PCMs in building envelope: characteristics, applications, key parameters and energy contribution

Qudama AL-YASIRI, Márta SZABÓ
Department of Building Services and Environmental Engineering, Institute for Process Engineering, Faculty of Mechanical Engineering, Szent István University, Gödöllő, Hungary.

Abstract

The present paper discusses the main aspects of incorporation phase change materials (PCMs) for building envelope applications. A brief overview of PCM types, properties and desired characteristics for building applications are presented. Besides, the possible incorporation applications in practice are discussed for several building envelope elements and construction materials. The key parameters that affect the thermal performance of PCMs in building applications are presented and discussed. Finally, some state-of-the-art studies reported in the literature are investigated and analysed to highlight the contribution to building efficiency gained by PCMs. It has been shown that PCMs plays an essential role in building envelope and can improve its thermal efficiency significantly. However, more investigations regarding this technology still need to be maintained as presented in the conclusions.

Keywords

PCMs, Building envelope, Energy saving, PCM applications

1. Introduction

Building envelope is a crucial component on building energy efficiency as it adjusts the thermal load and responsible for approximately 50% of heating and cooling loads. In this regard, the International Energy Agency (IEA) reported that in 2018, the building envelope construction activities are responsible for 36% of final global energy used and 39% of CO_2 emissions generated.

Numerous solutions and strategies have been applied to minimise these ratios towards and efficient buildings. Among new technologies, incorporation of phase change materials (PCM) into building elements and components is a viable option for this purpose. PCMs are materials that can store and release the thermal energy through latent heat at an almost constant temperature. Moreover, a considerable amount of heat energy can be maintained by a limited PCM volume, making it in need for today's fast-growing building developments.

PCMs applied to improve building efficiency through different contributions. PCM can shave the temperature entering through the building envelope, which decrease the cooling loads. Besides, incorporation of PCMs in hot locations can shift the peak load to off-load hours, minimising the reliance on air-conditioning devices. Under cold locations, PCM can work as a heat supplier through storing heat during day hours to utilise it during night hours, or by restricting the escaping heat from indoor towards outdoor.

This paper briefly presents the main aspects of PCM technology in building envelope applications through several sections. Section 1 gives a short overview of PCMs, and their role in the building is given. Section 2 presents the main properties and desired characteristics of PCMs. Section 3 details the possible practical incorporation methods of PCM with building elements and construction materials. Section 4 describes the key parameters that influence PCM's thermal performance. Section 5 investigates some reported PCM contributions to buildings' energy. This paper gives a valuable description of this technology for the researchers and newcomers in this area.

2. Properties of PCMs

PCMs are mainly classified as organic, inorganic and eutectic materials. Organic PCMs are widely used in building applications and further classified as paraffins, fatty acids, alcohols, esters and glycols [Faraj et al., 2020]. Each group has specific thermal and physical properties making it appropriate for a specific building application location. In general, the main properties of each PCM group are tabulated in table1.

Table 1. Advantages and disadvantages of organic, inorganic and eutectic PCMs [Al-Yasiri & Szabó, 2021]

PCM category	Advantages	Disadvantages
Organics	- Available with a wide temperature range - High heat of fusion - Low subcooling - Physically and chemically stable - Compatible with many containers and building materials - Environmentally safe and non-radiative. - stabile after many cycles - Recyclable	- Low thermal conductivity and enthalpy - No sharp melting point - High volumetric change during phase transition - Unstable under high temperatures - Costly for pure materials - Toxic (some types)
Inorganics	- High thermal storage and good thermal conductivity - Available with low cost - Sharp melting temperature - Low vapour pressure	- Considerable volumetric change during phase transition - Show phase segregation and subcooling - Incompatible with metals
Eutectics	- Sharp melting temperatures - High storage capacity	- Costly - Limited in building applications

In building applications, the appropriate PCM candidate must be characterised by several desired characteristics to work effectively. These characteristics are mainly thermophysical, chemical, kinetic, economic and environmental properties, as shown in figure 1.

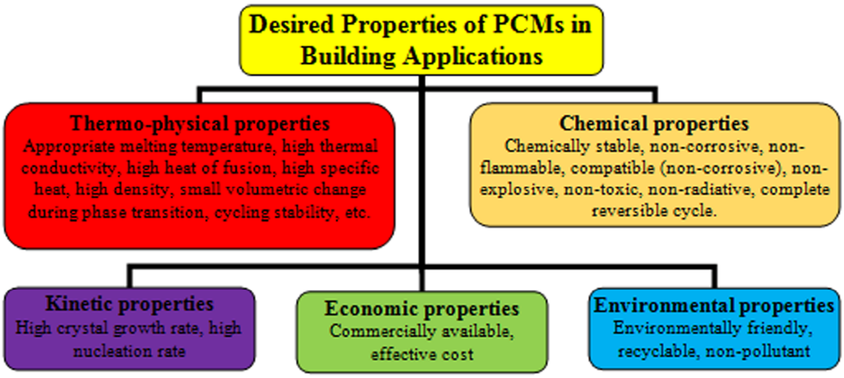

Figure 1. Desired properties of PCMs for building applications.

3. Building envelope applications

PCMs can incorporate with building envelope elements by different methods such as direct mixing, immersing, encapsulation (micro or macro-encapsulation), shape-stabilised and form-stabilised. Accordingly, the PCM can be added directly to the construction materials or inserted independently as a separate component/layer.

Generally, PCM can be integrated with building envelope elements in passive or active strategies. In *passive* strategy, the charging and discharging of heat through the PCM is taken place without any active means. Therefore, the heat would be moved to and from the PCM due to conduction and natural convection. This strategy needs careful selection of PCM type considering the temperature variation throughout the day to satisfy the melting and solidification phases. An external means in an *active* strategy are required to charge or remove the heat from the PCM, such as fans, pumps, thermal collectors, etc. This strategy is more complicated and costly than the passive strategy but utilises the PCM storage capacity efficiently.

Practically, the incorporation of PCM with building elements can be performed in one of the following applications:

Concretes and mortars: The PCM can be combined with the concrete and mortars as a micro-encapsulated form mixed with the raw materials during installation. In such a case, the thermal properties of the mixture would be changed. Therefore, the quantity of PCM microcapsules should be specified to preserve the strengthening of the mixture.

Bricks: PCM either poured inside bricks directly or involved after suitable encapsulation. In the first incorporation form, the brick must be prepared carefully to avoid any possible leakage during the melting phase. Besides, a proper encapsulation container should be used when considering the latter form.

Walls, roofs and floors: PCMs can be a separated layer using panels, sheets or pipes. The effect of element thermal resistance influences the PCM in this application. Therefore, the position of the PCM layer should be adequately studied.

Others: The PCM can be involved in other elements such as slabs and suspended ceilings in the form of sluts, pushes, shelters and packages. In these applications, the PCM is installed as a separate layer utilised actively by blowing a stream of air through the fan. In this case, the PCM is employed as a heat recovery system or a storage medium for heating applications. Some practical applications of PCM are presented in figure 2.

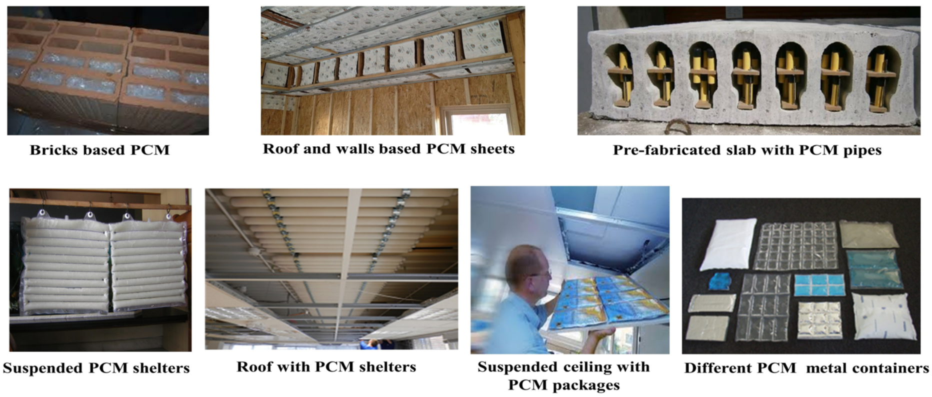

Figure 2. Practical PCM incorporation applications

4. Key parameters of PCM performance in building applications

Several parameters have to be studied when selecting the PCM candidate for a particular building application. These parameters are either related to the PCM itself or the incorporation method used. Generally, these parameters are as follows:

Melting temperature

Melting temperature is the leading thermal property of PCM that should be specified adequately for building applications. PCM melting temperature depends highly on incorporation (heating/cooling) and temperature variation in the studied location. In general, PCMs of melting temperature in the range (~20-30 °C) are suitable for cold locations, whereas higher melting temperature PCMs (~30-50 °C) are effective in hot climates.

Heat storage capacity
This thermo-physical property influences the amount of heat charged into PCM. Therefore, high storage capacity allows more heat to be stored inside the PCM and work efficiently. As mentioned in section 2, the heat storage capacity is varied among PCMs depends on their categories. The total energy storage capacity can be estimated by considering the mass of PCM, PCM enthalpy content, and the number of cycles (daily, each day represent one cycle for melting and solidification).

Effective position
The position of PCM within a building envelope influences the thermal performance of PCM. This parameter has to be studied carefully considering the influence of weather conditions, the thermal resistance of construction materials, incorporation method and mechanical concerns of the building element. It has been reported that the best position of PCM is near the heat source [Al-Absi et al., 2020]. PCM applied in hot locations should be close to the outdoor to restrict the heat from outside and work as insulation. Likewise, PCM should be positioned close to the indoor to trap the heat from inside toward the outside in cold locations. However, PCM optimal position still opens for discussion and should be studied on an annual basis considering weather conditions throughout the year.

Effective quantity (thickness)
This parameter is essential as it links PCM's performance and its effect on envelopes' mechanical properties with economic concerns. Higher quantity should increase the effectiveness of PCM as a result of increased energy storage capacity. However, the extra quantity may not be utilised due to the lack of heat charging/discharging medium. Therefore, building element mechanical strength and incorporation feasibility will be affected.

5. PCM contribution to the building energy

PCMs showed remarkable advancements to the building efficiency in terms of energy-saving, thermal comfort, heating and cooling load reduction, saving of CO_2 emissions, envelope thermal management and peak load delay.

Most of the literature studies were incorporated PCM with building envelope passively. For instance, Hu and Yu [2019] has numerically investigated the performance of PCM board embedded inside wall under five different climate conditions in China. They presented the total energy saving and CO_2 emission reduction, taking into account the PCM type and its position and thickness. The results revealed that incorporating PCM could save energy consumption through building walls by 6% and reduce CO_2 emissions by 1% in the warm locations. They also reported that the PCM position within the building wall is sensitive; thus, placing the PCM layer inside the wall insulation can save 1%–7% more energy than the PCM layer outside the insulation. Moreover, the increase in PCM thickness can save 2%–6% more energy in severe and hot climate zones. Mohseni and Tang [2021] numerically studied a range of melting temperatures (19 °C -29 °C) with 5 mm and 10 mm thicknesses to specify the optimal case for under Australian climate conditions. Results showed that the best melting temperature depends on the season in which the best melting temperature in summer was 25 °C, whereas the best one in winter is 21 °C. The cooling and heating energy consumption was reduced by 23% and 12%, respectively when the PCM thickness increased from 5 mm to 10 mm. The study concluded that a maximum of 6146 kg/year of CO_2 was saved. Younsi and Naji [2020] investigated the thermal performance of microencapsulated PCM-mortar layer incorporated into the wall. The aim of this study was to improve thermal comfort, downsize heating/cooling systems and shift the peak load. The study considered the mass fraction of PCM within the mortar, the melting temperature, and the wallboard's thickness as effective parameters. Findings showed that the best melting temperature was varied between 24 °C and 28 °C. Moreover, the PCM–mortar layer reduced the interior temperature by 3 °C, and the thermal comfort was improved at PCM mass fraction of 20%–30%. Tunçbilek et al. [2020] numerically studied PCM's thermal performance in conventional bricks on a seasonal and annual basis under the Marmara conditions, Turkey. They studied different PCM melting temperatures range from (18 °C – 26 °C) with different quantities and positions concerning the interior and exterior environment. The results showed that filling brick gaps near the interior environment resulted in better energy conservation and the optimal PCM performance depends highly on the season. However, the best thermal performance was reported for PCM of 18 °C melting temperature. Furthermore, the heating and cooling loads were reduced by 17.6% and 13.2%, respectively, which provided adequate thermal comfort.

For active systems, PCMs were incorporated with solar thermal systems to improve the performance of both technologies. Navarro et al. [2016] experimentally studied the thermal performance of PCMs encapsulated using pipes and inserted inside a prefabricated concrete slab. Two cubicles with active slab (contains PCM) and conventional slab (without PCM) were fabricated to compare the energy saving obtained from the utilisation of PCM under severe and mild winter conditions of Spain. The active slab incorporated with 52 kg of paraffin (RT-21) of 21 °C-22 °C melting temperature and exposure to a hot air stream provided by solar air collector. Findings indicated that the active slab was saved energy by up to 20% during partial melting of the PCM, and 55% at complete melting and solidification cycles compared with the conventional slab. The study further revealed that an energy-saving of 25% and 40% was achieved during the severe and mild winter conditions. Kong et al. [2020] fabricated a hybrid PCM-solar system composed of perlite-based composite PCM wallboard coupled with a solar heating system by capillary pipes. The system was incorporated inside the tested room's wall and compared with other conventional room under winter conditions of Tianjin, China. The results showed that the daily heating energy consumption was reduced by 44.16% for the room provided with the hybrid system compared with the conventional one.

Conclusion

The utilisation of PCMs into building applications is one of the fast-growing technologies adopted in the building industry to improve building efficiency. This paper presented and discussed several aspects of this technology, highlighting the primary key research for future studies. For that, several conclusions and remarks raised from this work are listed, as follows:

- PCMs, despite their types and properties, can efficiently increase the building efficiency. However, the majority of investigated PCMs in the literature are organics and inorganics versus very limited eutectics. The main reason for that is that eutectics have a high range of working temperatures for building applications. New mixtures involving organic and eutectic materials are out of scope.
- Majority of literature studies were investigated the PCM in passive strategies more than active strategies. Although the passive strategy was effective in several locations, many issues such as uncontrolled heat transfer, lack of full PCM utilisation, and lack of heat charging/discharging at specific times. Therefore, adopting new active strategies with minimal operational costs are required.
- Key parameters are essential for the efficient use of PCM in building applications for both the performance and feasibility point of view.
- Most of the published studies were numerical compared with the experimental ones. It is commonly known that numerical studies depend on approximations and forecasting, which make them inaccurate. Therefore, experiments are important to prove the numerical outcomes rely on actual weather conditions and climate effects.

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