An overview of phase change materials for construction architecture thermal management in hot and dry climate region

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HIGHLIGHTS

- The statistical usage of PCM, and their thermal storage performance in the building are reviewed.
- PCM materials could be extensively used in building structures to reduce the electricity demand.
- Paraffin waxes is suitable source for PCM storage in households.

ARTICLE INFO

ABSTRACT

Worldwide, the demand for environmental friendly energy is ever-increasing due to the rapid growth of economy and living standard. Construction industry being the foremost consumer of material and energy resources has great prospect to developing innovative energy saving and thermally efficient construction materials. Phase change materials (PCMs) as thermal energy storage (TES) systems are potential due to their tailored thermal mass and heat comfort. These latent heat storage (LHS) materials possess extremely high energy storage density than conventional one. Lately, using microencapsulation technology finely dispersed PCMs are incorporated into other materials to create large surface area to improve heat transfer. This article provides a comprehensive overview on the exotic set of features of PCMs, their recent development and future trends with applications directed towards building architectures. Four aspects of PCMs are emphasized: the statistical usage, type, incorporation methods, and their thermal storage performance in the building applications. It is established that PCMs owing to their large heat capacity, high density, and excellent LHS renders as innovative energy saving strategy for sustainable built environment. Furthermore, the inclusion of PCMs in the building parts including walls, floors, and roofs are demonstrated to improve the thermal mass. Consequently, both the energy utilization for space conditioning and extreme temperature variations inside the building gets reduced. The considerable part of electricity is consumed by heating, ventilating, and air conditioning (HVAC) systems during the summer seasons and PCMs technique could be extensively applied in building structures to reduce the electricity demand. Petroleum refining industry produces a wide variety of petroleum products and paraffin wax oil is one of the most important petroleum industry byproducts. Therefore, a valuable source of paraffin waxes is available to be employed as the base PCM storage in households.

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Contents

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Nomenclature

BS	butyl stearate	PCMM	phase change material mortar
DSC	differential scanning calorimeter	PCMs	phase change materials
EG	expanded graphite	REFM	reference mortar
HVAC	heating, ventilating, and air conditioning	SEM	Scanning Electron Microscopy
LHS	latent heat storage	SHS	sensible heat storage
MMA	methyl methacrylate	ss	shape-stabilized
MEPCM	microencapsulated phase change materials	St	styrene
PCES	phase change energy solutions	TES	thermal energy storage

1. Introduction

The mounting energy consumption in residential areas arises from the thermal climate optimization. This thermal comfort is achieved at the cost high energy consumption, where heating, ventilating and air conditioning (HVAC) systems are heavily exploited. Certainly, this approach is detrimental sustainable structures unless some favorable alternatives are explored. Consequently, positive measures are essential to ease the burden of energy consumption of residential buildings. Unquestionably, building is the foremost sectors in terms of energy spending and economic investment. In 2009, it was reported that the building sector of United States and European Union consumed around 40% of the total fossil fuel [1].

The energy utilization for HVAC systems is still increasing with the escalating demand for thermal comfort. Hence, the importance of the insulation materials in the buildings has been highlighted. The commonly employed insulation materials are fiberglass, cotton, and foams. In this standpoint, TES systems are attractive due to their energy economy in buildings. Currently, the major concern involving the modern built environment is related to the necessity of energy efficient sustainable structures together with intuitive design and architecture. Management of energy supply and demand equilibrium requires their constant preservation.

2. Development of phase change materials technique in residential buildings

Based on heat storage capability TES media are classified into sensible heat storage (SHS) and latent heat storage (LHS). In SHS during phase change, the heat is stored or released in the storage media together with temperature alteration. Conversely, in the LHS materials heat is stored or released during phase change processes in the form of fusion/solidification. PCM undergoes a phase change from a solid to liquid or vice versa when the temperature increases or decreases. It is the phenomena of phase transformation that enables the PCM to store and release significant amounts of latent heat during the phase changes. LHTES systems are created by impregnating organic, inorganic, or eutectic compounds into construction elements including wallboard and concrete. They are promising due to their prevalent acceptance and subsequent adaptation as building materials in the entire built environment. PCMs exhibit several notable advantages such as high energy storage density and relatively low temperature swings [2].

The practical application of PCMs in residential buildings entails their union inside LHTES systems. This allows forming a superior construction material (wallboard or concrete) with thermally enhanced properties to mitigate temperature swings, yet suitable for lightweight housing applications. However, implementation of PCMs in residential building designs needs a meticulous review on their distinctive physical and chemical properties as well as effective inclusion into LHTES system. Conversely, LHS systems with PCMs provide a high heat storage density with large capacity of storing heat during phase transformation, where volume and temperature variation is minimal. Employment of LHS media in the buildings fulfils the demand for thermal comfort and conserves the energy [3].

Recently, intensive efforts are dedicated to enhance the features of PCMs via the improvement of the thermal stability [4,5]. The

target is to achieve a wider operating temperature range and better material stability along with improved material response. This implies a better mechanical design, controller systems and superior fabrication processes [6].

3. Thermal energy storage

3.1. Sensible heat storage

In general, engine oil, concrete, brick, rock, and water are used in SHS systems. By raising the solid or liquid temperature in SHS media, thermal energy is preserved, where the material's heat capacity is exploited [7]. The materials temperature is increased during charging and decreased through discharging. The temperature of the material is increased while charging and reduced while discharging. The quantity of stored heat is linked to the quantity of materials, temperature, and specific heat. Its volumetric heat storage potential is low whereas the temperature differs in the entire process of heat transfer [8–10]. Seemingly, water is the ideal SHS material because of its high-specified heat as well as economical nature for moderate range operation. Conversely, for operations that require high temperatures of over 100 °C, molten salts, oils, and liquid metals are used for storing thermal energy. For purposes of heating air, rock bed-type storage materials are used [11].

3.2. Latent heat storage

The working principle of LHS systems are based on the absorption or liberation of latent heat during phase transformation from solid to liquid or vice versa. Based on phase transformation process, they are classified into solid–liquid, solid–gas, solid–solid and liquid–gas. The complex and unreliably large volume alteration that occurs during liquid–gas and solid–gas phase transformations is unsuitable for energy storage [9]. However, the small volume alteration during solid–liquid phase transformation and the absorption of latent heat at constant temperature makes the process favorable for heat storage. In contrast, the heat storage or liberation for solid–solid phase change is decided by the transformation between two different crystalline states. Furthermore, the involvement of low latent heat and tiny volume change in solid–solid transitions makes them attractive for LHS systems [12]. Because of minimum heat losses during charging and discharging, the LHS media possess higher heat storage capacity than SHS one. The volume occupancy of LHS systems is two times lower than water for the same heat storage capacity. A comprehensive review on LHS systems development (paraffin, non-paraffin, hydrate salts, eutectics, etc.) is presented by Farid et al. [6].

4. Phase change mechanisms

PCM can store and release large amounts of heat energy. Although phase transformation between any two phases (gas, liquid, or solid) can happen but the conversion between liquid and solid phases are commercially most viable. PCM in its solid phase absorbs heat and produce cooling effect. Conversely, in its liquid phase PCM releases heat and results warming [13]. PCM possessing elevated heat of fusion, melting and solidification at certain temperature is capable of storing and releasing high amount of energy [14]. PCMs latent heat storing capacity is achieved through solid-solid, solid-liquid, solid-gas and liquid-gas phase transformation as illustrated in Fig. 1 [12].

Conversion from solid to liquid or from liquid to solid is the commonly used in PCM for LHS. This is suitable for the developing heat-storage and thermo-regulated textiles and clothing. Heat transfer processes critically depend on the materials phase. For
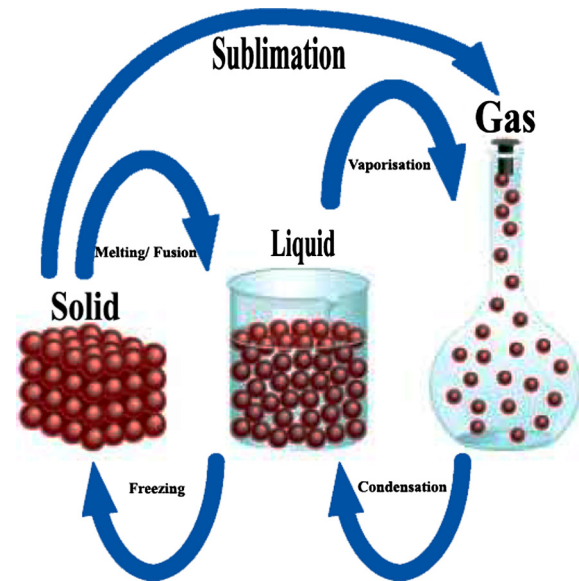

Fig. 1. Solid-liquid-gas phase change [12].

instance, in solid phase heat transfer is dominated by conduction mechanism. Conversely, for liquids convection is the predominant mechanism and for vapors convection and radiation are the principal modes of heat transfer. Only solid to liquid or reverse phase transformation is employed for textile applications. Transformation from the solid to the liquid phase of PCM occurs when the melting temperature is attained during heating [15]. Fig. 2 depicts a typical differential scanning calorimeter (DSC) heating thermogram for PCM melting process, where it absorbs large amount of latent heat from the surroundings [13].

It undergoes repeated conversion between solid and liquid phases via the utilization of latent heat of fusion to absorb, store and release heat thereby produces warm and cool ambience. The storage capacity of LHTES devices is expressed as [16]:

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m\Delta h_m + \int_{T_m}^{T_f} mC_p dT \xrightarrow[Substitution]{After} Q$$

$$= m[C_{sp}(T_m - T_i) + a_m\Delta h_m + C_{lp}(T_f - T_m)] \qquad (1)$$

where Q is the storage capacity, C_p is the specific heat, h is the enthalpy, T_i, T_m, and T_f are the initial, melting and freezing temperature, respectively.
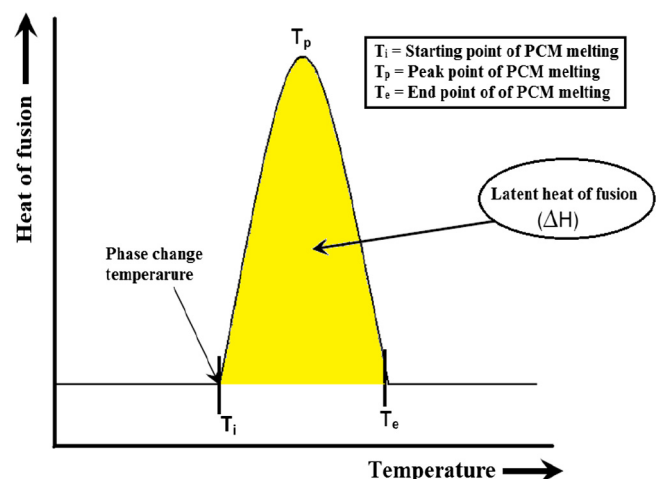

Fig. 2. DSC thermogram of PCM [13].

Notably, the only solid-liquid PCMs phase transformation can be done practically. The existence of high pressures and large volumes reduces the gas storage phase of the PCMs liquid-gas phase and is not practically viable [17]. Moreover, liquid-gas transitions caused by excessive transformation heat than those for solid-liquid PCMs transformation are not advantageous for practical use. Conversely, solid-solid conversion phase being slow contains low transformation heat. The SHS materials are similar in performance to solid-liquid PCMs [18]. Compared to conventional SHS, solid phase PCMs on attaining the melting temperature tend to absorb huge quantities of heat at constant temperature until transformation of all materials into liquid phase is completed. Then, PCM is solidified by emitting its preserved latent heat after the ambient temperature surrounding the liquid falls. In the required temperature range of −5 to 190 °C, PCMs quantity is significant [19]. Indeed, some PCMs are efficient in the human comfort ranging from 20 to 30 °C. Such PCMs categories preserve 5–14 times more heat per volumetric unit compared to the traditional storage materials such as rock, masonry, and water. The rising demands for portable and more strong heat storage materials, especially within the cooling and heating systems led to the growth of PCMs commercialization from 1975 [7]. Thermodynamically, energy in the form of latent heat is stored during the phase transformation from ice to water and it gets released when water transforms into ice. It is very efficient to storing the latent heat but the transition temperature not very human friendly [20]. Fig. 3 demonstrates the typical heat storing and melting cycle of PCM [21].

Phase Change Energy Solutions (PCES) takes advantage of energy storage and release concept via PCMs, where the temperature transition is between 0 and 20 °C [22]. Each PCM product should have a thermal mass for holding a required temperature for a long period. Any thermal quantity exceeding 0 °C melts all the ice completely [23]. This is replicated on large scale in commercial buildings and homes. For maintenance of a controlled temperature, PCM emits and absorbs heat energy. The same thing happens at a larger scale inside homes and commercial structures. PCM absorbs and releases thermal energy to maintain a regulated temperature. PCM absorbs heat in solid phase, particularly when there is an increase in external temperature. The PCM temperature would be a replica of the external temperature until the PCM attains the melting point. When the external temperature attains the PCM melting point, the PCM would start melting (change phase). During the process of phase transition, the PCM would accumulate huge thermal quantities without undergoing temperature change. In this period, the PCM offers a "cooling effect". The quantity of time required for the PCM to produce a cooling effect is influenced by the PCM's melting point (latent fusion heat). The variation in enthalpy depends on the PCM material, which is mainly measured in units called Joules or gram. When the enthalpy is higher, the PCM would provide a longer cooling effect. The reverse cycle takes place when there is cooling in external temperature. The PCM, currently in the liquid phase, is capable of emitting the absorbed heat when the external temperature drops. At this time, the PCM solidifies, thus providing a "warming effect" [24].

5. Properties of PCMs

The distinctive nature of PCMs lies in their ability of providing a totally passive heat regulation system. Simply put, no quantity of power or electricity is required for creation of a significant temperature decrease or increase. Additionally, PCMs are beneficial because they are used repeatedly. This means:

(i) Structure and building owners save huge quantities of energy.
(ii) Small electronic gadgets, for instance, smart phones and laptops may undergo cooling without use of active cooling fans/systems.
(iii) High performance textiles may be designed to offer heat regulation in different areas that include infant car seats, outdoor gear, hospital linens and active wear apparels among others.
(iv) A better sleep at night through heat regulated comforter products such as pillows and mattresses.
(v) Confidence in transporting the containers carrying food products, vaccines and pharmaceuticals under required temperatures.
(vi) Heating and cooling relief in areas that have no electricity.
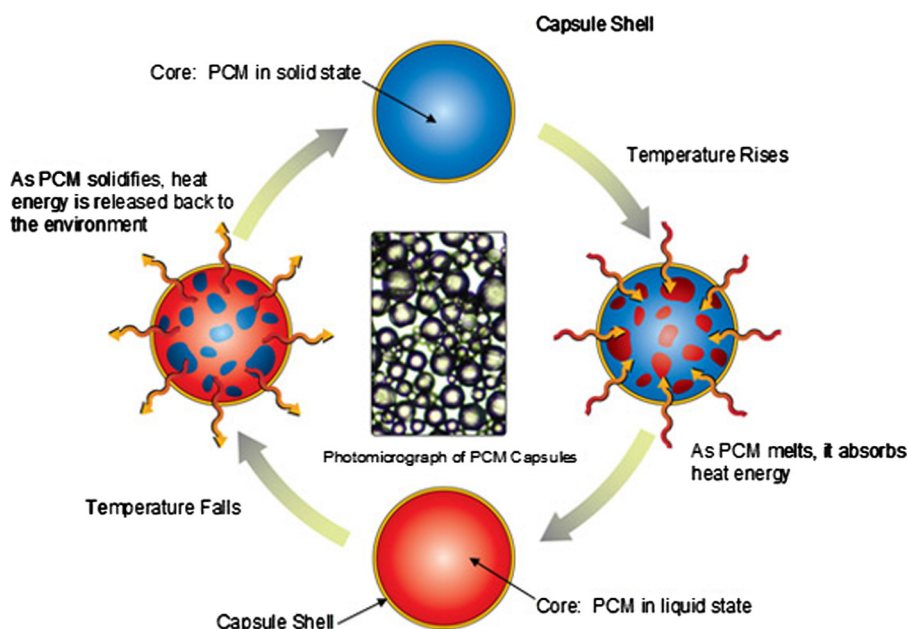(vii) Release and storage of heat combined with solar energy systems.

Fig. 3. PCMs cycles [21].

Table 1
General characteristics of PCMs [30].

Thermal properties	Physical properties
• Suitable phase change temperature	• High density
• High specific heat	• No or little sub-cooling during freezing
• High latent heat	• Low vapor pressure
• High thermal conductivity in both liquid and solid phase	• Small volume change
Chemical properties	**Kinetic properties**
• Prolonged chemical stability	• No super-cooling
• Compatible with capsule material	• Sufficient crystallization rate
• Non-toxic, non-flammable, and non-explosive	
Economic properties	
• Abundant	
• Inexpensive	

The major features associated with PCMs differ from a manufacturer to another. Existing PCM may not be used simply for developing an efficient heat energy storage gadget [21]. The economy, chemical, physical and thermal properties illustrated in Table 1 play an essential role in enabling PCM to be used as TSs [25].

6. Classifications of PCMs

Fig. 4 illustrates the broad classification of PCMS in terms of organic compounds, inorganic salt hydrates, eutectics of organic or inorganic materials and natural elements.

Among these, organic and inorganic materials, PCMs are extensively implemented in various applications. Zalba et al. [26] classified 118 organic substances, inorganic substances, organic eutectics, inorganic eutectics, fatty acids and non-eutectic mixtures of inorganic substances as prospective PCMs. Lane [16] identified 210 organic, inorganic and eutectic materials suitable for building temperature regulation. These materials revealed phase change without any segregation. Kuznik et al. [27] underscored 21 experimental investigations those are performed on PCM wallboards for thermal properties improvement. PCMs selection criteria are critically decided by their thermal, physical, chemical and economic aspects.

PCMs are variously termed as thermal flywheel, heat of fusion device, latent heat device and fusible mass device. Alawadhi [28] referred PCMs as 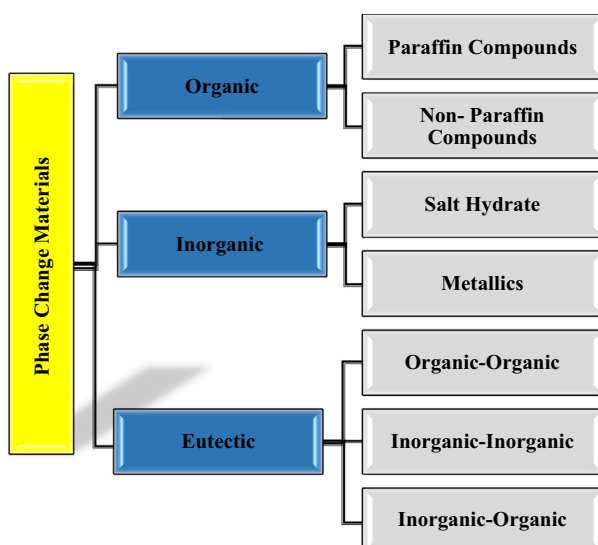capacitive insulation types owing to their delayed heat flow via thermal absorption. PCMs acted as a heat reservoir in buildings walls and removed excess heat from the building envelope to maintain the comfort levels. PCMs are used in several thermal applications such as waste heat recovery, spacecraft temperature systems, heat pumps, electrical equipment cooling, transportation of sensitive materials such as blood or chemicals, storage of perishable items, industrial cold store, thermal energy storage and thermal conditioning of buildings. Betz and Turpin [29] evaluated the concrete construction application of PCM in three ways as follows:

(i) Increase in energy storage capacity of concrete for houses.
(ii) Decrease in temperature rise and subsequent temperature reduction during the first days of hydration of concrete.
(iii) Limits the number of freeze/thaw cycles of bridge deck concrete.

The melting temperature and enthalpy are the two important features of PCMs, which depend on molecular effects in terms of chemical bonding. Fig. 5 shows the range of melting enthalpy and melting temperature of common PCMs [30].

Other different PCMs cover temperatures ranging between 0 and 130 °C; they include sugar alcohol, fatty acid and paraffin, and are considered organic material. Salt hydrates refer to salts containing a significant quantity of water crystals whereas clathrates refer to crystalline structures, where both kinds of molecules exist in interpenetrating lattices. Clathrates become gas hydrates when enclosed molecules emanates from a gas whereas the adjacent crystalline structure is in liquid form. Their coverage in terms of temperature ranges from 0 to 30 °C. For temperatures exceeding 150 °C, a variety of salts alongside their mixtures are used. According to Fig. 6, the energy density lies proportionally to the PCMs melting temperature that is based on Richard's thermodynamic theory (Table 2). It can be inferred that the quantity of bonds for each molecule and its density divided by molar mass relating to the molecular or atomic packing density are essential for the proportionality. Previously, various single materials alongside their components (two or multiple) mixtures are exploited in the same manner as PCM [31]. Inorganic materials cover an extensive range in temperature compared to organic materials. In general, the former has same melting enthalpies per mass, but higher for each volume due to higher density. However, their incompatible nature with metals restricts them because of the existence of serious corrosion in certain PCM-metal combinations. Eutectic water-salt solution with melting temperatures of less than 0 °C presents a
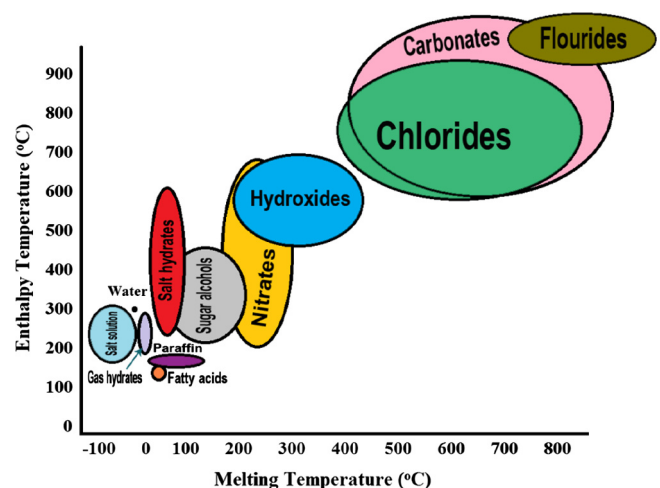

Fig. 4. Classification of PCMs.

Fig. 5. Typical range of melting temperature and enthalpy of PCMs [30].

Fig. 6. PCM integrated CSM panel [72].

suitable storage density. The salient characteristics of eutectic, inorganic, and organic PCMs are presented in Table 2. Besides, some exceptions are common. For example, a high volumetric heat fusion, a low heat fusion per unit weight, instability during temperatures, different toxicity level and inflammability emerge as the common demerits associated with certain PCMs [32].

Sharma et al. [31], Shalaby and Bek [33] and Demirbas [34] observed that the eutectic group does not indicate any form of phase separation. They freeze and melt constantly without separation because they freeze under a combined crystalline mixture without an opportunity for separating components. After melting the two components liquefy concurrently again without the possibility of separation [35]. Tyagi et al. [36] observed that certain PCMs have negligible ultra-cooling and phase separation. They can be absorbed in different building materials. Mehling and Cabeza [30] demonstrated the main drawback associated with inorganic components as well as their compatible nature with metals based on serious corrosion. To overcome such redundant features, different attempts are initiated.

Oya et al. [37] designed a phase transition composite for porous nickel/erythritol. They used a laser flash technique, differential scanning calorimeter (DSC) and vacuum impregnation to prepare composite PCMs and to subsequently classify their thermophysical features. The outcomes indicated little pore size effect on the melting temperature of erythritol. Notably, a proportional impregnation ratio towards fusion heat can be seen. Furthermore, the heat conductivity showed a considerable effect with 15 vol.% of porous nickel, whereby a pore size measuring 500 mm and 85 vol.% for PCM at 11.6 W/mK is attained. The value appears to exceed that for pure erythritol (0.733) by 16 times. Phase separation in salt hydrates may be prevented through component thickening or gelling, whereby heavier phases are prevented from occupying the bottom. Super-cooling may be controlled using a nucleating agent. Low heat conductivity in kerosene (paraffin) may be enhanced through insertion of metals into the phase changing component or application of finned surfaces. Notably, it is critical to conduct a brief discussion of various kinds of PCMs.

6.1. Organic PCMs

Organic PCMs (paraffin and non-paraffin) render congruent melting without phase segregation and super-cooling over the large number of melting/freezing cycles at the cost of latent heat of fusion. Hale et al. [38] overviewed 500 engineering organic PCMs significant for efficient thermal design in storage devices. Paraffin waxes, polyethylene glycol, fatty acids, and their derivatives are the major types of organic PCMs. They undergo solid–liquid phase transition during heating and subsequent cooling. Polyalcohols and polyethylene are the other classes of organic PCMs, which reveal solid–solid phase transformation at a fix temperature by absorbing/releasing huge amounts of the latent heat. Several organic PCMs are discovered and categorized over the years [39,40]. Despite several benefits of organic PCMs their low thermal conductivity mediated reduction of charging/discharging rate, super cooling effect in cooling cycles and leakage in the containers are the main demerits that need to be overcome [41,42]. Their melting points of these PCMs can be modified by mixing organic materials which cover comparatively a small temperature range (−5 to 150 °C) yet sufficient for building applications (fatty acids and sugar alcohol) [43,44]. Commonly, their density is smaller than 1 g/cm^3. Consequently, paraffin and fatty acid enclose smaller melting enthalpies per volume than inorganic materials.

6.1.1. Paraffin as PCM

Organic Paraffin or paraffin wax contains a straight chain n-alkanes mixture written chemically as CnH_{2n+2}, whereby $20 \leqslant n \leqslant 40$. Depending on the length of their chain, paraffin is categorized as odd-chained (iso-paraffin) or even-chained (n-paraffin) [45]. Paraffin tends to have a higher mass storage density, and it melts and solidifies with negligible or without any sub-cooling. Furthermore, it has a low heat conductivity and produces little vapor pressure within the container. After melting, paraffin shows an increase in volume ≈10 vol.% that is same as that for various inorganic components; however, it is less important because of its softness and thus, cannot create huge forces after expansion. Paraffin does not only dissolve in water but it is hydrophobic, thus unable to react with various chemical reagents. At higher temperatures, paraffin bonds may break leading to the evaporation of the ensuing short molecular chains. The compatibility of paraffin with metals is good, and it can be used safely as it burns easily.

Table 2
Important characteristics of organic, inorganic and eutectic PCMs [37].

Properties	Types		
	Organic	Inorganic	Eutectic
Supercooling	No	Yes	Not much data is available on thermo-physical
Phase segregation	No	Yes	properties. They are relatively new class of
Temperature range	Large	Low	PCMs
Thermal conductivity	Low	High	
Compatibility with materials	High	Medium	
Chemical stability	Yes	–	
Recyclability	Yes	Yes	
Flammability	Yes	No	
Heat of fusion	High	High	
Corrosion resistance	High	Low	
Volumetric storage density	Low	High	High
Cost	High	Low	High

However, it is capable of softening plastics when in contact with them. Increasing the quantity of C atoms within CnH_{2n+2} escalates paraffin's melting temperature, where Polyethylene serves as the limit with numerous C atoms. The paraffin that exists in low C atom quantities (for instance, in propane C_3H_8, ethane C_2H_6 and methane CH_4) is gaseous in ambient conditions. The smallest n-alkane, which can melt above 0 °C, is Tetradecane. Examples of organic PCMs are Paraffin, 1-Teradecanol Paraffin, 1-Dodecanol Paraffin, Erythritol, High Density Polyethylene, Palmitic acid and Capric Acid [46]. Earlier investigations displayed that paraffin waxes are able to absorb, store and release an enormous amount of heat over a large number of phase change cycles [47]. They are excellent building materials for energy storage having heat capacity in the range 2.14–2.4 kJ/kg K and latent heat between 200 and 220 kJ/kg. No phase segregation occurs in paraffin despite many phase transition cycles. They exhibit many favorable characteristics such as chemically inert, non-corrosive, colorless, durable, inexpensive, abundant, ecological safety and are nontoxic [48]. Conversely, the high latent heat requirement during the freezing cycle of paraffin can be improved using metal fillers and other techniques in the base materials.

6.1.2. Non-paraffin

Non-paraffin organics are PCMs that exist abundantly and contain various properties. Unlike paraffin, all non-paraffin has unique characteristics. Khudhair and Farid [49] conducted an extensive study of organic components and came up with several glycols, alcohols, fatty acids and esters that could serve as ideal PCMs for storing energy. Due to their highly flammable nature, these components should be kept in extremely low temperatures, away from oxidizing agents or flames. They have some common properties such as high temperature instability, varying toxicity levels, low flash points, low heat conductivity, inflammability and high fusion heat. In general, they are acidic in nature and their chemical formulae is $CH_3(CH_2)_2nCOOH$ [34]. Fatty acids are obtained from animal and vegetable sources; this makes them non-polluting supply sources [50]. They are classified into six categories namely stearic, palmitic, myristic, lauric, capric and caprylic [45]. These materials, unlike paraffin have a suitable phase transition (solid–liquid) characteristics; however, they are three times expensive compared to paraffin [11].

6.1.2.1. Fatty acids.
Fatty acids being promising PCMs are attractive for various energy efficient building architectures. They have many desirable characteristics including high energy storage density, good phase change reversibility, freezing and melting congruency with minimum super-cooling and without phase segregation, small volumetric change between solid and liquid phase, chemically and thermally stable, non-toxic, biodegradable and non-corrosive. However, their lower thermal conductivity limits them from widespread application. Usually, substances with high thermal conductivity are added into fatty acids to improve their heat conductivity property. Fauzi et al. [51]. improved the conductivity of myristic acid/palmitic acid eutectic phase change material by adding 10 wt.% of sodium laureate. Karaipekli et al. [52] modified the thermal conductivity of stearic acid by incorporating expanded graphite (EG) and carbon fiber. Addition of EG in the mass fraction of 2%, 4%, 7% and 10% is found to increase the thermal conductivity of the stearic acid up to 27.6%, 58.6%, 179.3% and 279.3%, respectively. Conversely, incorporation of carbon fiber in the same mass fractions as EG is observed to improve the thermal conductivity by 24.1%, 106.9%, 162.1% and 217.2%, respectively. Thermal properties of fatty acids during their phase change are intensively studied by several authors [53–55]. Most fatty acids undergo through solid–liquid phase change process when applied to buildings for energy storage. Thus, the processed fatty acids must be thermally stable and leakage free during phase transition. Methods such as adsorption method, polymer blends, and microencapsulation are used to process them. Adsorption is a simple and cheaper method to prepare stable PCMs. The melting temperatures of fatty acids vary between −5 and 70 °C and the latent heat ranges from 45 to 210 kJ/kg [56]. They are capable to retain the shape of host material due to their high surface tension of $(2–3) \times 10^{-4}$ N/cm. Recently, Yuan et al. [57] presented a great insight of fatty acids. The main advantage is with their ability to undergo through several thermal (melting/freezing) cycles without any notable degradation in thermal properties. The fatty acids and their eutectic mixtures are thoroughly examined as possible phase change materials for low/medium energy storage applications such as solar energy storage and residential applications. Feldman et al. [58] evaluated the thermal properties of different fatty acids and elaborately discussed their promise as PCMs in space heating applications. The melting point of these acids was measured between 30 and 65 °C and latent heat ranged from 153 to 182 kJ/kg. The thermal performance of myristic acid is examined by Sari and Kaygusuz [59], where better stability at low temperature is revealed. Furthermore, these PCMs are found to be more effective as heat exchanger in horizontal position. Sari and Kaygusuz [60,61] studied the thermal performance of stearic acid and palmitic acid. It was pointed out that the melting and solidification times of the PCM can be decrease conspicuously by placing the tube containing the PCM in a horizontal position rather than a vertical one. Karaıpekli et al. [62] tested the eutectic mixture of capric and stearic acid. These acids are determined to be potential for low temperature solar energy in building applications. Rozanna et al. [63] and Sarier and Onder [64] comprehensively reviewed the organic PCMs.

To improve the thermal performance of organic PCMs for extensive application, the eutectics of fatty acids and other PCMs are processed. Shieli et al. [65] assessed the thermal performance of a mixture of capric and lauric acids as possible phase change material for low temperature thermal energy storage purpose. Later, Dimaano and Watanabe [66] added pentadecane in the capric–lauric mixture and found that 50% of pentadecane in the mixture provides the highest heat charged. Zhang et al. [67] inspected the solid–liquid phase transition in lauric, palmitic, stearic acid and their binary systems. They affirmed that the thermal properties of 23% lauric–palmitic acid eutectic system remained stable after 100 heating–cooling cycles at 32.8 °C. Sarı et al. [56] evaluated the thermal properties of lauric-stearic, myristic–palmitic and palmitic–stearic acid and tested the thermal stability for 360 melting–freezing cycles. It is concluded that these materials can be effectively used for a one-year period. In another attempt, Sarı [68] examined the thermal performance of eutectic mixtures of lauric–myristic acid, lauric–palmitic acid and myristic–stearic acid as PCM. It was shown that these PCMs acquired good thermal stability for at least four years.

6.2. Inorganic PCMs

Inorganic PCMs cover an extensive temperature range. Although they contain similar latent heat per unit mass as that for organic PCMs, their latent heat per volumetric unit tends to be higher because they have higher density. Salt hydrates ($KF·3H_2O$, $LiNO_3·3H_2O$ and $CaCl_2·6H_2O$) constitute a type of inorganic components containing one or multiple water molecules to an extent that the emerging crystalline solid would have a chemical formulae of $AB·nH_2O$. They have several properties that include higher heat conductivity of ∼0.5 W/m °C, incongruent melting, less corrosive and non-flammable, and non-toxicity unlike organic PCMs. Salt hydrates possess melting temperatures that range from 5 to 130 °C, which is ideal for developing applications. In general, inorganic components being hydrated salts having metallic properties

are used extensively in solar energy [69]. The components can retain the fusion heat of ~350 MJ/m^3 even under large cycle quantities.

6.2.1. Salt hydrates

Glauber salt ($Na_2SO_4 \cdot H_2O$) with 44 wt.% Na_2SO_4 and 56 wt.% H_2O is amongst the most affordable inorganic components that is ideal for storing heat energy. Although its latent heat of 254 kJ/kg and melting point of ≈32.4 °C is high, it is vulnerable to sub-cooling and phase separation. Another concern lies in the salt corrosion on mineral containers [70]. The application of thickening agents, for instance, Bentonite clay as well as nucleating agent such as Borax helps to control the sub-cooling. However, they decrease the rate of thermal transfer by reducing the heat conductivity. In general, most salt hydrates experience the same problem.

In terms of mass, salt hydrates usually contain high storage density, but this tends to be higher in terms of volumes because of the high density. Salt hydrates have various materials with about one salt as well as water. Consequently, they are capable of separating into different phases and have cycling instability. Indeed, phase separation is a constant issue found in salt hydrates. Their heat conductivity is same as that for water and eutectic water-salt solutions. The sub-cooling of many salt hydrates extents up to 80 K and their vapor pressure tends to be lower compared to that for water as the salt decreases the vapor pressure. Their melting is almost or over 100 °C and exhibit significant vapor pressure in the melting process. The volumetric change for salt hydrates is about 10 vol.%. In most cases, salt hydrates exhibit high chemical stability; however, most are corrosive towards metals [30]. With regard to their safety, a huge difference exists. They are affordable with 1–3 €/kg unless when purchased in pure form. Several salts may be used as substitutes for PCM, particularly in temperatures of over 150 °C. Inorganic components cover an extensive range of temperature with density exceeding 1 g/cm^3. Apart from the inorganic components, some organic components may be used as PCM. The components in these categories have their temperatures ranging from 0 to 200 °C. Many organic components are not stable in higher temperatures as they are formed by covalent bonds. Mostly, the organic PCM density (103 kg/m^3) is lower compared to that for inorganic components such as salt hydrates and water. In most cases, the melting enthalpies per volume of organic components and sugar alcohols are negligible compared to inorganic those for inorganic components [6].

7. Incorporation methods of PCMs into construction

7.1. Conventional methods

According to Hawes et al. [71], PCMs can be integrated into the traditional building materials using three common methods. Such encompass macro-encapsulation, immersion, and direct incorporation. The freezing and melting temperatures for PCMs tend to change slightly when integrated into construction materials.

(i) Direct incorporation: It constitutes the simplest technique in which powdered or liquid PCMs are incorporated directly to construction materials that include plaster, concrete, or gypsum during production. This method does not require any additional equipment. However, the major pitfalls associated with building materials include incompatibility and leakage.

(ii) Immersion: In this technique, the "building structure" materials namely concrete, brick or gypsum are immersed in melted PCMs for absorption into the internal pores with capillary initiated elevation. Some studies confirmed that the

issue of leakage undermines prolonged usage. Although, direct immersion and incorporation have varied operation processes, the two integrate PCMs directly in traditional building materials.

Macro-encapsulation: Here, the encapsulation of PCMs in containers that include panels; spheres or tubes are undertaken. RUBITHERM generates a kind of PCM panel known as CSM modules that are formed by aluminum having an effective anti-corrosion coating as indicated in Fig. 6 [72].

They are ideal for various commercialized PCMs, where leakage may be overcome, thus there is no effect to the functions of the building structure. The main drawbacks are redundant heat conductivity, tendency of edge solidification coupled with complex incorporation to the construction materials. Alkan et al. [73] observed that polyurethanes (PU), melamine–formaldehyde (MF) resin and urea–formaldehyde (UF) resin are ideal microcapsule shell material. In most cases, macro-encapsulation is used because it is readily available in different sizes and shapes. This is commonly used for holding the liquid PCM and preventing changes in composition because of reaction with the surrounding. Moreover, it improves mechanical stability to a structure, especially when the container is very strong.

7.2. Micro-encapsulation

Currently, microencapsulated PCMs are used for storing heat energy in buildings. In this method, PCM particles are wrapped in a slender, sealed, and "high molecular weight polymeric film" that helps to retain the shape and prevent leakage of PCM from during the process of phase transition. It is easier and cheaper to integrate the microencapsulated PCMs into building materials [74]. The PCM should be encapsulated to prevent it from adversely affecting the building material's function. This PCM encapsulation technique in concrete is characterized by certain pitfalls, where the concrete's mechanical strength is affected. The heat performance of PCMs acquired through the process is largely influenced by the material's size and encapsulation. Several methods are used in micro-encapsulation; they include poly-addition polymerization [75], condensation [76,77], emulsion [78–80], suspension [81,82] and coacervation [83,84].

Sánchez-Silva et al. [85] studied the microencapsulation of various PCMs using the suspension copolymerization of styrene (St) and methyl methacrylate (MMA). The influences of the monomers/paraffin on the encapsulation process and thermo-physical properties are determined. The ratio of MMA and St is found to affect the polymerization rate and the time at which the identity point is reached. Rao et al. [86] encapsulated the n-docosane in the melamine resin shell by poly-condensation technique. Melted paraffin is emulsified in water using water-soluble mixers (melamine resin) to achieve the desired size and stability. Addition of acid initiates the poly-condensation. Microencapsulated phase change materials (MEPCM) with a core mass fraction of 60% showed a latent heat of 150 kJ/kg. This encapsulation process is found to be thermally and chemically stable and reliable. Recently, Amin et al. [96] prepared the MEPCM by encapsulating n-octadecane as a core in silica shells at various pH values using the interfacial polycondensation technique [87]. Scanning Electron Microscopy (SEM) images showed the strong dependence of morphology and microstructure on the acidity of the reaction solution. An optimum sample was achieved at pH value of 2.89 and particle size of 17 μm. Sukhorukov et al. [88] stipulated that nanocapsules are more stable than microcapsules. Deformation in 10 nm capsules is found to be significantly lower than that in the 10 μm for the same force exerted on the capsule. Unlike the microcapsules, in the nanoencapsulation technique the core material is kept in
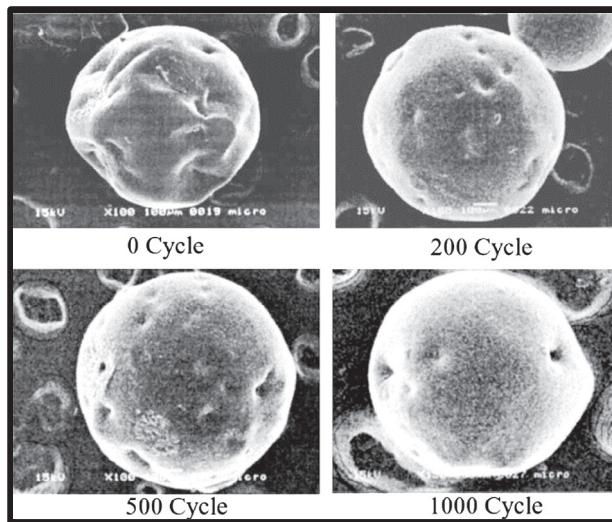
Fig. 7. SEM images of microencapsulated paraffin at different thermal cycles [97].

the shell during freeze/thaw cycle [89]. Tumirah et al. [90] prepared the n-octadecane filled nanocapsules and made thermophysical characterization. The melting and freezing point are observed to be 29.5 °C and 24.6 °C, respectively. The influence of shell material St/MMA on the encapsulation efficiency is evaluated. Nanocapsules revealed superior thermal properties over 360 thermal cycles. The effects of capsule geometry are also reported. The geometry is determined to be a significant parameter to improve the thermal performance of PCMs. Regular geometries such as square [91–93], cylinder [94,95] and sphere [96] have been intensively tested. However, research on irregular geometries, for instance, trapezoidal and triangular is not available. Hawlader et al. [97] performed heat analyses and heat cycle tests on microencapsulated paraffin and discovered that the storage capacity for energy and geometrical profile remained even after 1000 cycles as illustrated in Fig. 7.

It is thought that the microencapsulated PCMs integrated within the building structures might have an effect on the mechanical strength. Cabeza et al. [98] developed two concrete cubicles having similar size and shape; one was made of microencapsulated PCMs known as Mopcon concrete whereas the other lacked PCMs. The likelihood of applying microencapsulated PCMs within building materials to conserve significant size of energy without simultaneously reducing the concrete structures' mechanical strength was determined. Mopcon concrete reaches a compressive strength of more than 25 MPa as well as a tensile splitting strength of more

than 6 MPa, already fulfilled the standards in a structure meant for general purpose. However, the use of microencapsulated PCMs still requires more inspection to ascertain its safety (fire extinguishing capability). Recently, National Gypsum produced wallboard panels having mirconal PCM similar to those manufactured by BASF. These panels are known as National Gypsum Thermal CORE Panel and contain a latent capacity of 22 BTU/ft^2 and melting point of 23 °C as illustrated in Fig. 8.

7.3. Shape-stabilized PCMs

In shape-stabilized PCMs, materials such as paraffin are distributed in a separate phase containing supportive materials that include high-density polyethylene to create a stable composite material. Their attractive nature was caused by their ability to effectively perform several heat cycles in a long duration, ability of maintaining PCM shape stabilized within the phase transition process, ideal heat conductivity and significant heat [99]. According to Zhang et al. [100], shape-stabilized PCM may be used as potential TSSs as it can be prepared easily without including other special gadgets or containers for PCM encapsulation as shown in Fig. 9. These common advantages for shape-stabilized PCM make them ideal for smart energy buildings where interior linings, for instance, the floor, ceiling and inner wall may be built.

Zhou et al. [101] demonstrated the heat performance for a "direct-gain room" using the shape-stabilized PCM plates as inner linings. Many influencing aspects for the shape-stabilized PCM to heat performance, for instance, board thickness, location, fusion heat and melting temperature are evaluated. Their outcomes showed that the PCM plates are useful in direct-gain passive solar buildings.
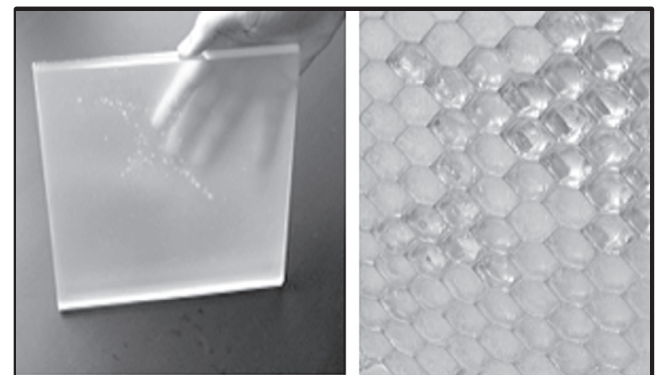

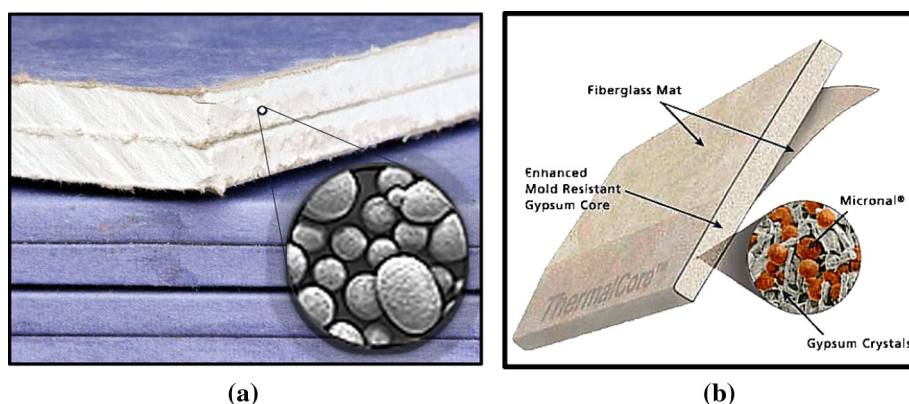**Fig. 9.** Shape-stabilized PCM plate as day-lighting panels [100].

(a)   **(b)**

Fig. 8. (a) Gypsum wall-board with Micronal PCM (from BASF) and (b) thermal CORE phase-change drywall (from National Gypsum).

8. Methods for PCM selection

According to Aranda-Usón et al. [102], the most critical factor in determining the viability and ultimate success of PCMs is selection. Common features, which improve the PCMs efficiency, are their economic, chemical, kinetic, and thermal physical qualities. The selection of a particular kind of PCM for integration into the LHTES system may influence the PCM's capacity of maintaining an ideal interior condition by controlling temperature variations. Sharma et al. [103] examined the heat performance of various commercially graded fatty acids used as solid-liquid PCM for LHTES systems. The heat features are computed by measuring the PCM's weight percentages. Such organic PCMs exhibited self-nucleating, non-toxic, and non-corrosive properties combined with significant heat and chemical stability. The heat parameters for the eutectic mixtures of fatty acid and capric acid are determined through the DSC method to establish the melting solidification temperatures and latent fusion heat. A combination of stearic acid and capric acid is considered as ideal alternatives for building applications because of the good phase transition temperatures ranging from 20 to 30 °C and latent thermal competence. Kuznik and Virgone [104] used an experiment to analyze the PCM copolymer composite wallboard's thermal features. It was observed that the chosen PCMs freezing and melting temperature range should be closer to the building's average room temperature. Besides, there should be a correlation between the daytime temperatures and the PCMs thermo-physical features. PCMs are extensively used and their efficiency has been demonstrated within plasterboard appliances. In a given experiment, it was found that gypsum's 25 wt.% PCM absorption minimized the overheating; this led to a reduction in the energy consumed within the residential house. Additionally, the application of PCMs has been found to decrease the overheating of wall surface temperatures and increase natural convection of the room. Although fatty acids are associated with huge benefits, some compositions, which form eutectic mixtures have strong smell that undermine their use as PCM enhanced wallboards [35]. Li et al. [105] prepared a polyethylene glycol/silicon dioxide shape-stabilized (ss) PCM and classified the effects through confinement within a silica gel. The ss-PCM thermal conductivity and thermal stability against pure polyethylene glycol and different ss-PCM mass fractions are examined. The ss-PCMs is found to be "thermally" good with durable core shell structure, abundant thermal conductivities and ideal phase transition. These ideal characteristics supported their use in LHTES systems in constructing envelopes.

A critical factor, which has a predominant effect on the PCMs efficiency, is the adjacent environment; this is because thermal and physical properties are determined by the adjacent climate and the prevalent climatic circumstances. Aranda-Usón et al. [102] examined three kinds of PCMs integrated into the LHTES systems as tiles through the life cycle evaluation technique. They measured the energy saving balance for the PCMs because the environmental effect emanated from the production and installation of the PCM enhanced wall tiles. An environmental advantage of about 34% is attained for buildings, which integrate PCM for a period of 5 decades. Sá et al. [106] provided a comprehensive overview regarding the formulation and use of microencapsulated PCM for interior cement-based mortars. The outcomes from the two test cells conducted by "the authors" using regular motor and PCM mortar in assessing their heat performance during summer and spring seasons in Portugal are indicated in Fig. 10.

Unlike the reference mortar (REFM), PCM mortar reference mortar (PCMM) test cell contains a temperature variation of 2.6 °C. Moreover, the integration of PCMs caused peak temperatures to fluctuate and minimum temperatures to increase. Therefore, PCMs function by decreasing internal daytime temperatures, balancing them and positioning them near comfort levels of temperature for spring and summer season. The PCMs' performance has been found to be affected considerably by the adjacent environment. This notion was re-evaluated by Zwanzig et al. [107] using a PCM wallboard numerical seasonal comparative analysis whereby Crank-Nicolson's discretization scheme was used. Outcomes indicated that the positioning and installation of the PCM constituted a critical factor and that centrally positioned PCM composite wallboards were effective compared to their internal or external installation. Similarly, Heim [108] examined an isothermal HSs "encapsulated with" PCMs, which conserved thermal energy and emitted it during the cold season. A comparison of a transparent insulation system and PCM impregnated gypsum plasterboard is undertaken against a non-PCM design. Parameters that include overall PCM's latent heat, temperature range, thickness, and dimensions play an important role in efficient LHS.

9. PCMs encapsulation in the building structure

Electricity consumption varies significantly in daytime and nighttime, winter and summer periods, depending on the demand from residential, commercial, and industrial activities. Due to this change, energy consumption prices also vary during off peak and peak season. An ideal management system for thermal energy may help in conserving energy during the off peak period; this may used in the peak period when there is high demand. Because of this, an encapsulated phase transition material may come in handy in increasing the conservation of heat energy in ceiling, floor, and walls of a building. The function of the capsule surface entails absorbing the solar energy and maintaining the building's
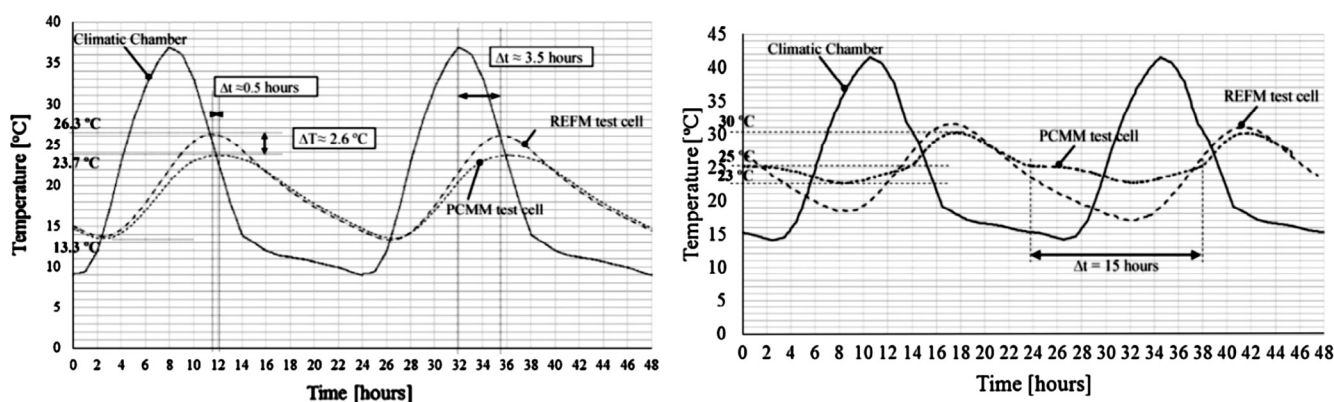

Fig. 10. Temperatures profiles of PCMM and REFM during (a) spring and (b) summer [106].

internal temperature for a prolonged period. In the last 20 years, different types of bulk encapsulated PCM were sold for passive as well as active solar applications, inclusive of the direct gain. However, the size (surface area) of various encapsulated commercial products was not enough for heating the building following the melting of PCM from direct solar radiation. On the other hand, the building's ceilings and walls provide a large surface area for passive thermal transfer in each location in the building [109]. The use of PCM in buildings could be achieved through three methods as illustrated in Fig. 11 [110]. These include in: cold and heat conservation units, floors and ceilings, and building walls. In the last two cases, heat storage or release is automated and this depends on the ambient temperature. Therefore, they are classified as passive systems. Conversely, the first type is considered an active system, where release of heat depends on demand. The applications, thermal performance and manufacturing methods of gypsum wallboard as well as concrete block impregnated PCMs are discussed in the next section [111].

9.1. PCMs impregnated wallboards

Wallboards are readily available, efficient, and easy for use within buildings. Such features make them ideal for PCM encapsulation. In wallboards, the PCM is located in the structures of other buildings, plaster, or gypsum board. However, the principles for storing latent heat may be used on any suitable construction materials. Processes whereby the PCM might be integrated into the plasterboard either through postproduction siphoning of liquid PCM into the plasterboard's pore space or by adding in the plasterboard manufacture's wet stage were demonstrated effectively. The concept of enhancing the heat comfort for lightweight buildings through integration of PCMs into the structure of the building is conventional. Most of the attempts used macro-capsules or direct immersion processes that were laden with numerous pitfalls. Because of these issues, all the PCM materials have been unsuccessful within the expansive market. An emerging substitute for microencapsulate PCMs, a key technology, which mitigates some of the aforementioned issues might enhance the accessibility of PCM products in the building sector. Shapiro [112,113] explained the ideal nature of various PCMs for integration into the gypsum wallboard using potential heat storage applications within Florida. These components were mixtures between short-chain acids and, lauric and capric acid; methyl stearate, methyl palmitate and methyl esters. Although the materials contained high latent thermal capacity, the temperature ranges needed to achieve the heat conservation did not lie in the comfort range for buildings within hot environments.

Neeper [114] discovered that the heat storage offered by the PCM wallboard is enough to enhance a significant solar heating capacity with "direct gain". In another outcome, he measured the heat dynamics for a gypsum wallboard impregnated using paraffin waxes and fatty acids as PCMs, which are subject to diurnal room temperature variation but under the sun's indirect illumination. There is modification of the PCMs melting temperatures using different ingredients. Three PCM wallboard parameters, which may affect the energy that may be released and absorbed passively in a daily process, are evaluated. Such encompass the PCM melting temperature, the melting temperature range and the wallboard's latent heat potential per unit area. The "maximum diurnal energy storage" tends to exist at the encapsulated PCM melting temperature value adjacent to the moderate comfort room temperature under different circumstances. Additionally, the diurnal energy storage is found to reduce when phase change took place over a temperature range.

Stovall and Tomlinson [115] observed that 30% of PCM exists in a normal wallboard. They concluded that it constitutes an ideal energy saver in passive solar systems whose payback period is 5 years. Salyer and Sircar [116] came up with a definition of an ideal cheap linear alkyl hydrocarbon PCM from refined petroleum and developed techniques for controlling the plasterboard PCM for elimination of freezing and melting expansion issues, and leakage. Notably, there is a demonstration of procedures involved in the incorporation of this PCM into the plasterboard through post manufacturing siphoning of liquid PCM into the plasterboard's pore space or through an additive, which might be integrated into the wet phase of manufacturing plasterboard. The creation of an energy-storage wallboard with a laboratory capacity using gypsum is achieved by incorporating between 21 and 22% of commercial grade butyl stearate (BS) in the mixing phase of manufacturing conventional gypsum board. The kind and existence of small quantities of dispersal agents strongly enhances BS integration. The physio-mechanical features of the heat storage wallboard manufactured in the laboratory were consistent with the standard gypsum board values. The board's energy storage capacity increases by ten times, whereas the thermal discharge increases compared to those having only gypsum wallboard [43].
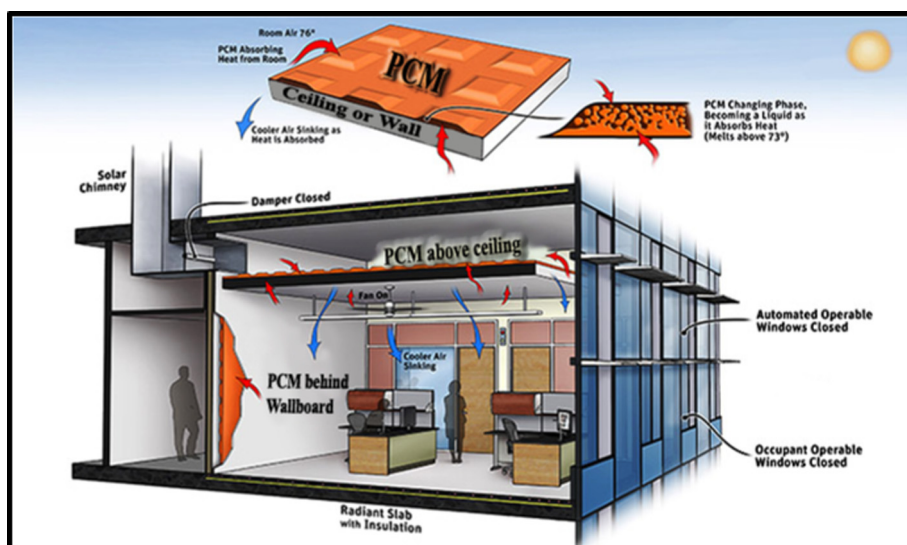

Fig. 11. PCMs encapsulated building structure [110].

Because the volume of the wallboard is 41% air vacuum, the matrix for gypsum wallboard is a suitable for supporting the PCM medium. The suitable freezing and melting temperature of 24.9 °C was the criteria used for selecting coconut fatty acid for the conducting room-scale PCM wallboard tests in line with the requirements of a "small-scale first differential scanning calorimetry test". Nevertheless, the procedure for developing the PCM wallboard yielded the large scale coverage concept, which could be incorporated and distributed successfully in a building having a considerable effect of heat storage [117]. The potential uses of PCM storage within buildings were estimated through energy simulations. Kissock [118] used an experiment to examine the wallboard's thermal performance in simple buildings treated to 30 wt.% using commercially paraffinic PCM (K18). Simulation was conducted on test cells, particularly with regard to interior temperatures, ambient temperature, and solar radiation and was monitored for 2 weeks. The outcomes showed that an increase occurred within the phase transition test-cell by 10 °C but lower than that for control test cell in sunny days. An improved "finite difference simulation" is capable of predicting the temperature of the interior wall within the test cells with considerable accuracy (average error <1.7 °C) depending on environmental data and measured characteristics. Shilei et al. [119] used lauric and capric acid mixtures as wallboard PCM to measure the stability of heat. They discovered that after numerous cycles, the mixture maintained the thermal-physical characteristics whereas the PCM impregnated wallboards might significantly decrease the thermal energy alongside the HVAC system cost as illustrated by Fig. 12.

Kuznik and Virgone [104] examined the heat performance of PCM copolymer wallboard under a full-scale test room for winter, mid-season and summer. It is asserted that the PCM wallboards can decrease the effect of overheating. Izquierdo-Barrientos et al. [120] numerically examined the transient thermal transfer using an exterior wall of a building having a PCM layer for two separate

durations (6 days during summer and 6 days during winter). In the two scenarios, there is variation of phase transition temperature, the PCM position in the wall and the wall orientation to determine the maximum parameters of reducing the fluctuation of energy. A decrease in the HVAC system's power consumption for control of thermal load is seen. Moreover, the overall heat lost in the day during the winter period decreases and at night, it escalates. Additionally, the summer season is characterized by reverse events. Oliver [121] came up with a new building material: gypsum board with PCM 45 wt.% and conducted thermal classification in various positions as indicated in Fig. 13. A gypsum board with a thickness of 5 cm and containing PCMs stores five-fold has 9.5 times more heat energy for a laminated gypsum board compared to a brick wall and three-fold more energy per unit mass compared to a common gypsum board.

Mandilaras et al. [122] conducted an experiment aimed at determining the thermal properties of a Mediterranean residential house with PCM (BASF-micronal PCM having a melting point of 23 °C) impregnated walls as illustrated by Fig. 14. The house is not occupied and installed with energy system, and it is monitored for 12 months. The building's thermal mass is checked for increase in autumn, early summer and late spring. A fluctuation in the "decrement factor" by about 30–40% coupled with an escalation in the time lag ≈100 min is attained.

Lai and Hokoi [123] examined the thermal properties of MEPCM wallboards designed in form of a honeycomb structure as illustrated by Fig. 15.

It is established that the structure of MEPCM integrated honeycomb shows good surface temperature control and is ideal for application in areas where the external surface temperature should be regulated. Recently, Sarı et al. [124] created a type of composite PCM and determined its heat properties. This encompassed polyethylene glycol (PEG 600) serving as base PCM with natural clay and gypsum. The optimum absorption ratio for PEG 600 in gypsum
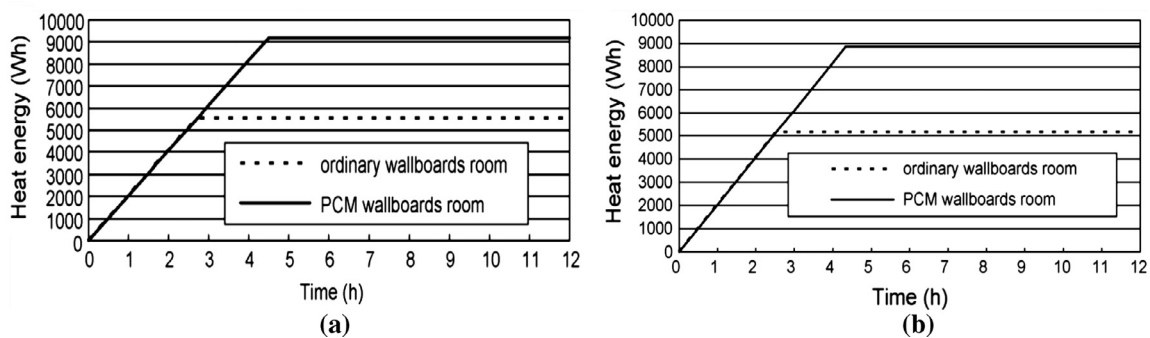

Fig. 12. Time dependent supplied heat energy for temperatures (a) 11–24 °C and (b) 12–24 °C [119].
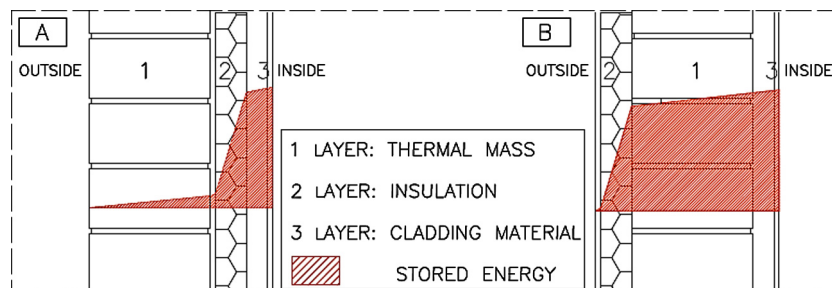

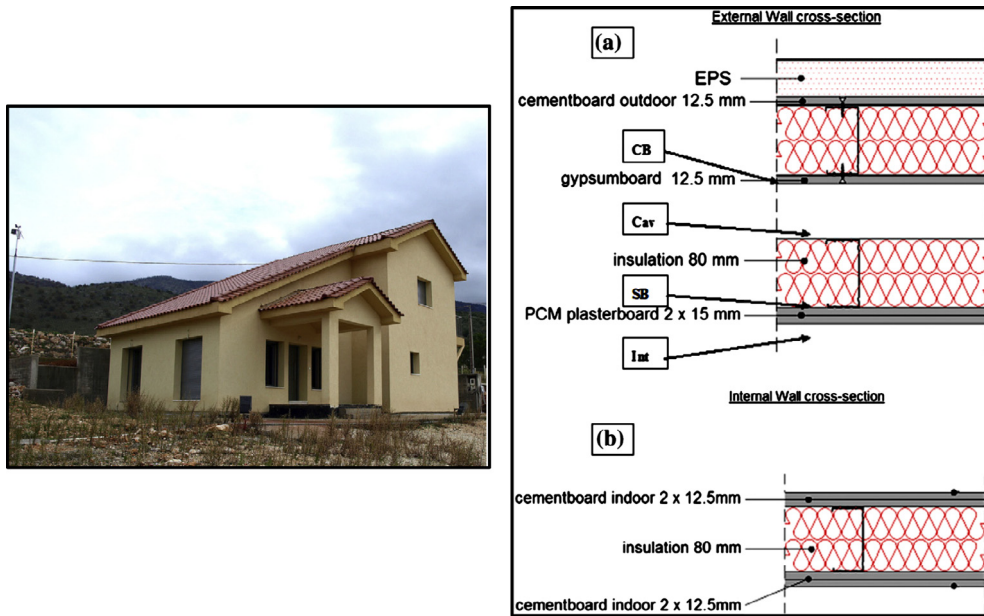**Fig. 13.** Thermal inertia accumulation due to PCM insulation position within the wall [121].

Fig. 14. External cross-section view of the house: (a) the external wall, where "CB", "Cav", "SB", "Int" correspond to temperature sensors position in the LVR east wall and (b) the partition wall with cement boards [122].
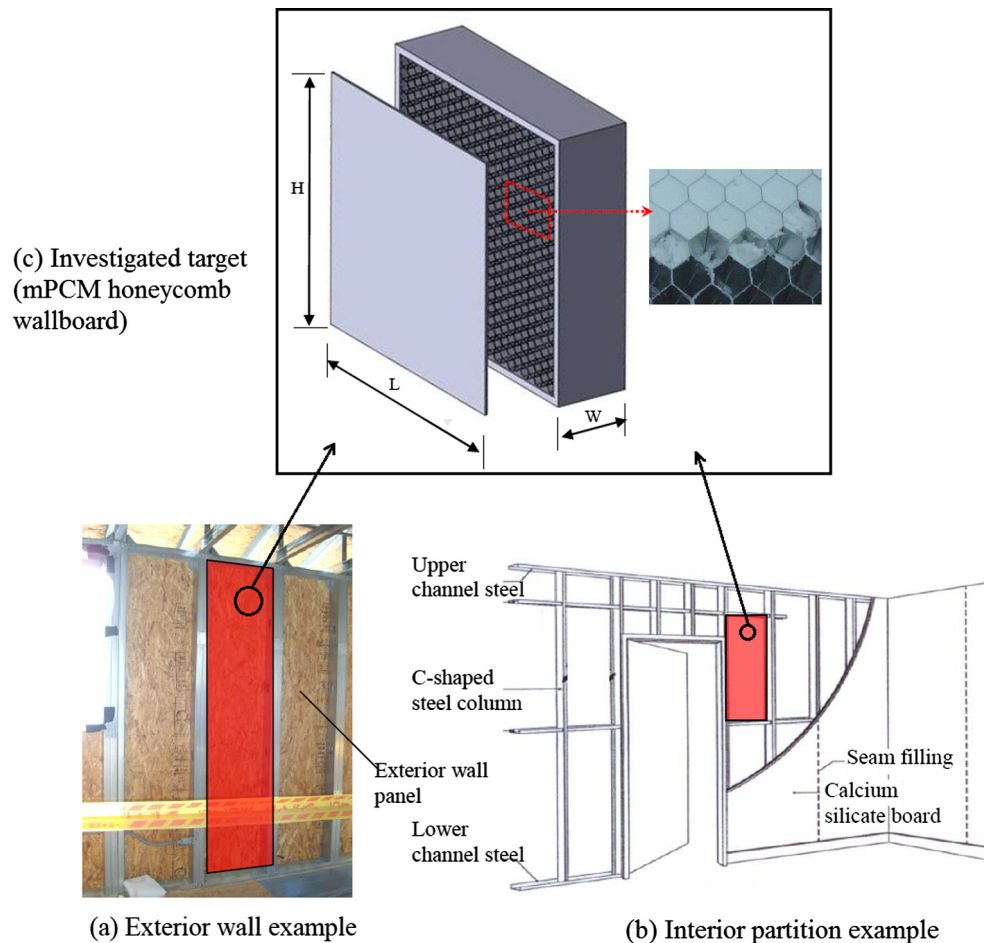

Fig. 15. Possible installation locations (marked in red) of the mPCM honeycomb modules in the (a) exterior wall, (b) interior partition, and (c) investigated target (mPCM honeycomb wallboard) [123]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
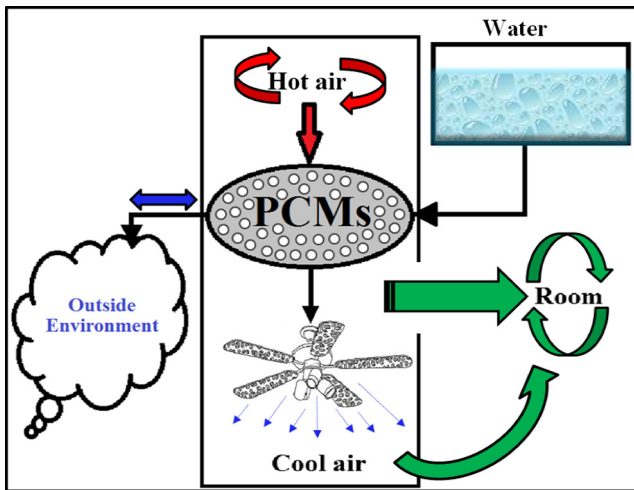
Fig. 16. A ceiling fan design with PCM Stalin et al. [127].

natural clay and gypsum-based composites were 22 wt.% and 18 wt.%. Thermal cycling test indicates that the chemical and thermal stability of the material is good and its thermal reliability is superior. Additionally, the material exhibited outstanding performance in terms of heating and cooling.

9.2. PCMs impregnated floors and ceilings

For cooling and heating to be considered efficient, the floor and ceiling, which constitute the essential components of a room, should be used. The encapsulation of organic PCMs within the ceiling for storage of solar radiation may be achieved using different means. Turnpenny et al. [125] have suggested an insulation system, where a latent thermal storage unit is developed by integrat-

ing the embedded thermal pipes in PCMs. One-dimensional (1D) mathematical model for transferring heat from air towards PCM was unveiled to improve test unit sizing. The system was able to conserve coolness at night and released it during the day.

Gutherz and Schiler [126] developed a space heating system, which integrated a PCM installed in the ceiling vacuum. Solar reflectors are used for directing the sun energy entering through the windows on to the PCMs. The major benefit associated with the system revolves around the presence of a large surface area for storing heat without requiring huge storage medium volume for storing sensible heat. Such type of system was capable of recovering 17–36% of the heat lost on the first gains. Stalin et al. [127] developed a PCM ceiling fan. A spherical PCM (paraffin wax) disc 30 cm above the fan is installed as indicated in Fig. 16. Within the spherical PCM disc, the small-sized aluminum tubes containing the inlet from the building's water tank and an outlet leading to the surroundings. This investigation is seen as a comparison reference against numerical outcomes of the PCM cold storage simulation model in buildings. This modified ceiling fan appears efficient in the provision of cooling solutions.

Bénard et al. [128] designed a solar roof based PCM for a chicken brooder and used an experiment to test it. Two semi-circular tanks, each carrying 42 kg of paraffin wax are placed below the roof of the glass. This design seems appropriate for maintaining the temperature ranging between 22 and 30 °C. Kodo and Ibamoto [129] investigated the effects associated with air conditioning system's peak shaving control using phase change material (PCM) for an office building's ceiling boards. Micro-capsulate PCM, containing a melting point of ≈25 °C can be used for enhancing rock wool PCM ceiling board. In such system, a PCM ceiling board serves as a replacement for rock wool ceiling board. They discovered in nighttime heat storage, the cold air released by the AHU enters into the chamber space of the ceiling and cools the PCM ceiling board, thus preserving cool heat energy. Trigui et al. [139] conducted an experiment that sought to analyze a building's cooling using paraffin
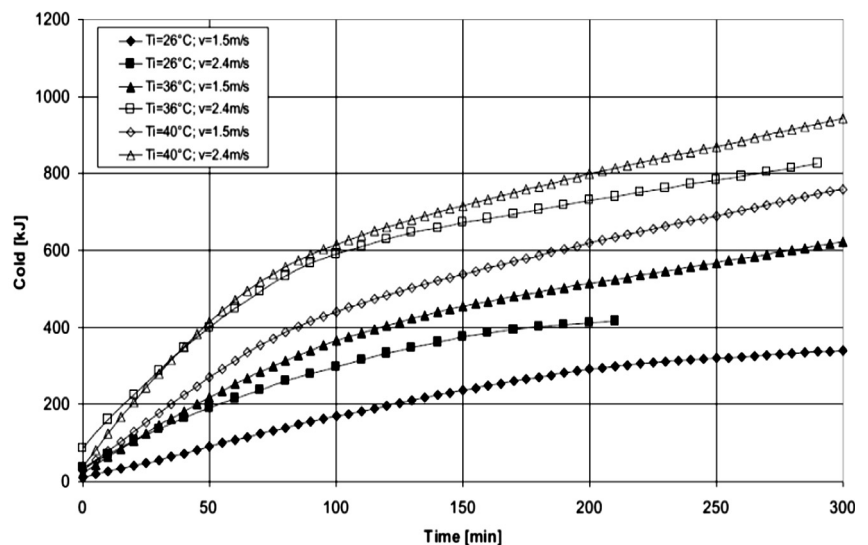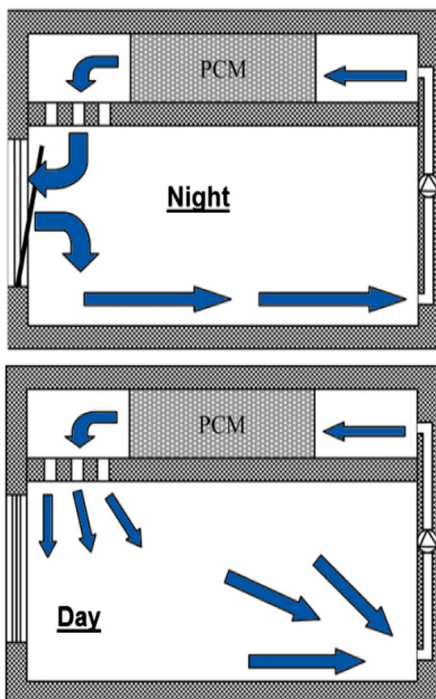

Fig. 17. Building with paraffin impregnated ceiling board [130].

(with a melting point of 22 °C) impregnated ceiling board as illustrated by Fig. 17. The PCM cooling during nighttime was monitored for a whole week and it was found that in this duration, the external temperature maintained stability. The quantity of cool air from the PCM is computed from 0 to 300 min. The system appears to ideal for providing cool conditions in buildings.

Floor furthermore, floor heating plays a critical role in providing comfortable interior conditions compared to convective heating systems. Athienties and Chen [131] examined the transient thermal transfer involving floor heating systems. Their focus was on the way energy consumption and incidental solar radiation, and cover layer affect distribution of temperature on the floor. Full and partial (area) carpets and hardwood cover layers on gypcrete (a mixture of gypsum and concrete) or concrete heat storage. Numerical and experimental simulation for an external test room indicated that the solar beam radiation might trigger a local floor surface temperature within the area under illumination 8 °C higher compared to that within the shaded region. Moreover, partial carpet increased the temperature of the floor surface by 15 °C after the absorption of solar radiation. Solar radiation preserved within the thermal mass of the floor has been found to decrease the consumption of heating energy (30% or more). Increasing the thickness of thermal mass from 5 cm to 10 cm did not result in considerable energy storage with conventional proportional-integral control. There is need of developing complex control algorithms to increase energy conservation while retaining appropriate thermal comfort. Lin et al. [132] investigated the heat performance of under-floor

electric heating system having a shape-stabilized phase transition material (75% paraffin wax +25% polyethylene) as illustrated in Fig. 18. This system recharged heat using available nighttime electricity and discharged it during daytime. During the experiment period, the mean indoor temperature was 31 °C whereas the temperature variation between nighttime and daytime stuck at 12 °C. This caused optimum indoor temperature without any change within the temperature shift.

Unlike convective air heating systems, radiant heating is associated with numerous benefits. For instance, it saves working and living space because it is incorporated into the envelope of the building. Additionally, the integration of thermal mass into the heating system of a floor may be used for storing heat energy during the off-peak period. Therefore, when the cost of electricity is lower, peak loads could be decreased and transferred to nighttime [133]. From the perspective of application, dense materials, for instance, concrete can result in significant indoor temperature fluctuations, whereas PCMs may provide considerable latent thermal storage on narrow temperature ranges experienced in buildings, therefore, they are capable of enhancing heat comfort level. Nagano et al. [134] developed a floor conditioning system having paraffin mixture and foamed waste glass beads as change material. The PCM packed bed with a thickness of 3 cm was installed below the floorboard with numerous tiny holes. The stored heat quantity and room temperature change was determined and outcomes indicated the likelihood of a shift in the cooling load when packed granulated PCM are used.
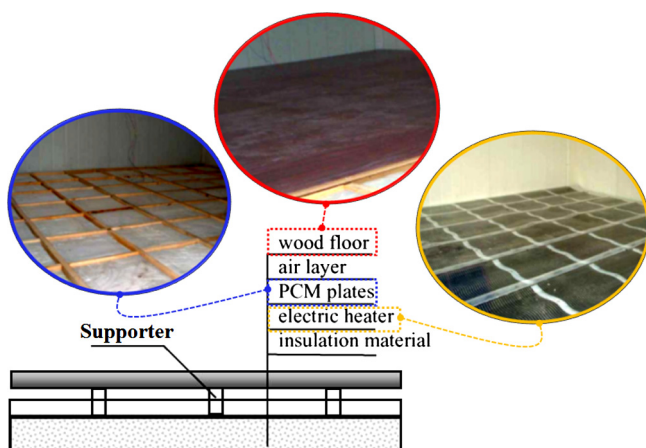
9.3. PCMs impregnated trombe wall and shutter

In the concept, shutter-based PCM is placed on the external areas of the window. In daytime, they are let open exposing the external side to solar radiation, heat absorption and PCM melting takes place. During nighttime, windows are shut to allow PCM radiated heat to enter the rooms. Mehling [135] proposed that windows be installed with PCM shutters. It was suggested that using PCM shutters in windows reduced room temperature by 2° and delayed the optimum shading temperature by 3 h. Castellón et al. [136] examined the trombe wall effect within the envelope of the building, as illustrated in Fig. 19. Nine rooms of equal size were constructed, two using concrete, five using conventional bricks, two using alveolar bricks, and one room of each type is incorporated with a PCM. The experiment was conducted in actual setting called Puigverd de Lleida (Lleida, Spain). Domestic heat pumps were installed on all brick rooms and trombe wall added in concrete walls. It was found that within the concrete rooms,

Fig. 18. PCMs impregnated under-floor electric heating system [132].
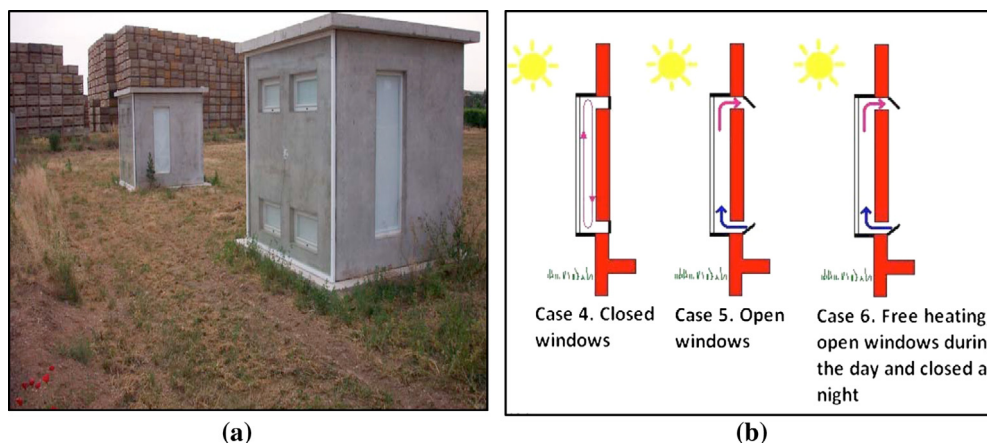

(a)	(b)

Fig. 19. (a) View of the cubicles with trombe wall and (b) different cases using the trombe wall [136].

the rotation of temperature is decreased to 4 °C. In winter, the trombe wall room was capable of maintaining warmth in the concrete room.

Khalifa and Abbas [137] conducted a comparative quantitative study with three separate materials that include paraffin wax (n-eicosane), hydrated salt (CaCl₂·6H₂O) and concrete. They conducted the investigation with different wall thickness and discovered that 8-cm hydrated salt thick wall had better performance compared to 5-cm paraffin wall. Trigui et al. [138,139] developed a resin/paraffin based composite for trombe wall as a circular composite illustrated in Fig. 20. It is found that the rate of thermal transfer increase and maximum thermal storage capacity emanated from the use of paraffin based composite.

The external shading instruments that are installed externally on window sides to decrease the thermal gain within the room are called shutters. In daytime, they are flung open for absorption of solar radiation and melting of PCM and are closed during nighttime to reduce thermal loss via the window and supply the heat that is absorbed in the room and maintain its warmth. The extensive use of organic PCM in shutters has been explored in earlier studies. Alawadhi [140] undertook a quantitative study regarding the PCM shutter performance using various PCMs, which are used as window shutter in Kuwaiti residential building as illustrated by Fig. 21. In this study, P116 paraffin, n-eicosane and n-octadecane was used. It was established that thermal gains could be reduced by about 16% when P116 is used. Additionally, the study findings
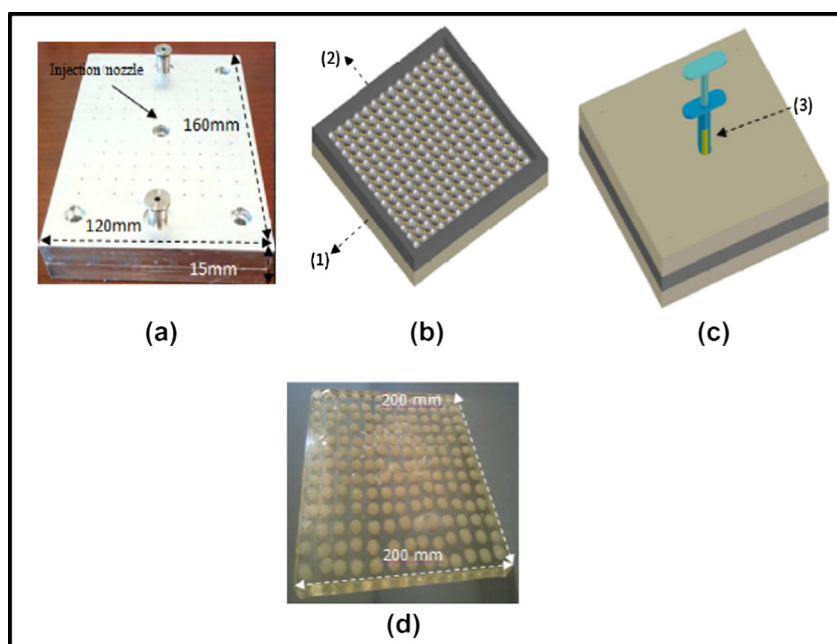

Fig. 20. Manufacturing of Epoxy resin/paraffin spheres composites: (a) mold of paraffin spheres, (b) positions of spheres into a mold, (c) process of injection, and (d) sample. Here the numbers signifies: (1) inferior plate of the mold, (2) support of regularly spaced paraffin spheres, and (3) injection hermetic syringe [139].
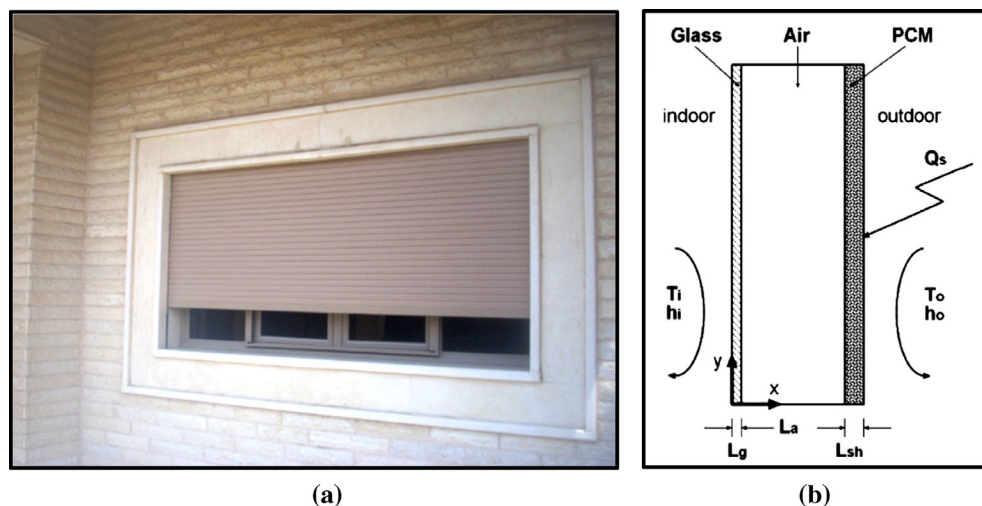

Fig. 21. (a) A typical windows shutter used in residential building in Kuwait and (b) schematic representation of the windows PCM system and the boundary conditions [140].
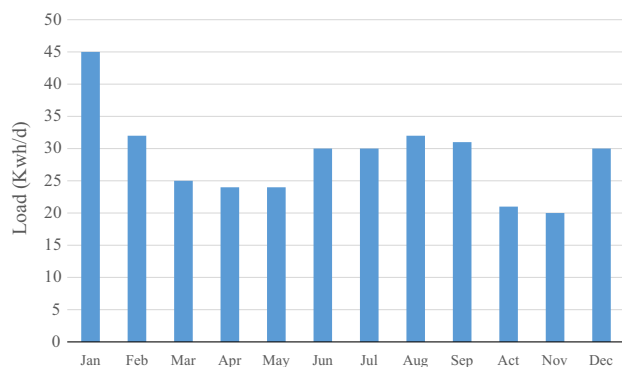
Fig. 22. Monthly electrical load for a house with 200 m² area in Iraq [143].

indicated that when the P116 PCM shutter was maintained at 3 cm, thermal gain reduced by about 23%.

Soares et al. [141] quantitatively examined the shutter effects in an envelope of the building situated in Coimbran, Portugal and increased it with a two-dimensional (2D) simulation model. Outcomes indicated that the PCM's maximum melting temperature in the region is 20 °C and the overall energy conserved was 20501.3 kJ in an entire day's cycle.

10. PMC utilization in Iraqi buildings

Most houses in Iraq are single storey buildings made of bricks or concrete. The building measures 100 by 200 m² in terms of area. The buildings have flattened rooftops, which are accessed by staircases, thus making it easier to install PCM materials. The mean for total radiation in a year within Iraq's northern and southern region was about 7263.97 MJ m^{-2} day^{-1} and 6318.83 MJ m^{-2} day^{-1} [142]. The impact for electricity demand in Iraqi buildings is conspicuous. The consumption of primary energy is around 40%, which translates to 50% of electricity in Iraqi residential buildings. The monthly electrical load of an Iraqi residential house measuring 200 m² is illustrated in Fig. 22 [143].

The peak demand in summer season has surpassed actual production by about 50%, leading to electricity shortages, especially in Southern Iraq. Therefore, to correct the power shortage, businesses and households in Iraq should use expensive off-grid, private diesel-fuelled generators during summer season. In Iraq, where a significant quantity of electricity is used by HVAC systems in summer, the heat insulation materials might be utilized extensively in buildings to decrease the heat flowing into the indoor space of the building through provision of an efficient thermal resistance to the flowing heat.

The petroleum-refining sector in Iraq generates various petroleum products. However, the final product from void (vacuum) distillation is reliable. The most common by-product in the petroleum sector in Iraq is paraffin wax. Thus, Iraq has abundant source of paraffin wax for use as base PCM storage in residential buildings.

11. Conclusions

This article encompassed the PCMs thermo-physical properties, their encapsulation and characterization techniques together with domestic and commercial applications. The feasibility of PCMs utilization in the households was highlighted due to shortages of electricity in the hot seasons and valuable source of paraffin wax in the petroleum industry. It is established that PCMs as TESS at various temperature ranges are non-corrosive. They exhibit reproducible melting, and freezing characteristics even after a large number of thermal cycles. For buildings applications, PCMs must meet ther-

mal comfort criteria in terms of phase change temperature (between 8 and 30 °C). In addition, PCMs selections for construction management must consider the properties such as chemical stability, fire characteristics, and compatibility. The use of LHS with PCMs in the walls, ceilings, and floors displayed a significant impact on reducing the temperature fluctuation by storing the solar energy during the sunlight hours for passive solar heating. It is also efficient for off-peak thermal storage, ventilation, and cooling. The encapsulation of organic PCMs is appearing an essential part of TESs in construction architecture due to their excellent mixing properties with building materials. Therefore, focused attention must be made on increasing the strength of the capsule materials, where nanoencapsulation may be widely explored. Thermal performance evaluation of PCMs for energy-saving buildings is prerequisite. The significance of LHTES is considerably in contrast to the sensible storage because of the large storage energy densities and various melting temperatures. The applications of PCMs in the air-conditioning networks are focusing on the air distribution, chilled water fluid, and slurries. However, thermal power for absorption and desiccant applications are not explored. Thus, PCMs are recommended as a storage medium for air-conditioning systems due to their reduced costs and sizes. The heat storage applications used as a part of solar water-heating systems, solar air heating systems, solar cooking, solar green house, space heating and cooling application for buildings, off-peak electricity storage systems, and waste heat recovery systems. The melt fraction studies of few identified PCMs for various applications in storage systems with different heat exchanger container material is demonstrated.

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