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Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis

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ABSTRACT

Building envelope is a key element in providing adequate energy and thermal comfort performance to buildings. In this regard, improvement solutions are implemented in recent studies that focus on new techniques and methods. The main techniques adopted in this context are discussed to identify modern and effective methods with a particular focus on phase change materials (PCMs). Incorporating PCMs with building construction materials is a booming technology, owing to their enhancement potential of storing and releasing heat during phase transition. This work highlights the importance of PCMs in building envelope, focusing on roof and external wall applications. PCM types, general and desired properties and application area are presented and discussed. Influential parameters, incorporation techniques and methods, main numerical tools, and modelling equations are used to describe the thermal behaviour of PCM. A comprehensive assessment on the basis of recent studies has been conducted to point out the potential of PCM with the most appropriate techniques under different locations. The main findings of PCM thermal performance have been described, considering the cooling/heating load reduction, energy-saving and thermal comfort gained along with several research hiatuses for future studies.

1. Introduction

Energy consumption in buildings has become amongst the urgent issues in most countries worldwide. Globally, the energy consumed for space heating and cooling is as high as 40% and 61% out of the total energy demand in commercial and residential buildings, respectively [1]. According to the International Energy Agency (IEA), the building sector is most responsible for the highest share of the total energy consumption worldwide. Furthermore, this trend will continue, where the energy consumed for space heating and cooling is predicted to be high by up to 12% and 37%, respectively, in 2050 [2].

Building envelope plays a predominant role in controlling building energy by adjusting the heating/cooling loads between the indoor and outdoor environments to satisfy the building's thermal requirements. A building envelope is a shield that protects the building. It plays a crucial role in regulating the thermal energy of the indoor environment. It is also a critical component of the energy-efficient building performance, in which approximately 50% of the heating and cooling loads are directly obtained from the building. The latest report of IEA stated that most investments and expenditures in the building sector had been spent on the renovation and construction of building envelopes [3], as shown in Fig. 1. The report further revealed that building construction and operations accounted for 36% of the final global energy used in buildings and 39% of the energy-related CO_2 emissions in 2018.

Different solutions have been introduced to minimise the heating and cooling loads through building envelope towards energy-efficient buildings [4–6]. Amongst other successful strategies, the incorporation of phase change materials (PCM) into building envelopes has proven a desired impact of controlling the thermal load, thereby resulting in a remarkable energy saving [7–14]. PCMs are implemented to minimise the cooling and heating loads through the building envelope due to their massive potential of energy storage during melting and solidification, thereby maintaining an acceptable thermal comfort [15–20]. The research on this area is still ongoing, considering new types of PCM and applying different techniques to reach the optimal thermal behaviour and highest performance. In this regard, Fig. 2-a shows the increasing number of published work in this research area in recent years, namely, from 2015 up to date, using the keywords 'PCM-incorporated building envelope'. Furthermore, the analysed publications in the current work are presented by year and are the most relevant to the scope of this work

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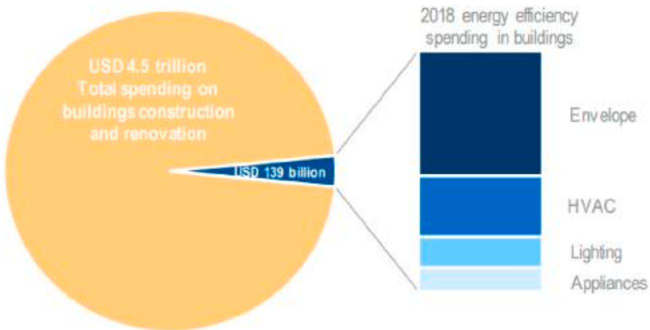

Fig. 1. Global spending and investments on building energy in 2018 [3].

(Fig. 2-b).

This work is composed of five sections, including the introduction. Section 2 provides a short overview of thermal energy, thermal comfort and the main passive and active techniques used to enhance the thermal mass of building envelope. Section 3 deals with a general overview of PCMs, their classification, characteristics and main applications in heat transfer areas. Section 4 comprehensively discusses the implementation of PCMs into building envelope materials, considering the selection criteria, incorporation methods, influential parameters, modelling procedure of PCM and software tools and assessment and summary of the recent research. Finally, the article ends with a conclusion and recommendations for future studies.

2. Thermal energy in buildings

2.1. Thermal comfort in the built environment

Generally, people spend more than 90% of their daily activities inside indoor environment, such as houses, offices and shopping malls [21]. Therefore, thermal comfort is necessary not only for their health but also for their ability to function effectively. Thermal comfort is the condition of mind that expresses satisfaction about the thermal environment inside a building. This satisfaction cannot be described in degrees or range of temperatures because it varies amongst occupants. According to Fanger, sensitivity of occupants to thermal comfort does not depend only on the indoor air temperature (dry air-bulb temperature) but is also profoundly influenced by the relative humidity of air, the mean radiant temperature, air velocity, personal clothing and activity level [22]. This statement indicates the influence of building envelope on the indoor thermal comfort shown by the so-called operative temperature. Operative temperature *OT* (°C) represents the temperature that the occupants feel inside the buildings. It is the average value of indoor air temperature T_a (°C) and the mean radiant temperature $\overline{T}_r$ (°C); it is also called comfort temperature. Operative temperature can be calculated according to Eq. (1) [23]:

$$OT = \frac{T_a + \overline{T}_r}{2} \tag{1}$$

This equation is considered for occupants of normal physical activity with metabolic rates between 1.0 and 1.3, under indirect sunlight and not exposed to air velocities higher than 0.2 m/s [23]. Mean radiant temperature is the radiative exchange between the occupants and the surroundings. This magnitude can be determined in different ways; the most straightforward equation, Eq. (2), is used as follows [22]:

$$\overline{T}_r = \frac{T_1A_1 + T_2A_2 + \ldots + T_nA_n}{A_1 + A_2 + \ldots + A_n} \tag{2}$$

where T_1, T_2 and T_n are the surface temperatures of surface *1, 2* and *n* inside the room (°C), respectively. A_1, A_2, A_n are areas of each surface of the room (m^2).

2.2. Thermal load reduction techniques

The building envelope is a pivotal solution to minimise the energy consumption for heating and cooling towards energy-efficient buildings in cold and hot climates. Globally, the cooling demand is expected to grow by approximately 150% in 2050 and between 300% and 600% in developing countries [24]. Different solutions are recommended to minimise the energy consumption in hot climates, such as using low-cost reflective materials for walls and roofs, interior and exterior shading and using low emissivity coating for windows. The use of passive heating sources, advanced windows and glazing systems is recommended for cold climates [24].

Many techniques are currently under investigation to improve the thermal performance of the building envelope and increase its thermal storage capacity. These techniques, which are either implemented passively or actively, have shown advanced improvements in decreasing the heating and cooling loads and controlling the energy of the building. Reducing the building energy by up to 20% by 2030 is technically possible by using such cost-effective technologies [25]. A brief description of the popular techniques used to improve building performance through its thermal mass is introduced in the following section. These techniques include Trombe wall, thermally activated buildings and PCM incorporation, which is the target of the current work.

Trombe wall, also called mass wall, solar wall and thermal storage wall, is a passive wall design firstly introduced by Professor Félix Trombe [26]. It is a south-facing wall that aims to store the thermal energy gained from the sun during day time. The system has a regular wall of high storage capacity material, dark painted and covered by a glass panel, which spaced a suitable distance. It functions as a thermal storage of solar radiation that passes through the glass. Then, the hot air

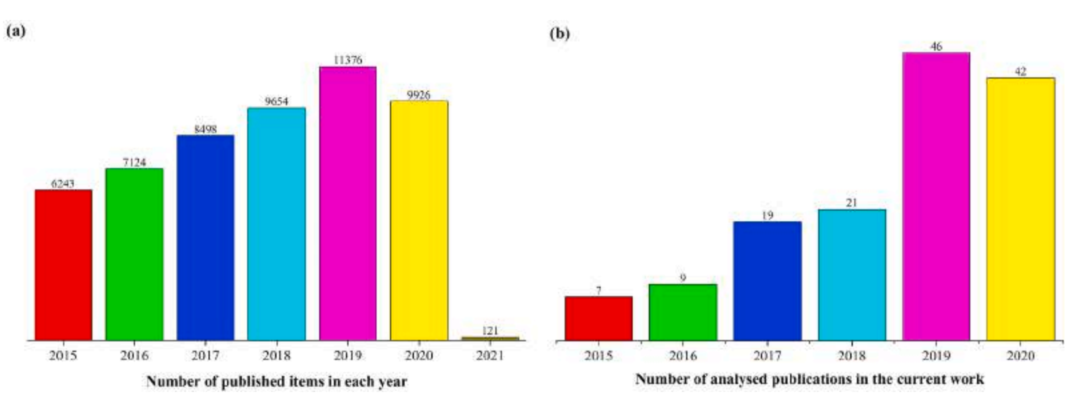

Fig. 2. Statistics of publications on PCM-incorporated buildings: (a) Published items from 2015 up to date (considering Scopus database, accessed in September 14, 2020), (b) Number of analysed publications in the current work.

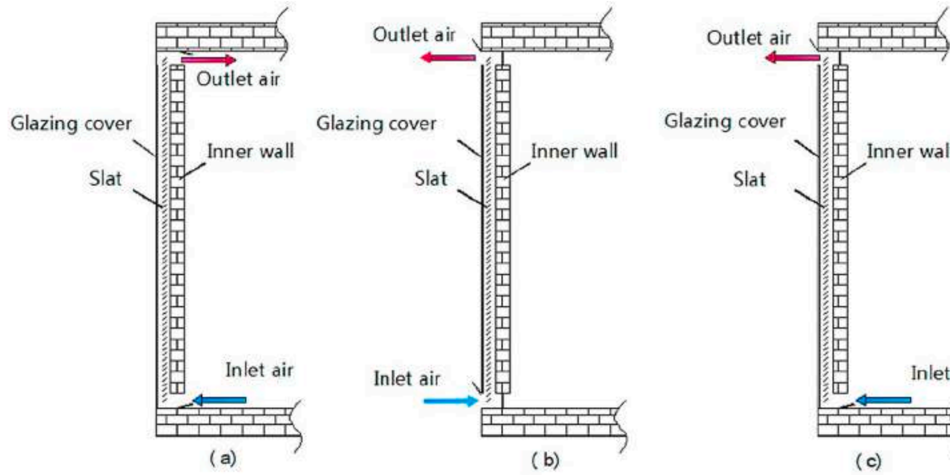

Fig. 3. Trombe wall arrangements used for (a) space heating; (b) outside circulation; (c) ventilation [27].

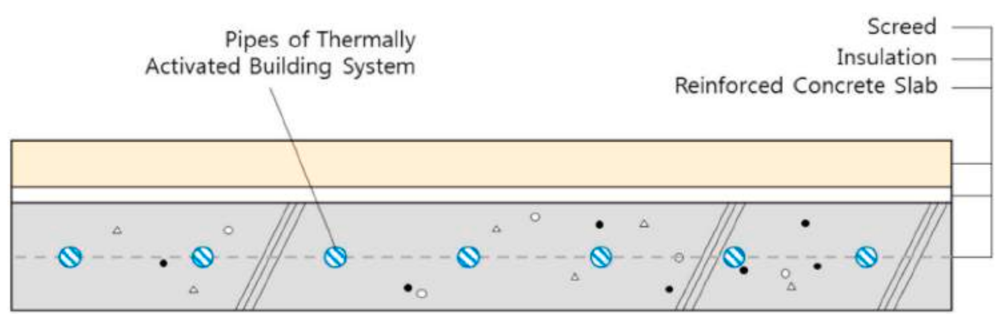

Fig. 4. Section view of TABS in concrete structure [29].

circulates through upper and lower vents to the conditioned space. In some cases, Venetian blinds are placed between the glass panel and the wall to control the conditioned space during the heating and cooling period for heating or ventilation purposes, as shown in Fig. 3.

Thermally activated building system (TABS), or thermal mass activation system, is used to activate the building envelope thermally mainly by four ways, as follows: (i) surface activation via preheating or precooling, (ii) air flow through cavities, (iii) hydronic (water pipes) and (iv) electric systems (heating cables) imbedded inside the thermal mass for heating purposes. Hydronic type is a widely known type, also known as an embedded water-based system; it is a combination of a heating/cooling system with the building structure. In this system, tubes are embedded inside concrete elements, such as the roofs, walls and floors (Fig. 4) to utilise their thermal mass. The water of high/low temperature works as a heat transfer fluid (HTF), which forcefully flows inside the tubes and transports the energy between the heat source/sink and the building. In addition to the conventional energy sources (electric and gas), TABS could be engaged with renewable energy sources, such as the geothermal and solar energy, to provide cooling and heating, thereby augmenting the economic benefits [28].

Although TABS has advantages of improving building efficiency, reliability, energy-saving and maintaining a suitable thermal comfort, it

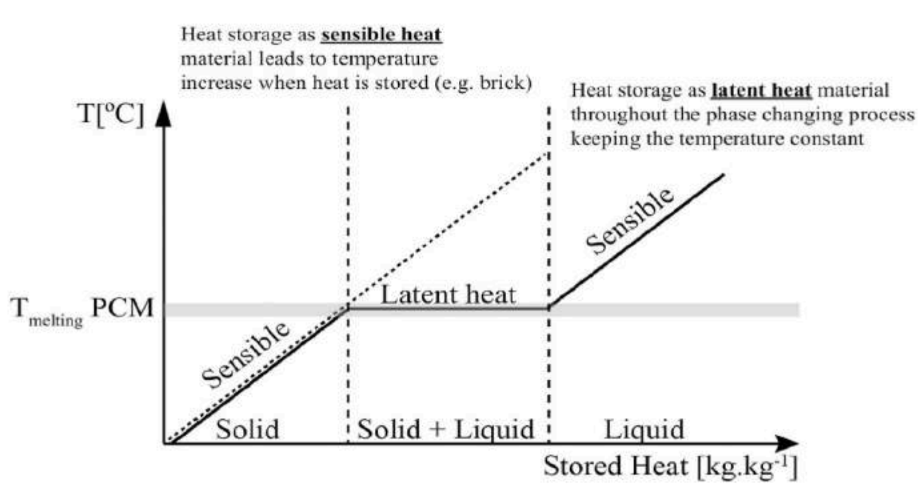

Fig. 5. Heat transition regions of PCM [36].

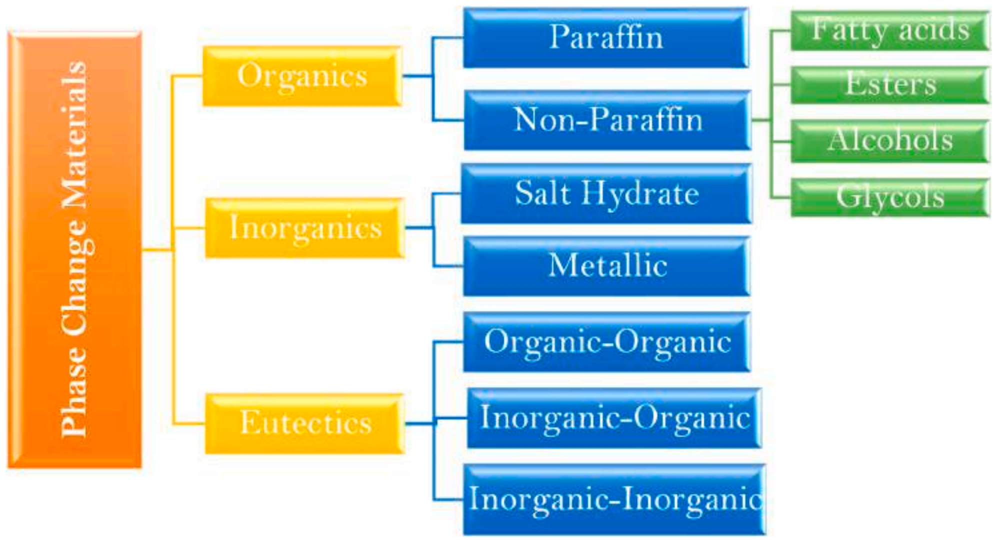

Fig. 6. Classification of PCMs [37].

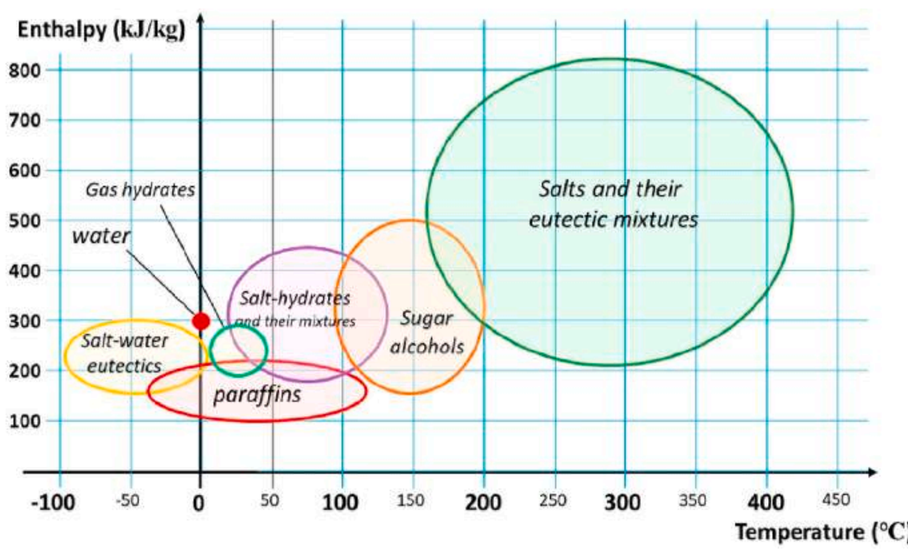

Fig. 7. Working range of enthalpy and temperature of various PCMs [38].

also has several limitations. The main drawback is that TABS cannot be installed in an existing building because it should be implemented during construction. Moreover, the complexity of control and humidity issues may limit its application in several locations worldwide [30].

PCM incorporation is a fast-growing and promising technology in building industry, where thermal energy management and energy saving are used in buildings. They have been mainly investigated to bridge the thermal energy source with energy consumption (building loads). PCMs are used in buildings for different purposes including thermal load shaving and shifting, cooling/heating load reduction, thermal comfort, control of building material temperature and increase in building durability, efficiency and energy saving. According to IEA/SHC Task 42 (ECES Annex 29) Compact Thermal Energy Storage, PCMs have an essential role in improving building efficiency and thermal comfort. They should be used in building products to offer better temperature control in buildings, especially those that suffer from overheating during summer [31]. PCMs have shown a remarkable enhancement of the building envelope when they are integrated with the proposed technology, such as TABS [32], Trombe walls [33] and other building enhancement techniques.

3. PCMs

3.1. Concept of PCMs

PCMs can absorb and release heat during phase transition (mainly from the solid to liquid state and vice versa) under a relatively constant temperature, as shown in Fig. 5. These materials have the potential to store and release vast amounts of heat per limited unit volume. PCMs can efficiently manage the energy in different applications by storing the heat during the melting/charging phase and releasing it during the solidification/discharging phase, thereby controlling the need for energy. Moreover, PCMs are applied to shift the peak-load to the off-peak time, positively affecting the efficiency of buildings [34,35].

3.2. Classification and characteristics of PCMs

On the basis of their chemical composition, PCMs are mainly classified as organic, inorganic and eutectic materials (Fig. 6). Each category has a range of working temperatures (Fig. 7) and thermo-physical properties; thus, they are more suitable for specific application than

Table 1
Characteristics of PCMs [39,40].

PCM Type	Advantages	Disadvantages
Organics (Paraffin wax, fatty acids and vegetable oils)	• Availability in a wide temperature range • High heat of fusion • No subcooling • No segregation • Stable after many cycles • Chemically and physically stable • Compatibility with a wide range of containers • Corrosiveness materials • Environmentally safe, nonreactive • Recyclable	• Low thermal conductivity • Large volume change during phase transition except for some fatty acids. • Unstable at high temperatures • No sharp phase transition • Noncompatible with the plastic containers • Costly in pure form • Low enthalpy • Flammable • Different toxicity levels
Inorganic (Salt hydrates)	• High thermal storage capacity • Good thermal conductivity • Low cost • Available easily • Sharp melting points • Low vapour pressure • Nonflammable	• Show subcooling • Considerable change in volume • Show phase segregation • Incompatible with metallic containers
Eutectic	• Sharp melting and boiling points • Higher volumetric storage density than the organic PCM	• Costly • Limited data available for thermo-physical properties

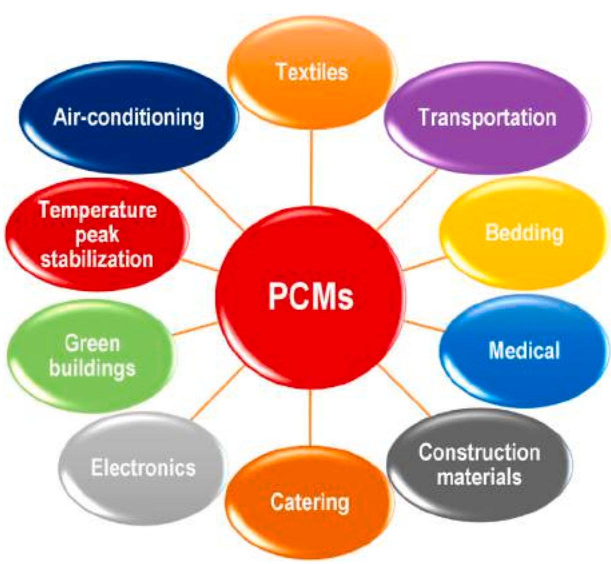

Fig. 8. Applications of PCM [53].

others.

The common characteristics of the three categories are listed in Table 1, indicating their main advantages and drawbacks. The appropriate selection of PCM depends highly on the operating temperature range of the application and melting temperature of the selected PCM, in addition to the other desired characteristics.

3.3. Applications of PCMs

PCMs have been proven to have remarkable potential in different heat transfer and energy storage applications. The recent work on PCMs focuses on their potential in many solar applications because they show high performance in many heat transfer systems [41]. Other studies have investigated the potential of PCMs as thermal storage media in refrigeration and air-conditioning systems [42,43], heat storage tanks [44–46], solar distillers [47] and solar cookers [48]. They are often used as heat sink media in electronic devices [49] and photovoltaic modules [50]. Furthermore, PCMs are utilised as insulation materials in shipping containers [51], for heat dissipation in electrical distribution transformers [52] and efficiently incorporated with building envelope as heat barriers or suppliers. Other applications are illustrated in Fig. 8.

4. PCM-incorporated building envelope

Building envelope represents the shield that wraps the building and separates the internal atmosphere from the outside by its elements, such as the roof, floor, external walls and windows. Therefore, it regulates the thermal loads, impacts the need for heating and cooling and manages the human comfort. The application of PCM is a revolutionary approach to enhance the thermal mass of the building structure and, as a result, the performance of the building. PCMs are applied into a building envelope in numerous techniques and configurations to be part of the construction materials and ensure maximum utilisation of its heat storage potential. The properties of PCM and the incorporation process provide a complex range of parameters to be considered in this research area.

4.1. Selection criteria of PCM

The type of PCM should be adequately selected, considering the desired properties for effective use in a particular application. These properties can be grouped as follows:

- *Thermo-physical properties*: Melting temperature in the range of mean temperature of application, high heat storage capacity (latent heat), high specific heat and thermal conductivity, no subcooling, high density, low vapour pressure, small volumetric change during phase changes and completed cycles (melting/solidification) over a long term of service. Table 2 shows the main properties of PCMs used in different studies.
- *Chemical properties*: Nontoxic, irradiative, nonflammable, noncorrosive, nonexplosive, no segregation, no interaction with the encapsulation material and stable phase transition cycles over a long service life.
- *Other*: Available easily, low cost, environmentally friendly and recyclable.

The thermo-physical properties of PCM are usually tested to ensure its suitability in the building application under study. The PCM is tested using different methods, and differential scanning calorimeter (DSC) is the most adapted method. DSC is widely used to analyse the thermo-physical properties of PCMs. This method can specify the melting temperature, solidification temperature, enthalpies, heat storage capacity and specific heat of the PCM. However, researchers report some limitations of DSC, mostly owing to the small size of the tested PCM sample (in millilitres), thereby influencing the thermal characteristics of the tested PCM and resulting in inaccuracies [63]. Generally, the manufacturers and suppliers of PCM provide a technical data sheet of their products, indicating all necessary thermo-physical properties over a certain number of heat transition cycles.

Weather conditions should be considered and appropriately studied when selecting the PCM type, especially for changeable climate locations. Similarly, the design and implementation should be cautiously performed to prevent segregation and subcooling, representing significant issues restricting the applicability of PCM technology [64]. In practice, satisfying all desired properties in one PCM candidate is difficult or even impossible. Instead, a trade-off may be made to select the excellent PCM. Thus, some studies recommend multiple attribute decision-making methods for this purpose [65].

Table 2
Thermo-physical properties of PCM reported in different literature analyses.

PCM type	Melting temperature [°C]	Heat of fusion [kJ/kg]	Thermal conductivity [W/(m.K)] (Liquid/Solid)	Density [kg/m^3] (Liquid/Solid)	Specific heat [kJ/(kg.K)] (Liquid/Solid)	Ref.
Paraffin	27–29	245	0.2 (Liquid)	770/880	2 (Liquid)	[54]
BioPCM	28.85	219	0.2/0.2	860/860	1.97/1.97	[55]
OM32	31.85	200	0.145/0.219	870/928	2.3/1.95	
PureTemp 23	22.23–24.17	170.71	0.15/0.25	830/910	2.06/1.56	[56, 57]
OM35	35	160	0.16/0.2	870/900	2.71/2.31	[58]
Eicosane	36–38	202	0.15/0.39	780/815	2.46/1.92	
Paraffin wax	44	174.12	0.13 (Liquid)	783/830	2.53/2.44	[59]
Paraffin RT27	28	147	0.2 (Liquid)	750/870	–	[60]
OM37	35–40	218	o.13 (Liquid)	860	–	[61]
HS29	26–29	190	0.55/1.05	1530/1681	2.62 (Liquid)	[62]

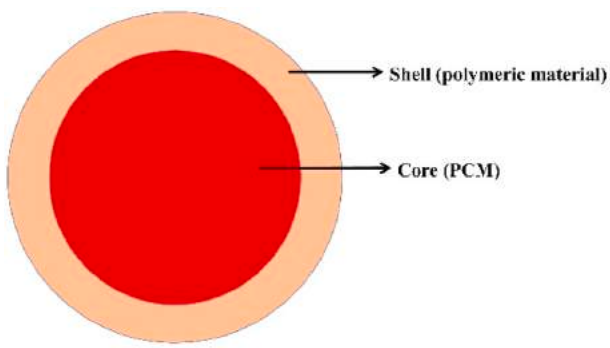

Fig. 9. Microencapsulation concept.

4.2. Methods of incorporation

Practically, PCMs are incorporated into building envelope elements by one of the following methods:

a) Direct incorporation
b) Immersion
c) Encapsulation (micro or macro encapsulation)
d) Shape-stabilised PCMs
e) Form-stable PCM composites.

In the *direct incorporation* method, the PCM in powder or liquid state is added directly to the construction material, such as gypsum mortar, cement mortar and concrete mixture. This method is the easiest and most economical because it does not require any experience and is easy

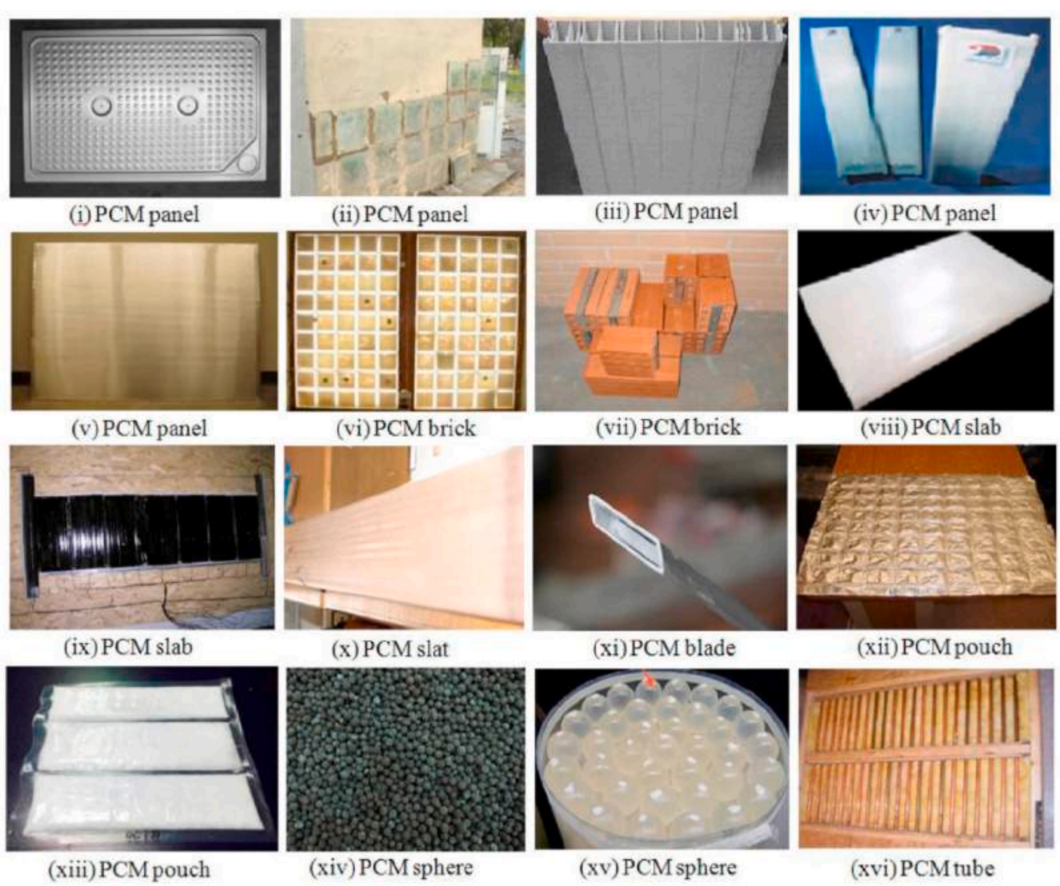

Fig. 10. Different macroencapsulation forms used with building structure [65].

to incorporate [66]. On the contrary, the major drawback of this method is the leakage of PCM during the melting phase. This leakage causes incompatibility of mixed materials and increases the risk of fire (for flammable PCMs). In addition, this method weakens the mechanical properties of constructed elements during high temperatures given that the PCM is added to the mixture in a liquid state, thereby decreasing the water content ratio [67].

In the *immersion method*, a porous construction material immerses into the liquid PCM; it is absorbed due to capillarity. The main drawbacks of this method are leakage, construction incompatibility and the corrosion of reinforced steel when incorporated with concrete elements, thereby affecting its service life [68].

Encapsulation is a suitable method to avoid the leakage issues of PCM and to enhance its compatibility with the building structure. Encapsulation is performed by covering the PCM by a shell for protection from the outside environment as well as for leakage prevention. This method is also essential to increase the heat transfer area and, hence, the thermal conductivity of PCM to ensure effective utilisation of its storage capacity [39]. The PCM can be macroencapsulated using shells, tubes, channels and thin plates or microencapsulated when the microsized PCM is covered by unique polymeric material (Fig. 9) [69,70].

In both methods, the encapsulation material should have unique characteristics, such as preventing leakage, retaining all thermal characteristics of PCM, not reacting with PCM, compatible with PCM and its application, providing structural stability and securing handling [71]. Furthermore, it should control any volumetric change of PCM during phase changes and provide appropriate protection for the PCM against environmental degradation and good thermal conductivity and mechanical strength over PCM life cycles [72]. Pipes, panels and foils made from aluminium, copper and stainless steel are commonly used for macroencapsulation because they offer excellent thermal conductivity, compatibility and support to the mechanical strength of building materials [73]. More macroencapsulation forms are shown in Fig. 10.

The *shape-stabilised* method contains the PCM inside a carrier matrix. This method is promising because it provides better thermal conductivity, large specific heat and maintain the shape over many cycles of phase transition. More information regarding its configurations and preparation techniques have been described by Refs. [74,75].

The *form-stabilised* PCM is also an advanced method of incorporation. It is a specific definition of composite material, retaining the maximum amount of one or more types of PCM and showing no leakage at melting temperatures. Although the two latter methods are expensive to implement, they are the most reliable amongst others. Reliability indicates that the PCM cycles (melting/solidification) are repeated in high performance without degradation, and this feature is crucial for applications that require high performance for long-term, such as buildings [76].

4.3. Influential parameters on PCM performance in the building envelope

Incorporation of PCM within the building envelope can reduce the peak temperature by up to 4 °C, thereby maintaining stable thermal comfort conditions during summer daytime [77]. The thermal performance of PCM is affected by several parameters, which influence its activity; sometimes, it performs negatively. Dealing with such parameters is highly recommended to ensure the best performance of PCM and exploit its potential efficiently. The most influencing parameters are discussed in the following section.

4.3.1. Melting temperature

The melting temperature of PCM is the most determining parameter on its performance because it impacts the charging and discharging processes. Thus, the potential of heat storage is utilised fully or partially. PCM melting temperature should be suitable to utilise the low solar radiation during winter to boost the heating demand. On the contrary, it should be sufficiently high to restrict the high solar radiation and heat transfer during summer, thereby minimising the cooling load. Jelle and Kalnæs [78] suggested that for water heating applications, the optimal PCM melting temperature lies between 29 °C and 60 °C, between 22 °C and 28 °C for human thermal comfort and up to 21 °C for cooling applications. Table 3 shows the operating melting temperature of several commercially available PCMs incorporated into the building envelope in different literature studies.

Table 3
Commercially available PCMs [56].

PCM type	PCM symbol	PCM from manufacturer's data sheet (°C)	Manufacturer
Bulk	RT21 HC	21	Rubitherm
	RT22 HC	22	Rubitherm
	RT25 HC	25	Rubitherm
	RT27	27	Rubitherm
	PureTemp 23	23	Entropy Solutions
Microencapsulated	Micronal DS5040X	23	BASF
	Micronal DS5008X	25	BASF
	MPCM24D	24	BASF
	Micronal DS5038X	25	Microteklabs
Microencapsulated	MacroPCM28	28	Microteklabs
	MacroPCM24	24	Microteklabs

4.3.2. PCM quantity/thickness

The quantity of PCM incorporated into building envelopes considerably affects the amount of thermal energy stored during phase transition. For example, when a small amount of PCM is included into building elements to decrease cooling loads during summer, the PCM stores limited heat in the charging phase and reaches the full liquid state in a short time. Thus, it cannot absorb more energy. By contrast, larger PCM amount stores more heat during the charging process and restricts the heat from passing through the element. At the same time, larger stored heat requires more time to be discharged in addition to the negative impact on the building element mechanical strength and the economic concern. This parameter needs to be studied carefully along with the effect of melting temperature to guarantee a positive performance of the PCM without affecting the mechanical strength of the building element.

The volume of PCM required for any application V_{PCM} can be easily obtained using Eq. (3) by dividing the mass m of PCM (kg) over its density ρ (kg/m^3).

$$V_{PCM} = m_{PCM} / \rho_{PCM} \tag{3}$$

The overall heat storage capacity of the PCM, E_{latent} (kJ) can be determined, considering its amount (m), the total energy exchange of PCM enthalpy content H_f (kJ/kg) and the number of cycles during the day n, in accordance with Eq. (4) [79], as follows:

$$E_{latent} = n \times m \times H_f \tag{4}$$

4.3.3. PCM position

The position of the PCM layer depends on the location of the building under study and the purpose of PCM implementation, whether used for reducing the heating or cooling loads. The incorporation of PCM has shown better performance for cooling load reduction than for heating load reduction. Moreover, the PCM can work actively under temperatures higher than its melting point [80]. Many studies reported that the PCM layer should be positioned closer to the heat energy source [81]. Other studies stated that mid-element position results in better performance for the building, annually [82]. For cooling purposes, the PCM layer should be installed to the exterior side of the building element. By contrast, it should be installed closer to the interior for heating purposes

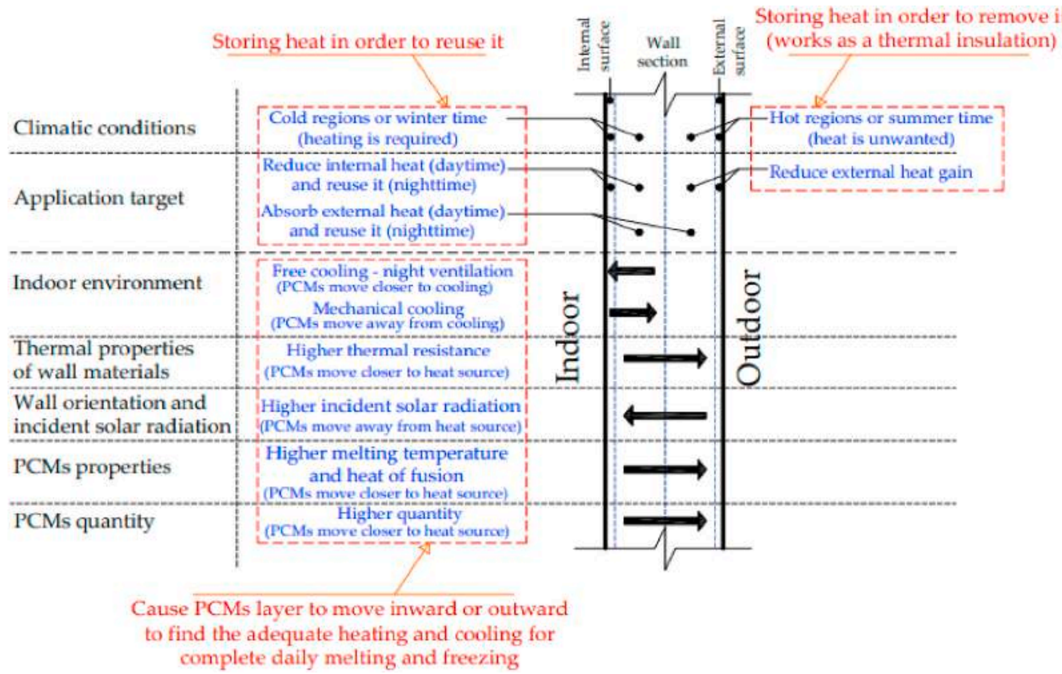

Fig. 11. Optimal position of PCM in cold and hot climates for wall application [86].

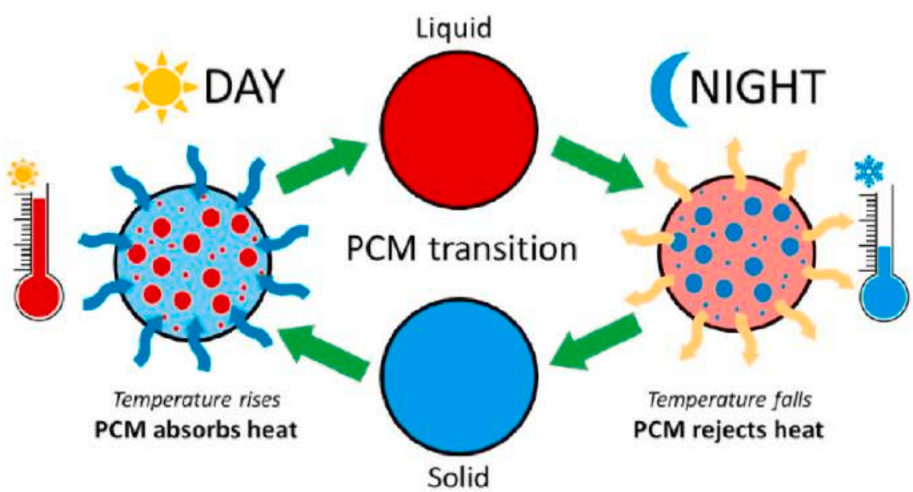

Fig. 12. Daily PCM transition cycle [37].

[83]. The melting temperature of the PCM layer profoundly influences the optimal position. For instance, Lagou et al. [84] numerically investigated the optimal position of PCM within the building envelope, along with the best melting temperature for six different European cities under summer and winter conditions. The analysis was conducted using COMSOL multiphysics software for walls of nonconditioned rooms at different orientations, locations and various building types. The study revealed that the PCM layer should be installed to the interior surface of the walls in all cases and conditions. Furthermore, the PCM should have a melting temperature of 16 °C for the southern locations, 11 °C for the central areas and 20 °C for the northern European cities for optimal PCM thermal performance. Darvishi et al. [85] numerically investigated the best position of three PCM types with 21 °C, 23 °C and 25 °C melting temperatures for two Iranian cities with different climate conditions. The heating and cooling load reductions in addition to the annual energy saving were considered in their study. They concluded that on an annual basis, placing the PCM in the middle or near the interior zone reduced the thermal load and increased energy saving regardless of the climatic conditions. Fig. 11 indicates more details about the best position of PCM, considering the main influential parameters under cold and hot locations.

4.3.4. Heat transfer fluid

PCM is typically utilised passively or actively. In the passive scenario, the heat is stored into the PCM and releases from it naturally. However, in the active scenario, the heat is stored and/or released by means of pumps, fans and blowers, where the HTF is important. Under hot climate applications, HTF is required to discharge the heat accumulated in the PCM and solidify it for the following cycle. The relatively low temperature during night period (typically called night cooling) is usually utilised for this purpose because it is free and has good potential to solidify the melted PCM especially when used in a controlled manner [87,88]. In the usual design of night cooling systems, the PCM cycle is considered once a day, where the rising temperature during day hours melts the PCM and then solidifies it by using low air temperature at night, as illustrated in Fig. 12. The potential of night cooling is limited in severe hot climate regions because it effectively works when the diurnal temperature variation is sufficiently large (up to 15 °C) [89]. Several limitations, such as partial solidification, have been reported in studies that considered natural night cooling an effective HTF for PCM-accumulated heat [87]. In some cases, full solidification of PCM cannot be achieved at night due to the high surface temperature of building envelope, resulting from high diurnal solar radiation and heat stored by envelope materials. Consequently, the PCM is melted partially in the next cycle and loses its ability to act as a heat storage medium. Furthermore, the active night ventilation should be controlled by several parameters, such as the range of night air temperature, the quantity of solidified PCM, air flow rate and ventilation period [90].

Alternative HTF is recommended to maintain the solidification process, especially in locations with harsh weather conditions during the summer period. The shading and building orientation techniques were investigated and showed to be beneficial in avoiding the direct solar impact and reaching an acceptable night cooling effect [91]. For the cold climate applications, the HTF is also required for improving the charging phase. The solar radiation is poor under cold locations and cannot reach the PCM layer naturally. Therefore, using active means (such as solar collectors, where water or air is implemented as HTF) is necessary to harvest, as much as possible, the heat during day-hours to be stored in the PCM.

4.4. Modelling of PCM-enhanced building envelope

In recent years, different types of modelling and simulation tools have been applied to describe the thermal behaviour of PCM and energy-saving gained from its incorporation with building components. Experimentally, some researchers work on a laboratory-scale level whilst others work on whole-building level to validate the tools. The most widely used tools for modelling and simulating PCM behaviour are ANSYS FLUENT [92], COMSOL multiphysics [84,93], EnergyPlus software [94], TRYNSYS [95], MATLAB software [96], ABAQUS™ solver [97] and DIANA–finite element analysis [98]. Although many researchers reported good agreement of computational tools with the experimental results, IEA states that the confidence level of these tools is still low and cannot be adapted for designing and coding [63].

To model PCM-incorporated buildings, most researchers deal with the building element as a 1D convective heat transfer, unsteady-state without internal heat source to describe the heat behaviour of PCM [99]. For instance, the thermal behaviour of the composite wall, containing the PCM layer can be determined using Eq. (5) [100]:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{5}$$

where T is the temperature of the element (°C), t is time (s), x is the element thickness (mm), and α is Thermal diffusivity (m^2/s), which is the ratio of the material thermal conductivity to its density and specific heat ($\frac{k}{\rho c}$).

To handle the melting and solidification processes of PCM, Eq. (5) can be modified to Eq. (6) as follows [101]:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - \frac{L_H}{c_p}\frac{\partial f}{\partial t} \tag{6}$$

where c_p is the specific heat at constant pressure (kJ/kg.K), L_H is the latent heat of fusion (kJ), and f the liquid fraction (ratio of the melted PCM during phase transition). The liquid fraction ranges from 0 to 1, as shown in Eq. (7):

$$f = \begin{cases} 0 & if\ T \geq T_l\ (Solidification) \\ \dfrac{T - T_s}{T_l - T_s} & if\ T_l > T \geq T_s\ (Mushy\ zone) \\ 1 & if\ T < T_s (Melting) \end{cases} \tag{7}$$

where T_l and T_s refer to the liquidus and solidus temperatures of PCM, respectively.

The boundary conditions of the interior and exterior surfaces of the envelope are introduced according to Eq. (8) [102]:

$$-k\frac{\partial T}{\partial x}|_{in} = h_{in}[T_a - T_{in}] - k\frac{\partial T}{\partial x}|_{ex} = h_{ex}[T_{ex} - T_{air}] + \varepsilon\sigma F_{sky}\beta\left[T_{ex}^4 - T_{sky}^4\right] + \varepsilon\sigma(1-\beta)\left[T_\alpha^4 - T_{air}^4\right] + \varepsilon\sigma F_{ground}\left[T_{ex}^4 - T_{air}^4\right] - \alpha_G I \tag{8}$$

where k is the thermal conductivity (W/mK), and h_{in} and h_{ex} stand for the internal and external heat transfer coefficients (W/m^2K), respectively. T_{room}, T_{in} and T_{ex} are the temperature of the tested room (indoor air temperature) and internal and external surface temperatures, respectively. ε is the emissivity factor of the external surface (in most cases, it is assumed to be equal to 0.9 [103]), and σ is Stefan–Boltzmann constant (5.67×10^{-8} W/m^2. K^4). β is used to divide the long-wave heat exchange of the sky dome between the sky and air radiation. T_{air} and T_{sky} are the temperatures of ambient air and sky temperature (K), respectively, and T_{sky} can be estimated by the clear-sky approximation suggested by Swinbank, according to Eq. (9) [104], as follows:

$$T_{sky}(t) = 0.0552[T_{air}(t)]^{1.5} \tag{9}$$

where F_{sky} and F_{ground} are the view factor between the exterior surface of the external envelope and the sky dome, respectively. The ground surfaceα_G, indicates envelope absorptivity, and I represents solar radiation (W/m^2). h_{ex} can be estimated by Eq. (10) [105], as follows:

$$h_{ex}(t) = \begin{cases} 6 + 4\ v(t) & if\ v(t) \leqslant 5m/s \\ 7.4\ v(t)^{0.78} & if\ v(t) > 5m/s \end{cases} \tag{10}$$

where v is the wind velocity (m/s).

The energy-saving E, decrement factor DF and time lag TL are essential indicators to show the performance improvement of incorporating PCM into buildings. They can be calculated by Eq. (11), as follows:

$$\dot{Q}(t) = \begin{cases} h_{in}(T_a - T_{in})\ for\ heating\ period \\ h_{in}(T_{in} - T_a)\ for\ cooling\ period \end{cases} \tag{11}$$

where $\dot{Q}$ is the instantaneous heat gain/loss through the envelope (W/m^2), which can be calculated by Eq. (12) [102], as follows:

$$Q = d\left[\left(\sum_{t=0}^{p}\dot{Q}(t)\right)\Delta t\right] \tag{12}$$

where d is the number of days of the month (30 days), and p is the daily period (86 400 s).

The energy-saving E can be presented as the energy consumption of reference envelope minus that consumed by the PCM-incorporated envelope, as shown in Eq. (13), as follows:

$$E_{PCM} = Q_{reference} - Q_{PCM} \tag{13}$$

DF and TL could be estimated in terms of the internal heat flux Φ_{in} and external heat flux Φ_{ex} (W/m^2), according to Eq. (14)–Eq. (16) [106], as follows:

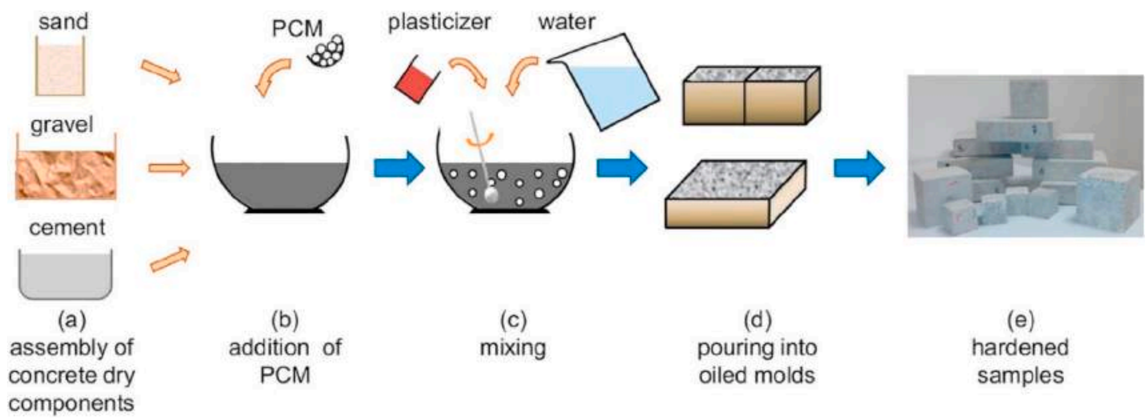

Fig. 13. Preparation of concrete samples using micro- and macroencapsulated PCM [115].

$$DF_{\Phi} = \frac{\Phi_{in}^{max} - \Phi_{in}^{min}}{\Phi_{ex}^{max} - \Phi_{ex}^{min}} \tag{14}$$

$$TL_{\varphi}max = t_{\Phi_{in}^{max}} - t_{\Phi_{ex}^{max}} \tag{15}$$

$$TL_{\varphi}min = t_{\Phi_{in}^{min}} - t_{\Phi_{ex}^{min}} \tag{16}$$

where Φ_{ex} and Φ_{in} could be calculated according to Eq. (17) and Eq. (18), as follows [107]:

$$\Phi_{ex} = h_r\left(T_{sky} - T_{ex.s}\right) + h_c(T_{ex.a} - T_{ex.s}) + \alpha_G I \tag{17}$$

$$\Phi_{in} = h_{in.s}(T_{in.s} - T_a) \tag{18}$$

where h_r and h_c are the radiative and convective heat transfer coefficients of the external environment. $h_{in.\ s}$ is the heat transfer coefficient of the internal surface of the envelope.

4.5. Assessment of PCM incorporated buildings

The literature has many practical techniques to incorporate PCMs into building elements. PCM is usually included during the construction process or added as a separate layer within the building structure. PCMs of different types, methods, quantities and operational characteristics have been applied in different building elements, such as roofs, exterior walls, floors and windows, thereby showing spectacular enhancements. Studies that deal with PCM incorporating floors and windows are less than those on walls and roofs. As a building envelope element, the floor usually has the least effect on the building's energy on the bases of heating and cooling loads because it is far from the effect of weather conditions and deals with a relatively stable temperature of the ground. Thus, several researchers investigated the role of PCM incorporating floor systems [108]. Although several PCM applications in windows have been conducted for frame and glazing cavities, serious issues regarding leakage and low transparency of glazed pans were reported, thereby limiting its implementation [109]. The incorporation of PCM in building envelope has been assessed, focusing on the roofs and exterior walls, which share the largest area of the building and are exposed to changeable weather conditions. Therefore, they represent the primary source of undesired heating and cooling loads [110].

In this section, up-to-date studies on PCM-incorporated building envelope have been reviewed and presented in accordance with the PCM installed into the construction materials. These methods are primarily categorised as (i) mixed with concrete, cladding and finishing materials, (ii) inserted separately with building construction in the form of sheets/boards/layers, (iii) contained inside bricks and (iv) pipe-encapsulated.

4.5.1. PCM-incorporated concrete and cladding/finishing materials

The concrete has been used as a primary construction material worldwide. Similarly, mortars (gypsum and cement mortar in particular) are used widely in constructions as an exterior and interior finishing materials [110]. Mixing of PCM with these materials has shown high potential in regulating and controlling the indoor thermal comfort and energy saving for heating and cooling applications [74]. However, this method suffers from several limitations, such as risk of fire, low mechanical strength of mixed materials and poor thermal conductivity

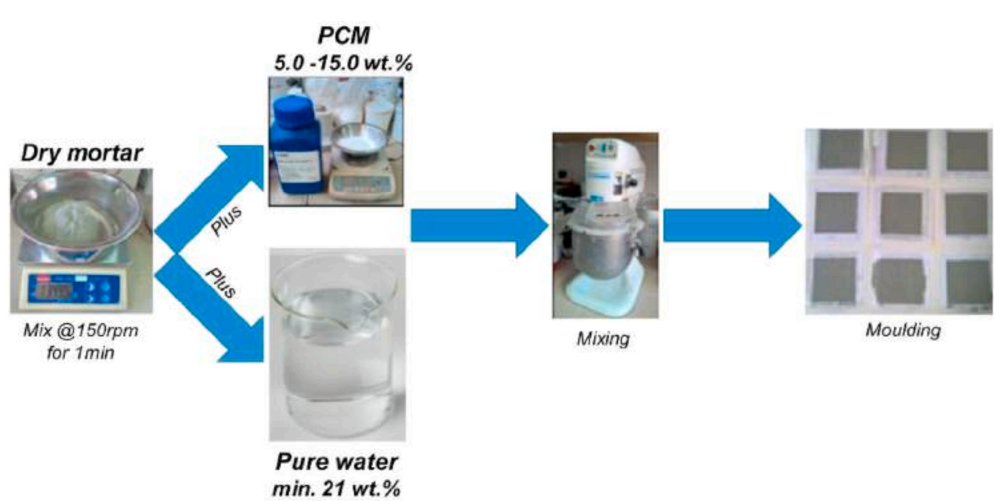

Fig. 14. Preparation process of PCM-cement mortar samples [116].

of PCM because of the polymeric materials used for PCM microencapsulation (prevalent technique used in this approach) [111]. Yun et al. [112] examined the mixture of PCM/concrete to control the heat within the concrete and evaluate its fundamental properties. The strontium-based powder ($Sr(OH)_2$–$8H_2O$) was selected as PCM given its excellent ability to store heat during phase transition and other desired properties tested by DSC. Results showed that the heat through concrete was reduced by 15%–21% along with slight reduction in its compressive strength. Moreover, the results revealed that the addition of PCM to the concrete mixture decreased the thermal stresses and cracks remarkably. Cabeza et al. [113] investigated the long-term performance of concrete-based PCM to conduct the thermal and mechanical properties after a decade. They tested built cubicles made in 2005 (one with 5 wt% PCM and the other without PCM) and repeated the same test procedure conducted at that time to compare the results. The study reported no change in the thermal response given the heat reduction, time delay and thermal fluctuations between day and night. Furthermore, the mechanical property-based compressive strength test was the same. Although the PCM-incorporated concrete had many thermal advantages, it often showed serious drawbacks, such as subcooling of PCM, thereby leading to segregation and leakage in case of immersion and direct methods. Furthermore, limited PCM types can only be used due to concrete alkali nature and the corrosion of steel used for reinforcement [114]. An advanced type of concrete-based PCM in micro- and macro-encapsulation forms was introduced by Antonella et al. [115]. Fig. 13 shows the procedure used in their experiment. The new produced concrete was reported to have good thermal stability. Moreover, it optimised the thermal insulation effect by up to 9 h compared with the standard concrete. Results reported good mechanical properties, such as compressive strength, ductility, low weight and good reliability.

Mortar-based PCM also had a considerable improvement in terms of thermal comfort and energy saving. Frazzica et al. [116] numerically and experimentally designed and tested two microencapsulated PCM-based paraffin composites (Micronal 5038X and Micronal 5040X of melting points 25 °C and 23 °C, respectively) mixed with cement mortar in different percentages (Fig. 14). The samples were analysed under weather conditions of Sicily, Italy to reduce the energy consumption and maintain suitable comfort conditions inside the building during summer and winter based on ASHRAE comfort conditions. They used COMSOL multiphysics software to validate the obtained results by solving a numerical model and defined the optimal melting point temperature, which was 27 °C. The results showed that Micronal 5038X had higher heat of fusion than Micronal 5040X. Furthermore, an increase of approximately 15% in the comfort conditions in terms of reduced internal surface temperature was achieved with 15 wt% of PCM-mortar compared with the pure cement mortar sample.

Younsi and Naji [117] numerically investigated the microencapsulated PCM-mortar layer incorporated into the wall to manage the building thermal comfort, downsize heating/cooling equipment and shift the peak load. The factors examined during the simulation included the mass fraction of PCM, the thickness of the wallboard and the melting temperature, which varied between 24 °C and 28 °C. The results indicated that the microencapsulated PCM–mortar layer reduced the temperature by 3 °C, and the PCM mass fraction of 20%–30% was required for efficient thermal storage and better thermal comfort. The study also concluded that the PCM-mortar layer added to the walls was a good option in summer period because it reduced the heat transfer entering the building and shifted the cooling peak loads to the late hours of the day. Abden et al. [118] experimentally investigated the thermal performance of a composite PCM-incorporated gypsum board false ceiling for cooling load reduction. The composite PCM was prepared from methyl stearate and diatomite mixed with the gypsum mortar to develop a form-stable PCM board with excellent thermal stability and physical properties. The results showed that the temperature was reduced by 4.9 °C during the first day of the experiment. Furthermore, an average reduction of 3.5 °C was obtained during the three-day experiment compared with an identical chamber of standard gypsum board. The study concluded that such board type was efficient to save the cooling loads by 16.2% and economically feasible with 1.7 years of payback period. Li et al. [119] fabricated a composite PCM wallboard containing three types of PCMs with different melting points (12 °C, 18 °C and 29 °C) to maintain thermal comfort and increase energy saving under different climate conditions. Two models of PCM boards were fabricated with varying concentrations of PCM and tested considering the heat flux and temperature changes. The results showed high energy saving by up to 30% for the wallboard-based PCM with reasonable thermal control of temperature fluctuations compared with the standard gypsum wallboard. Kusama and Ishidoya [120] investigated the thermal comfort and energy storage efficiency of using the plaster integrated microcapsuled PCM as a finishing layer for a room's wall and ceiling. The study revealed that the microcapsuled PCM has the potential to store heat that passes through windows and release it to maintain thermal comfort. The PCM plaster was tested in the laboratory to determine the melting temperature and heat storage capacity and then used as a finishing layer of a testing room. The results showed a higher solar radiation utilisation rate of up to 82% of the PCM plaster room than another conventional method. This finding confirmed a stable comfort temperature and humidity level under cold climate conditions of Japan.

4.5.2. PCM-sheet/board/layer inserted into building element

In this category, the sheets, boards or layers of macroencapsulated PCM are installed as an additional layer in the building structure and activated passively or actively. The main advantage of this method is that a vast amount of PCM could be contained in the building elements without influencing its mechanical properties. Hu and Yu [94] simulated the performance of a wall-embedded PCM board in five different climate conditions in China using EnergyPlus tool. The study investigated the total energy saving and CO_2 emission reduction, considering the PCM board type and its thickness. The findings stated that incorporation of PCM could save energy consumption through building walls by 6% and reduce CO_2 emissions by 1% in the warm climate buildings. The study also reported that the position of the PCM layer within the wall is sensitive; thus, placing the PCM layer inside the wall insulation can save 1%–7% more energy than the PCM layer outside the wall insulation. Moreover, the increase in PCM thickness can save 2%–6% more energy in severe and hot climate zones. Ahangari and Maerefat [121] numerically investigated the thermal comfort and building energy-saving by applying double PCM layers in a room at five Iranian climatic conditions (mostly dry and semi-arid). The layers had different melting temperatures installed one by one close to the interior zone, in which the PCM layer with low melting temperature was placed closer to the interior. The thermal performance was evaluated using EnergyPlus software and Fanger model for thermal comfort. The results pointed out the effectiveness of double layer system, where the thermal comfort period improved from 73% to 93% in a dry climate and from 63% to 75% in semi-arid climate in winter. Moreover, a reduction of heating energy consumption was achieved at 17.5% and 10.4% in a dry and semi-arid climate, respectively. Zhu et al. [122] numerically studied the effectiveness of paraffin compounds as PCMs for a Trombe wall during summer and winter seasons of Wuhan City, China using TRNYS software. The study proposed two PCM layers with different melting temperatures to maintain the necessary thermal comfort within the whole year. One of these layers was placed externally with respect to the wall and coupled with a solar chimney. By contrast, the other layer was placed internally to the wall and combined with a solar heating system. The simulated results stated that the best melting temperature was 30 °C and 18 °C for the external and internal PCM layers, respectively. Furthermore, the maximum reduction of cooling and heating load was 9% and 15%, respectively, compared with the wall without PCM. In addition, the PCM layers decreased the indoor temperature by 3.28 °C in summer and increased the indoor temperature by 0.11 °C.

The location of the PCM layer within the building envelope is

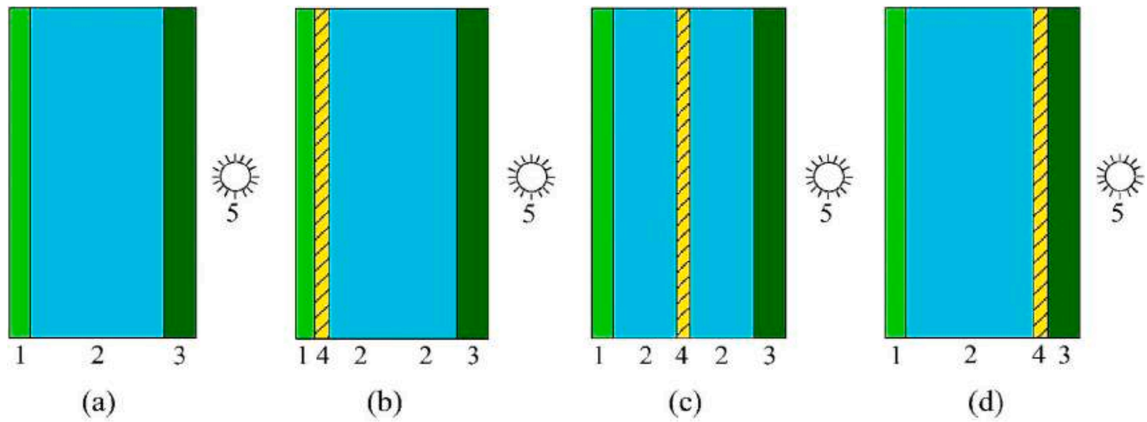

Fig. 15. Schematic of the studied PCM locations: (a) regular wall, (b) PCM layer placed close to the interior, (c) PCM layer placed in the middle and (d) PCM layer placed close to the exterior. 1. gypsum board, 2. insulating layer, 3. oriented strand board, 4. PCM layer and 5. outdoor [83].

essential and affects the thermal performance significantly. Arıcı et al. [102] numerically studied the effect of the PCM layer position, the melting temperature and layer thickness on the basis of the energy-saving of cooling and heating loads of three Turkish locations. They revealed that the optimal exploitation of PCM latent heat could be achieved with a time lag of 10.3 h when the melting temperature of the PCM varies from 6 °C to 34 °C with 1–20 mm PCM layer thickness on the basis of the building climate conditions. Jin et al. [83] numerically and experimentally studied the optimal position of a thin PCM layer incorporated with a frame wall to reduce the heat flux that passes through it. The layer was placed in different locations with respect to the exterior and interior wall layers, as shown in Fig. 15. The simulated results revealed that the optimal PCM layer position depended on the thermal properties of the PCM layer and the environmental conditions. Two places were found effective, namely, the one closer to the interior wall surface (case a) when the interior temperature increased and the layer closer to the exterior wall surface (case d) when the PCM layer thickness, the heat of fusion and the melting temperature of PCM increased. Moreover, the heat flux reduction increased with the increase in the thickness of the PCM layer.

PCM layer incorporation together with other technologies can further enhance the performance of building envelope and reach better thermal comfort. Zhang et al. [123] investigated the effect of matching PCM sheets with cool paints for roof cooling load reduction and energy saving. They experimentally studied the following types of roof: normal roof, cool painted roof, PCM-roof and a cool roof coupled with a PCM sheet. The results showed that the performance of the roof was enhanced using the PCM sheet, and the cool roof incorporated with PCM sheet had the best performance. This combination reduced the cooling load of the tested room by 6.6 °C, and the heat entering the room also decreased by 52.9%. The study clarified the impact of PCM position and thickness on the roof performance, where the internal position of the PCM sheet inside the roof can reduce the indoor temperature by 1.2 °C compared with the middle position. Furthermore, the thicker PCM layer performed better, where the PCM with 5 mm thickness was sufficient to maintain a comfort level in the range of 22 °C-28 °C for the entire day. The dynamic thermal performance of PCMs combined with the waterproof membrane was investigated by Piselli et al. [124] for temperature reduction of the lightweight roof. Two membrane types (cool and dark coated) were used in the experiment together with different PCM layers of varying melting temperatures under the climate conditions of Rome, Italy and Abu Dhabi, UAE. The results demonstrated that the roof performed well in Rome when the PCMs with melting temperatures of 25 °C and 45 °C were integrated with the cool and dark roof membranes, respectively. By contrast, the PCMs with melting temperatures of 35 °C and 55 °C performed better in Abu Dhabi. The study also indicated that the PCM layer with 25 °C and 31 °C melting temperatures combined with cool and dark membranes had the best roofing thermal performance for Rome and Abu Dhabi. Furthermore, the study concluded that the climate conditions, roofing medium, PCM position and its melting temperature should be considered when selecting appropriate PCM to obtain the best cooling effect for roofs. Gracia [125] numerically implemented a movable PCM layer (7 mm polymeric sheet) with a changeable position with respect to the insulation layer inside the wall, as shown in Fig. 16. The system aimed at reaching full solidification of PCM and avoid heat discharge in the indoor, thereby representing the main practical issue of PCM passively incorporated building. In addition, the system can work as a cooling supplier in hot days. With the optimal control of the system, the researcher claimed that cooling loads can be minimised by 379% compared with a wall without PCM.

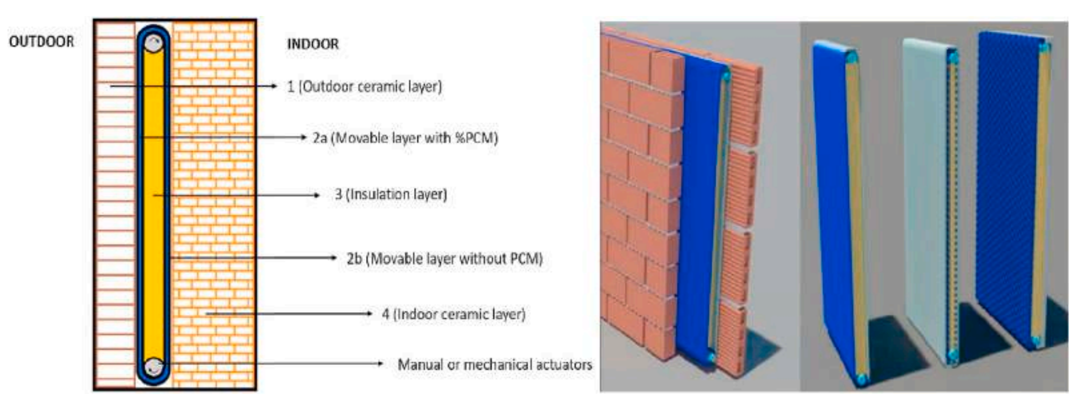

Fig. 16. Sketch of the dynamic PCM system [125].

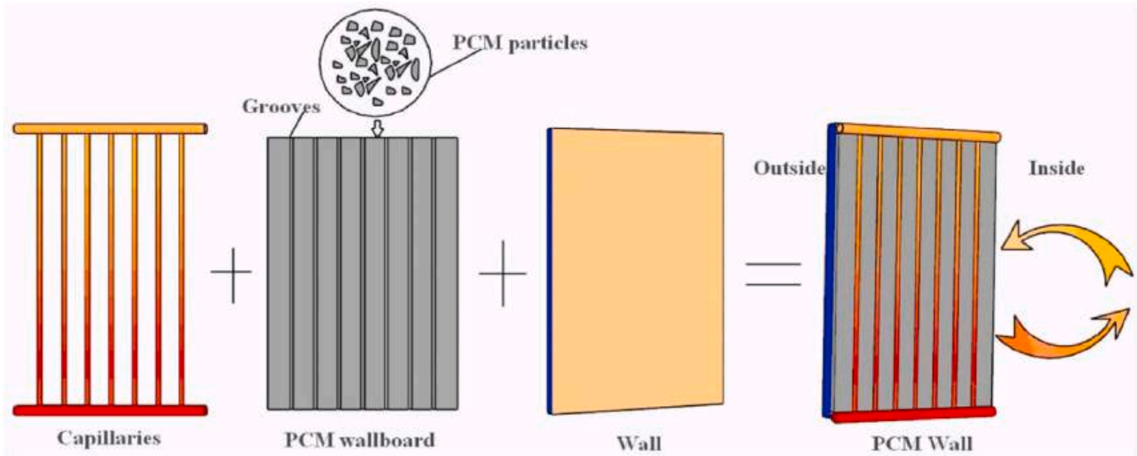

Fig. 17. Proposed design of hybrid PCM wall [127].

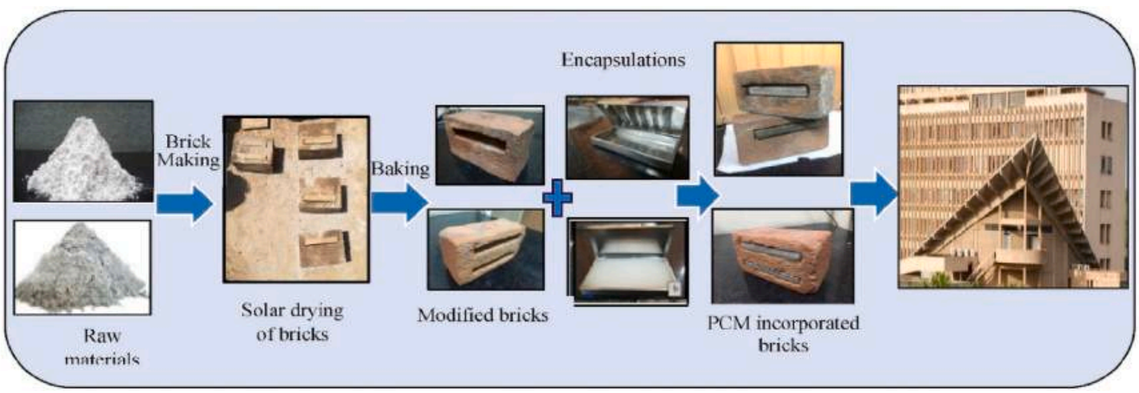

Fig. 18. Preparation of PCM-incorporated conventional bricks [58].

Combining PCM with an active solar heating system is a novel technique to utilise the potential of PCM to maintain indoor thermal comfort and increase the efficiency of the building. This technique can effectively be implemented at locations suffering from low solar radiation in winter. Rucevskis et al. [126] numerically compared the performance of passive and active incorporation of PCM for cooling load reduction through the building's roof under summer conditions of Baltic States. They proposed a replaceable PCM layer, which can be installed between the concrete slab and the inside finishing layer. The PCM layer provided with a capillary pipe system, where cold water flows, utilised the night cooling effect. The system was analysed using ANSYS FLUENT, considering an indoor temperature range of 21 °C-28 °C. The results reported that the indoor air temperature was reduced by a maximum of 4 °C using the passive system (without water flow) and approximately 10.5 °C when actively circulating the night-cold water compared with the standard case without the PCM. The study also indicated that the amount of PCM was not fully utilised during the simulation, where 65.7% of PCM was melted during the hottest day compared with only 24.1% in the regular days. This outcome clearly emphasised the need for appropriate calculation of PCM amount to be incorporated with the building envelope, which dramatically affects the cost and thermal performance of the system. Kong et al. [127] fabricated a hybrid system composed of perlite-based composite PCM wallboard (passive technique) coupled with a solar heating system (active technique) through capillaries. The system was placed inside the tested room's wall, as shown in Fig. 17. The room of the hybrid system was compared with another reference room without PCM over three working days under winter conditions of Tianjin, China. The analysis results showed a reduction of 44.16% in the daily heating energy consumption of the hybrid system at actual scale room. Moreover, the study concluded that such a hybrid system could maintain the required comfort environment and enhance the efficiency of buildings.

4.5.3. PCM-incorporated bricks

Bricks are important construction elements that are generally available in rectangular shape. Specifically, fired clay bricks are popular types (particularly for walls) used in different constructions worldwide due to their availability, durability, ease of installation and high mechanical properties [128]. PCM incorporation with bricks is an effective method to increase the thermal mass of the constructed element to control the daily temperature fluctuations. A proposed practical procedure to fabricate bricks based on PCM is illustrated in Fig. 18.

The researchers have numerically and experimentally observed the potential of different PCM types containing conventional bricks of different types and configurations. Elnajjar [129] numerically investigated the thermal performance of different types of PCM (n-Octadecane, n-Eicosane and P116 with a melting temperature of 27 °C, 37 °C and 47 °C, respectively) embedded in bricks under the climate conditions of United Arab Emirates, on the basis of one and seven days of assessment. The research aimed to decrease the power consumption and greenhouse gas emissions by decreasing the heat gain through the building envelope and to shift the peak period. The results revealed that the use of PCM for building envelope should be assessed appropriately and required at least seven-day analysis given that the one-day assessment is misleading and insufficient to evaluate the thermal behaviour of the PCM. The results also showed that the n-Octadecane PCM had a good behaviour on the first day, and the PCM P116 had the best performance with 30% heat flux reduction and energy saving based on the seven-day assessment.

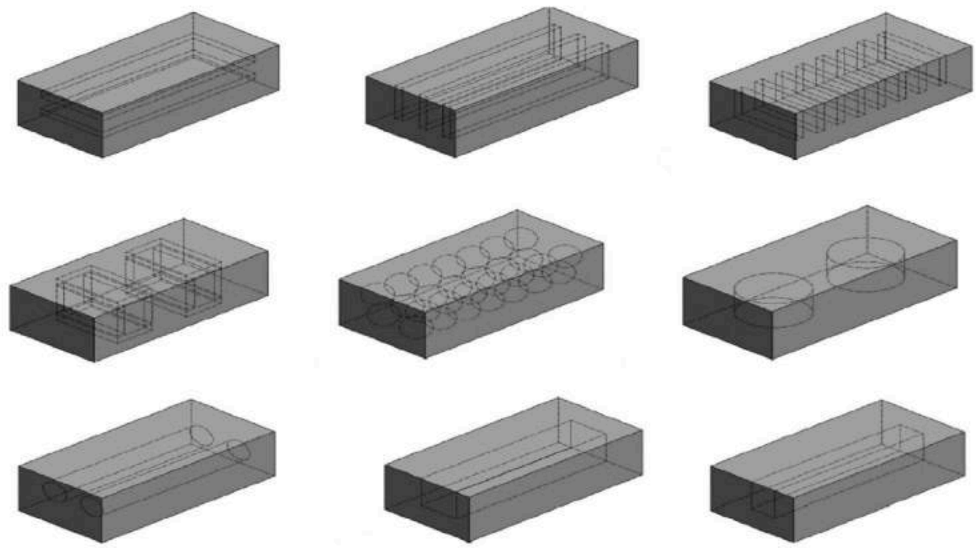

Fig. 19. Design of possible PCM containers incorporated with concrete blocks [130].

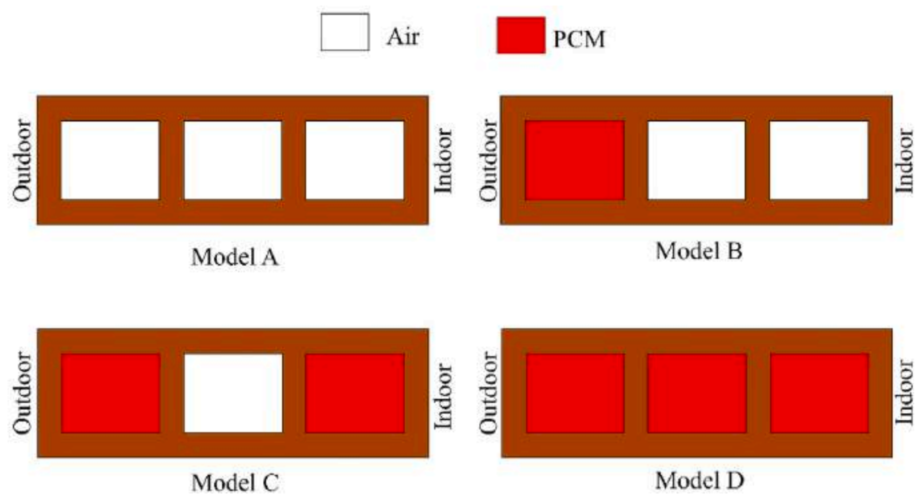

Fig. 20. Proposed models of bricks [132].

Erlbeck et al. [130] comprehensively investigated the best thermal performance of PCM incorporated with concrete blocks. The study considered different shapes of PCM, such as plate-shaped, cuboid, cylindrical and spherical containers filled with PCM and placed in different positions and orientations, as shown in Fig. 19. The study revealed that the thin plate-shaped PCM container had the best design because it showed better heat transfer during melting and solidification in different positions and orientations.

Kant et al. [131] numerically investigated the latent heat of fusion of PCM embedded in bricks and analysed its effect on the building's thermal comfort under actual solar radiation and ambient temperature conditions. The study compared three cases, namely, the standard bricks, bricks with air-filled in the cavity and bricks with PCM filled in the cavity. For the bricks filled with PCM, the performance of the three PCM types (Capric acid, Paraffin and RT-25) was evaluated to identify the best thermal performance. Results presented that the bricks filled with PCM performed well, and the reduction of heat flux of Capric Acid, Paraffin and RT-25 was 8.31%, 6.07% and 3.61%, respectively. The study also pointed out that the reduction of mechanical strength of bricks due to the cavities was the main drawback of PCM incorporation. Tunçbilek et al. [132] numerically evaluated the seasonal and annual performance of PCM-incorporated bricks and energy saving of its latent heat for cooling and heating load under climate conditions of Marmara, Turkey. They investigated different models of brick-filled gaps with PCM (Fig. 20), considering the position of PCM, melting temperature and PCM quantity compared with the conventional air-filled gap brick. The results indicated that the PCM-filled gap, model D, placed near the indoor side had higher energy saving, and the optimal melting temperature depended on the season, which varied between 18 °C and 26 °C. They also conducted an annual analysis to determine the optimum PCM melting temperature for all seasons, which was 18 °C; 17.6% thermal demand reduction is obtained annually. The study revealed that incorporating PCM into bricks could provide better thermal performance in winter more than in summer season. Furthermore, appropriate selection of PCM melting temperature is necessary to avoid overheating, which increases the cooling load considerably.

Saxena et al. [58] experimentally studied the heat transfer and change in temperature across the PCM embedded into bricks under peak summer conditions in Delhi City, India. Two types of PCM, namely, Eicosane and OM35, were selected because they showed good stability and thermo-physical characteristics for melting/solidification processes. The PCMs were weighed and then encapsulated using aluminium containers with appropriate shape and size. Furthermore, the capsules were inserted inside the bricks of single and dual layer arrangements (Fig. 21).

Fig. 21. Fabricating steps of PCM-incorporated bricks; (a) Single-slot brick, (b) Encapsulation container, (c) Macroencapsulated PCM, (d) Double-slot brick, (e) Encapsulation container with fins, (f) PCM-incorporated brick with twin slots, (g) Installation of bricks and (h) Final setup [58].

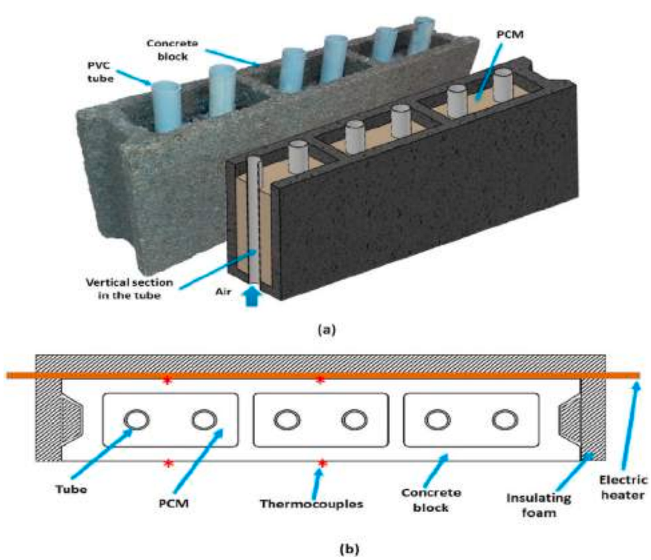

Fig. 22. PCM-incorporated block with air ventilation [133].

The proposed bricks were tested and compared with a standard brick without PCM. The results showed a reduction of 4.5 °C-7 °C in the inner surface temperature of PCM-incorporated bricks compared with the standard material. The heat across the bricks with single and dual PCM layers was reduced by 40% and 60%, respectively. In addition, the heat transfer of bricks that contained Eicosane was reduced by 8% and by 12% for OM35.

Kumar et al. [62] experimentally investigated the thermal performance of PCM-integrated hollow bricks for walls under warm and humid weather conditions of Chennai, India. One of the two tested identical rooms (3*3* 3.65 m) had a macroencapsulated PCM in an aluminium foil packet placed inside the air holes of bricks with a total quantity of 750 kg of PCM (HS 29 type). The results showed a temperature reduction of up to 2 °C-6 °C in the room containing PCM compared with the other room without PCM during the tested months of summer. Therefore, the electric energy consumption for cooling and greenhouse effect was highly avoided. The experimental results compared with the numerical results obtained using Design Builder software revealed good agreement with the experimental work.

Active incorporation of PCM with concrete blocks by using air ventilation was investigated by Laaouatni et al. [133]. The experimental prototype, shown in Fig. 22, aims to solve the problem of antisymmetry of heat energy stored in PCM blocks to allow walls to work efficiently under different fixed climates. The study reported that the thermal performance of tested elements was improved by confirmed phase-shifting and increased inertial capability of the elements. The study was validated using two numerical tools and stated that the method could be applied to actual wall scale, considering several parameters. These parameters are the dimensions of air tubes to the PCM amount, airflow velocity, geometry of tubes, PCM type, PCM melting temperature and the position in the cavities of blocks.

4.5.4. PCM macroencapsulated pipes

Generally, PCMs have poor thermal conductivity [134,135]. Microencapsulation increases this matter given that the PCM is covered using polymeric materials of low thermal conductivity. The thermal conductivity of PCM can be improved using metal pipes made from copper, brass and aluminium in addition to their resistance against corrosion over a long term of service [136]. The PCM macroencapsulation pipes have better potential than microencapsulation because they can be produced easily with low cost [137], they have larger space that allows more PCM quantity to be involved and preserve volumetric change during cycles [138]. In addition, they can be installed into the building envelope as separated elements and do not affect the mechanical or thermo-physical properties of the element, especially for concrete

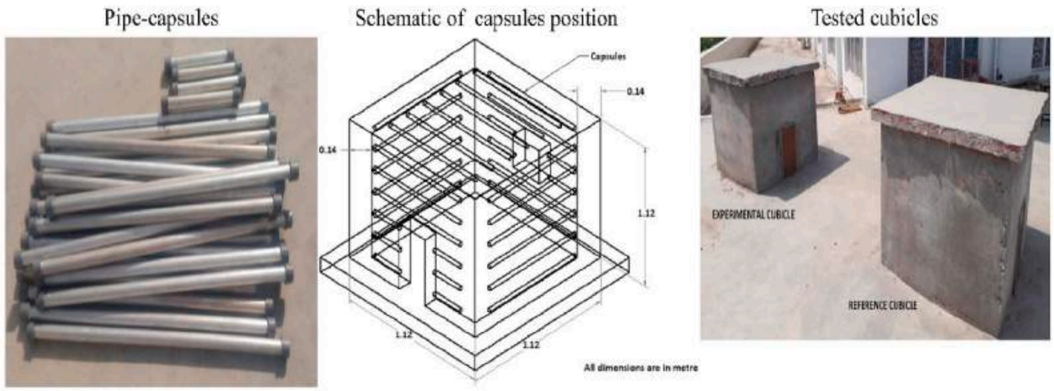

Fig. 23. Installation steps of pipe macroencapsulated PCM proposed by Ref. [61].

installations [139]. Several experimental studies were reported in the literature regarding this trend for passive and active techniques and showed excellent results in minimising cooling loads in summer or maintaining warm thermal comfort in winter. Rathore and Shukla [61] experimentally investigated the thermal response of pipe macro-encapsulated PCM into the roof and walls under the outdoor climate conditions of India. Aluminium pipes filled with a commercially manufactured inorganic PCM (OM37) and a melting temperature of 36 °C to °40 °C were incorporated with a building envelope shown in Fig. 23. The experiment was conducted to reduce the cooling loads passively by studying the reduction of peak temperature, thermal amplitude and time lag on two cubicles, namely, PCM cubicle and a standard one. The results reported peak temperature reduction in the indoor temperature of PCM cubicle by 7.19%–9.18%, and the thermal amplitude was reduced by 40.67%–59.79%. Moreover, the cooling load of PCM cubicle was minimised by 38.76%, thereby saving electricity by approximately 28.31 Rupees/day (~0.40 US$/day) along with 60–120 min of peak load delay.

Sun et al. [60] experimentally investigated the effect of pipe diameter and its location on the thermal behaviour of PCM passively incorporated walls. Two pipes with sizes 1.27 and 1.9 cm and filled with PCM with melting temperature ranging from 26 °C to 28 °C were installed horizontally in two positions, namely, near the interior and middle position. Six light bulbs of 200 W were used as heat flux sources to conduct the heat reduction and time delay of the experiment. The results revealed that the small pipe size performed better than the larger pipe size under the same conditions. However, the PCM in the two cases did not fully solidify to complete the cycle on the first day of the experiment. For the pipe with 1.27 cm diameter installed in the middle position, a maximum heat flux reduction of 36.49% was achieved with a time delay of 89 min when the wall surface temperature was 55 °C. Furthermore, a maximum energy saving of 63.81 W-hr/m^2 and 116 min time delay were recorded at 69 °C for the 1.27 cm compared with 32.67 W-hr/m^2 obtained from the 1.9 cm pipe size. The experiments also concluded that the higher potential of PCM could be achieved at high temperatures, and the optimal pipe position is located between the interior and middle positions to guarantee full-phase transition. Hasan et al. [59] experimentally investigated the potential of paraffin wax at 44 °C melting temperature as an insulation material to minimise the cooling load under hot Iraqi weather conditions. Paraffin wax, in liquid form, was poured inside an aluminium frame (square cross-section area) and installed to the interior of the ceiling and walls of a tested room at a volume of 1.5*1.5*1 m. The results showed that the cooling load reduction across the ceiling was 6.83%. By contrast, the reduction was 19.95%, 14.36%, 7% and 11.7% across the southern, western, northern and eastern walls, respectively. They also found that the maximum cooling load reduction of 20.9% was achieved, equivalent to electricity saving of approximately 1.35 $/day m^3 at 1 cm thickness of PCM.

The passive incorporation of PCM into building envelope is not always sufficient due to the noncompletion of melting or solidification processes either because of the high solar radiation, which overheats the PCM or lacks solidifying medium. In such cases, active techniques are recommended to complete the PCM cycles and prepare for the following day. Sun et al. [140] experimentally investigated the effect of active charging of energy into the PCM for rectangular slabs. A small wind tunnel was used to supply hot air with various velocity and temperature

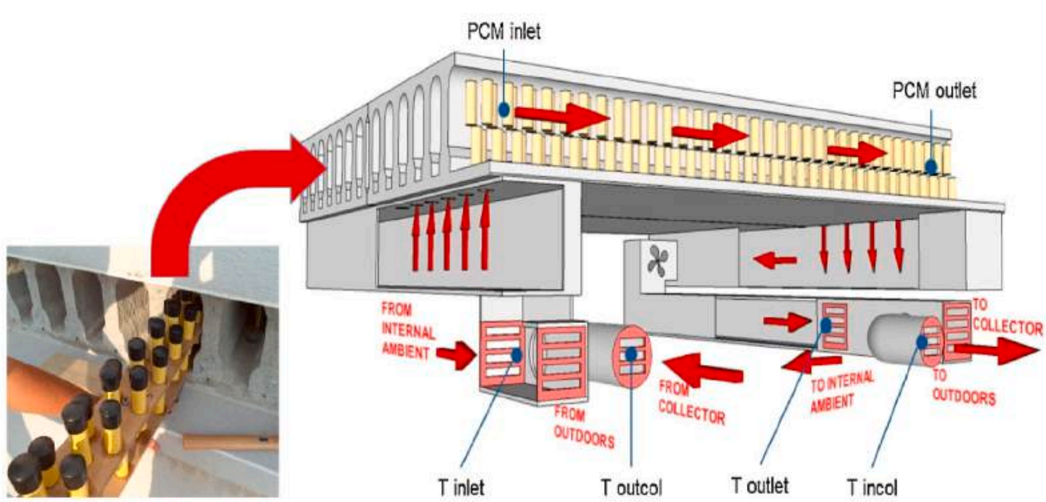

Fig. 24. Scheme of active slab system showing the PCM-encapsulated tubes and their position in the slab [141].

Table 4
Summary of recent studies of PCM-incorporated building envelope.

PCM type (MT, °C)	Location Country (city)	Study type	Envelope element	Incorporation method	Application	Findings and remarks	Ref.
BioPCM (26) n-docosane (44)	South Korea	E	Roof	PCM packs	Cooling	• Indoor temperature reduction up to 5.40 °C obtained, • n-docosane was more effective than BioPCM.	[142]
BioPCMs (20–32)	Saudi Arabia, Egypt, India	N	Roof + walls	PCM layer	Cooling	• The maximum temperature reduced by 2.04 °C, • ES of 17.97–34.26% gained.	[143]
Paraffin Wax (58.5)	Thailand	E	Walls	Concrete filled PCM	Cooling	• CL reduced by 9%, ES of 31% and TL of 184 min obtained.	[144]
Enerciel 22 (18–29) $CaCl_2$. $6H_2O$ (28.9)	Iran (Isfahan)	N	Walls	PCM layer	Cooling	• Heat transfer reduced for Enerciel 22 in the range 15.6–47.6%, and in the range of 2–7.8% for $CaCl_2$. $6H_2O$.	[145]
BioPCM (25) RUBITHERMPCM (29)	South Korea (Seoul), Japan (Tokyo), and China (Hong Kong)	N	Roof + walls	PCM board	Heating & Cooling	• PCMs showed ES of 4.48–8.21%, 3.81–9.69%, and 1.94–5.15% for Seoul, Tokyo and Hong Kong, respectively.	[146]
Nine types PCM19 (19), PCM20 (20), PCM21 (21), ..., PCM27 (27)	Canada (McMurray and Val-d'Or), Russia (Bratsk, Arkhangelskand Surgut), Finland (Oulu), and Sweden (Umea)	N	Roof + walls	PCM layer	Heating & Cooling	• PCM23 and PCM24 indicated the highest ES of 4000–10000 kWh, • The payback period for all cities ranged from 16 to 32 years, • PCMs could reduce up to 4817.44 kg/year of CO_2 emissions.	[147]
PCM (26)	Algeria	N	Walls	PCM clay mixed with stones	Cooling	• CL reduced by 73%, • The peak load shifted by 5 h, • Wall inner temperature reduced by 2 °C.	[148]
RT28 (80 wt%) + Expanded graphite (20 wt%) (26.5–28.5)	China (Wuhan)	N	Walls	Pipe-encapsulated PCM	Cooling	• Resist 55.6–82.8% of the heat coming from the outdoor, • Reduction of 32.4–55.5% of the accumulated heat entering into indoor.	[149]
Micronal DS 5038 (25)	Lab. conditions	E	Walls	Cement based PCM (concrete & mortar)	–	• Thermal conductivity of mortars decreased by 37% and about 30% for concrete. • The heat capacity increased by 13% for mortars versus 9% for concrete specimens.	[150]
PCM_Q21 (21) PCM_Q23 (23) PCM_Q25 (25) PCM_Q27 (27)	Northern Morocco	N + E	Roof + walls	PCM layer	Cooling	• PCM_Q23 and PCM_Q25 lead to optimal thermal performance, • The east wall showed the best condition (lowest DF = 0.017 and highest TL = 7 13 min), • The worst condition presented by the roof (highest DF = 0.031 and lowest TL = 466 min), • PCM reduced the DF by 60% (north-facing wall) and 35% (roof).	[151]
Bio-PCMTM (27)	Australia	N	Ceiling + walls	Cladding layer	Cooling	• PCM refurbishment can efficiently reduce indoor heat stress risks and improve occupant health and thermal comfort, • Discomfort period reduced by 65% during extreme heatwave conditions.	[152]
Energain® PCM	Lab. conditions	N + E	Wall	Separated PCM layer	Cooling	• Maximum heat flux reduced by 15% and delayed by 2 h.	[153]
n-octadecane (18.80–37.83) Beeswax (33.41–61.05)	United States (Chicago, Los Angeles, Miami and Phoenix)	N + E	Wall	PCM impregnated gypsum/cement (G/C) board	Heating & Cooling	n-octadecane and Beeswax impregnated G/C board increased thermal conductivity by 129% and 150% compared with the original G/C board. In Chicago, n- octadecane performed better than Beeswax during the cooling season in terms of CL and TL, In Miami, ES of 7.8% and 6.4% achieved when n-octadecane and Beeswax applied during the heating season, In Miami and Phoenix, CL reduction	[154]

(*continued on next page*)

Table 4 (*continued*)

PCM type (MT, °C)	Location Country (city)	Study type	Envelope element	Incorporation method	Application	Findings and remarks	Ref.
						of 3.6%–4.3% was obtained using n-octadecane based G/C board.	
Eicosane (36–38) **OM35 (35)**	India (Delhi)	E	–	PCM incorporated bricks	Cooling	Temperature reduced by 4–7 °C during peak hours, Heat flow reduction by 8% for Eicosane and 12% for OM35.	[155]
OM37 (39.1)	India (Mathura)	E	Roof + walls	Aluminium pipe encapsulated PCM	Cooling	Indoor peak temperature reduced by up to 0.2–4.3 °C, Annual TL of 97.5 min and the annual DF reduction of 24.69% obtained. The peak heat flux reduced by 17.37%, annually, Cost-saving in peak CL of 1.47 rupees/kWh/m^2/day obtained.	[156]
PCM24D (21.9) **RT21 (21)**	Norway (Oslo)	N	Walls	PCM24D integrated concrete and RT21 added as a separate layer	Heating & Cooling	The annual ES reached 28%, Energy reduction during the summer of 32% versus 23% during the winter.	[157]
n-octadecane (23.55) **n-eicosane (34.99)**	China (Hangzhou)	N	Walls	Double PCM layers integrated walls	Cooling	Peak indoor temperature reduced by 2.9–6.7 °C in summer, thermal comfort hours increased by about 12%, Thermal energy charge time increased as PCM thickness increased.	[158]

N: Numerical, E: Experimental, MT: Melting Temperature, ES: Energy Saving, CL: Cooling Load, DF: Decrement Factor, TL: Time-Lag.

range of 35 °C–55 °C. The hot air was used to melt paraffin (26 °C-28 °C melting temperature) embedded inside the slab, and their effect on charging speed was investigated. The results indicated that the increase in air temperature from 35 °C to 55 °C increased energy charging by 201.7% (from 36.3 W to 109.4 W). On the contrary, it was slightly enhanced with the increase in air velocity from 4 m/s to 5 m/s. Similarly, the maximum PCM storage capacity of 97.2 W h was obtained at 55 °C air temperature and 3 m/s air velocity at 109.4 W energy charging speed, thereby showing that the increase in air temperature had greater effect on charging time than the increase in air velocity. Navarro et al. [141] experimentally studied the thermal performance of pipes, and encapsulated PCMs were inserted inside a prefabricated concrete slab, under severe and mild winter conditions of Spain. Two cubicles with active slab (contains PCM) and conventional slab (reference) were fabricated to compare the energy saving obtained from the utilisation of PCM. The active slab had 14 cavities incorporated with 52 kg of paraffin (RT-21) of 21 °C-22 °C melting temperature, poured in 1456 tubes of aluminium (12 mm diameter and 100 mm length). The slab, shown in Fig. 24, was activated using an air solar collector to reach the melting temperature of PCM and provide heating stream to the indoor environment by controlled gates. The control system worked on the basis of actual weather conditions to handle the charging and discharging processes, prioritising the latter. The PCM performance varied due to changing weather conditions, and melting temperature was not reached over time.

The results stated that the energy saving of the active slab reached 20% during partial melting of the PCM, and 55% was obtained at the complete melting and solidification cycles compared with the referenced slab. Furthermore, the study indicated that the energy-saving achieved was 25% and 40% during the severe and mild winter conditions, respectively.

A summary of other studies that used different PCM types under different locations is presented in details in Table 4, showing their application, incorporation methods and their main findings.

5. Conclusions and future studies remarks

5.1. Conclusions

The work reviewed the potential of PCM-incorporated building envelope, which is a growing technology to improve building performance at present. The PCM technology showed a remarkable enhancement of building thermal energy either by decreasing undesired thermal loads or managing the thermal demand, thereby positively influencing the thermal comfort and building energy saving. A general revision of recent studies was investigated, considering the main PCM types, encapsulation methods, influential parameters and incorporation techniques with building envelope materials, mainly for roofs and external walls. Several conclusions can be drawn from the current work as follows:

- The incorporation of PCMs with roofs has received less attention than the wall-related studies (roofs/walls studies ~1:3 in the current work).
- The number of recent numerical research is much higher than the experimental studies (in the ratio of ~2:1 in the current work).
- Limited research work has been conducted for cold climate conditions compared with many investigations under hot climates, where the PCM functions better. Such investigations can provide great support for heating systems in cold locations.
- The weather condition is the main factor for specifying the type of PCM, quantity, effective position and the method of encapsulation.
- The optimal position is still a critical key factor in the installation of PCM into the building envelope. Nevertheless, the most acceptable statement is that the PCM layer should be positioned closer to the heat source. For instance, the PCM should be positioned close to the outdoor envelope layers under hot climates. The leading cause is that PCM works as a heat barrier (insulation) in these conditions. Thus, the stored heat should be as far as possible from the indoor to avoid any undesired emittance of heat towards the indoor and to utilise the night cooling effect during the evening. Under cold conditions, the PCM layer works as a heat supplier (i.e., prevents/restricts the heat that escaped from indoor towards outdoor, stores the heat and then releases it back to the indoor due to temperature difference); thus, it should be as close as possible to the interior.

- The passive incorporating technique has drawbacks mainly associated with the limitation to reach full exploitation of PCM storage capacity, unguaranteed phase transition (charging/discharging) and uncontrolled direction of stored heat.
- Night cooling/ventilation is an effective method in hot climate applications. However, it has a limit in the extreme hot locations, where the cold air is insufficient. Therefore, an alternative discharging HTF is required. This alternative HTF should be available, easy to implement, able to discharge heat from PCM in a short time and has an acceptable operational cost. Some proposed alternatives are evaporative cooling, geothermal energy and underground water.
- Active techniques can efficiently control the thermal performance, especially under locations, where the PCM potential has a limit to be utilised passively.

5.2. Remarks for future studies

PCMs have high potential to enhance the building energy when installed with building materials. For future studies, the following concepts can be adopted for further investigations and improvements:

- The thermal behaviour and beneficial aspects of PCM-incorporated buildings under harsh weather conditions have received little attention. Under severe hot locations, the PCM reaches a full melting state in early day hours. Thus, instant discharge of retained heat is required to avoid any malicious behaviour. In such a case, the passive method is insufficient, and the night ventilation technique is useless. Therefore, adopting an alternative discharging medium is necessary to prepare the PCM for the following day cycle, such as geothermal energy. Under cold locations, the building element exposed to the sun passively stores the heat in the PCM during the day, and then releases it as the temperature decreases. Nonetheless, the solar radiation is typically low in the cold regions, which cannot heat the envelope layers, including the PCM. Therefore, the utilisation of solar energy by an active means, such as solar collectors, is required.
- The poor thermal conductivity of PCM represents the main downside problem reported in the building applications. This issue causes partial charging and discharging during the phase transition, thereby influencing the PCM storage capacity in the following cycle. Few researchers experimentally investigated this issue using different methods, such as the use of high thermal conductivity encapsulation materials, immersion of nanoparticles [159] and implementation of fins, copper fume, metal matrix and carbon fibres to accelerate the time for melting and freezing processes [65,160]. More experimental investigations of adopting such techniques are required.
- The use of plastic products as macroencapsulation containers under hot climates seems to be a novel idea. Such materials can restrict the heat from outdoor, thereby providing more insulation support. These materials influence the low thermal conductivity of PCM. Therefore, appropriate care should be given for efficient use.
- Long-term research that provides a clear vision of PCM performance over a long time of service in buildings is limited.
- Studies on the feasibility of using PCM for whole-building application are also limited. These studies are necessary for technology commercialisation.

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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NomenclatureAbbreviations

DF: Decrement factor
DSC: Differential scanning calorimeter
ECES: Energy conservation through energy storage
HTF: Heat transfer fluid
IEA: International energy agency
TL: Time lag
PCM: Phase change material
SHC: Solar heating and cooling program
TABS: Thermally activated building systemSymbols
A: Area [m^2]
c_p: Specific heat capacity at constant pressure [kJ/kgK]
d: Number of days each month
E: Energy-saving [unitless]
E_{latent}: Overall heat storage capacity [kJ]

f: Liquid fraction [unitless]
F_{sky}: View factor between the exterior surface of the external envelope and the skydome [unitless]
F_{ground}: View factor between the exterior surface of the external envelope and the ground surface [unitless]
h_{in}: Internal heat transfer coefficient [W/m^{2}K]
$h_{in: ,s}$ Heat transfer coefficient of the internal surface of envelope [W/m^{2}K]
h_{ex}: External heat transfer coefficient [W/m^{2}K]
h_c: Convective heat transfer coefficient [W/m^{2}K]
h_r: Radiative heat transfer coefficient [W/m^{2}K]
H_f: Enthalpy [kJ/kg]
I: Solar radiation [W/m^2]
k: Thermal Conductivity [W/mK]
L_H: Latent heat of fusion [kJ]
m: Mass (kg)
n: Number of PCM cycles
OT: Operative temperature [°C]
p: Daily period [s]
Q: Heat flux [W]
$\dot{Q}$: Instantaneous heat gain/loss through the envelope [W/m^2]
T: Surface temperature [°C]
T_a: Indoor air temperature [°C]
T_{air}: Sky temperature [°C]
T_{ex}: External surface temperature [°C]
T_{in}: Internal surface temperature [°C]
T_l: Liquidus temperature of PCM [°C]
T_s: Solidus temperature of PCM [°C]
T_{sky}: Ambient air temperature [°C]
$\overline{T}_r$: Mean radiant temperature [°C]
t: Time [s]
V: Volume [m^3]
v: Wind velocity [m/s]
x: Thickness of the element (mm)Greek Letters
σ: Stefan-Boltzmann constant (W/m^{2}K^4)
β: Factor used to divide the long-wave heat exchange of the sky dome between the sky and air radiation
α: Thermal diffusivity [m^2/s]
α_G: Envelope absorptivity [unitless]
ε: Emissivity factor [unitless]
Φ_{in}: Internal heat flux [W/m^2]
Φ_{ex}: External heat flux [W/m^2]
ρ: Density [kg/m^3]