renew. Sustain. Energy Rev. 11 (9) (2007) 1913–1965.
[71] L. Liu, D. Su, Y. Tang, G. Fang, Thermal conductivity enhancement of phase change materials for thermal energy storage: A review, Renew. Sustain. Energy Rev. 62 (2016) 305–317.

[72] S.N. Gunasekara, V. Martin, J.N. Chiu, Phase equilibrium in the design of phase change materials for thermal energy storage: state-of-the-art, Renew. Sustain. Energy Rev. 73 (2017) 558–581.
[73] E. Oró, A. De Gracia, A. Castell, M.M. Farid, L.F. Cabeza, Review on phase change materials (PCMs) for cold thermal energy storage applications, Appl. Energy 99 (2012) 513–533.
[74] V.V. Tyagi, D. Buddhi, PCM thermal storage in buildings: A state of art, Renew. Sustain. Energy Rev. 11 (6) (2007) 1146–1166.
[75] A. Safari, R. Saidur, F. Sulaiman, Y. Xu, J. Dong, A review on supercooling of phase change materials in thermal energy storage systems, Renew. Sustain. Energy Rev. 70 (2017) 905–919.
[76] N. Beaupere, U. Soupremanien, L. Zalewski, Nucleation triggering methods in supercooled phase change materials (PCM), a review, Thermochimica Acta 670 (2018) 184–201.
[77] V. Tyagi, K. Chopra, R. Sharma, A. Pandey, S. Tyagi, M.S. Ahmad, A. Sarı, R. Kothari, A comprehensive review on phase change materials for heat storage applications: development, characterization, thermal and chemical stability, Solar Energy Materials and Solar Cells 234 (2022) 111392.
[78] S. Chandel, T. Agarwal, Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials, Renew. Sustain. Energy Rev. 67 (2017) 581–596.
[79] Z.M. Png, X.Y.D. Soo, M.H. Chua, P.J. Ong, A. Suwardi, C.K.I. Tan, J. Xu, Q. Zhu, Strategies to reduce the flammability of organic phase change materials: A review, Solar Energy 231 (2022) 115–128.
[80] M. Ostrý, S. Bantová, K. Struhala, Compatibility of phase change materials and metals: experimental evaluation based on the corrosion rate, Molecules 25 (12) (2020) 2823.
[81] X. Mi, R. Liu, H. Cui, S.A. Memon, F. Xing, Y. Lo, Energy and economic analysis of building integrated with PCM in different cities of China, Appl. Energy 175 (2016) 324–336.
[82] L. Navarro, A. De Gracia, D. Niall, A. Castell, M. Browne, S.J. McCormack, P. Griffiths, L.F. Cabeza, Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system, Renew. Energy 85 (2016) 1334–1356.
[83] D.P. Bentz, R. Turpin, Potential applications of phase change materials in concrete technology, Cem. Concr. Compos. 29 (7) (2007) 527–532.
[84] P. Schossig, H.-M. Henning, S. Gschwander, T. Haussmann, Micro-encapsulated phase-change materials integrated into construction materials, Solar Energy Materials and Solar Cells 89 (2–3) (2005) 297–306.
[85] A. Borreguero, J. Valverde, J. Rodríguez, A. Barber, J. Cubillo, M. Carmona, Synthesis and characterization of microcapsules containing Rubitherm® RT27 obtained by spray drying, Chem. Eng. J. 166 (1) (2011) 384–390.
[86] A. Jamekhorshid, S. Sadrameli, M. Farid, A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium, Renew. Sustain. Energy Rev. 31 (2014) 531–542.
[87] Y. Sheikh, M.O. Hamdan, S. Sakhi, A review on micro-encapsulated phase change materials (EPCM) used for thermal management and energy storage systems: fundamentals, materials, synthesis and applications, J. Energy Storage 72 (2023) 108472.
[88] R. Methaapanon, S. Kornbongkotmas, C. Ataboonwongse, A. Soottitantawat, Microencapsulation of n-octadecane and methyl palmitate phase change materials in silica by spray drying process, Powder Technol. 361 (2020) 910–916.
[89] S. Ushak, M.J. Cruz, L.F. Cabeza, M. Grágeda, Preparation and characterization of inorganic PCM microcapsules by fluidized bed method, Materials 9 (1) (2016) 24.
[90] X. Qiu, W. Li, G. Song, X. Chu, G. Tang, Microencapsulated n-octadecane with different methylmethacrylate-based copolymer shells as phase change materials for thermal energy storage, Energy 46 (1) (2012) 188–199.
[91] C. Alkan, A. Sarı, A. Karaipekli, O. Uzun, Preparation, characterization, and thermal properties of microencapsulated phase change material for thermal energy storage, Solar Energy Materials and Solar Cells 93 (1) (2009) 143–147.
[92] R. Dubey, Microencapsulation technology and applications, Def. Sci. J. 59 (1) (2009) 82.
[93] J. Zhang, Y. Xu, X. Li, H. Li, C. Yao, S. Chen, F. Xu, Leak-free, high latent heat and self-cleaning phase change materials supported by layered cellulose/Fe3O4 skeleton for light-to-thermal energy conversion, Energ. Conver. Manage. 256 (2022) 115357.
[94] J.T. McCann, M. Marquez, Y. Xia, Melt coaxial electrospinning: a versatile method for the encapsulation of solid materials and fabrication of phase change nanofibers, Nano Lett. 6 (12) (2006) 2868–2872.
[95] H. Liu, X. Wang, D. Wu, Innovative design of microencapsulated phase change materials for thermal energy storage and versatile applications: a review, Sustainable Energy Fuels 3 (5) (2019) 1091–1149.
[96] R. Parameshwaran, R. Naresh, V.V. Ram, P. Srinivas, Microencapsulated bio-based phase change material-micro concrete composite for thermal energy storage, J. Build. Eng. 39 (2021) 102247.
[97] E. Alehosseini, S.M. Jafari, Nanoencapsulation of phase change materials (PCMs) and their applications in various fields for energy storage and management, Adv. Colloid Interface Sci. 283 (2020) 102226.
[98] X. Wang, W. Li, Y. Huang, S. Zhang, K. Wang, Study on shape-stabilised paraffin-ceramsite composites with stable strength as phase change material (PCM) for energy storage, Construct. Build Mater. 388 (2023) 131678.
[99] T.Y. Lo, Preparation and characterization of phase change material for thermal energy storage in buildings, in: Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, and Civil Infrastructure 2016, 2016, p. 9804.
[100] S. Hasanabadi, S.M. Sadrameli, S. Sami, Preparation, characterization and thermal properties of surface-modified expanded perlite/paraffin as a form-stable phase change composite in concrete, J. Therm. Anal. Calorim. 144 (2021) 61–69.
[101] M. Frigione, M. Lettieri, A. Sarcinella, Phase change materials for energy efficiency in buildings and their use in mortars, Materials 12 (8) (2019) 1260.
[102] X. Wang, W. Li, Z. Luo, K. Wang, S.P. Shah, A critical review on phase change materials (PCM) for sustainable and energy efficient building: design, characteristic, performance and application, Energ. Buildings 260 (2022) 111923.
[103] S. Wi, S.J. Chang, S. Kim, Improvement of thermal inertia effect in buildings using shape stabilized PCM wallboard based on the enthalpy-temperature function, Sustain. Cities Soc. 56 (2020) 102067.
[104] H. Zhang, F. Xing, H.-Z. Cui, D.-Z. Chen, X. Ouyang, S.-Z. Xu, J.-X. Wang, Y.-T. Huang, J.-D. Zuo, J.-N. Tang, A novel phase-change cement composite for thermal energy storage: fabrication, thermal and mechanical properties, Appl. Energy 170 (2016) 130–139.
[105] P.K.S. Rathore, S.K. Shukla, N.K. Gupta, Potential of microencapsulated PCM for energy savings in buildings: A critical review, Sustain. Cities Soc. 53 (2020) 101884.
[106] D. Zhang, Z. Li, J. Zhou, K. Wu, Development of thermal energy storage concrete, Cem. Concr. Res. 34 (6) (2004) 927–934.
[107] U. Berardi, A.A. Gallardo, Properties of concretes enhanced with phase change materials for building applications, Energ. Buildings 199 (2019) 402–414.
[108] M. Bahrar, Z.I. Djamai, M.E. Mankibi, A.S. Larbi, M. Salvia, Numerical and experimental study on the use of microencapsulated phase change materials (PCMs) in textile reinforced concrete panels for energy storage, Sustain. Cities Soc. 41 (2018) 455–468.
[109] S. Ramakrishnan, X. Wang, J. Sanjayan, J. Wilson, Thermal energy storage enhancement of lightweight cement mortars with the application of phase change materials, Procedia Engineering 180 (2017) 1170–1177.
[110] B. Xu, Z. Li, Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage, Appl. Energy 105 (2013) 229–237.
[111] M. Hunger, A. Entrop, I. Mandilaras, H. Brouwers, M. Founti, The behavior of self-compacting concrete containing micro-encapsulated phase change materials, Cement and Concrete Composites 31 (10) (2009) 731–743.
[112] V.D. Cao, S. Pilehvar, C. Salas-Bringas, A.M. Szczotok, J.F. Rodriguez, M. Carmona, N. Al-Manasir, A.-L. Kjøniksen, Microencapsulated phase change materials for enhancing the thermal performance of Portland cement concrete and geopolymer concrete for passive building applications, Energ. Conver. Manage. 133 (2017) 56–66.
[113] P. Meshgin, Y. Xi, Effect of phase-change materials on properties of concrete, ACI Mater. J. 109 (1) (2012) 71.
[114] T. Lecompte, P. Le Bideau, P. Glouannec, D. Nortershauser, S. Le Masson, Mechanical and thermo-physical behaviour of concretes and mortars containing phase change material, Energ. Buildings 94 (2015) 52–60.
[115] S. Pilehvar, V.D. Cao, A.M. Szczotok, L. Valentini, D. Salvioni, M. Magistri, R. Pamies, A.-L. Kjøniksen, Mechanical properties and microscale changes of geopolymer concrete and Portland cement concrete containing micro-encapsulated phase change materials, Cem. Concr. Res. 100 (2017) 341–349.
[116] I. Asadi, M.H. Baghban, M. Hashemi, N. Izadyar, B. Sajadi, Phase change materials incorporated into geopolymer concrete for enhancing energy efficiency and sustainability of buildings: a review, Case Studies in Construction Materials 17 (2022) e01162.
[117] D. Hawes, D. Banu, D. Feldman, The stability of phase change materials in concrete, Solar Energy Materials and Solar Cells 27 (2) (1992) 103–118.
[118] S. Pilehvar, A.M. Szczotok, J.F. Rodríguez, L. Valentini, M. Lanzón, R. Pamies, A.-L. Kjøniksen, Effect of freeze-thaw cycles on the mechanical behavior of geopolymer concrete and Portland cement concrete containing micro-encapsulated phase change materials, Construct. Build Mater. 200 (2019) 94–103.
[119] S. Drissi, T.-C. Ling, K.H. Mo, A. Eddhahak, A review of microencapsulated and composite phase change materials: alteration of strength and thermal properties of cement-based materials, Renew. Sustain. Energy Rev. 110 (2019) 467–484.
[120] Z. Wei, G. Falzone, B. Wang, A. Thiele, G. Puerta-Falla, L. Pilon, N. Neithalath, G. Sant, The durability of cementitious composites containing microencapsulated phase change materials, Cement and Concrete Composites 81 (2017) 66–76.
[122] U. Stritih, V. Tyagi, R. Stropnik, H. Paksoy, F. Haghighat, M.M. Joybari, Integration of passive PCM technologies for net-zero energy buildings, Sustain. Cities Soc. 41 (2018) 286–295.
[123] Y. Han, J.E. Taylor, Simulating the inter-building effect on energy consumption from embedding phase change materials in building envelopes, Sustain. Cities Soc. 27 (2016) 287–295.
[124] K. Zhong, S. Li, G. Sun, S. Li, X. Zhang, Simulation study on dynamic heat transfer performance of PCM-filled glass window with different thermophysical parameters of phase change material, Energ. Buildings 106 (2015) 87–95.
[125] C. Arkar, S. Domjan, S. Medved, Lightweight composite timber façade wall with improved thermal response, Sustain. Cities Soc. 38 (2018) 325–332.
[126] K.K. Roman, T. O'Brien, J.B. Alvey, O. Woo, Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities, Energy 96 (2016) 103–117.
[127] A.A. Chowdhury, M. Rasul, M.M.K. Khan, Thermal-comfort analysis and simulation for various low-energy cooling-technologies applied to an office building in a subtropical climate, Appl. Energy 85 (6) (2008) 449–462.
[128] J.F. Nicol, Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans, in: Proceedings of the seventh international IBPSA conference, Rio 2, 2001.

[129] S. Lu, B. Xu, X. Tang, Experimental study on double pipe PCM floor heating system under different operation strategies, Renew. Energy 145 (2020) 1280–1291.
[130] J. Mazo, M. Delgado, J.M. Marin, B. Zalba, Modeling a radiant floor system with Phase Change Material (PCM) integrated into a building simulation tool: analysis of a case study of a floor heating system coupled to a heat pump, Energ. Buildings 47 (2012) 458–466.
[131] F.L. Rashid, A.K. Hussein, M.A. Al-Obaidi, B.M. Alshammari, B. Ali, R. Hajlaoui, M.M. Boudabous, L. Kolsi, A review of radiant heating and cooling systems incorporating phase change materials, J. Therm. Anal. Calorim. (2024) 1–27.
[132] L. Royon, L. Karim, A. Bontemps, Optimization of PCM embedded in a floor panel developed for thermal management of the lightweight envelope of buildings, Energ. Buildings 82 (2014) 385–390.
[133] K. Peippo, P. Kauranen, P. Lund, A multicomponent PCM wall optimized for passive solar heating, Energ. Buildings 17 (4) (1991) 259–270.
[134] N. Hichem, S. Noureddine, S. Nadia, D. Djamila, Experimental and numerical study of a usual brick filled with PCM to improve the thermal inertia of buildings, Energy Procedia 36 (2013) 766–775.
[135] W. He, C. Yu, J. Yang, B. Yu, Z. Hu, D. Shen, X. Liu, M. Qin, H. Chen, Experimental study on the performance of a novel RC-PCM-wall, Energ. Buildings 199 (2019) 297–310.
[136] J. Belmonte, P. Eguía, A. Molina, J. Almendros-Ibáñez, Thermal simulation and system optimization of a chilled ceiling coupled with a floor containing a phase change material (PCM), Sustain. Cities Soc. 14 (2015) 154–170.
[137] L.F. Cabeza, C. Castellon, M. Nogues, M. Medrano, R. Leppers, O. Zubillaga, Use of microencapsulated PCM in concrete walls for energy savings, Energ. Buildings 39 (2) (2007) 113–119.
[138] C. Barreneche, M.E. Navarro, A.I. Fernández, L.F. Cabeza, Improvement of the thermal inertia of building materials incorporating PCM. Evaluation in the macroscale, Applied Energy 109 (2013) 428–432.
[139] F. Kuznik, J. Virgone, Experimental assessment of a phase change material for wall building use, Appl. Energy 86 (10) (2009) 2038–2046.
[140] M. Ahmed, O. Meade, M.A. Medina, Reducing heat transfer across the insulated walls of refrigerated truck trailers by the application of phase change materials, Energ. Conver. Manage. 51 (3) (2010) 383–392.
[141] A.C. Evers, M.A. Medina, Y. Fang, Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator, Build. Environ. 45 (8) (2010) 1762–1768.
[142] R. C-m Lai, Chen, and C-Y Lin., Heat transfer and thermal storage behaviour of gypsum boards incorporating micro-encapsulated PCM, Energ. Buildings 42 (8) (2010) 1259–1266.
[143] Y.A. Kara, A. Kurnuç, Performance of coupled novel triple glass and phase change material wall in the heating season: an experimental study, Sol. Energy 86 (9) (2012) 2432–2442.
[144] X. Kong, S. Lu, J. Huang, Z. Cai, S. Wei, Experimental research on the use of phase change materials in perforated brick rooms for cooling storage, Energ. Buildings 62 (2013) 597–604.
[145] D. Banu, D. Feldman, D. Hawes, Evaluation of thermal storage as latent heat in phase change material wallboard by differential scanning calorimetry and large scale thermal testing, Thermochimica Acta 317 (1) (1998) 39–45.
[146] I. Mandilaras, M. Stamatiadou, D. Katsourinis, G. Zannis, M. Founti, Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls, Build. Environ. 61 (2013) 93–103.
[147] X. Shi, S.A. Memon, W. Tang, H. Cui, F. Xing, Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels, Energ. Buildings 71 (2014) 80–87.
[148] T. Silva, R. Vicente, N. Soares, V. Ferreira, Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: A passive construction solution, Energ. Buildings 49 (2012) 235–245.
[149] D. Heim, J.A. Clarke, Numerical modelling and thermal simulation of PCM–gypsum composites with ESP-r, Energ. Buildings 36 (8) (2004) 795–805.
[150] P. Principi, R. Fioretti, Thermal analysis of the application of pcm and low emissivity coating in hollow bricks, Energ. Buildings 51 (2012) 131–142.
[151] B.M. Diaconu, Thermal energy savings in buildings with PCM-enhanced envelope: influence of occupancy pattern and ventilation, Energ. Buildings 43 (1) (2011) 101–107.
[152] O. Acuña-Díaz, N. Al-Halawani, M. Alonso-Barneto, A. Ashirbekov, C. Ruiz-Flores, L. Rojas-Solórzano, Economic viability of phase-changing materials in residential buildings–A case study in Alice Springs, Australia, Energy and Buildings 254 (2022) 111612.