Phase Changing Materials

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1. Abstract

Building envelope is a key element in providing adequate energy and thermal comfort performance to buildings. 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. 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.

Keywords: PCMs, PCM-integrated buildings, Building envelope, Thermal comfort, Energy saving, Heating/cooling load reduction.

2. 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. 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 [1].

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 [2]. 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. 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. 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.

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. 1. 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 [3-4].

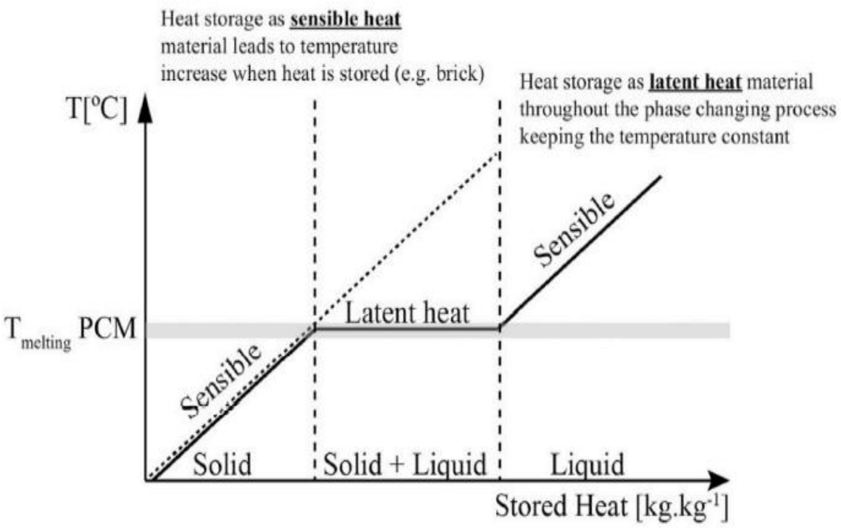

Fig. 1. Heat transition regions of PCM [5].

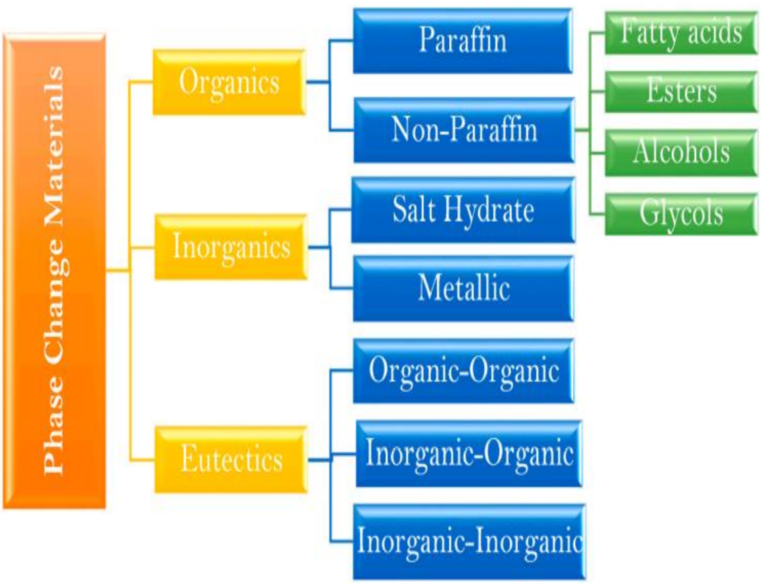

Fig. 2. Classification of PCMs [6].

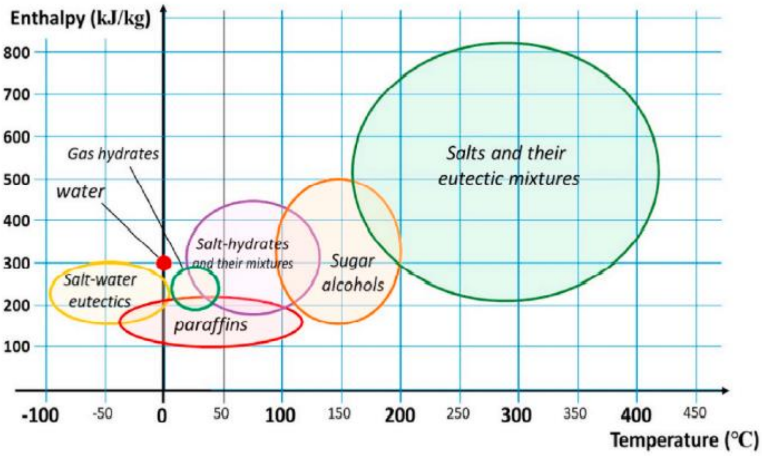

Fig. 3. Working range of enthalpy and temperature of various PCMs [7].

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. 2). Each category has a range of working temperatures (Fig. 3) and thermo-physical properties; thus, they are more suitable for specific application than 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.

Table 1 Characteristics of PCMs [8-9].

PCM Type	Advantages	Disadvantages
Organics (Paraffin wax, fatty acids and vegetable oils)	• Availability in a wide temperature range • High heat of fusion • No sub-cooling • 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 • Non-compatible 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 • Non-flammable	• Show sub-cooling • Considerable change in volume Show phase segregation • Incompatible with metallic containers
Eutectic	• Sharp melting and boiling points	• Costly • Limited data available

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	• Higher volumetric storage density than the organic PCM	for thermo-physical properties

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. Other studies have investigated the potential of PCMs as thermal storage media in refrigeration and air-conditioning systems, heat storage tanks, solar distillers and solar cookers. They are often used as heat sink media in electronic devices and photovoltaic modules. Furthermore, PCMs are utilised as insulation materials in shipping containers, for heat dissipation in electrical distribution transformers and efficiently incorporated with building envelope as heat barriers or suppliers. Other applications are illustrated in Fig. 4.

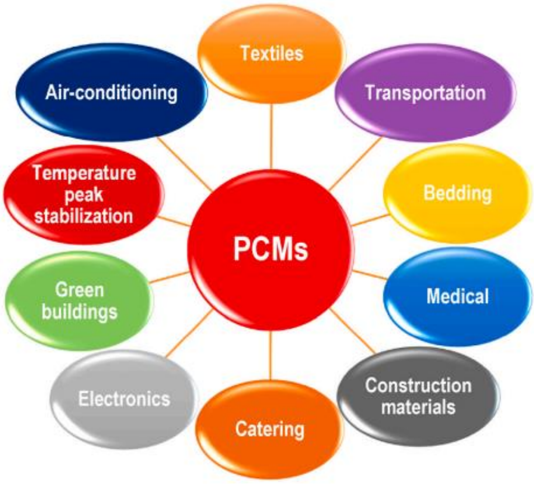

Fig. 4. Applications of PCM [10].

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 sub-cooling, 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, non-flammable, non-corrosive, non-explosive, 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 [11]. 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 sub-cooling, representing significant issues restricting the applicability of PCM technology. 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 [12].

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/m3] (Liquid/ Solid)	Specific heat [kJ/(kg.K)] (Liquid/Solid)	Ref.
Paraffin	27–29	245	0.2 (Liquid)	770/880	2 (Liquid)	[13]
Bio PCM	28.85	219	0.2/0.2	860/860	1.97/1.97	[14]
OM32	31.85	200	0.145/0.219	870/928	2.3/1.95	
Pure Temp 23	22.23–24.17	170.71	0.15/0.25	830/910	2.06/1.56	[15,16]
OM35	35	160	0.16/0.2	870/900	2.71/2.31	[17]
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	[18]
Paraffin RT27	28	147	0.2 (Liquid)	750/870	-	[19]
OM37	35–40	218	0.13 (Liquid)	860	-	[20]
HS29	26–29	190	0.55/1.05	1530/1681	2.62 (Liquid)	[21]

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 to incorporate. 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 [22].

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 [23].

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. The PCM can be macro encapsulated using shells, tubes, channels and thin plates or microencapsulated when the micro sized PCM is covered by unique polymeric material (Fig. 5) [24].

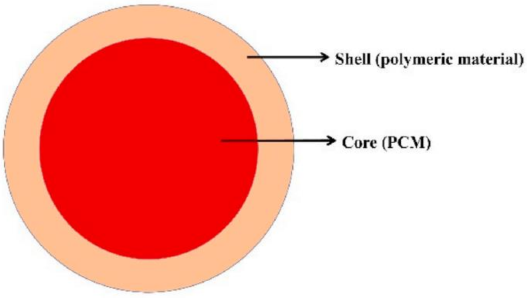

Fig. 5. Microencapsulation concept.

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. 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. Pipes, panels and foils made from aluminium, copper and stainless steel are commonly used for macro encapsulation because they offer excellent thermal conductivity, compatibility and support to the mechanical strength of building materials [25]. More macro encapsulation forms are shown in Fig. 6.

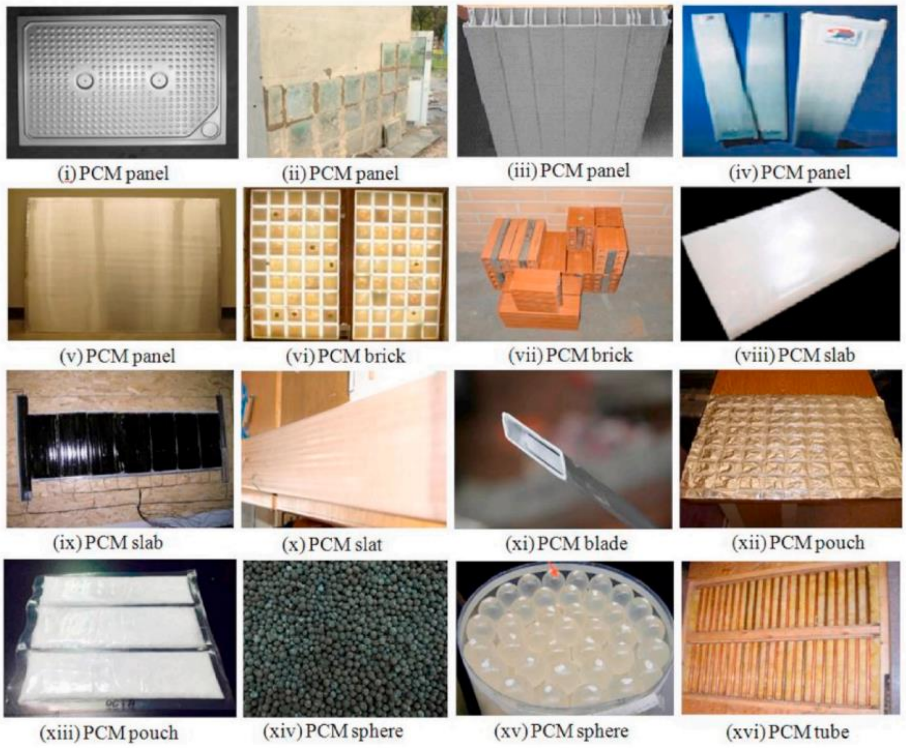

Fig. 6. Different macroencapsulation forms used with building structure [12].

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 maintains the shape over many cycles of phase transition. More information regarding its configurations and preparation techniques has been described by Refs. 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.

4.3. 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. 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. 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 [26].

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

In this category, the sheets, boards or layers of microencapsulated 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 [27] simulated the performance of a wall-embedded PCM board in five different climate conditions in China using Energy Plus tool. The study investigated the total energy saving and CO2 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 CO2 emissions by 1% in the warm climate buildings.

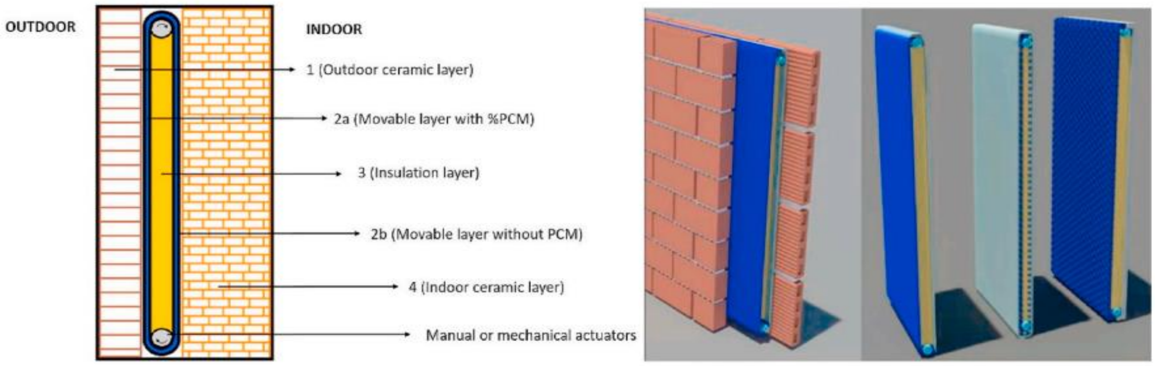

Fig. 7. PCM-sheet/board/layer inserted into building element [28].

4.3.2. 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 [29]. 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. 8.

The researchers have numerically and experimentally observed the potential of different PCM types containing conventional bricks of different types and configurations. Elnajjar [30] 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.

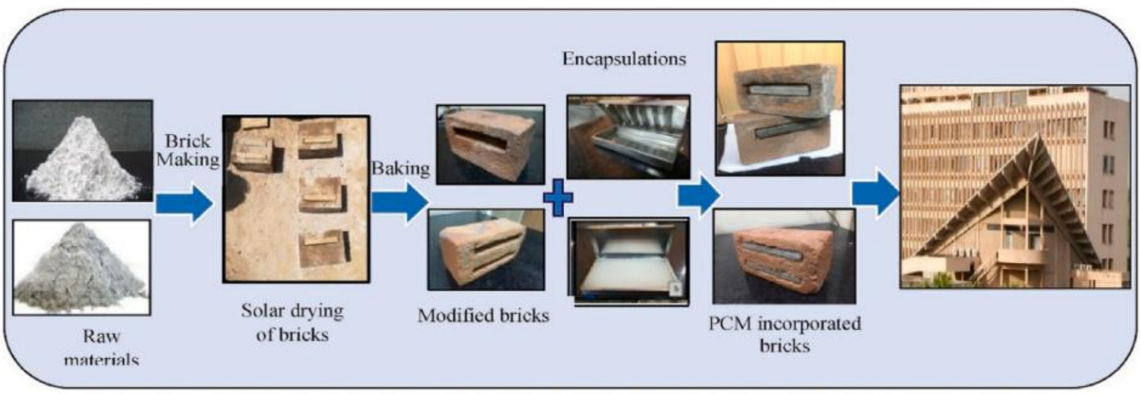

Fig. 8. PCM-incorporated bricks [17].

4.3.3. PCM macroencapsulated pipes

Generally, PCMs have poor thermal conductivity [31]. 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. The PCM macroencapsulation pipes have better potential than microencapsulation because they can be produced easily with low cost, they have larger space that allows more PCM quantity to be involved and preserve volumetric change during cycles [32]. 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 installations [33]. 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 [20] experimentally investigated the thermal response of pipe macroencapsulated 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. 9.

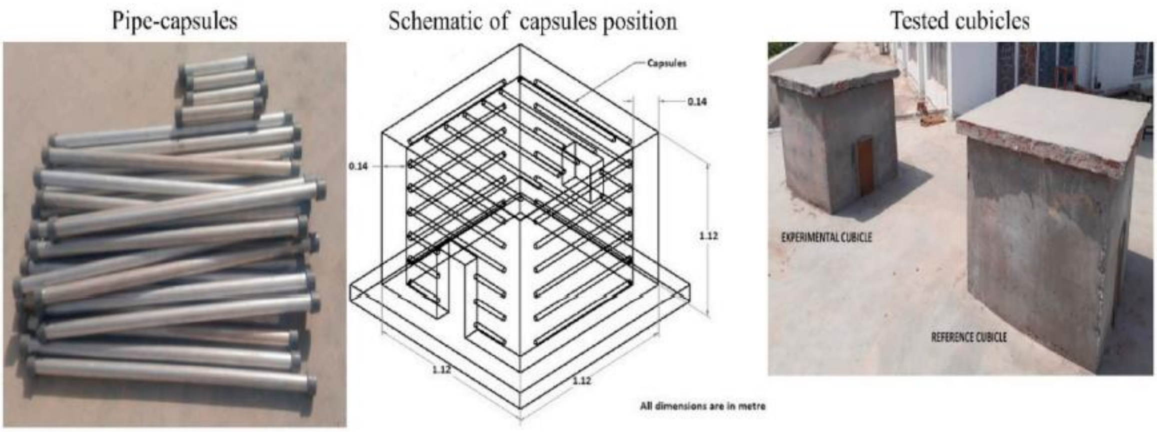

Fig. 9. PCM microencapsulated pipes [20].

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.

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