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A review of microencapsulated and composite phase change materials: Alteration of strength and thermal properties of cement-based materials

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ABSTRACT

Due to the population growth and the increased reliance on cooling and heating systems, buildings have become the largest energy consumer worldwide. The use of phase change material (PCM) has shown great potential to reduce the annual cooling and heating load by up to 50%. Nowadays, the direct incorporation of PCM in cement-based materials (CBM) is creating a considerable debate in the research community with regards to the proper selection and the beneficial utilization of PCM (microencapsulated or composite) in CBM. Therefore, this paper reviews the pros and cons of using microencapsulated and composite PCM in CBM by highlighting the mechanisms involved in the mechanical strength loss and thermal properties enhancement. Generally, a high thermal energy storage CBM was obtained. However, PCM exhibited a negative effect on the compressive strength of CBM. In view of the literature review, the compressive strength reduction varies considerably with no clear trend which is understandable in view of the differences in mix designs as well as the variety of materials used in each study. Finally, an up-to-date PCM case studies, gaps and future directions are also presented to provide a reliable basis and helpful reference for the future development of eco-friendly and energy-efficient building materials containing PCM.

1. Introduction

The building sector has a huge impact on the environment. This is mainly due to buildings' life cycle (design, construction, operation, demolition and waste treatment) which contributes to a large share of CO_2 emission [1]. In fact, most of the CO_2 emission is coming mainly from the production of building materials as well as electricity to provide modern comfort for buildings [2]. Luckily, many techniques, such as carbon dioxide capture and storage (CCS), have been proposed to reduce the CO_2 concentration in the atmosphere [3,4]. The development of low cost means to capture CO_2 can promote the use of this technology at an industrial scale. The enrichment of indigenous microorganism present for example in activated sludge seems to be an economical and promising way to capture CO_2 [5,6].

The energy consumption by buildings is projected to increase by about 48% from 2012 to 2040 [7] which is mostly caused from the rapid growth of some of the non-OECD (Organization for Economic Co-operation and Development) countries [8]. According to the international energy outlook 2016 reference case (IEO2016), the residential energy use in China (non-OECD country), is expected to grow by an average of 2.4% from 2012 to 2040 compared to only 0.1% in the USA (OECD country) [9]. This increased demand will result in a shortage of fossil fuels and consequently a sharp increase in the energy cost. Therefore, there has been a growing interest in applying energy storage systems in building to overcome the mentioned problem.

For the past few decades, the feasibility of using PCM as a thermal energy storage system in buildings was extensively investigated [10–12]. PCM can obviously reduce energy consumption due to its phase change process by maintaining a small fluctuation between indoor and outdoor temperatures. This phase change process occurs only

Abbreviations: PCM, Phase change materials; CO_2, Carbon dioxide; CCS, carbon dioxide capture and storage; OECD, Organization for economic co-operation and development; IEO2016, International energy outlook 2016; CBM, Cement-based materials; mPCM, Microencapsulated phase change materials; cPCM, Composite phase change materials; SiO_2, Silica gel; $CaCO_3$, Calcium carbonate; TiO_2, Titanium dioxide; ECA, Expanded clay aggregates; LWA, Lightweight aggregate; LDPE, Low density polyethylene; EVA, Ethylvinylacetate; CA, Capric acid; LA, Lauric acid; MA, Myristic acid; PEG, Polyethylene glycol; DP, Diatomite; EP, Expanded perlite; EG, Expanded graphite; PCMOW, PCM-panel mounted on the outer surface of walls; PCMIW, PCM-panel mounted on the inside surface of walls

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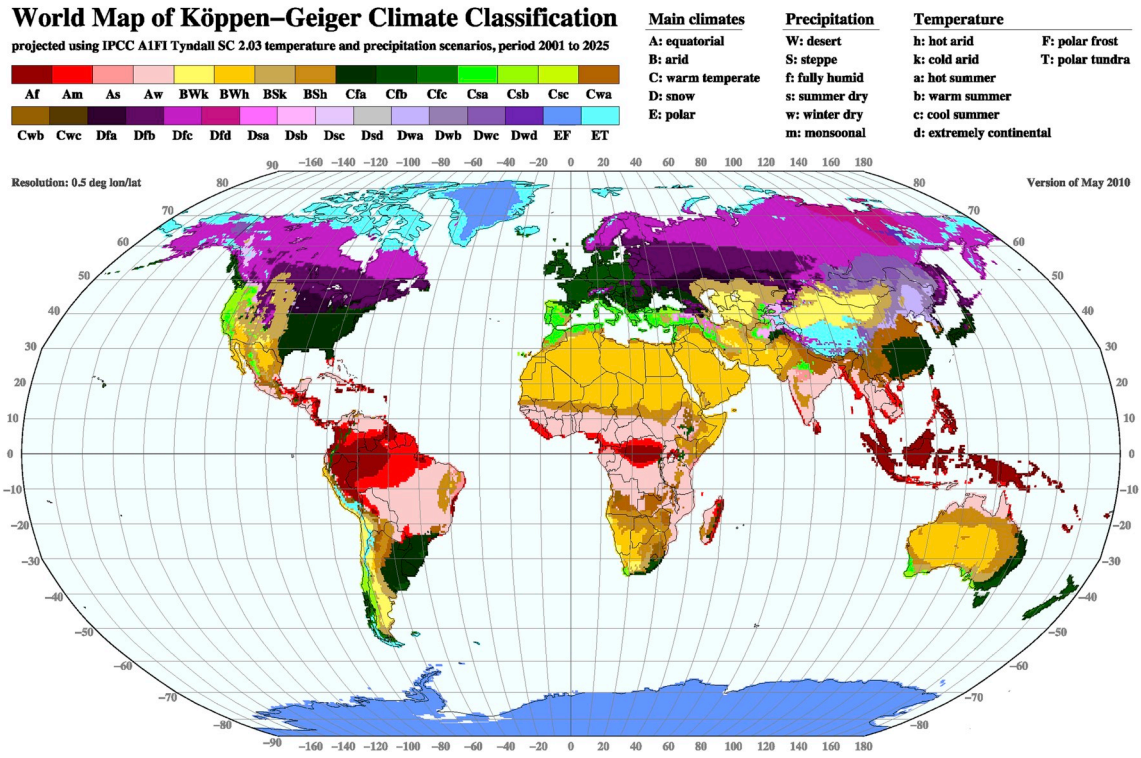


Fig. 1. Observed and projected climate classification (2001–2025) [17]. Copyright (2019), with permission from authors.

due to the outdoor/indoor temperature variation and does not require any electrical energy (electrical power or fuel). Therefore, the careful selection of PCM's phase change temperature specifically according to the outdoor climatic conditions is crucial to achieve better thermal performances [13].

As known, there are mainly five climatic zones (Fig. 1) as defined by Köppen-Geiger climate classification [14]. For a very cold or hot climate, characterized by little temperature variation and fluctuations, PCM showed a very limited impact on the energy consumption of buildings whereas PCM was more efficient when the climate has large temperature swings covering the PCM's phase change temperature. For example, the total energy demand of a typical Mediterranean climate could be reduced by about 23.5% (heating) and 37.4% (cooling) when using PCM [15] while the heating demand can be reduced only by about 15% for cold climate [16].

Moreover, it is well known that each season is distinguished by a special climate condition and weather patterns. Therefore, the effect of PCM on the building will vary also during seasons and based on weather conditions [18]. As can be seen in Fig. 2, the energy saving that could be achieved in the same city during summer differs from that achieved in winter. A more detailed survey on the PCM's applications in different climate zones can be found in Refs. [19,20].

However, the relatively high cost of PCM technologies is limiting their widespread application. Therefore, extensive studies are carried out in both OECD and non-OECD countries, in particular during the last 10 years (Fig. 3 and Fig. 4) to investigate the feasibility of incorporating PCM directly in cement, mortar and concrete (hereafter referred to as cement-based materials or CBM) in order to save the cost associated with installation of PCM in buildings as a separate component [21]. The main efforts devoted in this specific scientific research topic is to explore and provide sustainable technologies to face the growing trend in energy consumption. According to the literature survey, China and the USA are the most active in this particular research topic. Furthermore, the majority of countries conducting research on PCM in buildings are located in the Mediterranean climate zone. It should be noted also that only few published researches are available on evaluating the effect of

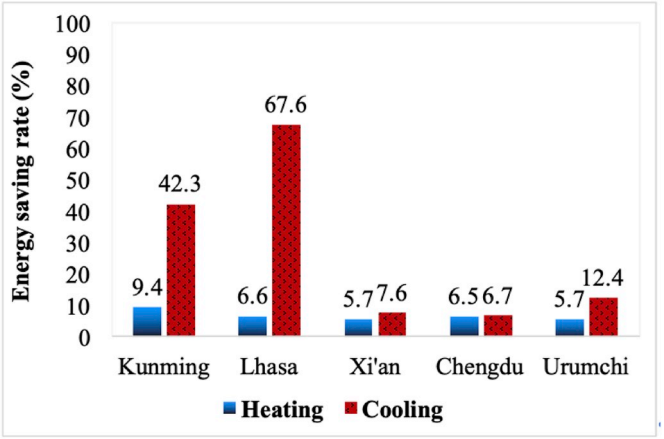


Fig. 2. Heating and cooling energy saving rate in different Chinese cities (modified from Ref. [18]). Copyright (2019), with permission from Elsevier.

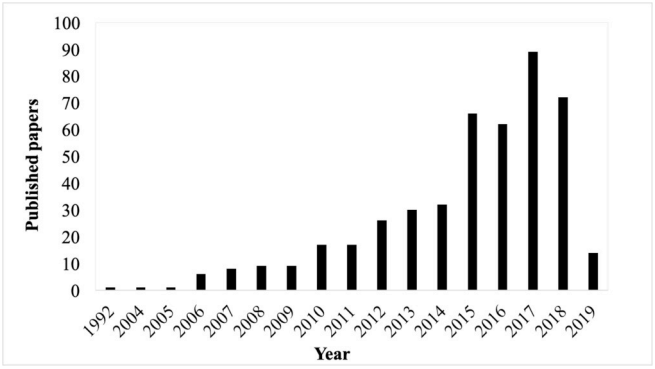


Fig. 3. Number of published research in the area of PCM in construction building technology since 1992 according to the web of science database.

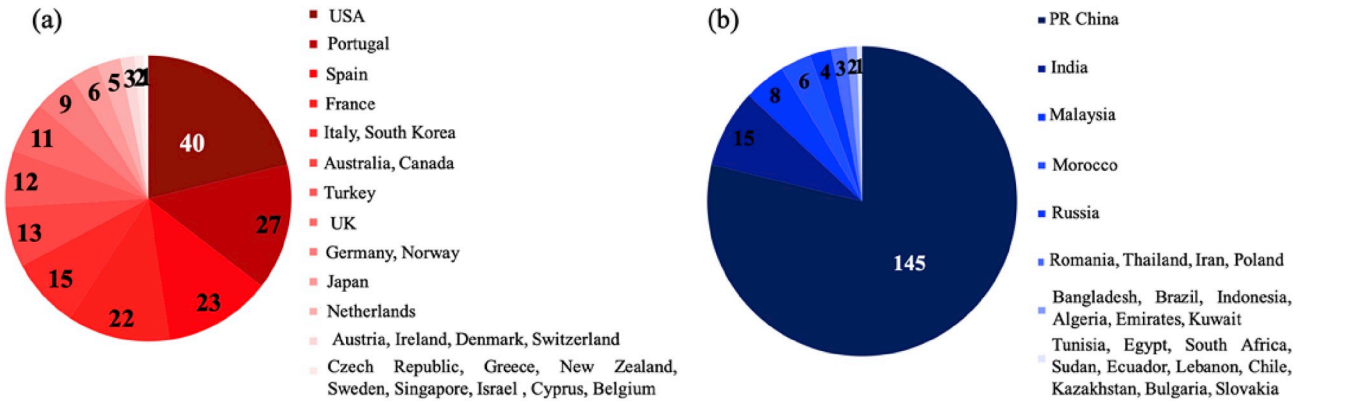


Fig. 4. Distribution of published research worldwide: (a) Developed and, (b) Developing countries (the countries were selected based on the corresponding author address).

PCM in buildings (case studies) under real outdoor conditions and some of them are reviewed in this paper.

Various strategies have been practiced in the literature to efficiently utilize PCM in CBM. One of these methods consisted of incorporating bulk PCM (e.g. paraffin) as a latent heat material in CBM [22]. Despite the economic benefits of this method, the direct contact of paraffin wax with highly alkaline cementitious environment often results in the poor stability of PCM which can affect its thermal properties [23–25]. To overcome this issue, researchers are focusing on developing shape stabilizing PCM by using encapsulation (micro and macro) techniques [26,27]. Besides, PCM suffers also from a very low thermal conductivity which limits its overall performances and results in a low heat transfer [28,29]. For this, recent studies suggested to use both PCM and insulation materials in the building elements (such as walls) [15]. The total energy saving that can be achieved was about 66.2% which is 2.3 times and 1.09 times higher than that achieved by PCM or insulation materials, respectively. This results in a significant reduction of the long payback period. On the other hand, other researchers suggested adding high thermal conductivity nanofillers during the encapsulation process of PCM [30–33].

Obviously, the application of PCM in buildings is not limited only to thermal energy storage systems but also to micro electro mechanical systems, data storage, smart textiles, etc. [34–36]. Most of the previous reviews regarding the potential application of PCM in CBM were focused mainly on the synthesizing process of PCM and the potential benefits of adopting PCM-CBM systems in terms of energy saving and indoor comfort improvement. Cabeza et al. [37], Paloma et al. [38] and Soares et al. [39] presented a detailed summary of the different type of bulk PCM and the main criteria that should be considered when selecting PCM for building applications as well as the different methods to investigate its thermal properties. The encapsulation techniques (micro and macro) were extensively reviewed in Refs. [38,40–46] and compared in Ref. [47]. Furthermore, the different methods employed in the literature to enhance the thermal conductivity of PCM were comprehensively reviewed in Refs. [31,33,48–50]. The effect of PCM in particular microencapsulated PCM (mPCM) on the fresh and hardened properties of CBM was briefly discussed in Ref. [51]. Rao et al. [52] gathered information regarding the effect of PCM on different type of mortars. They highlighted that geopolymer mortar is more suitable to be a medium for PCM than lime and cement based mortar. Several other papers reviewed the numerical simulation methods used to analyse the passive cooling potential of PCM when integrated in buildings [20,39,53,54]. Finally, Gracia et al. [55], Tyagi et al. [45], Zhu et al. [56] and Song et al. [57], provided an insight into the application of PCM in the building envelope (wall, roof, floors) and building systems (heat pump, ventilation systems, etc.).

The previous reviews provide generally repeating information related to PCM itself, the encapsulation techniques and heat transfer, the different methods to evaluate its thermophysical properties, the PCM's thermal conductivity enhancement as well as its application in CBM. However, none of the published reviews highlighted the pros and cons or compared the use of mPCM and cPCM in CBM. Understanding the difference between the effect of mPCM and cPCM on the fresh and hardened properties of CBM is crucial for real concrete building applications. Therefore, this paper summarizes the main studies related to PCM in CBM and highlights the pros and cons of using mPCM and cPCM in CBM. On the other hand, most of the available reviews have neglected the effect of PCM on the compressive strength of CBM. To bridge this gap, this paper will give a clear overview on how mPCM and cPCM affect the strength of CBM by pointing out the underlying mechanisms involved in this strength loss. Finally, the recent case studies across different countries and climate regions, as well as research gaps are also provided to possibly establish future directions in basic research and real application of PCM in CBM.

2. Phase change material for building application

PCM can be incorporated into buildings as a passive (wall, ceiling, façade element) or active (separate heat and cold storage devices) system to increase their thermal energy storage and efficiency [23,58]. It presents a promising solution to increase the thermal mass of buildings by providing inertia against temperature fluctuations. Different organic materials (paraffin, fatty acids), inorganic materials (hydrated salts, metals) and eutectics with various phase change temperatures and thermal energy storage densities have been studied by several researchers for building applications. A database was published based on the type and working temperature of PCM to facilitate its selection for building applications [59]. Recently, several studies have focused on the incorporation of solid-liquid phase change PCM in CBM. Different methods were considered for incorporating PCM into CBM, namely direct incorporation, immersion and encapsulation [11].

Nowadays, the use of microencapsulated PCM (mPCM) and composite PCM (cPCM) have attracted great attention since they can prevent liquid leakage during the solid-liquid phase transition of PCM. In general, organic PCM, typically paraffin with a melting point that is close to the average temperature range for human comfort (18 °C–28 °C) and high storage densities up to 240 kJ/kg [60], is chosen as the core material in mPCM and cPCM. Other advantages of using paraffin as PCM are its chemical stability, effective cost and low supercooling phenomenon and phase segregation [61]. As can be seen in Fig. 5, mPCM is composed of a core material encapsulated in a shell, while cPCM is composed of a porous material that can retain PCM by capillarity [62–64].

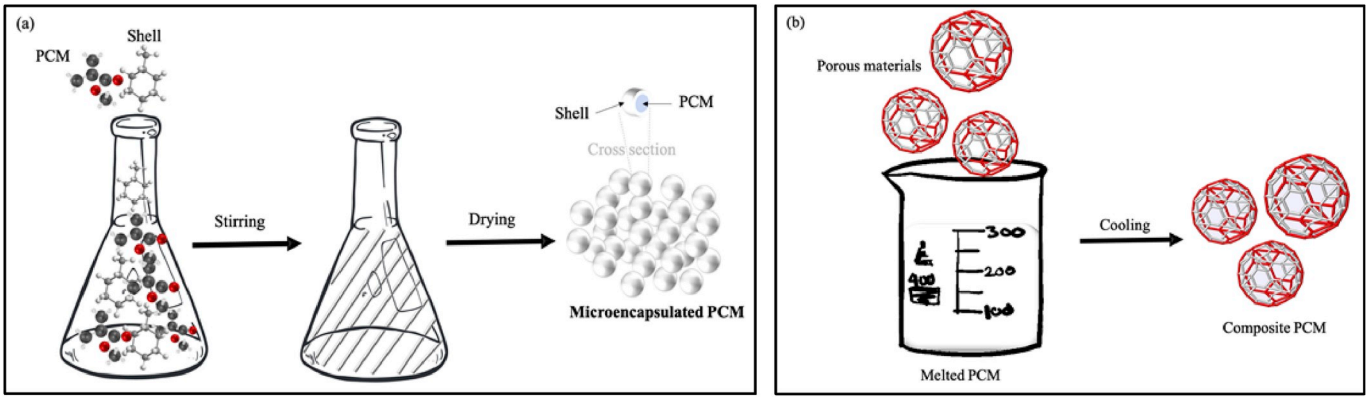


Fig. 5. Schematic representation of (a) mPCM and (b) cPCM (modified from Ref. [65]). Copyright (2019), with permission from Elsevier.

2.1. Microencapsulated PCM (mPCM)

The mPCM consists of a core (active) material microencapsulated/coated in a thin spherical shell or capsule (usually polymers). The shell can be formed using various techniques including physical and chemical methods which are detailed in Refs. [40,46,66,67]. The most often used physical methods include pan coating, spray drying, solvent evaporation, centrifugal and fluidized bed processes while the chemicals methods include in situ polymerization, interfacial polymerization, sample or complex coacervation, phase separation, suspension-like polymerization and other methods [68]. Generally, microcapsules smaller than 100 μm cannot be synthesized by physical methods, therefore, chemical methods, in particular in situ polymerization, are widely used [40].

After the manufacturing process, mPCM particles (up to 5 μm in diameter) agglomerate together and form spherical capsules ranging between 100 and 500 μm as illustrated in Fig. 6 [25,61,69]. Organic polymer shells (e.g. poly methyl methacrylate, melamine-formaldehyde resin, urea formaldehyde resin, etc.) were usually employed to protect the PCM core and improve its structural, impermeability and thermal stability properties [40].

As known, PCM has to maintain good physical and thermal stability upon thermal cycling [24]. According to the previous experimental study [71], mPCM had excellent thermo-physical stability. In fact, the geometrical shape and energy storage capacity of mPCM remained stable after 3000 repetitive dynamic cycles of fusion and solidification [72,73]. However, the undesirable properties of mPCM such as the low strength and stiffness of the shell usually caused it to be susceptible to damage (Fig. 6 (b)) [62]. Another typical drawback of mPCM was its relatively low thermal conductivity; for example, the thermal conductivity of paraffin waxes and poly methyl methacrylate shell is only about 0.2–0.4 W/m.°C and 0.17–0.25 W/m.°C, respectively [67]. To overcome this problem, graphite powder with a thermal conductivity of 390 W/m.°C (nearly 1000 times higher than paraffin) was added to PCM during the microencapsulation process [74,75]. Inorganic shells were also used to improve the thermal conductivity of mPCM such as SiO_2 [76], $CaCO_3$ [77] and TiO_2 [78], and the resulting microcapsules (Fig. 7) had also a spherical shape with an average size of 80–800 nm. Although these inorganic shells could provide higher thermal conductivity and stability as well as better phase change performance to mPCM, microcapsules formed by the silica shell, for example, could still be easily damaged (Fig. 7 (c)) [77–79].

2.2. Composite PCM (cPCM)

Recently, cPCM was also developed by several researchers. The process consisted of absorbing liquid PCM into highly porous inorganic materials such as expanded graphite [80], expanded clay [81], diatomite [82] and expanded perlite [83]. Before the impregnation process, porous materials were usually treated in order to improve their absorbability and purity as well as to expand their interlayer spacing [44]. Several techniques were adopted in the literature to prepare cPCM. One of these methods is the fusion adsorption process [84,85]. This method consists of placing the porous materials in melted paraffin then drying the composite using either compressed air or combination of compressed air and ventilated oven to remove any superficial residue of PCM. Compared to the previous method, a higher encapsulation ratio can be achieved when using the vacuum absorption technique [86–89]. Generally, it is recommended to coat the developed cPCM with a mixture of epoxy, graphite powder and silica fume to enhance the thermal conductivity and prevent the leakage of PCM [81].

Compared to mPCM, it is noteworthy that the use of a porous material in cPCM had mainly no effect on the encapsulation efficiency (ratio) since the percentage of the absorbed PCM in porous materials

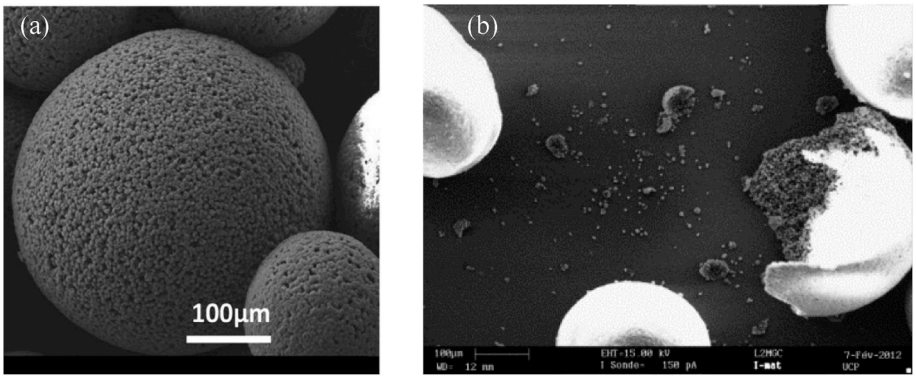


Fig. 6. SEM observation of mPCM capsules: (a) Agglomeration of small mPCM capsules [21], and (b) Damaged capsules [70]. Copyright (2019), with permission from Elsevier.

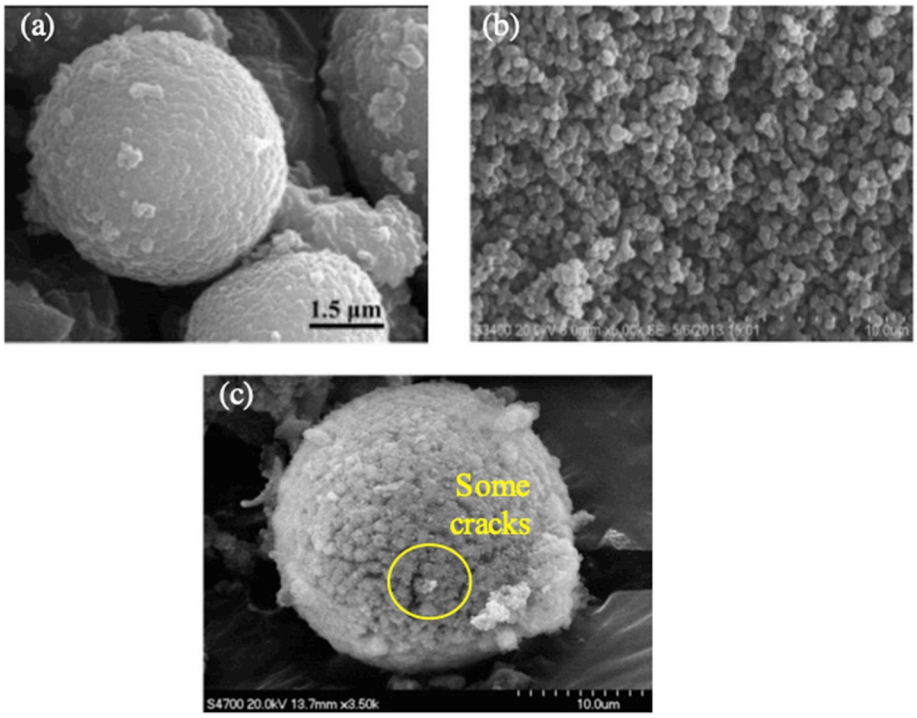


Fig. 7. Example of mPCM encapsulated in inorganic shells: (a) $CaCO_3$ shell, (b) TiO_2 shell, and (c) SiO_2 shell [77–79]. Copyright (2019), with permission from Elsevier.

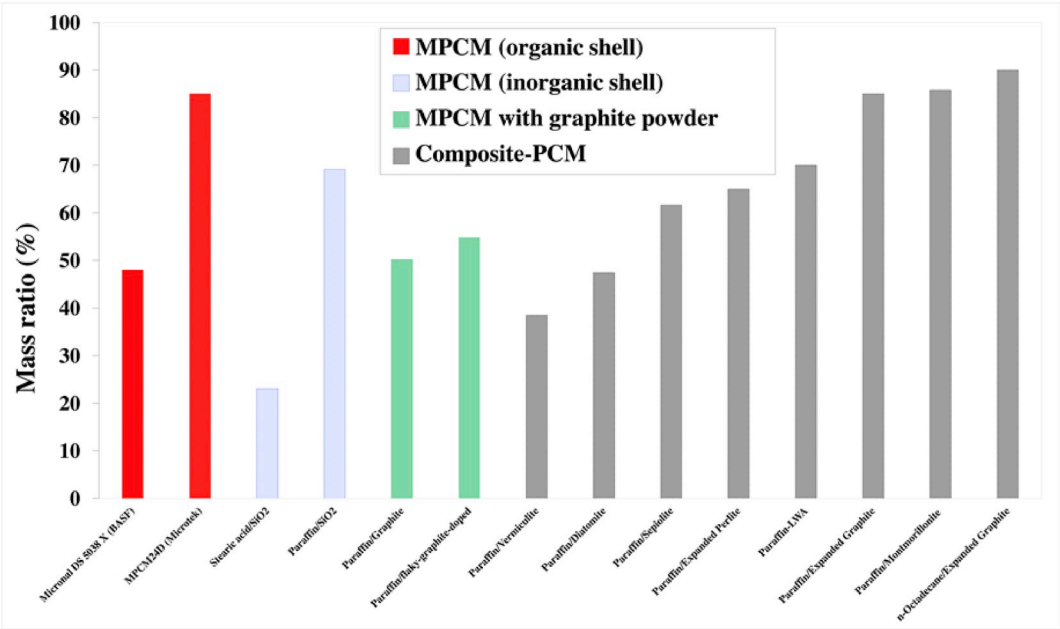


Fig. 8. Mass ratio of organic active PCM in different supporting materials (data taken from Refs. [44,61,74–76,80–82,86,87,91,92]).

could be up to 70% (Fig. 8). Therefore, the total energy storage capacity of cPCM was usually comparable to that of mPCM [90]. On the other hand, as shown in Fig. 8 the type of medium had an obvious influence on the encapsulation efficiency. For example, the encapsulation ratio of paraffin in the Micronal DS 5038 X, Microtek MPCM24D, SiO_2, diatomite and expanded graphite capsules was about 48%, 85%, 69%, 47% and 85%, respectively.

Studies also indicated that cPCM had good chemical stability and thermal behavior over time [86,93,94]. Moreover, improved compatibility with cementitious materials was noticed in comparison to the performance of mPCM in CBM [63,64,74,80,82]. Studies reported that the use of hydrophobic supporting materials and hydrophobic surface protective coating (hydrophobic fumed silica, precipitated silica, epoxy) or mixing the cPCM with dry powder (e.g. silica fume) before being added to the CBM could improve the bonding with cement matrix and prevent the leakage of PCM. This is particularly obvious for hydrophilic supporting materials [63,81,87,91,95,96].

3. Properties of CBM mixed with PCM

In the past decade, most studies have concentrated on examining the feasibility of incorporating mPCM and cPCM into CBM. The

reported literature has excessively emphasized their effect on compressive strength and thermal properties. Lately, other properties including workability, hydration behavior, etc. of CBM incorporating PCM have also been studied and reported.

3.1. Fresh properties

3.1.1. Workability

In order to optimize the mix design, it is important to understand the impact of adding PCM on the fresh properties to minimize any consequential drawbacks on the CBM's mixing process as well as the resulting hardened properties of CBM. One of the main factors influencing the workability of CBM is the leakage of paraffin from the composite (micro or macro) [96].

Generally, the incorporation of mPCM in CBM significantly reduced its workability. In fact, the presence of fin spherical mPCM particles increases the specific surface area and thus decreases the amount of water available to lubricate the CBM system [97]. Moreover, the water absorption characteristics of the polymeric shell of the microcapsules as well as the adsorption of water by the hydrogen bonds of the hydroxyl and imino groups of the microcapsule could contribute to the increase in the water demand of the CBM mix [22,98]. As can be seen in Fig. 9, the incorporation of mPCM significantly reduced the amount of free water and resulted in an increase in the mix water demand (up to 22%) in order to compensate the workability loss [11,29,62,99,100].

With regards to the effect of cPCM, there is relatively limited information reported on the workability in the literature. In general, the high-water affinity of cPCM [63] could contribute to the increase of water demand of the CBM mix. In addition, the use of superplasticizer to maintain constant workability for all mixes (with and without PCM) indicates that cPCM affected the workability [82,101].

Based on the above-mentioned findings, it is suggested that both mPCM and cPCM had similar impact on the workability of CBM. The use of extra water or an appropriate amount of superplasticizer were the common methods adopted to compensate for the loss of workability.

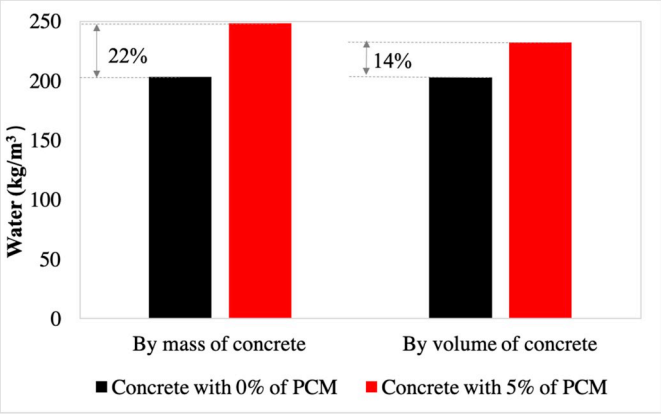


Fig. 9. Amount of water added to the mix before and after adding 5% of mPCM (data taken from Refs. [62,69]).

3.1.2. Hydration reaction

As known, PCM as a latent heat storage material is likely to absorb the heat released by the cement's hydration process. Hence, PCM has been suggested to be used to control temperature rise during the early age of cement hydration and mitigate the thermal stress for mass concrete structures. Generally, the same conventional isothermal and non-isothermal calorimetry were used to evaluate the hydration reaction of CBM incorporating PCM. As known, the isothermal calorimetry measures directly the heat rate (thermal power) produced by cement at a constant temperature condition while the non-isothermal (adiabatic and semi-adiabatic) calorimetry measures the temperature released during hydration and then the produced heat will be calculated [102]. Kim et al. [103] studied the adiabatic temperature rise of concrete using different types of binder. It was found that the maximum hydration temperature could be decreased by approximately 3 °C when mPCM was used in a ternary mix containing ordinary Portland cement, fly ash and slag.

Other than decreasing the hydration temperature [69], the addition of mPCM could delay the time required to reach the maximum hydration temperature, and could exhibit a disruptive effect for the development of the hydration reaction. This finding was highlighted in the work of Eddhahak et al. [61] who used the semi-adiabatic calorimetry test to study the hydration reaction of mortar incorporating 0%, 1%, 3% and 5% mPCM. Similarly, Li et al. [104] noticed that mPCM decreased the hydration heat peak by 5 °C and delayed it by 60 min. Furthermore, based on a numerical model, Savija and Schlangen [105] found that the low-temperature rise and the delay of maximum hydration temperature could help in minimizing the maximum tensile stress caused by thermal effects that occurs in the structure, consequently leading to less thermal cracking of CBM.

Similar to mPCM, the use of cPCM affected also the heat evolution of cement hydration. Sharifi et al. [106,107] used the semi-adiabatic calorimetry and isothermal calorimetry to study the hydration reaction of mortar with different contents of cPCM. For the semi-adiabatic test, the mortar was filled in an insulated cylinder while the temperature in the centre of the cylinder as well as the ambient air were recorded for three days using a k-type thermocouple. A 10% decrease in the released heat and a delay of approximately 120 min was noticed [107]. On the other hand, mortar was filled into two sealed capped ampoules in a machine maintained at 25 °C in order to measure the heat of hydration using isothermal calorimetry. A similar result to the semi-adiabatic test was observed [106]. Bentz and Turpin [108] developed a home-built semi-adiabatic calorimeter to evaluate the hydration reaction of PCM-mortars. Specimens were produced by adding expanded shale/PCM particles and paraffin wax particles as sand replacement in the mix. The presence of the cPCM successfully delayed the peak temperature by 60 min and lowered the temperature by 8 °C. In another study [109], the peak hydration development of mortar incorporating 2% cPCM was delayed by several hours and the maximum temperature was decreased by nearly 40%.

Based on these results, both mPCM and cPCM could be potentially used to control and mitigate the cracks of mass concrete structure caused by cement hydration, primarily because of the PCM's ability to absorb heat released by the fresh mixtures.

3.2. Compressive strength

The influence of PCM on the mechanical strength of CBM tends to be inconsistent in the literature, which is understandable in view of the lack of proper mix designs as well as the variety of PCM types and incorporation methods (e.g. replacement or addition to cement or for sand) used in the CBM production. Studies have highlighted that early strength development (up to 28 days) was strongly influenced by the presence of PCM. The mechanical strengths results of CBM modified with mPCM and cPCM are summarized in Table 1 and Table 2, respectively. In general, a significant decrease in the mechanical strength was noticed with the incorporation of PCM. The mPCM had a slightly higher loss in compressive strength as compared to mixes with cPCM. Moreover, it was clear that the mechanical strength loss was higher when the PCM dosages exceeded a certain optimum value, depending on the types of PCM used as shown in Tables 1 and 2. Additionally, the PCM's incorporation methods did not influence the mechanical strength loss when considering the same amount of PCM. For example, when approximately 5% of mPCM was incorporated into the mix either by total mass of concrete [69] or by weight replacement of fine aggregates in concrete [28], the relatively same mechanical strength reductions of

Table 1
Effect of mPCM on the mechanical strength of CBM.

(a) Replacement

Ref	MPCM type	MPCM (%)	Mix/technique	Increase/decrease* (%)	Reasons given by authors for the decrease or increase of strength
[21]	PCM-E	5	Mortar/Replacement (**wt%** fine aggregate)	23	- MPCM particles were uniformly dispersed
		10		34	- MPCM particles were not damaged and coated with the hydration product
		15		23	
		20		8	- The interface between mPCM particles and mortar was denser
	PCM-M	5		−14	- MPCM particles had low mechanical strength
		10		−20	- MPCM particles were damaged and the leaked organic PCM interfered with the hydration reaction
		15		−37	
		20		−39	- Agglomerated mPCM particles behaved like voids in the mortar
[110]	MPCM: paraffin encapsulated in melamine-formaldehyde shell	20(**)	Aerial lime-mortar/Replacement (**wt%** fine aggregate)	−50	- The water to binder ratio increased
		40		−75	- The porosity increased
		60		−90	
		20(**)	CEM II-mortar/Replacement (**wt%** fine aggregate)	−38	
		40		−57	
		60		−65	
[28]	Micronal DS 5040X, BASF	1	Concrete/Replacement (**wt%** fine aggregate)	−33	- MPCM particles had lower strength compared to sand
		3		−63	
		5		−69	- The porosity increased
		5	Mortar/Replacement (**vol%** fine aggregate)	−38	- High volume of mPCM made the mix more linear
		10		−14	
		20(**)		−27	
		35		−43	
		55		−50	
[111]	Wet cake	5	Concrete/Replacement (**vol%** fine aggregate)	−9	- MPCM had low mechanical strength
		10		−15	- The volume fraction of cement decreased with an increasing amount of mPCM
		15		−17	
		20		−26	
[100]	m-LDPE-EVA-Rubitherm RT27	3.2	Concrete/Replacement (**vol%** fine aggregate)	−42	- MPCM had low mechanical strength
					- The porosity increased
		2.7	Geopolymer concrete/Replacement (**vol%** fine aggregate)	−51	- The interface between mPCM particles and concrete was poor

(b) Addition

Ref	MPCM type	MPCM (%)	Mix/technique	Increase/decrease* (%)	Reasons given by authors for the decrease or increase of strength
[112]	Micronal DS 5008 X	10	Hydrated lime-mortar/Addition (**wt%** total solids)	−20	1/Mechanical strength increased:
		20		7	- MPCM contributed to a better pore size distribution (The pore size (macroporosity) of lime mortar decreased)
		30		53	
		10	CEM II-mortar/Addition (**wt%** total solids)	−13	2/Mechanical strength decreased:
		20		−24	- The total porosity increased
		30		−36	
[75]	MPCM/Flaky graphite-doped	10	Cement paste/Addition (**wt%** cement)	−28	- MPCM had low mechanical strength
		20		−41	- MPCM increased pores of samples
		25		−48	
		30(**)		−58	
[29]	MPCM28	14.8	Mortar/Addition (**vol%** mortar)	−50	- MPCM particles had higher absorption of water than other aggregates
		22.1		−62	
		29.3		−73	- MPCM acted as a lubricant and a fluid after the damage of capsules
		8.6	Concrete/Addition (**vol%** concrete)	−44	- MPCM particles behaved like voids in the mix in terms of mechanical strength
		13		−61	
		25		−85	
[61]	Micronal DS 5038 X	1	Concrete/Addition (**vol%** concrete)	−14	- The leaked paraffin affected the hydration reaction
		3(**)		−39	- MPCM-mortar released lower hydration heat than conventional mortar
		5		−47	
					- Cement hydration was delayed
[113]	CA-LA (inorganic PCM)	1	Concrete/Addition (**vol%** concrete)	−20	- The interfacial bond between MPCM particles and cement grains was weak
		2		−30	
	CA-MA (inorganic PCM)	1		−13	- Solid mPCM particles were difficult to distribute in the mix
		2		−28	- Agglomerated mPCM particles created irregular void space in the concrete
[74]	MPCM-graphite	5	Concrete/Addition (**wt%** cement)	−26	- MPCM had low mechanical strength
		10		−34	- MPCM increased pores in the cement mortar
		15		−43	- The interface between mPCM particles and concrete was poor
		20		−49	
[69]	Micronal DS 5008 X	1	Concrete/Addition (**wt%** concrete)	−30	- The leaked paraffin affected the hydration reaction by inhibiting the water transport
		3(**)		−53	
		5		−71	- The leaked paraffin could develop a phase interface

(*continued on next page*)

Table 1 (*continued*)

(b) Addition

Ref	MPCM type	MPCM (%)	Mix/technique	Increase/decrease* (%)	Reasons given by authors for the decrease or increase of strength
[111]	Wet cake	5	Concrete/Addition (**wt%** concrete)	−24	- MPCM particles had no mechanical strength - The volume fraction of cement decreased with an increasing amount of mPCM
		10		−40	
		15		−38	
		20		−41	
[11]	Micronal DS 5001X, BASF	3.2	Concrete/Addition (**wt%** concrete)	−68	- The incorporation method of mPCM - MPCM increased the water content in the mix
[114]	PEG/SiO2 (inorganic shell)	1.5	Concrete/Addition (**wt%** concrete)	−37	- MPCM had low density and compressive strength
		3		−50	
		4.5		−68	
		6		−71	
		7.5(**)		−81	
		9		−84	
		12		−90	
		15		−93	
		18		−95	

(*) the sign (−) and (+) means that the mechanical strength of cement-based materials decreased and increased respectively with the use of PCM.
(**) optimum amount of PCM defined by the authors.

Table 2
Effect of cPCM on the mechanical strength of CBM.

(a) Replacement

Ref	CPCM type	CPCM (%)	Technique	Increase/decrease* (%)	Reasons given by authors for the decrease or increase of strength
[82]	Paraffin/DP	10	Mortar/Replacement (**wt%** cement)	−27	- Not mentioned
		15		−29	
		20		−44	
		30		−49	
[87]	Paraffin/Vermiculite	50	Mortar/Replacement (**vol%** fine aggregate)	−47	- CPCM had lower mechanical strength compared to sand
		100		−56	
[101]	Paraffin/EP	20	Mortar/Replacement (**vol%** fine aggregate)	12	- CPCM had a low stiffness
		40		33	
		60		53	
		80		70	
[115]	Paraffin/EP $CaCl_2$-Paraffin/EP	30	Geopolymer **mortar** with EP/Replacement (**vol%** fine aggregate)	1 4	- CPCM improved the pore structure and decreased the porosity
[81]	Paraffin/LWA	50	Concrete with LWA/Replacement (**wt%** coarse aggregate)	7	- The coating material of cPCM had a high strength - Inclusion of silica fume as a layer for the coating material
		100		13	

(b) Addition

Ref	CPCM type	CPCM (%)	Technique	Increase/decrease* (%)	Reasons given by authors for the decrease or increase of strength
[91]	Paraffin/EP	5	Mortar/Addition (**wt%** cement)	−23	- CPCM had lower mechanical strength compared to sand and cement past
		10		−25	
		15		−41	
		20(**)		−43	
		30		−61	
[80]	n-Octadecane/EG	0.5	Mortar/Addition (**wt%** mortar)	−32	- Not mentioned
		1.2		−41	
		1.7		−49	
		2.5		−56	
[107]	PCM 28/LWA	15.7	Mortar/Addition (**vol%** mortar)	−25	- LWA was more porous and had less strength than sand
		22.6		−31	
[85]	Process A: surface dried with compressed air	13.1	Mortar/Addition (**vol%** mortar)	−29	- The interface between cPCM and cement paste was poor
		21.5		−41	
		33.6		−53	
	Process B: surface dried in oven	13.1		−26	
		21.5		−53	
		33.6		−56	

(*) the sign (−) and (+) means that the mechanical strength of cement-based materials decreased and increased respectively with the use of PCM.
(**) optimum amount of PCM defined by the authors.

about 71% and 69% were noticed, respectively. Also, in the case of cPCM, the mechanical strength loss of the mix was almost identical at a given cPCM content. In fact, when 20% of cPCM was used to replace cement (by mass) in the mix [82] or added as total mass of cement [91], about 43% of mechanical strength loss was reported.

Some explanations have been reported in the literature for this mechanical strength loss; however, the actual mechanism of the strength loss is still unclear. According to the summary in Tables 1 and 2, the increase/decrease of compressive strength of CBM incorporating PCM was mainly dependent on the type and content of PCM. Some researchers attributed the mechanical strength loss to the low intrinsic strength and density of PCM [28] whereby the inherent weaker nature of PCM became a weak point when subjected to loading. Furthermore, according to the "Bolomey" equation, PCM could be assimilated to voids [29]. The presence of voids in concrete or mortar was known to be the major cause of CBM's strength reduction. In addition, the agglomeration of PCM in the mix could also result in irregular void space in concrete [113]. On the other hand, the poor workability associated with the inclusion of PCM, the presence of increased entrapped air voids and the loss of free water could negatively affect the hydration process and consequently the mechanical strength of the matrix [29,62]. As reported earlier, additional water used to compensate for the workability loss could effectively increase the water/cement ratio in the CBM mix, hence decreasing the compressive strength [110].

The phase change process of PCM was known also to alter the hydration process of CBM. In addition, the increase of PCM volume resulted in the decrease of cement content which impacts also the hydration mechanism [61]. Moreover, the incompatibility between PCM and cement matrix could be another possible factor affecting the strength development of the CBM mixes. The poor bonding between the mortar matrix and PCM, the damage of PCM and the subsequent leakage of paraffin resulted in lower compressive strength [62,74]. In fact, the leaked PCM coated on the cement particles could prevent the cement hydration reaction and formation of the strength-bearing hydration products [109].

On the contrary, an opposite trend of mechanical strength results was also reported by few studies [21,81,112,115]. In fact, according to some researches, PCM capsules which were uniformly dispersed without damage in the mix could act as filler, contributing to a better pore structure and interfacial bond with cement, thereby increasing the compressive strength.

3.3. Thermal properties

The main objective of using PCM is to store and release heat, therefore, PCM should have a high thermal conductivity and latent heat in order to improve efficiently the storage capacity and heat transfer of CBM. A large number of experimental and theoretical studies have been conducted and some of their results are highlighted in the following section.

3.3.1. Thermal conductivity

The low thermal conductivity of PCM is considered as one of the major drawbacks for building applications. Because of this low thermal conductivity, PCM would lose their main functionality as a thermal energy storage material. Furthermore, this will impact the overall thermal conductivity of CBM. It was noticed that even at small amounts (up to 5%), mPCM (encapsulated in organic or inorganic shells) decreased the thermal conductivity of concrete by up to 37% [28]. Apart from the low thermal conductivity of mPCM, the reduction could also be related to both the low density and the increased entrapped air in CBM caused by PCM [100,114].

A similar trend was also found for the use of cPCM in CBM, where the thermal conductivity of mortar was found to decrease by 13.8%, 21.0%, 26.2% and 33.6% with the incorporation of 10%, 15% 20% and 30% of cPCM, respectively [82]. A similar range of reduction was observed in Ref. [101], where the thermal conductivity of mortar decreased by 15.8%, 31.6%, 52.6% and 65.8% with an increase of cPCM level at 20%, 40%, 60% and 80%, respectively. Likewise, the thermal conductivity of mortar decreased by 15.5% with an increase in the mass percentage of cPCM up to 2.5% [80]. Like mPCM, the reduction of thermal conductivity of CBM was also attributed to the increase of porosity and the reduction of CBM apparent density [80,101].

3.3.2. Thermal energy storage capacity

To the best of the author's knowledge, there is no standard or specifications related to the measurement of the thermal properties of PCM-CBM system [116]. Therefore, some self-made equipment, extensively reviewed in Refs. [117,118], were developed to determine the effect of PCM on the thermal energy storage capacity of CBM.

The performances of mortar and concrete samples exposed to thermal cycles are presented in Fig. 10 [29]. The experiments were performed on 2-cm-thick mortar and 5-cm-thick concrete samples. The contribution of mPCM could be clearly identified for the concrete sample. Compared with conventional mixes, the increase/decrease in temperature of mPCM mix was at a much slower rate before stabilization (Fig. 10 (b)). This reflects that mPCM could effectively improve the apparent thermal inertia of mortar and concrete which is in line with the results reported by Hunger et al. [69]. In fact, the thermal mass of PCM-concrete during the phase change process of PCM was clearly higher than that of the control mix [69]. A similar result was reported by other studies [62,70]. On the other hand, a shorter time was needed in the case of mortar to stabilize the temperature of the sample. This was attributed to the small size of the mortar samples compared to concrete samples [29].

Furthermore, mPCM can lower the temperature of cement modified with mPCM by up to 13.1 °C which highlight the positive effect of PCM in increasing the thermal mass of buildings [75].

Similar to mPCM, the use of cPCM exhibited a significant impact on the thermal energy storage capacity of CBM. Xu and Li [82] showed that the use of 30% of cPCM resulted in an increase in the thermal

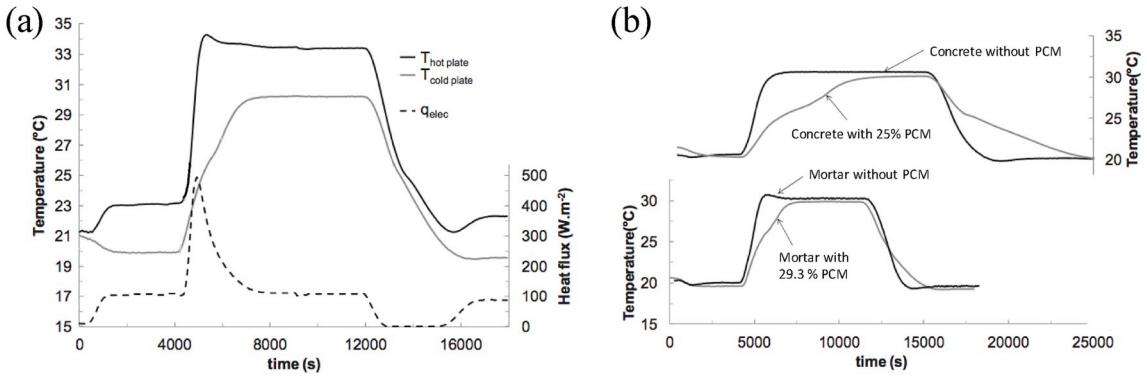


Fig. 10. (a) Thermal cycle, and (b) Thermal behavior of PCM-mortar and PCM-concrete specimens [29]. Copyright (2019), with permission from Elsevier.

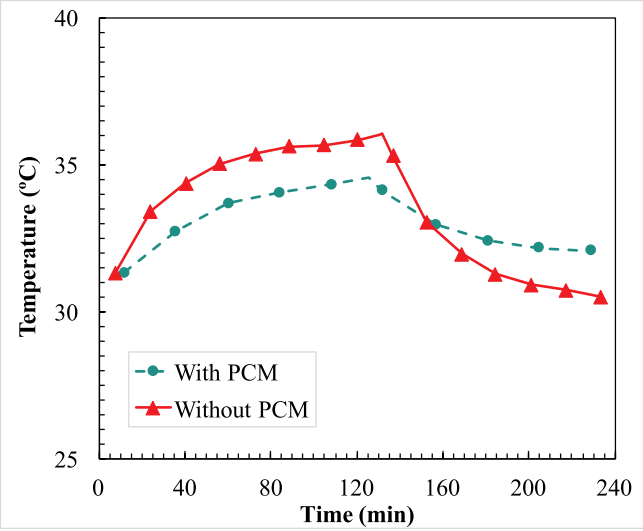


Fig. 11. Temperature evolution inside the room model (modified from Ref. [119]). Copyright (2019), with permission from Elsevier.

energy storage capacity up to 5.438 kJ/kg. Ramakrishnan et al. [95] demonstrated that a cPCM panel had higher thermal inertia compared to the control panel without PCM. The thermal inertia was determined by calculating the temperature difference between the top and bottom surfaces of the panels. The maximum temperature differences were about 2.4 °C and 5.2 °C for the control and PCM panels, respectively. In addition, it was noticed that both panels had the same initial heat storage rate during the heating and cooling process but subsequently the storage rate of the cPCM panel increased at a much higher rate. On the other hand, a reduction of about 37% and an attenuation of approximately 30 min were observed in the internal heat flux peak of the cPCM panel during the heating process. A significant reduction of the internal heat flux measurement during the cooling process was also recorded. These results underlined the improvement of indoor thermal comfort when using cPCM panels. Moreover, the cPCM panels exhibited a similar thermal performance after 100 thermal cycles. A smaller temperature fluctuation during heating and cooling of a small wooden room model was noticed when the top panel wall was modified with cPCM [119]. As shown in Fig. 11, the room modified with cPCM reduced the temperature by about 1.9 °C when the room was heated up to 50 °C. During the cooling process (to 25 °C), the temperatures of the control room and PCM room were reduced by 5.8 °C and 2.3 °C, respectively. This further indicates that the use of PCM is beneficial in reducing indoor temperature fluctuations.

4. PCM in CBM: case studies, current gaps and future directions

As discussed earlier, PCM is a very attractive technology in terms of energy saving and sustainable development, however, this technology has not yet been widely adopted in the construction industry. Only few case studies concerning space heating and cooling strategies using PCM were reported in the literature and these are summarized in detail in the following section.

4.1. Case studies

To promote actual field implementation of PCM in buildings, case studies focusing on the application of PCM (mPCM/cPCM) in house-like cubicles and real buildings have been carried out. In situ measurements of the thermal behavior, in particular thermal conductivity and temperature change within the building envelopes are the main parameters to assess the PCM efficiency in buildings. Wang et al. [120] evaluated the influence of temperature on the effective thermal conductivity of a wall prepared with cPCM (Fig. 12). The developed cPCM consisted of 70 wt% paraffin impregnated in 15 wt% high-density polyethylene and 15 wt% of expanded graphite. Control and PCM walls of size 1.5 m × 1.5 m × 0.24 m and 1.5 m × 1.5 m × 0.12 m, respectively were tested. The control wall was made with Portland cement vitrified bricks (225mmx115mmx45mm) while the cPCM bricks (240mmx120mmx90mm) mixture consisted of 37.5% Portland cement, 22.5% sand, 40% cPCM and water (the water to cement ratio was 0.2). Less than 5 mm thick mortar was used to bind the bricks. A good linear relationship has been found between the effective thermal conductivity and the temperature of the control wall. The same behavior was observed for the PCM-wall when the temperature was below 15 °C and above 30 °C; however, when the air temperature increased from 15 °C to 30 °C, the thermal conductivity decreased. This result suggested that cPCM was experiencing phase change under these temperature conditions since the thermal conductivity of PCM is mainly affected by the latent heat of fusion and solidification [120].

Kong et al. [121] prepared a PCM wallboard (0.5 m × 0.5 m × 0.02 m) by incorporating cPCM (paraffin/expanded perlite) in styrene acrylic emulsion glass fiber and environmental protection coating. As shown in Fig. 13, the wallboard was installed on the internal surface of the walls and ceiling of a test room (1.7 m × 1.7 m × 2.1 m) located in Tianjin, China. Three different cases were tested and are summarized in Table 3. As indicated in all three cases, cPCM could passively regulate the indoor air temperature by smoothing the temperature fluctuations. In fact, the cPCM absorbed the inside heat and released it by natural convection to the outside environment when the temperature was lower than the phase change temperature of PCM. However, it was noticed that cases 1 and 2 were

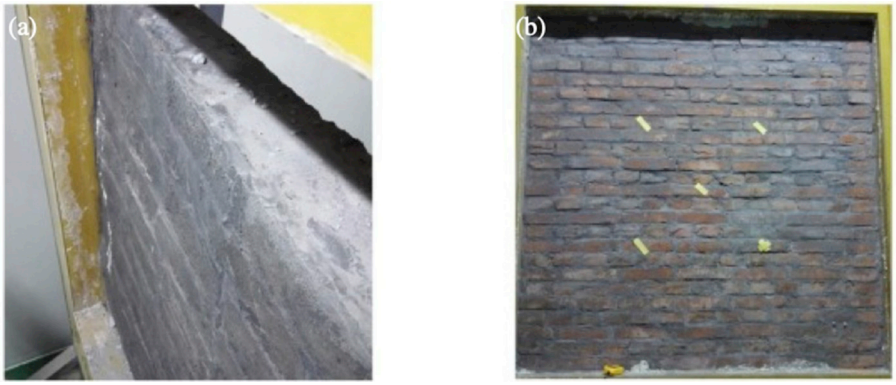


Fig. 12. An overview of the wall (a) With cPCM, and (b) Without cPCM [120]. Copyright (2019), with permission from Elsevier.



Fig. 13. cPCM wallboards installed on the ceiling and walls of the test cell [121]. Copyright (2019), with permission from Elsevier.

Table 3
Studied cases and temperature peak variation compared to conventional test cell. Data taken from Ref. [121].

Case no.	ΔT (°C) \with regards to conventional cell	Temperature peak delay (min)
Case 1: Doors and windows opened in the night	4.42	150
Case 2: Doors and windows kept closed until the outdoor temperature was lower than the phase change point	7.05	160
Case 3: Doors and windows closed	2.8	80

more effective in reducing and delaying the change in temperature of the room as compared to case 3 [121]. This indicated the importance of using night ventilation in order to enhance significantly the natural convection.

The thermal performances of paraffin/polypropylene/elastomer cPCM sheets in lightweight huts constructed in Chiba in Japan (Fig. 14) were evaluated [122]. Test results confirmed that cPCM was effective in reducing the peak indoor air temperature by 3.1 °C during daytime and increasing it by 2.5 °C during night, under natural condition. Additionally, cPCM could reduce the heating load by about 18.4%. However, it was reported that higher thermal benefits could be obtained when PCM received direct solar radiations.

In Portland, 130 Kg of PCM mats were installed in the second story of the west unit of a newly constructed duplex (Fig. 15). This region was characterized by a marine climate and a large diurnal temperature swing in the summer [123]. During summer, the indoor temperature of the PCM-unit was reduced by about 1.1 °C. Thus, the use of PCM reduced the annual overheated hours (the time outside thermal comfort) from 400 to 200.

A PCM panel composed of two aluminium sheets filled with PCM was designed by Kong et al. [124]. As indicated in Fig. 16, the PCM panels were installed in two different perforated brick test room (2 m × 2 m × 2.4 m). The panels were integrated on the outer surface walls and roof of the first test room (PCMOW) and on the inside surface walls and roof of the second room (PCMIW). Three different cases were evaluated namely case (1) free cooling experiments, case (2) open window and door at night and case (3) forced ventilation at night. According to the test results presented in Table 4, installing PCM panels inside the wall (PCMIW) was more effective in reducing and delaying the indoor peak temperature [124]. Additionally, opening windows and door along with ventilation at night-time had improved the discharging process of PCM and hence more heat can be stored during the daytime.



Fig. 15. The passive house duplex home [123]. Copyright (2019), with permission from Elsevier.

In order to investigate light-building envelope, a PCM test cell

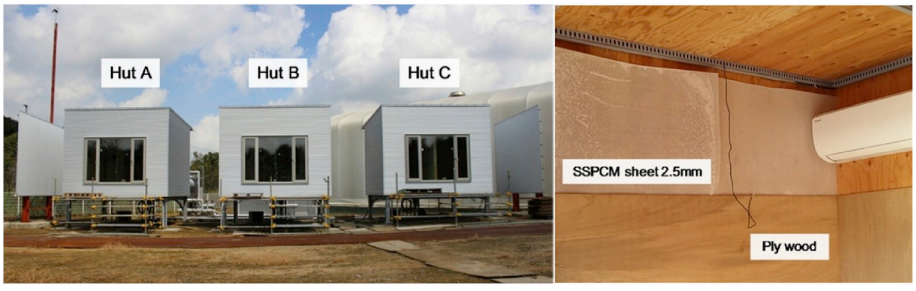


Fig. 14. Test huts and PCM sheets installed on the wall of the hut [122]. Copyright (2019), with permission from Elsevier.

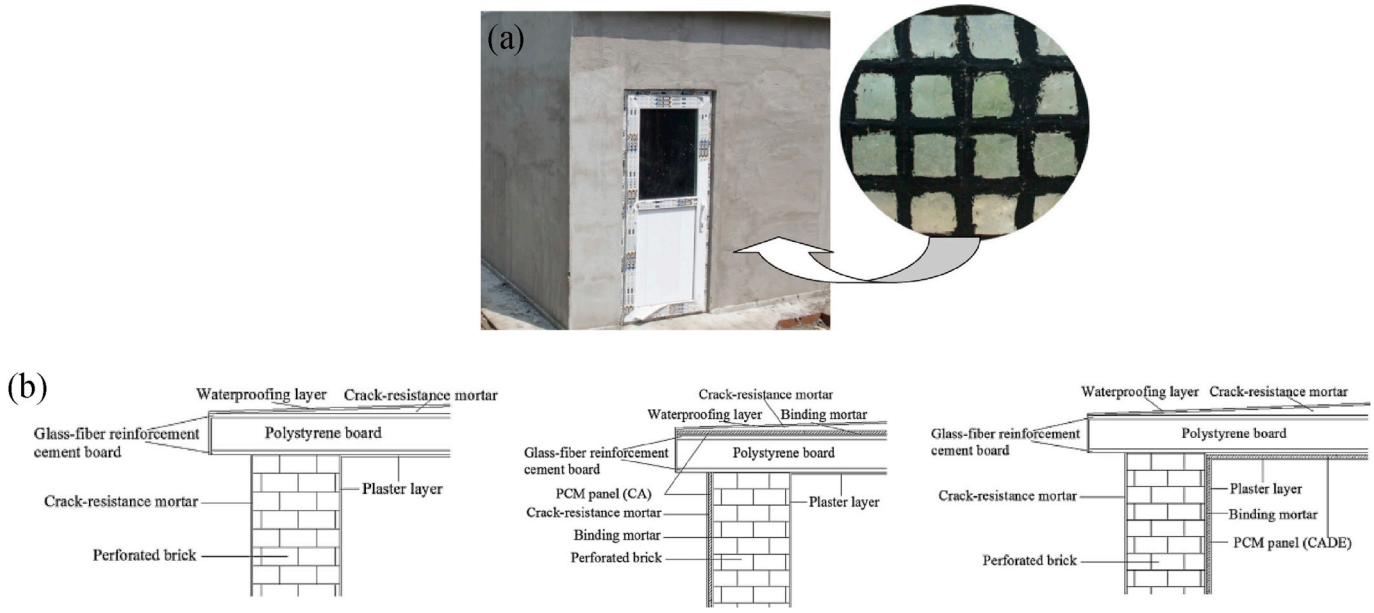


Fig. 16. (a) Test room, sections of the wall structure of the (b) Conventional test cell, (c) PCMOW, and (d) PCMIW [124]. Copyright (2019), with permission from Elsevier.

Table 4
Results of different studied cases. Data taken from Ref. [124].

Case no.	ΔT (°C) \with regards to conventional cell		Temperature peak delay (h)	
	PCMOW	PCMIW	PCMOW	PCMIW
Case 1	1	2.3	2.1	3
Case 2	0.41	2.46	Not mentioned	Not mentioned
Case3	Not mentioned	1.2	Not mentioned	Not mentioned

(3 m × 3 m × 3 m) was constructed at the University of Technology of Saint-Pierre in Reunion Island (tropical and humid climate) [125]. The PCM panels were integrated into the roof of the cell as shown in Fig. 17. For the purpose of verifying the efficiency of the suggested configuration (Fig. 17 (b)), a heat flux meter was installed on each surface of the roof layers. Test results showed (Fig. 17 (c)) that the PCM was effective for the given configuration. In addition, it was found that the temperature of the inside plasterboard surface was 5 °C higher than that of the outside PCM surface. Furthermore, the use of PCM lowered the indoor temperature by approximately 2 °C compared to the conventional test cell [125].

Most of the studies focused on testing the efficiency of PCM during summer. However, as known, PCM is designed to be used for both summer and winter applications. Therefore, recent studies [126,127] were conducted to investigate the efficiency of PCM in buildings during winter. A mPCM plaster was developed and applied on the walls and ceiling of a laboratory test cell (2.08 m × 4.55 m × 2.40 m) in Hokkaido, Japan [126]. The composition of the mPCM plaster and the thermal properties of the mPCM are presented in Fig. 18. The test cell was divided into two halves by an insulated partition wall, and one of the halves was finished with mPCM plaster. A 35% reduction in the heating load was reported when mPCM plaster was used. In addition,

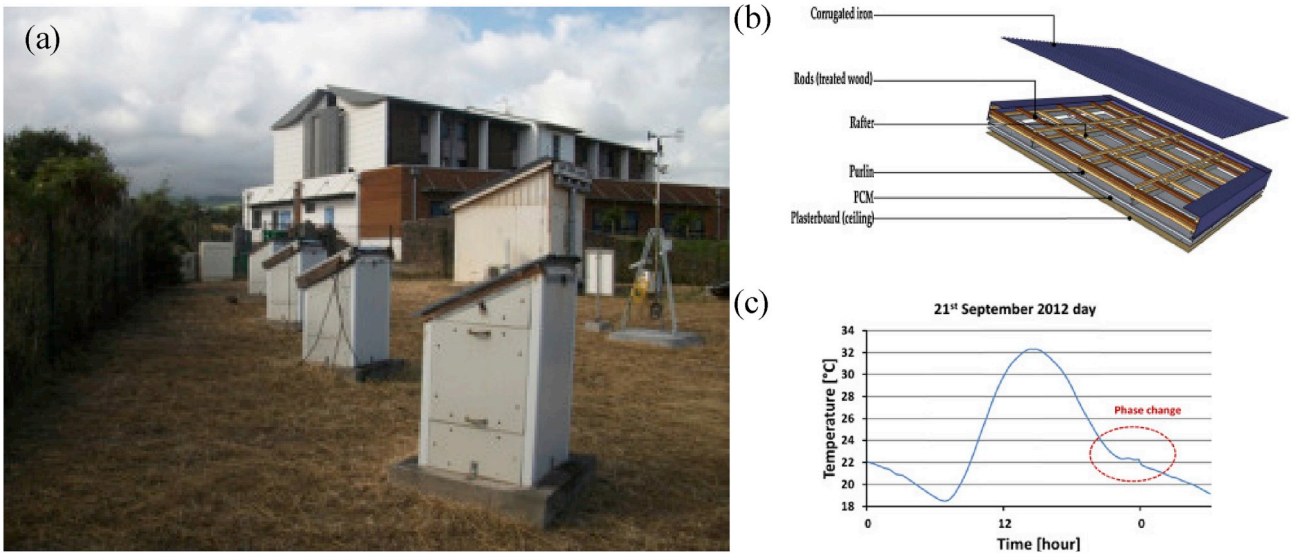


Fig. 17. (a) Test cell, (b) Schematic view of the roof, and (c) Temperature evolution of the roof [125]. Copyright (2019), with permission from Elsevier.

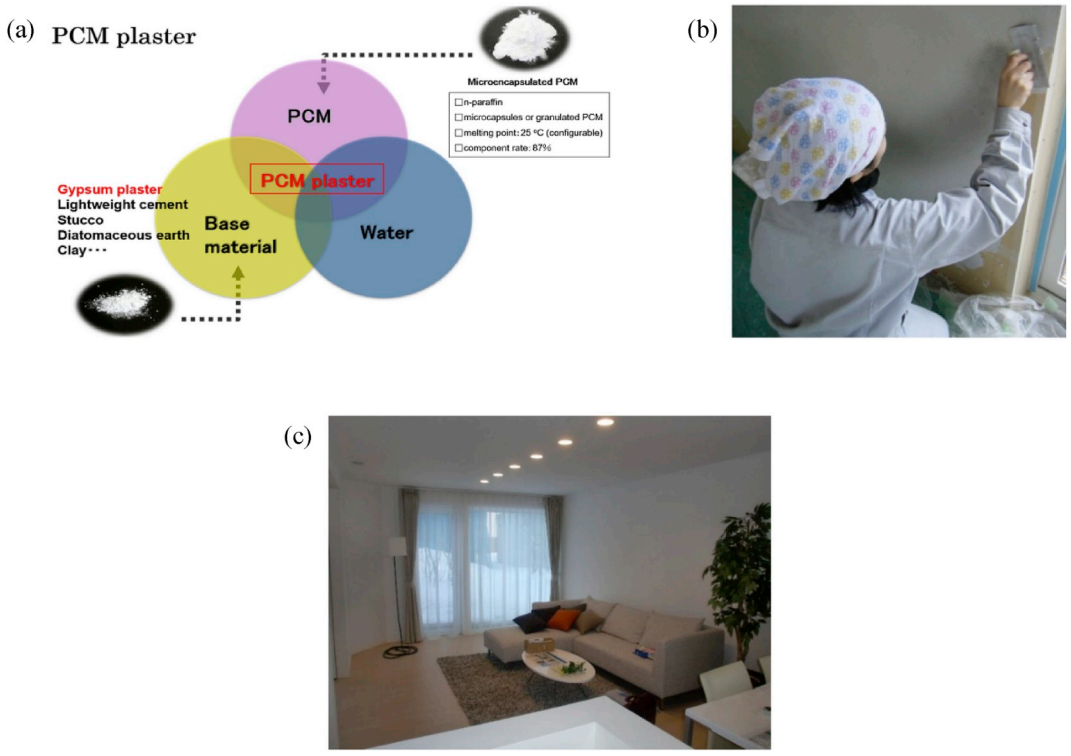


Fig. 18. (a) Thermal properties of PCM and composition of mPCM plaster, (b) Application of PCM plaster to the wall, and (c) Overview of the room after applying the mPCM plaster [126]. Copyright (2019), with permission from Elsevier.

PCM decreased significantly the temperature fluctuation. Later, PCM plaster (100 kg) was also applied in a full-scale residential building, offering a comfortable and stable indoor temperature around 20 °C [126].

A PCM-tile (660 mm × 660 mm × 52 mm) was installed into the floor of a full-scale bioclimatic house located at the University of Madrid in order to test the efficiency of PCM in controlling the indoor temperature during winter [127]. The tile consisted of 4 pieces as shown in Fig. 19: (1) pure clay stoneware (20 mm thick), (2) top metal sheet (3 mm), (3) metal container (32 mm thick) containing 4.8 l of paraffinic mixture; and (4) a layer of thermal insulation (22 mm thick). The surface temperature of the floor was measured in the morning, afternoon and night for 60 days. In comparison to the conventional floor tile without PCM (see Table 5), it was found that PCM tiles could release the stored energy to the room when the outside temperature was low and store the energy when the outside temperature was high. Furthermore, it was noticed that the amount of energy stored by the PCM-tile could be reduced by the presence of any obstacles which could cause any significant shadows on the tile and this might affect the discharge process of the PCM. Thus, in order to evaluate the effect of shadows on the performances of the PCM-tile, 3 different cases (Table 6) were tested [127]. According to Table 6, the temperature of PCM-tile that didn't receive direct sunlight was 0.5 °C higher than the conventional tiles while it could reach 2 °C when the PCM tiles received direct solar radiation. Thus, to maximize energy efficiency, it is necessary that PCM receives enough solar radiation during the thermal storage period [127].

Table 5
Temperature stored and released by PCM tile exposed to direct sunlight. Data taken from Ref. [127].

Outdoor temperature	ΔT (°C) \with regards to conventional tile	Phase change process
2–10 °C (low)	(−) 1.5–2 °C	Discharge
17–26 °C (high)	(+) 4–10 °C	Charge
Less than 26 °C	(−) Not mentioned	Discharge

(−) temperature released.
(+) temperature stored.

The effect of shadows provided by an awning on the performances of a full-scale outdoor test house (3 m × 3 m) with mPCM was also evaluated by Arce et al. [128]. The small house-sized cubicle was located at Lleida in Spain (Fig. 20) and constructed using a novel prefabricated concrete panel containing 5 wt% of mPCM. The awning (4.4 m × 4 m) was installed 12 cm above the roof of the cubicle. Unlike [127], it was concluded that the presence of shadows facilitated the

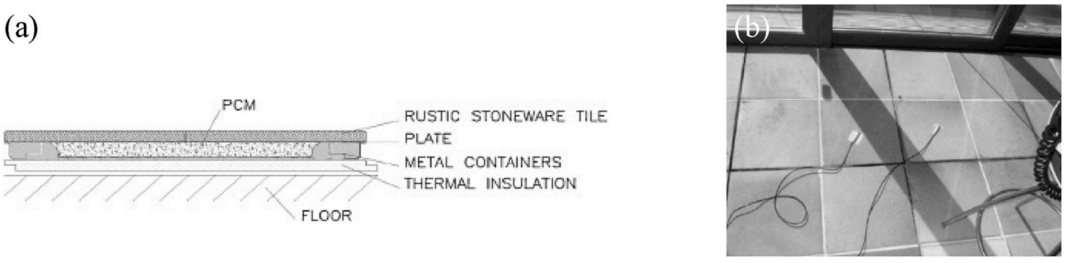


Fig. 19. (a) Cross section of the tile, and (b) Image of the tile installed onto the floor of the room [127]. Copyright (2019), with permission from Elsevier.

Table 6
Experiment set and energy stored and released by a tile with PCM not being exposed to direct sunlight. Data taken from Ref. [127].

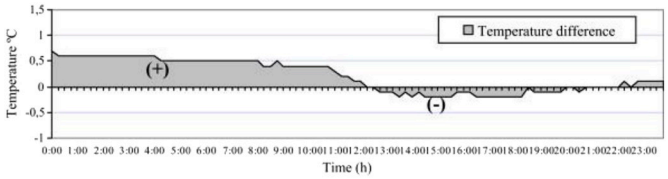
Case no.	Blinds	Tiles position	Temperature difference evolution
Case 1	Closed	Near the window	
Case 2	Opened	In the interior of the corridor	
Case 3	Closed	In the interior of the corridor	



Fig. 20. A house-like cubicle with awning [128]. Copyright (2019), with permission from Elsevier.

melting and solidification of mPCM, when incorporated in the roof and the walls of the test cell, which allowed higher comfort hours inside the cubicle during summer. In fact, compared to cubicle without awning and for a free cooling condition (windows remained open at night) the peak temperature reduction and the time delay of the peak increased by about 6% and 36%, respectively [128].

In order to optimize the cost of the experimental investigation, the real thermal behavior of the PCM-test cubicle was also numerically studied by changing the system variables. Mainly the numerical model considered the real environment conditions (i.e. temperature, wind speed) and took into account the phase change of PCM. The temperature changes inside a wall with and without PCM are presented in Fig. 21 [129]. Compared to the wall without PCM, the maximum and minimum temperature were reduced and increased by about 3 °C which contributed to 8% of energy saving. When the PCM wall received heat, PCM started to melt by absorbing the heat which resulted in lowering the indoor temperature. The heat absorption process ended when the PCM melted completely (PCM liquid fraction = 1). However, the absorbed heat couldn't fully discharge at night (PCM liquid fraction not equal to 0) as shown in Fig. 22. Therefore, selecting another PCM with a lower phase change temperature will be more efficient to release the stored heat and hence results in better management of the indoor temperature [129].

Different test cells (2 m × 2 m × 0.12 m) were built in Adana, Turkey [128]. The south and west walls of the mPCM-test cell were cast using a 0.06 m thick PCM-concrete layer (towards the inside of the room) and 0.06 m thick concrete layer (Fig. 23 (b)). The temperature variation of the walls was recorded (for 2 consecutive years) using an IR camera at noon during autumn (Figure (23)) and winter (Fig. (24)). As can be seen in Fig. 23 (a), the highest external temperature of the

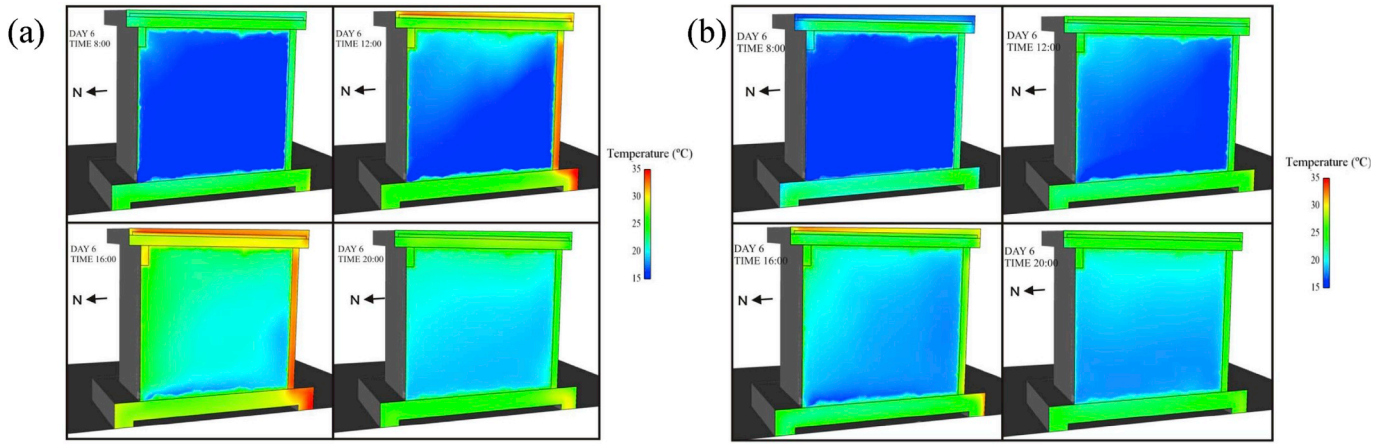


Fig. 21. Evolution of the temperature inside the wall (a) without PCM and (b) with PCM [129]. Copyright (2019), with permission from authors.

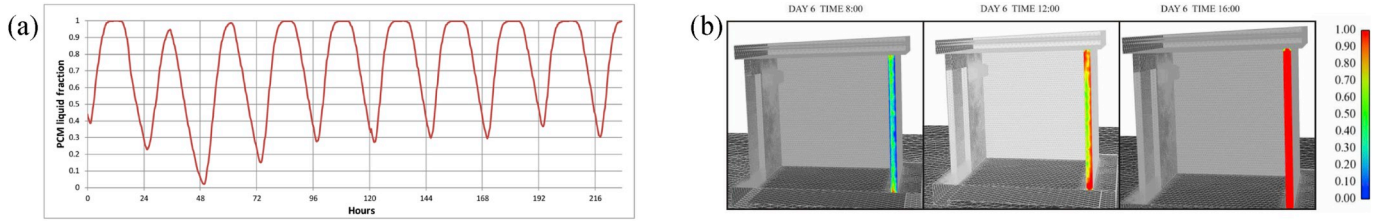


Fig. 22. Evolution of the PCM liquid fraction (a) during several hours (b) after 144 h [129]. Copyright (2019), with permission from authors.

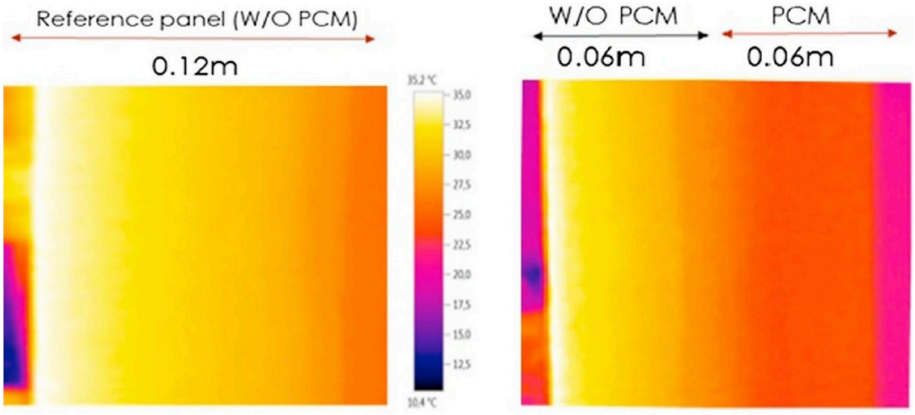


Fig. 23. Temperature distribution in a panel without PCM and with PCM recorded in November [130]. Copyright (2019), with permission from Elsevier.

reference test cell (0% mPCM) wall was about 35 °C. After being diffused in the wall, the temperature decreased and was about 27 °C. Compared to the reference panel, a similar temperature was observed in the first half layer (no mPCM) of the wall. However, the temperature on the right side of the wall (with mPCM) was 5 °C lower than that of the reference test cell [130].

On the other hand, during winter, the temperature of the PCM wall was 5 °C higher than that of the reference wall (Fig. 24) [130]. This result highlights that the use of this novel double layer panels can result in annual energy savings of up to 13%. The same results were recorded during the whole test duration (2 years) which demonstrated the good thermal stability of PCM inside the wall [130].

4.2. Current gaps and future directions for the application of PCM in CBM

So far, extensive research works on CBM incorporating PCM (mPCM/cPCM) have been undertaken worldwide to promote its use as an energy efficient building material. In overall, the examined literature findings showed that PCM could be a promising material to improve the thermal performances of CBM. However, several critical issues were identified including the selection of a suitable PCM which could meet all the desired properties. Based on the findings, PCM in the melted state could leak from its containment medium. In addition, PCM tended to have a very low thermal conductivity which affected the efficiency of energy storage and release. Therefore, innovative ways to develop a leak-free PCM with enhanced thermal conductivity have been recently studied, by using additives and coating materials to provide extended surfaces to the PCM. However, such solutions might in turn increase the overall cost and sometimes weaken the PCM performances. Therefore, there is still a need to explore alternative and economical mediums for PCM which will be able to contain and prevent the PCM leakage and provide it with sufficiently high thermal conductivity and good intrinsic strength. For example, one of the novel ideas consists of preparing a PCM-foamed cement and casting it into hardened hollow concrete block (Fig. 25). Another innovative approach consists of

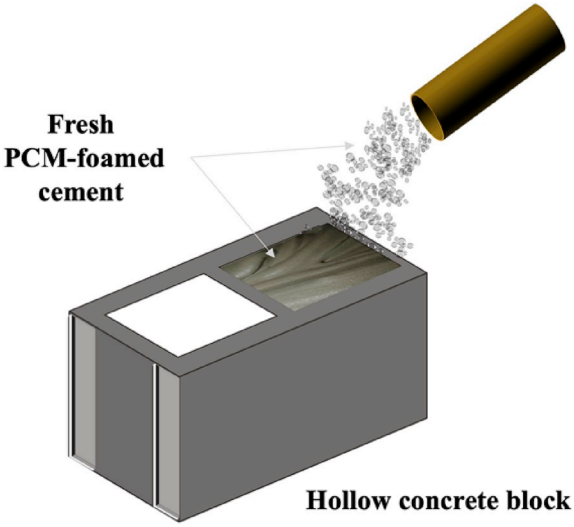


Fig. 25. Schematic overview of the filling process of PCM-foamed cement onto the concrete block.

incorporating PCM in artificial aggregate during the granulation process. The proposed benefits of this concept are the reduced cost when compared to cPCM as well as the prevention of both the damage of PCM particles and leakage problem due to the low friction induced during the pelletization process and the dense shell layer of the produced aggregate.

Another major research gap in utilizing PCM is to optimize both thermal and mechanical properties when using PCM for the development of a sustainable CBM for building application. As discussed in section 3.2, the use of PCM in CBM deteriorates its mechanical strength considerably. Thus, conducting a micro-mechanical studies will be beneficial to identify the underlying mechanism influencing this

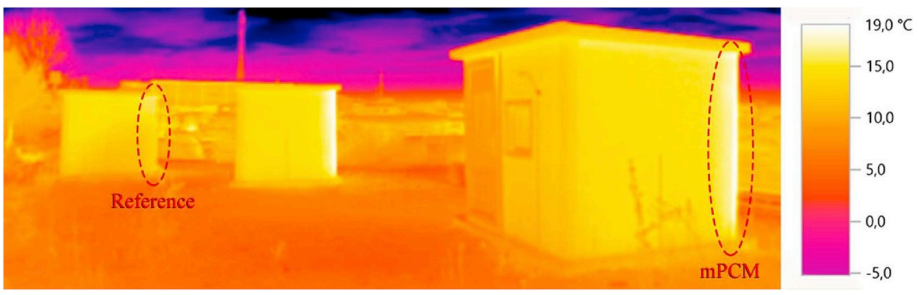


Fig. 24. General view of the test buildings in January [130]. Copyright (2019), with permission from Elsevier.

deterioration and to develop consistent optimal mixture composition for using PCM in CBM. As shown in Tables 1 and 2, the increase of CBM porosity was one of the factors causing the strength alteration. Therefore, it is important to identify and confirm whether the observed increase of CBM porosity is entirely related to the presence of PCM particles or because of the chemical degradation (dissolution and leaching) of cement hydration products following the leakage of PCM [131]. Furthermore, a comprehensive micro-mechanical study can shed light on the possible presence of micro-cracks in CBM containing PCM. The micro-cracks could occur due to the presence of extra water absorbed by PCM which could wet the cement particles and lead to the formation of additional hydration products, thus causing internal stress [132,133].

Finally, PCM-CBM is produced and tested currently using the conventional concrete/mortar standards. Therefore, adopting the conventional standards with appropriate modifications to consider the unique thermophysical properties of PCM is suggested to encourage and expedite wider acceptance of the product by the relevant industries.

5. Conclusions

Phase change materials (PCM) can be an effective solution to improve the energy efficiency of buildings. In the past decades, several studies have been conducted to incorporate mPCM and cPCM into cement-based materials (CBM). In general, mPCM and cPCM demonstrated similar negative and positive impacts on the overall performance of CBM with regard to workability, hydration reaction, compressive strength and thermal properties. Therefore, the authors couldn't select one type of PCM over the other. It was also highlighted that in some situations in particular when related to the compressive strength mPCM is more appropriate to be used than the other cPCM and vice versa. Therefore, through this comparison, it's apparent that further work is needed to develop a new PCM having a negligible effect on the compressive strength of CBM. Field studies also demonstrated that the use of mPCM and cPCM is feasible and can improve the indoor thermal comfort of buildings during summer and winter. Nevertheless, continuous research and development are still required for the use of PCM in CBM commercially in a larger scale.

Compliance with ethical standards

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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