Application of Phase Change Materials (PCMs) in Building Walls: A Review

Zeyad Amin Abdo Saeed Al-Absi(✉), Mohd Hafizal Mohd Isa, and Mazran Ismail

Architecture Department, School of Housing, Building and Planning, Universiti Sains Malaysia 11800, Penang, Malaysia
zeyadaminalabsi@yahoo.com, {hafizal,mazran}@usm.my

Abstract. The rapid growth of the population and overcrowded of urban areas forced building construction sector to focus more on economic consideration rather than climatic requirements. As a result, achieving comfortable living spaces was fully dependent on mechanical systems, which caused more energy consumption and greenhouse gas emissions. Passive design strategies become an attractive alternative to tackle this problem and to reduce the negative impacts on our planet. Phase Change Materials (PCMs) store superior amount of latent heat when changing their phase compared to sensible heat. PCMs application in buildings helps to lower indoor temperature and reduce temperature fluctuation and total hours of overheating. Additionally, PCMs can also absorb the internal heat dissipated by household equipment, lightings and occupants' activities. All this help to improve building indoor environment. This paper aims to review PCM applications for building walls. It was found that PCMs might be incorporated to building walls as pre-fabricated PCM-enhanced elements such as PCM-enhanced wallboards, panels, bricks and blocks. In addition, it might be incorporated on the site to fresh mixtures such as concrete, plaster and mortar and applied to buildings. The thermal performance of building walls was improved in all cases resulting in heating and cooling load reductions. Moreover, many researchers found that applying night ventilation further improves the thermal performance of PCMs in building walls.

Keywords: Phase change materials (PCM) · Building walls · Thermal energy storage (TES) · Passive building materials

1 Introduction

Buildings accounted for 40% of global energy consumption and the largest use of energy in buildings (i.e. 60%) is for heating and cooling. Hence, they offer a good opportunity to reduce energy consumption through the utilizing of other alternatives such as passive design strategies [1]. Thermal energy storage (TES) acts as a heat sink by storing energy for later use. This technology helps to increase the effective use of thermal energy equipment and systems and to improve heat exchange for energy efficiency in buildings, hence reduce the energy consumption. In addition, it helps to tackle the mismatch between the energy's supply and demand [2]. Type of TES is known as Phase Change Materials (PCMs) that is capable to utilize the latent heat

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absorbed or released during the phase change of the materials. PCMs can control the ambient temperature within a specific range corresponds to the PCMs' phase transition temperature. If the phase transition temperature of the material matches the required comfort temperature, it can help to absorb the extra heat leading to more stable and comfortable indoor environment, hence reduce the required heating and cooling loads. PCMs are attractive for many researchers and have been successfully implemented in buildings for thermal management due to their wide range of categories, several melting/frizzing temperature, relative steady melting/frizzing temperature, and high thermal density with small temperature intervals and negligible volume change [3]. PCMs can be classified to organic PCMs, inorganic PCMs, and eutectic PCMs, which further divided based on the several components of the PCMs (Fig. 1).

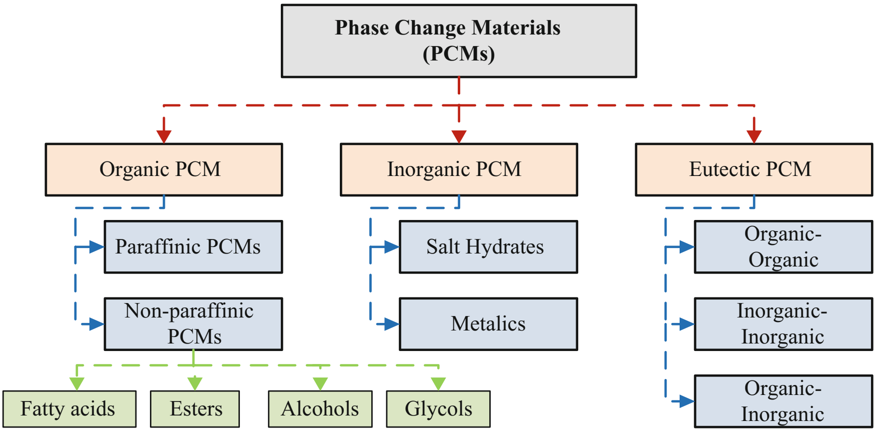

Fig. 1. PCMs classification

In addition, PCMs can be integrated into building materials by different strategies such as; direct incorporation, immersion, encapsulation and stabilization. [1, 4]. In buildings, walls and ceilings offer large areas in each zone for passive heat transfer [5] in which PCMs can be incorporated. Therefore, the objective of this paper is to review PCMs applications for building walls and the methods used for the incorporation of PCMs into buildings.

2 PCM Application in Buildings Walls

Based on the literature, PCMs might be applied to building walls using different methods including prefabricated elements or mixing on the site. These methods are discussed below.

2.1 PCM-Enhanced Wallboard and Panels

PCM wallboards and panels are of the most common ways used to integrate PCM into buildings due to their ease of installation. For example, liquid PCM was absorbed into gypsum board by soaking [6], microencapsulated PCMs were incorporated into wood-plastic composites to improve its thermal properties [7], two types of PCMs with different melting temperatures were macro-encapsulated by aluminum panels and tested for the summer and winter [8], PCM composite wall made by incorporation of shape-stabilized PCM particles in a polymer matrix [9] and Shape-stabilized PCM wallboard made of paraffin wax PCM and high-density polyethylene [10]. In all cases, the addition of PCM have shown improvement in thermal behaviour of building materials as well as the indoor thermal environment of buildings.

Zhu et al. [11] performed simulations to investigate the use of two different double-layer shape-stabilized phase change materials (SSPCMs) wallboard to save energy in five typical climate regions in China. The SSPCMs wallboards with the thickness of 30, 40 and 50 mm, were attached on the inner and outer surfaces of a common concrete wall in the south of the simulated room, while the other three walls, floor and ceiling were thermally isolated using insulation materials. The air-conditioner operated from 7:00 to 18:00 (i.e. office building) with set-point temperature of 26 °C for summer and 18 °C for winter in the regions that required heating or cooling. In this work, the external PCM layer was used to reduce the cooling load in summer or to reduce heat gain if there is no need for cooling. In contrast, the internal PCM layer was used to reduce heating load in winter or to reduce heat loss if there is no need for heating. In most cases, the maximum reduction is achieved with the highest thickness of SSPCM wallboards. This might suggest the largest PCM content in the PCM-wallboard panel. In addition, the optimal melting temperature of the external layer was mainly influenced by the outdoor air temperature while the internal layer was mainly influenced by the indoor air temperature. Furthermore, they stated that smaller average outdoor temperature had better effects on energy savings in summer, while bigger average outdoor temperature had better effects in winter.

Evola et al. [12] simulated a typical office building containing PCM wallboard in the partition walls. The PCM wallboard, with the thickness of 20 mm, is made of aluminium honeycomb matrix, which contains 60% of approximate 5 µm diameter microencapsulated paraffin, and covered with two aluminium sheaths. The partition walls are composed of 70 mm thick gypsum board to which the PCM wallboards are fixed. The results show that PCM wallboard reduced the peak operative temperature by about 1 °C. In addition, the surface temperature and the daily temperature swing for the east wall were reduced by 1.7 – 2.8 °C respectively and the time for peak surface temperature was shifted by 1.5 to 2 h.

Kong et al. [13] investigated the cold storage performance of PCMs in the summer for the middle latitude region of China. Aluminium sheets, Fig. 2 were used to produce macro-encapsulated PCM panels containing two types of PCM (i.e. capric acid used for the external wall surface and a mixture of capric acid and 1-dodecanol used for the internal wall surface to reduce the super-cooling effect of the capric acid and allow for frizzing within small range in the internal environment). Internal fins were used in the aluminium panels to increase the heat transfer into the PCM and to support the panels' structure. Three rooms (2000 × 2000 × 2400 mm) were constructed from perforated bricks for the walls and insulation sandwich board for the roofs. PCM panels were installed in the outer surfaces of one room (PCMOW) and the inner surfaces of the second room (PCMIW), while the third room was the base case. A door and a window were built in each room to allow night ventilation. They concluded that PCM panels helped to reduce the temperature by more than 1 and 2 °C for PCMOW and PCMIW respectively and to delay the time for peak temperature by 2–3 h. In addition, they stated that the use of PCM in the outside surface has more effect of thermal insulation than temperature regulator.

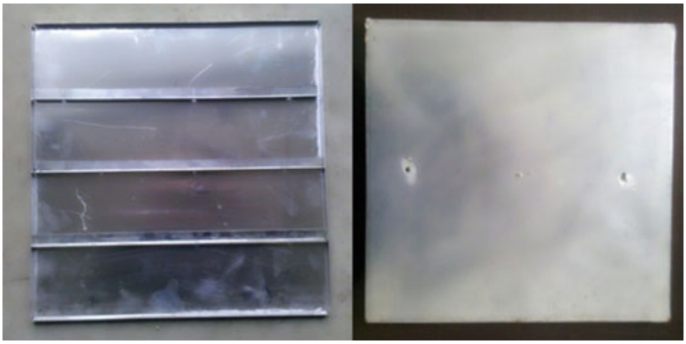

Fig. 2. PCM aluminum panels [13]

2.2 PCM-Enhanced Bricks and Blocks

PCM-enhanced bricks and blocks are subjected to investigate by many researchers. They offer large volume to incorporate PCMs. Incorporation of PCMs might be done by immersion, macro encapsulation or shape-stabilization. For example, macro-encapsulated PCMs-bricks were produced by filling the PCM into the cavity of the bricks [14–17], PCM macro-capsules made of steel were incorporated into brick masonry wall [18] and shape-stabilized PCMs were incorporated into cement mortar to produce PCMs-bricks [19–21].

In an experiment, Vicente and Silva [22] investigated the effect of PCM macro-capsules incorporated into brick masonry wall and the addition of Extruded polystyrene (XPS) insulation to the PCM-brick masonry wall. A metal steel macro-capsule (i.e. 300 × 170 × 28 mm with 0.75 mm thickness) were filled with paraffin and inserted in fired clay bricks with horizontal hollow (Fig. 3). Two brick masonry walls were constructed with PCM macro-capsules and one with normal brick as a base case. An insulation layer, XPS 10 mm thick, was installed on the outer surface of one PCM-brick masonry wall. The three walls were tested between two climatic chambers, for imposed conditions and free float mode.

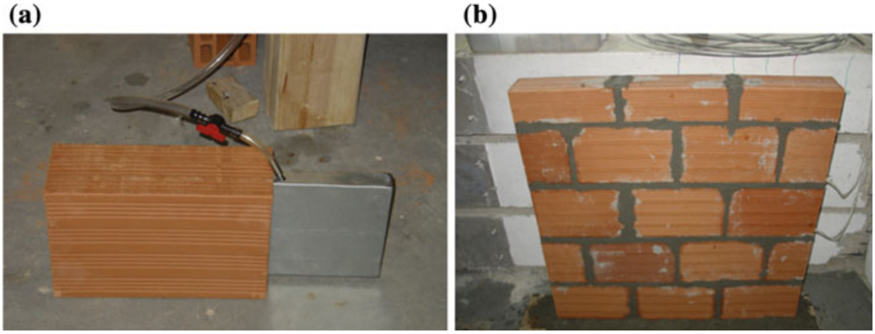

Fig. 3. **a** PCM macro-capsules; **b** wall specimen [22]

The results showed a delay of 3 h for the maximum peak temperature achieved by both PCM wall and insulated PCM wall compared to 1 h for the base case, which indicates how PCM can improve the thermal inertia of the wall. In addition, the PCM wall and insulated PCM wall reduced the temperature fluctuation by 5 and 8 °C (i.e. 50 and 80%) respectively. The insulated PCM-wall achieved the lowest maximum temperature and the highest minimum temperature; even though, the PCM wall resulted with superior improvements compared to the conventional wall. However, a comparison with insulated base case wall should be done to find out the role of the PCM with the insulation materials.

Wang et al. [23] investigated PCM bricks produced by incorporating shape-stabilized PCM into cement mortar (i.e. mass ratio was 37.5, 22.5 and 40% for portland cement, sand and shape-stabilized PCM respectively), which poured into 240 × 120 × 90 mm homemade wooden molds (Fig. 4). The PCM-bricks were used in one side of a ful-scale room of 3250 × 3860 × 2910 mm and compared to wall built with perforated vitrified bricks. The test were performed for the year-round. The results showed a reduction of 24.32% of the cooling load during summer and 10–30% of heating load during winter. In addition, when the air-conditioner was off, the heat lost from the interior wall surface can be reduced by 9–72%. They summarized that PCM-wall achieved better thermal behavior all the year round.

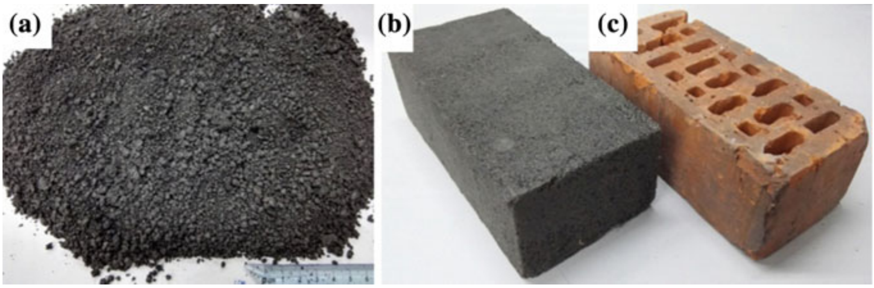

Fig. 4. **a** SSPCM; **b** SSPCM-bricks; **c** perforated vitrified bricks [23]

2.3 PCM-Enhanced Plaster

PCMs can be incorporated into mortars and applied to buildings walls as a PCM-plaster coating or casted to PCM-plaster wallboards. For example, PCM was incorporated into aerial lime and gypsum based mortars and tested as a coating in laboratory-scale prototypes [24], a novel PCM composite was integrated into ordinary cement mortar as partial replacement for fine aggregate and evaluated the thermal behaviour as a plaster in self-designed box [25], PCM-enhanced lime plasters were produced and evaluated to be compatible for renovation and retrofitting of existing traditional buildings in southern European climatic conditions [26] and a hybrid-PCM-plaster was developed by incorporating three types of PCM into cement mortar and tested as a coating in prototypes placed in a controlled climatic chamber [27]. This method makes it easy to integrate PCM into new buildings as well as to renovate existing buildings.

Lachheb et al. [28] investigated the thermal behaviour of new PCM-plaster composite as a component of passive solar walls. A sample with 10% microencapsulated paraffin was prepared and experimentally tested using guarded hot plates method for its thermo-physical properties. The results then used to validate the numerical investigation based on the enthalpy method using finite volume method. Both experimental and numerical results exhibit a similar behaviour, which indicated a good agreement. Then the numerical model was further used to investigate the effect of incorporation of PCM-plaster wallboard in building walls. The use of 10% PCM fraction within the plaster wallboard resulted in reduction of 2.7 °C and 11 Wm^{-2} in the wall inner surface temperature and heat flux respectively. Furthermore, by increasing the fraction of PCM to 15, 20 and 30%, they found that 20% of PCM greatly decreased the wall inner surface temperature to 25.8 °C and the heat flux to 16 Wm^{-2} compared to 28 °C and 35 Wm^{-2} respectively for normal plaster, while the 30% PCM achieved just a small reduction further to the 20% PCM. In addition, increasing the PCM-plaster wallboard thickness from 10 to 30 mm resulted in further reduction of 1.2 °C.

Sarı et al. [29] developed a novel cement based-composite phase change material (CB-CPCM) and tested its thermal performance as a plaster. The PCM was absorbed by cement using vacuum embedding method to prepare a form-stable CB-CPCM with maximum mass fraction of 28% without leakage. Thermal performance of the CB-CPCM plaster was studied using two polystyrene cubes (250 × 200 × 140 mm) coated internally with 5 mm-thickness of CB-CPCM plaster in one cube and ordinary cement in the other as a control cube (Fig. 5). The cubes were subjected to heat source until the indoor temperature raised 5 °C above the melting temperature then cooled until it was decreased bellow the frizzing temperature. Results showed the inner surface temperature of the cube with PCM plaster was lower and increased from 14.8 to 24 °C within 160 min compared to 125 min for the control cube. In addition, the time with comfortable temperature range (19–24 °C) was 100 min with PCM compared to 80 min without PCM. On the other hand, during the cooling process, the time required for the inner surface temperature to decrease from 24 to 19 °C was 90 and 65 min for the PCM cube and control cube respectively, which linked to the latent heat discharge. Similarly, the indoor temperature had a delay of 15 min with the PCM plaster to increase from 15 to 24 °C with an average temperature difference of 0.70 °C and a delay of 10 min to decrease from 24 to 19 °C with average temperature difference of 0.58 °C.

Fig. 5. Polystyrene cubes for thermal performance test [29]

3 PCMs and Ventilation

PCMs' performance and effectiveness are highly dependent on the surrounding environment. In some cases, the temperature at night may stay higher or just below the solidification temperature of the PCM for short period of time. Therefore, the PCM will not be able to fully transform from liquid to solid and release all the stored heat, which reduces its efficiency for the next day. Combining ventilation with PCM help to increase the rate of heat released by the PCM during night time, especially when the ambient temperature is close to the transition temperature of the PCM. Zhang et al. [30] found that ventilation can improve the thermal performance and energy saving efficiency of building utilizing PCM, though it is affected by ventilation periods. Furthermore, night ventilation is more effective in improving indoor thermal environment and reducing energy consumption for cooling. The optimum period for effective ventilation was found to be between 00:00 and 09:00. In addition, the more ventilation quantity used, the better performance of PCM can be achieved. However, the improvement in PCM performance becomes insignificant when more than 2 ACH was used. On the other hand, Ramakrishnan et al. [31] found that applying natural night ventilation with 8 ACH rate further decreased the peak indoor operative temperature, which indicates the role of night natural ventilation in discharging the stored heat in the PCM and preparing it for the next day cycle. The discomfort index (DI) illustrated that the sever discomfort hours (i.e. DI > 28 °C) for the five days were 36 h without the use of PCM and decreased to 28 h with the use of PCM. However, the sever discomfort hours further reduced to 25 h when applying natural night ventilation. The authors concluded that the combination of the PCM (optimum transition temperature and thickness of 29 °C and 30 mm respectively) and natural night ventilation resulted in reduction of 65% in the sever discomfort period during the heat wave. Furthermore, Barzin et al. [2] achieved 73% of weekly energy saving by applying cool night ventilation to charge the PCM rather than using air conditioning.

4 Conclusion

PCMs are suitable to be applied in building walls using different methods, which have shown improvement to thermal performance of building's walls, delay in peak temperatures and reduction in heating and cooling load. These methods are summarized below.

– PCMs wallboards and panels are one of the most common methods of PCM application on building walls due to their ease of installation in ether a new building construction or a retrofitting and renovation of existing buildings. They can be produced in mass quantities in controlled environment at the factories, which reduces the waste materials and provide higher quality control.
– PCMs-plaster also can be applied in new buildings construction and existing buildings retrofitting and renovation. However, this method required additional work at the site to be prepared, which may require some expertise or may not provide the quality of controlled environment production.
– PCMs-bricks and blocks can be produced at a controlled environment and transported to the site ready for construction. They can provide larger volume to incorporate PCMs, which overcome the limited thickness of wallboards, panels and plaster that may affect the amount of incorporated PCMs resulting in less thermal energy storage. However, their use is limited for new buildings construction or a major renovation of building's walls.

Additionally, night ventilation has shown great influence in the efficiency of PCMs products by increasing the rate of heat discharge, especially when ambient temperature is close to PCMs transition temperature. Therefore, effective night ventilation must be considered with any passive application of PCMs. To conclude, PCMs are promising as a passive technology for buildings sector. This study has reviewed methods of PCMs application into building walls. Each method was investigated separately in the literature. However, the effects of using multiple methods to introduce PCMs into building walls still unknown. The most common wall system is consists of a core (e.g. masonry and concrete walls) and two layers in both sides (e.g. wallboards and plaster). Incorporating PCMs to the whole wall system may perform better performance. The more PCMs amount is added, the more heat storage we can get. Therefore, further research in this point is required.

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