Phase Change Materials for Building Applications: A State-of-the-Art Review and Future Research Opportunities

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Abstract

Phase change materials (PCM) have received considerable attention over the last decade for use in latent heat thermal storage (LHTS) systems. PCMs give the ability to store passive solar and other heat gains as latent heat within a specific temperature range, leading to a reduction of energy usage, an increase in thermal comfort by smoothing out temperature fluctuations throughout the day and a reduction and/or shift in peak loads. The interest around PCMs has been growing significantly over the last decade. Hence, several commercial products have arrived on the market with various areas of use in building applications. This study reviews commercial state-of-the-art products found on the market and show some of the potential areas of use for PCMs in building applications. Examples of how PCMs can be integrated into buildings, and furthermore building materials and projects using PCMs that have already been realised, have also been reviewed. There seems to be a scarcity of data published on actual performance in real life applications so far. However, many laboratory and full scale experiments have shown positive results on energy savings. Furthermore, future research opportunities have been explored and challenges with the technology as of today have been discussed.

Keywords: Phase change material; PCM; Energy; Temperature; Building; State-of-the-art; Review.

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1 Introduction

The growing energy demand in the world is an ever-increasing issue with regard to climate change and energy supply. The world consumes large amounts of fossil fuels that drive climate changes and empties the supplies of fossil fuels more rapidly. One action that will benefit energy usage globally is to increase the energy efficiency of buildings. In the European Union, the building sector is a major energy consumer and accounts for around 40% of the total energy usage. Large parts of this energy usage is directly related to the heating and cooling of buildings (European Union [26]). An alternative to meet the increasing energy demand and reduce the negative environmental impacts would be to reduce energy usage in combination with higher utilization of environmentally friendly renewable energy technologies. These may be well-known technologies such as hydropower, wind energy and solar energy, or new emerging technologies such as ocean energy and enhanced geothermal systems to mention a few. Building integration of some of these technologies may also be found to be beneficial, e.g. building integrated photovoltaics (BIPV) (Jelle et al. [46], Jelle and Breivik [47], Jelle and Breivik [48]).

Several new technologies are emerging to help realize the goal of reducing energy usage in buildings. Some of these technologies are related to thermal insulation materials applied in the building envelope (Baetens et al. [9], Baetens et al. [11], Baetens et al. [12], Baetens et al. [13], Gao et al. [29], Jelle et al. [43], Jelle [44], Kalnæs and Jelle [56], Sandberg et al. [95], Tenpierik [118]). Also part of the thermal building envelope, although not a thermal insulation material in itself, is the promising technology of phase change materials (PCM) which has received considerable attention over the last decade. PCMs utilize the principle of latent heat thermal storage (LHTS) to absorb energy in large quantities when there is a surplus and releasing it when there is a deficit. Correct use of PCMs can reduce peak heating and cooling loads, i.e. reduce energy usage, and may also allow for smaller dimensions of technical equipment for heating and cooling. An added benefit is the ability to maintain a more comfortable indoor environment due to smaller temperature fluctuations. Over the past few years there have been written several reviews on the use of PCMs in buildings for thermal energy storage systems and indoor climate comfort purposes (Agyenim et al. [1], Al-Saadi and Zhai [2], Baetens et al. [10], Cabeza et al. [18], Khudhair and Farid [59], Kuznik et al. [67], Memon [78], Osterman et al. [82], Pomianowski et al. [85], Soares et al. [111], Tatsidjodoung et al. [117], Waqas and Din [120], Zhou et al. [128], Zhu et al. [129]), clearly showing that the interest for PCMs is increasing worldwide.

For building applications the possible areas where PCMs can be utilized are many. Some of the areas that have been studied to this day include ventilation systems, passive heating and cooling systems, floors, roofs and wallboards. PCMs can also be incorporated directly into building materials such as concrete (Ling and Poon [74]) and wallboards (Kuznik et al. [65]), enabling them to be applied in constructions with minimal alterations to the original design.

The objective of this study is twofold, i.e. (a) to present a comprehensive state-of-the-art overview of different PCM producers and products, including an evaluation of the effect and durability of these products, and (b) to explore possible future research opportunities. Furthermore, it is of interest to see how phase change materials are tested with respect to lifetime performance in building applications, and then especially with respect to cycle testing for long-term stability, fire safety and energy saving potential. These investigations may help developing guidelines for a new testing scheme and point to future research possibilities. This work presents many tables with a considerable amount of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendix. Some of these values are crucial to the performance of phase change materials. The tables should provide the readers with valuable information regarding phase change materials and their use. Unfortunately, it is currently hard to obtain all the desired information from every manufacturer. In general, many of the desired property values are not available on the manufacturers websites or other open information channels, which is hence seen as open spaces in the various tables. Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for consumers and users to demand these values from the manufacturers.

2 Phase change materials in general

2.1 General

Phase change materials (PCM) utilize the latent heat of phase change to control temperatures within a specific range. When the temperature rises above a certain point, the chemical bonds in the material will start to break up and the material will absorb the heat in an endothermic process where it changes state from solid to liquid. As the temperature drops, the material will give off energy and return to a solid state. The energy used to alter the phase of the material, given that the phase change temperature is around the desired comfort room temperature, will lead to a more stable and comfortable indoor climate, as well as cut peak cooling and heating loads (Baetens et al. [10]). Hence, phase change materials can provide an increase in heat storage capacity, especially in buildings with low thermal mass. The temperature range varies depending on the materials used as the phase change material.

Schröder and Gawron [101] summarized some of the desired properties that should be required from phase change materials:

- High heat of fusion per unit volume and unit weight, and high specific heat. This is desirable to gain more effect from latent heat storage with a small as possible volume of PCMs.
- Phase change temperature suitably matched to the application. To gain the most out of PCMs the phase change temperature must be in accordance with the climate, location in the building or the type of system where the PCM is used.
- Low vapour pressure at operational temperature. To avoid extra costs or danger of rupture because of pressure on the encapsulating material the vapour pressure should be as low as possible.

- Chemical stability and low corrosion rate. Chemically stable materials will allow for PCMs to operate at the given temperature and with the given effect for a longer period and reduce the chances that the PCM reacts with materials that are in contact with it, i.e. increasing the lifetime of PCMs.

- Not hazardous or poisonous. To be allowed in the building sector there can be no poisonous emissions during fire or if the encapsulation is ruptured during regular use. Production of the material should also not release dangerous emissions to the environment.

- Highly inflammable. Strict building laws with regards to fire safety must also be fulfilled by PCMs.

- Reproducible crystallization without degradation. Much the same as chemical stability, the reproduction of crystals over thousands of phase changes without degradation is vital to attain long lifetimes for PCMs.

- Small degree of supercooling and a high rate of crystal growth. Supercooling will alter the temperature of the phase change. An attractive PCM should have an exact phase change temperature so that the phase change is predictable to allow a material to be selected correctly for optimal design.

- Small volume change during solidification. A large volume change will mean that the encapsulation material has to allow for expansion of the PCM, thus decreasing the amount of PCM the encapsulation can hold.

- High thermal conductivity. A high thermal conductivity will allow heat to disperse through or leave the material more rapidly, allowing the PCM to absorb or release heat at a higher rate.

- Use materials that are abundant and cheap. To make the technology more attractive and possible to use at a large scale it is important that the materials to be used are abundant cost-effective.

2.2 General categorization of phase change materials

There are several materials that can be used as PCMs. A common way to distinguish PCMs is by dividing them into organic, inorganic and eutectic PCMs. These categories are further divided based on the various components of the PCMs (Fig.1). Figure 2 shows the difference in melting enthalpy and melting temperature for some of the most common materials used as PCMs.

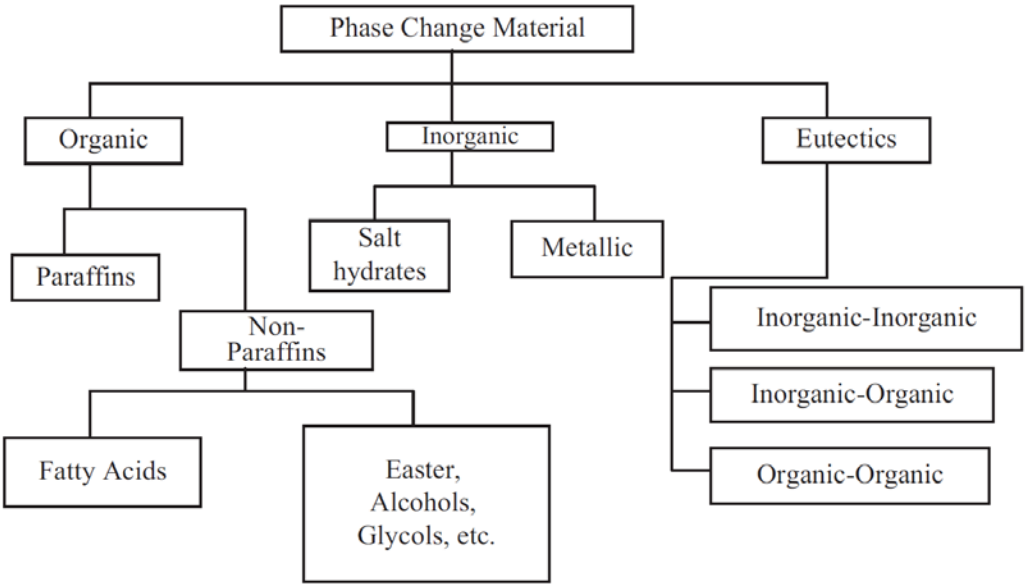


Figure 1 General categorization of PCMs (Rathod and Banerjee [88]).

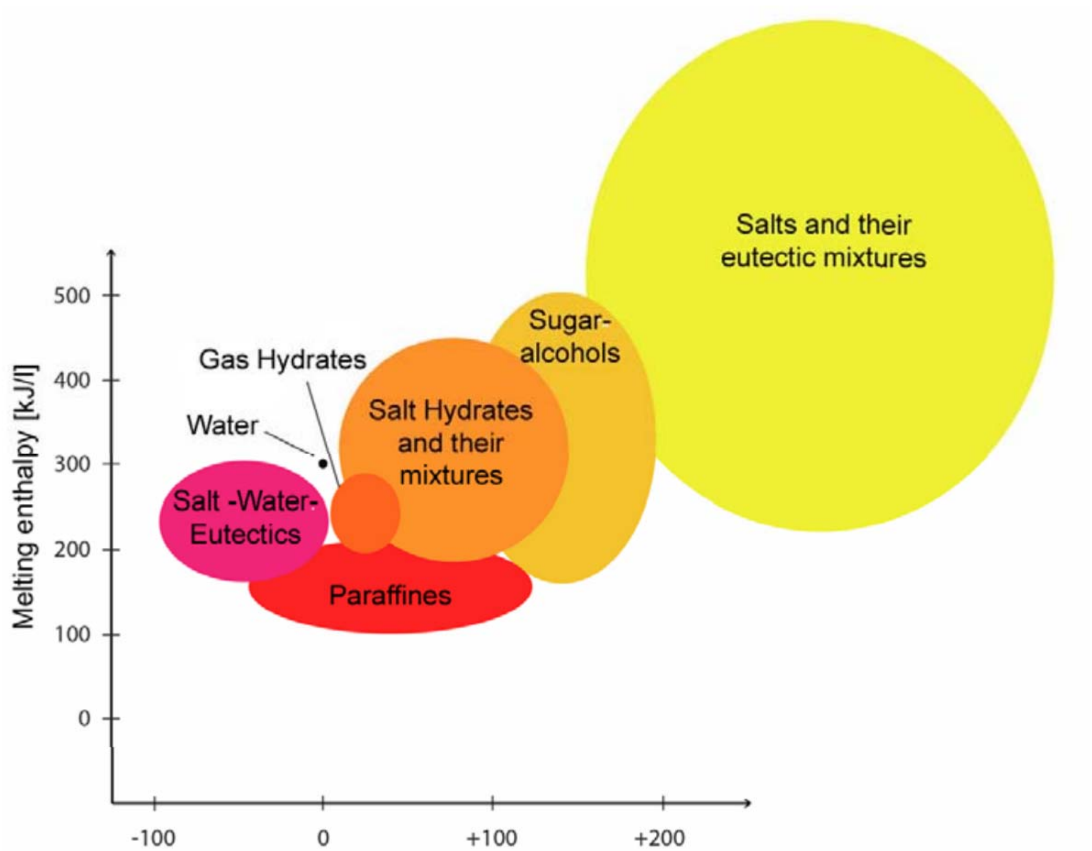


Figure 2 Melting enthalpy versus melting temperature for various materials used in PCMs (Dieckmann [25]).

2.2.1 Organic

Organic phase change materials are divided into paraffins and non-paraffins. In general, organic PCMs do not suffer from phase segregation and crystallize with little or no supercooling (Rathod and Banerjee [88]).

Paraffins are available in a large temperature range (Fig.2) opening up for use in various other areas besides building related applications. The latent heat is mass based, they show no signs of phase separation after repeated cycling through solid-liquid transitions, and have a low vapour pressure (Alkan [4]). However, paraffins used as PCMs have some drawbacks. They have low thermal conductivity (around 0.2 W/(mK)), they are not compatible with plastic containers and they are moderately flammable (Sharma et al. [105]).

Non-paraffins used as PCMs include fatty acids and their fatty acid esters and alcohols, glycols, etc. Fatty acids have received the most attention for use as PCMs in buildings. An extensive review on fatty acids used for PCM purposes has been written by Yuan et al. [124]. In this review fatty acids and their esters and alcohols were reviewed for their potential as PCMs. The most interesting fatty acids for PCM purposes include lauric acid, myrisitic acid, palmitic acid and stearic acid. As with paraffins, these also suffer from low thermal conductivity, ranging from 0.15 to 0.17 W/(mK).

In overall, organic PCMs have many qualities which make them suited for building applications. However, the fact that many organic PCMs are considered flammable is a crucial drawback for which impacts the safety aspect of organic PCMs considerably when aimed at building applications.

2.2.2 Inorganic

Inorganic phase change materials of interest consists of hydrated salts and metallics. For building applications however, metallics are not within the desired temperature range and in addition they have severe weight penalties making them unsuited. Hence, they will not be further addressed in this review.

Hydrated salts consist of an alloy of inorganic salts and water and enable a cost-effective PCM due to easy availability and low cost. The phase change transformation involves hydration or dehydration of the salts in a process that resembles typical melting and freezing. The salt hydrate may either melt to a salt hydrate containing less water or to an anhydrous form where salt and water is completely separated (Sharma et al. [105]).

Desirable properties of salt hydrates used as PCMs include high latent heat of fusion per unit volume, higher thermal conductivity than organic PCMs and small volume change and easy availability at a lower cost.

Hydrated salts suited for commercial use suffer from incongruent melting. This is a typical problem for hydrated salts as the melting process in many cases lead to the salt releasing water and turning into a salt in its anhydrous from, or a different salt. The density of the anhydrous salt may be higher, causing it to sink to the bottom of the container. When the temperature reaches the freezing point, the salt will be stacked at the bottom and some salt will be unable to reabsorb the water. Hence, the total volume of salt that can undergo phase change has decreased, and the effectiveness of the PCM is reduced. Another issue for hydrated salts is supercooling, which occurs because of poor nucleating properties in many salt hydrates. When supercooling occurs, the liquid phase of a PCM does not freeze (solidify) at the intended temperature, but reaches temperatures lower than the freezing point before actually solidifying. This is a critical flaw as it alters the temperature of the phase change.

2.2.3 Eutectic mixtures

An eutectic is a minimum melting composition of two or more components, each of which melts and freezes congruently. During the crystallization phase, a mixture of the components is formed, hence acting as a single component. The components freeze to an intimate mixture of crystals and melt simultaneously without separation (Lane [70]). Eutectics can be mixtures of organic and/or inorganic compounds. Hence, eutectics can be made as either organic-organic, inorganic-inorganic or organic-inorganic mixtures (Baetens et al. [10]). This gives room for a wide variety of combinations that can be tailored for specific applications.

Of organic eutectic mixtures, the most commonly tested consist of fatty acids. Some organic eutectics that have been studied include capric acid/myristic acid (Karaipekli and Sari [57]), lauric acid/stearic acid, myristic acid/palmitic acid and palmitic acid/stearic acid (Sari et al. [97]) and capric acid/lauric acid (Shilei et al. [107]). The most common inorganic eutectics that have been investigated consist of different salt hydrates.

The benefits of eutectic mixtures is their ability to obtain more desired properties such as a specific melting point or a higher heat storage capacity per unit volume.

Though it has been given significant interest over the last decade by researchers, the use of eutectic PCMs for use in (LHTS) systems is not as established as pure compound PCMs. Hence, thermophysical properties of eutectics is still a field for further investigations as many combinations have yet to be tested and proved.

2.2.4 Comparison summary

The advantages and drawbacks for organic, inorganic and eutectic PCMs are compared and summarized in Table 1.

Table 1 Overview of advantages and drawbacks for PCMs.

Organic		Inorganic		Eutectics	
Advantages	Drawbacks	Advantages	Drawbacks	Advantages	Drawbacks
-No supercooling -No phase segregation -Low vapour pressure -Large temperature range -Self-nucleating -Compatible with conventional construction materials -Chemically stable -Recyclable -High heat of fusion	-Flammable -Low thermal conductivity -Low volumetric latent heat storage capacity	-High volumetric latent heat storage capacity -Higher thermal conductivity than organic PCMs -Low cost -Non-flammable -Sharp phase change	-Corrosive to metals -Supercooling -Phase segregation -Congruent melting -High volume change	-Sharp melting points - Properties can be tailored to match specific requirements	-Limited data on thermophysical properties for many combinations - High cost

2.3 Encapsulation

As most PCMs designed for building applications go through a liquid phase, encapsulation is needed to avoid problems such as leaking of PCM to the surface and diffusing of low viscous liquids throughout the material (Özonur et al. [130]). Hence, methods such as direct incorporation and immersion of PCMs in building materials are not well suited for long-term applications (Zhou et al. [128]). As direct incorporation and immersion are techniques that are not wide spread for PCMs intended for building applications, they will not be discussed further in this study. PCMs undergo a change in phase, thus it is important to note that this may also lead to change in both volume and thermal conductivity. A large volume change is not desirable as it may put pressure on the encapsulating material.

The material used to encapsulate should not react with the PCM or show signs of deterioration over time. Currently, two main methods are used for encapsulating PCMs, i.e. micro- and macroencapsulation. These two methods give various sizes and shapes of the PCMs and affect how PCMs may be incorporated into a material or construction.

2.3.1 Microencapsulation

Microencapsulation of PCMs involves packing the PCM materials in capsules which range from less than 1 µm and up to around 300 µm (Hawlader et al. [34]). The end product consists of the outer shell and the PCM fill in the centre (Fig.3). The process can either be perfomed physically through e.g. spray-drying (Hawlader et al. [34]) or a coating process (Kaygusuz et al. [58]) or chemically through e.g. coacervation (Hawlader et al. [34], Saihi et al. [93]) or interfacial polymerization (Cho et al. [21], Liang et al. [73] and Saihi et al. [94]).

The shell materials commonly used for microencapsulation consists of organic polymers or silica. Recently materials such as SiO_2, AlOOH and TiO_2 have also been studied (Cao et al. [19]).

Figure 3 Model of a microencapsulated PCM with a wax core and polymeric shell (Phase energy [84]).

The advantages of microencapsulation include an increased heat exchange surface giving an increased heat transfer, reduced reactivity with surrounding materials and the PCM's volume can expand without affecting the structure around it. Due to the microencapsulated PCMs' small size they can be produced in either powder form or dispersed in a liquid (Fig.4) and they do not need additional protection from destruction (Tyagi et al. [119]). This makes it possible to add the PCM directly to materials such as concrete and gypsum without the risk of leakage. However, considerations have to be made as adding microcapsules may affect the structural strength of a material.

Microencapsulation has shown to be the most promising method of encapsulation for integration of PCMs in building materials. However, microencapsulation leads to a lower latent heat storage capacity per unit volume and unit weight than the pure PCM due to the adding of the encapsulating material.

Figure 4 Microencapsulated PCM dispersed in liquid and as powder (BASF [15]).

2.3.2 Macroencapsulation

Macroencapsulation refers to PCMs encapsulated in any type of container such as tubes, spheres or panels which can be incorporated into building materials or serve as heat exchangers by themselves (Fig.5). The size of these containers are usually larger than 1 cm (Cabeza et al. [18]). Because many PCMs have low thermal conductivity, a disadvantage of macroencapsulation is the tendency to solidify/melt at the edges leading to a slower energy uptake and release which may prevent the system from discharging completely overnight. The size of the macrocapsules imply that they have to be protected against destruction or perforation and may also make them more difficult to integrate into the building structure, which hence may make these systems more expensive (Schossig et al. [99]).

Figure 5 Examples of macroencapsulation of commercial PCMs (RGEES [89], RGEES [90], Salca [103]).

2.4 Long-term stability

For successful large scale application of PCMs into the building sector it is crucial that the PCM and PCM-container system can withstand cycling over an extended period of time without showing signs of degradation. There are two main factors which govern the long-term stability of PCM storage materials. Poor stability of the materials, e.g. supercooling and phase segregation, and corrosion between the PCM and the container system (Mehling et al. [77], Shukla et al. [109]). Degradation of PCMs may result in decreased ability to store latent heat and a difference in phase change temperature.

Accelerated ageing tests on stearic acid and paraffin wax, both organic PCMs, have been conducted by Sharma et al. [104]. Both stearic acid and paraffin wax performed well and showed no regular degradation of their melting point over 1500 thermal cycles. However, of the fatty acids, palmitic acid and myristic acid showed to have the best long-term stability (Sari and Kaygusuz [96]), which may make them more suited for building applications compared with other fatty acids.

A comprehensive review on the thermal stability of organic, inorganic and eutectic PCMs have recently been given by Rathod and Banerjee [88]. This work covers the investigations on thermal stability of PCMs done over the past few decades. Paraffins have shown good thermal stability. For fatty acids the purity plays an important role. Industrial grade fatty acids may experience changes in its thermal behaviour over time and should be tested by accelerated ageing. Of inorganic PCMs, salt hydrates are the most widely studied. Most studies have shown that the thermal stability of salt hydrates is poor due to phase separation and supercooling. However, the thermal stability may be improved to a certain extent by introducing gelled or thickened mixtures and suitable nucleating materials. In general, new building materials, components and structures should be examined by accelerated climate ageing (Jelle [49]), PCMs being no exception. Furthermore, a robustness assessment may also be performed (Jelle et al. [52]).

3 State-of-the-art phase change materials

As mentioned earlier, PCMs can be found in a wide variety of temperature ranges. The PCMs in this study have been limited to PCMs with phase change temperatures in the appropriate range for efficient in buildings. Cabeza et al. [18] has listed several tables of PCM properties where the potential areas of use have been divided by the PCMs' phase change temperature. For use in buildings, three temperature ranges were suggested. i) up to 21 ^{o}C for cooling applications, ii) 22-28 ^{o}C for human comfort applications and iii) 29-60 ^{o}C for hot water applications. For this study, PCMs with phase change temperatures ranging from 15-32 ^{o}C have been included. Note that many of the manufacturers included in this study offer PCMs outside this temperature range as well.

3.1 Phase change material compounds

By PCM compounds it is referred to products that are made up of PCMs and their prospective encapsulation materials. These are products that have not been combined into products ready for building applications.

Table 2 shows an overview of manufacturers and their commercial products with some important properties. More information about the products can be found in the appendix.

Table 2 Manufacturers and properties of commercial PCMs (see Table A1 in appendix for further information).

Manufacturer	Product	Phase change temperature Melting/freezing (°C)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
BASF	DS 5030	21/n.a.	37	Dispersed wax mixture	Organic	Microencapsulation
	DS5007	23/n.a.	41	Dispersed wax mixture	Organic	Microencapsulation
	DS 5000	26/n.a.	45	Dispersed wax mixture	Organic	Microencapsulation
	DS 5029	21/n.a.	90	Powder form wax mixture	Organic	Microencapsulation
	DS 5008	23/n.a.	100	Powder form wax mixture	Organic	Microencapsulation
	DS 5001	26/n.a.	110	Powder form wax mixture	Organic	Microencapsulation
RGEES	PCM-OM21P	n.a./21	120	Organic chemicals	Organic	
	PCM-HS22P	23/22	185	Inorganic salts	Inorganic	
	PCM-HS24P	24/25	185	Inorganic salts	Inorganic	
	PCM-HS29P	29/29	190	$CaCl_2$ and other salts	Inorganic	
	PCM-OM32P	n.a./32	235	Organic chemicals	Organic	
Phase change products	PC14	14/n.a.	145	Hydrated calcium chloride and calcium bromide	Inorganic	
	PC17	17/n.a.	145	Hydrated calcium chloride and calcium bromide	Inorganic	
	PC25	25/n.a.	150	Hydrated calcium and magnesium and chlorides	Inorganic	
	PC29	29/n.a.	188	Hydrated calcium chloride	Inorganic	
Entropy Solutions Inc.	PureTemp 15	15/n.a.	165	Vegetable based		Micro- and macroencapsulation
	PureTemp 18	18/n.a.	189	Vegetable based		Micro- and macroencapsulation
	PureTemp 20	20/n.a.	180	Vegetable based		Micro- and macroencapsulation
	PureTemp 23	23/n.a.	203	Vegetable based		Micro- and macroencapsulation
	PureTemp 24	24/n.a.	185	Vegetable based		Micro- and macroencapsulation
	PureTemp 25	25/n.a.	185	Vegetable		Micro- and

Manufacturer	Product	Phase change temperature Melting/freezing (^oC)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
				based		macroencapsulation
	PureTemp 27	27/n.a.	200	Vegetable based		Micro- and macroencapsulation
	PureTemp 28	29/n.a.	205	Vegetable based		Micro- and macroencapsulation
	PureTemp 29	29/n.a.	189	Vegetable based		Micro- and macroencapsulation
	PureTemp 31	31/n.a.		Vegetable based		Micro- and macroencapsulation
Salca	Thermusol HD26	26/n.a.		Salt hydrate	Inorganic	Microencapsulation
	Thermusol HD32	32/n.a.	150	Salt hydrate	Inorganic	Microencapsulation
Climator Sweden AB	ClimSel C21	21/n.a.		Sodium sulphate	Inorganic	
	ClimSel C24	24/n.a.		Sodium sulphate	Inorganic	
	ClimSel C28	28/n.a.		Sodium sulphate	Inorganic	
	ClimSel C32	32/n.a.		Sodium sulphate	Inorganic	
Phase Change Material Products Ltd.	S15	15	160	Salt hydrate	Inorganic	
	S17	17	160	Salt hydrate	Inorganic	
	S19	19	160	Salt hydrate	Inorganic	
	S21	22	170	Salt hydrate	Inorganic	
	S23	23	175	Salt hydrate	Inorganic	
	S25	25	180	Salt hydrate	Inorganic	
	S27	27	183	Salt hydrate	Inorganic	
	S30	30	190	Salt hydrate	Inorganic	
	S32	32	200	Salt hydrate	Inorganic	
	A15	15	130		Organic	
	A16	16	213		Organic	
	A17	17	150		Organic	
	A22	22	145		Organic	
	A22H	22	216		Organic	
	A23	23	145		Organic	
	A24	24	145		Organic	
	A25	25	150		Organic	
	A25H	25	226		Organic	
	A26	26	150		Organic	
	A28	28	155		Organic	
	A29	29	226		Organic	
	A32	32	130		Organic	
	X25	25	110			Solid-solid phase change
	X30	30	105			Solid-solid phase change
PCM Energy P. Ltd.	Latest 18T	17-19	175	Inorganic salts	Inorganic	
	Latest 20T	19-20	175	Inorganic salts	Inorganic	
	Latest 25T	24-26	175	Inorganic salts	Inorganic	
	Latest 29T	28-30	175	Inorganic salts	Inorganic	
	Latest 32S	31-32	>200	Inorganic salts	Inorganic	
Microtek Laboratories	MPCM 18	18/n.a.	163-173	n-Hexadecane	Organic	Microencapsulation
	MPCM 18D	18/n.a.	163-173	n-Hexadecane	Organic	Microencapsulation
	MPCM 24	24/n.a.		Special blend		Microencapsulation
	MPCM 24D	24/n.a.		Special blend		Microencapsulation
	MPCM 28	28/n.a.	180-195	n-Octadecane	Organic	Microencapsulation
	MPCM 28D	28/n.a.	180-195	n-Octadecane	Organic	Microencapsulation
	MPCM28D-IR	25-32/n.a.	160-180	Special blend		Microencapsulation
	MPCM 32	32/n.a.		Special blend		Microencapsulation
	MPCM 32D	32/n.a.		Special blend		Microencapsulation
Cristopia	AC 27	27				Nodules filled with PCM

Manufacturer	Product	Phase change temperature Melting/freezing (°C)	Latent heat capacity (kJ/kg)	Material	Type*	Encapsulation
Rubitherm Technologies GmbH	RT 18 HC	17-19/19-17	250			
	RT 21	18-23/22-19	160			
	RT 21 HC	20-23/21-19	190			
	RT 22 HC	20-23/23-20	200			
	RT 24	21-25/25-21	150			
	RT 25	22-26/26-22	148			
	RT 25 HC	22-26/26-22	230			
	RT 27	25-28/28-25	179			
	RT 28 HC	27-29/29-27	245			
	RT 31	27-33/33-27	170			
	SP 21 E	22-23/21-19	160	Salt hydrates and organic compounds		
	SP 22 E	22-23	180	Salt hydrates and organic compounds		
	SP 24 E	24-25/23-21	222	Salt hydrates and organic compounds		
	SP 25 E	24-26/24-23	200	Salt hydrates and organic compounds		
	SP 26 E	25-27/25-24	200	Salt hydrates and organic compounds		
	SP 31	31-33/30-28	220	Salt hydrates and organic compounds		
	PX 15	10-17/17-10	85			Microencapsulation
	PX 25	22-25/25-22	96			Microencapsulation
	PX 27	25-28/28-25	102			Microencapsulation
	PX 31	27-31/33-27	110			Microencapsulation

* Many manufacturers do not give a full description of the mixtures used in PCMs. Hence, type has only been limited to organic and inorganic, though some of these may be eutectic mixtures as well.

3.2 Phase change materials in products for building applications

The PCM technology has already been combined with several other products which are directly aimed at the building sector. PCM enhanced materials include e.g. wallboards, floor tiles, ventilation systems, mats and tubes. Table 3 shows an overview of manufacturers and their commercial products with some important properties. More information about the products can be found in the appendix

Table 3 Manufacturers of products ready for building applications (see Table A2 in appendix for further information).

Manufacturer	Product	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	PCM material	Type*	Building product
Dupont	Energain	18-24	515 kJ/m^2	Paraffin wax compound	Organic	Thermal mass panels
Knauf	Comfort board			BASF micronal		Gypsum board with microcapsules of PCM
	Smartboard 23	23	200 kJ/m^2	BASF micronal		
	Smartboard 26	26	330 kJ/m^2	BASF		

Manufacturer	Product	Phase change temperature (^oC)	Latent heat capacity (kJ/kg)	PCM material	Type*	Building product
				micronal		
RGEES	PB29P	29	33 kWh/cbm		Organic	Spheres of 75 mm in diameter filled with PCM
	PB22P	22	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM
	PB24P	24	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM
	PB29P	29	0.1 kWh/(ft^2)		Inorganic	Tubes filled with PCM
Phasechange energy solutions	BioPCMat M27	23		Bio-based	Organic	Mats filled with PCM
	BioPCMat M51	25		Bio-based	Organic	Mats filled with PCM
	BioPCMat M91	27		Bio-based	Organic	Mats filled with PCM
	Thermastix			Bio-based	Organic	Stick filled with PCM
Dörken	Delta-cool 24					No longer available on the market?
	Delta-cool 28					No longer available on the market?
Salca	K-Block		590 kJ/m^2	Salt hydrate	Inorganic	Mat filled with PCM
SGL Group	Ecophit GC20	22	85 (kJ/kg)			
	Ecophit LC20	22	140 (kJ/kg)			
Phase Change Material Products Ltd.	FlatICE					Flat container filled with PCM
	TubeICE					Tubes filled with PCM
	BallICE					Spheres filled with PCM
National gypsum	ThermalCORE			BASF micronal		Gypsum board with microcapsules of PCM covered with a fibreglass mat
H+H Deutschland	CelBLoc Plus			BASF micronal		Concrete blocks with microcapsules of PCM
Maxit Deutschland	Maxit clima					Plaster with integrated microcapsules of PCM
Ilkazell Isoliertechnik	Ilkatherm air conditoning systems					
Monodraught	Coolphase					Ventilation system with PCM
Tate	EcoCore	75.2 ^oF	147 Btu	vegetable bio based	Organic	Floor tiles
Emco	Emcovent					Decentralised PCM modules
Autarkis						PCM heat exchangers
Armstrong World Industries	Coolzone			BASF micronal	Organic	Chilled roof system
Trox	FSL-B-PCM					Supply air unit with PCM

* Many manufacturers do not give a full description of the mixtures used in PCMs. Hence, type has only been limited to organic and inorganic, though some of these may be eutectic mixtures as well.

3.3 Phase change materials in windows

Windows incorporating PCMs are highly limited on the market. There can be several reasons for this. First of all, the PCM relies on a process where the materials solidifies below a certain temperature. Windows are in many cases used for aesthetic purposes, to allow visibility towards the outside or allow daylight in to the building. Most PCMs in use on the market are not transparent in both their liquid and solid state. Hence, PCM windows will be blurry and reduce transmission of daylight and solar radiation in general. Only one manufacturer of windows including PCMs has been found in this study. The products currently on the market are categorized as translucent. Table 4 shows an overview of the manufacturers of PCM windows and some of their important properties.

Table 4 Manufacturers of windows incorporating PCMs (see Table A3 in appendix for further information).

Manufacturer	Product	Phase change temperature (^oC)	Heat storage capacity (Wh/m^2)	T_{vis} solid/liquid (%)	Material	Type
GLASSX	GLASSX crystal	26-30	1185	0-28/4-45	Salt hydrates	Inorganic
	GLASSX comfort	26-30	1185	0-38/4-55	Salt hydrates	Inorganic
	GLASSX slim	26-30	1185	0-38/4-45	Salt hydrates	Inorganic
	GLASSX store	26-30	1185	0-38/4-55	Salt hydrates	Inorganic

3.4 Comparison of commercial products

Commercial PCMs come in a variety of forms and solutions, e.g. PCM infused wallboards, microcapsules filled with a PCM dispersed in a liquid or in powder form or mats that can be installed directly. There is no clear preference towards organic or inorganic PCMs in commercial products and both are ready and available for use. A market study performed by Markets and Markets [75] showed that organic PCMs held the highest market share in terms of value due to higher cost, while inorganic PCMs held the highest market share in terms of volume.

The tables includes manufacturers who produce the raw PCM material, as well as manufacturers who produce building materials based on their own or other manufacturers PCMs. All commercial building materials produced with PCMs use some form of encapsulation. None of the commercial building products found in this study are created using direct incorporation or immersion. This may be due to the fact that these techniques will lead to a material with a large probability of leakage of the PCMs to the surface. Hence, it does not meet the strict requirements for building applications with regard to lifetime expectancy.

Both products created by macro- and microencapsulation are already commercialized. Macroencapsulated products include tubes, flat containers and spheres ranging from some millimetres up to about 75 millimetres. Microencapsulated PCMs are generally already integrated into building materials such as gypsum and plaster.

Several producers state that there is no sign of degradation after 10 000 cycles for their organic PCMs, giving the PCMs a lifetime of approximately 30 years or more.

An aspect which is of most importance is how the various manufacturers have solved the issue of organic PCMs with respect to fire resistance. Materials that are aimed for building applications have to overcome some strenuous requirements with regard to safety. And as mentioned earlier, one drawback of organic materials is the fact that many of them are flammable and may release toxic fumes during combustion.

An interesting point is the phase change temperature. Some manufacturers state both melting and freezing temperatures, some state a "phase change temperature", which does not tell whether the material freezes or melts at the same temperature or if it is simply one of the two temperatures, and some manufacturers state the range over which freezing and melting occurs instead of a single temperature where the phase change is at its peak. The variation in how manufacturers choose to state the phase change temperature is an interesting point also with respect to the uncertainty of describing the enthalpy curve of the PCMs that still exists, and the difficulty of giving a value that properly represents the phase change reaction.

The latent heat capacity also varies for the presented products, and it is hard to determine why there are such differences as the materials used are not always given. The parameters that affect a PCM's latent heat capacity is something that should be more clearly stated to be able to compare products. The total latent heat capacity does after all describe the total energy that can be absorbed during phase change, and is one of the most vital parameters when selecting PCMs. By evaluating the studied products the latent heat capacity seems to vary due to encapsulation methods, the application method of the PCM, e.g. slurries or powder. Altering of the phase change temperature of the same product from the same manufacturer also gives changes to the latent heat capacity, this is most likely due to changes in the PCM mixture to attain the desirable temperature. What changes are made in the material to attain a desired phase change temperature is not so clearly defined, so it has not been possible to determine which parameters that has been altered and why it affects the latent heat capacity.

4 Phase change materials in building applications

4.1 Building applications

Zhu et al. [129] presented an overview of research conducted on PCMs with regards to their dynamic characteristics and energy performance in buildings. This overview divided the possible building applications of PCMs into four categories:

- Free cooling.
- Peak load shifting.
- Active building systems.
- Passive building systems.

Besides these suggested applications, another interesting possible benefit of PCMs is their ability to increase thermal comfort by smoothing out temperature fluctuations. The study given herein is mostly focused on the effect of passive building systems through the integration of PCM enhanced building materials. However, a short overview and explanation of some of the research that has been performed and possibilities for the other systems will be given.

4.1.1 Free cooling

Free cooling systems with PCMs work by storing outdoor coolness (e.g. during the night) and release the coolness indoors during the day. The PCM can then be used during the day to absorb the heat from e.g. passing air in a ventilation system or water in a pipe system, and stored as latent heat, to cool the building in the day when temperatures are higher and the need for cooling arises. These systems work as long as the ambient temperature allows the PCM to freeze and melt over the day, i.e. the ambient temperature must be above the phase change temperature during the day and below during the night (Fig.6) (Zalba et al. [125]).

Mosaffa et al. [80] described a free cooling system using PCM slabs separated by air gaps for air to flow through (Fig.6). The model developed from this can be used to evaluate performances of latent heat storage systems for free cooling air conditioning systems.

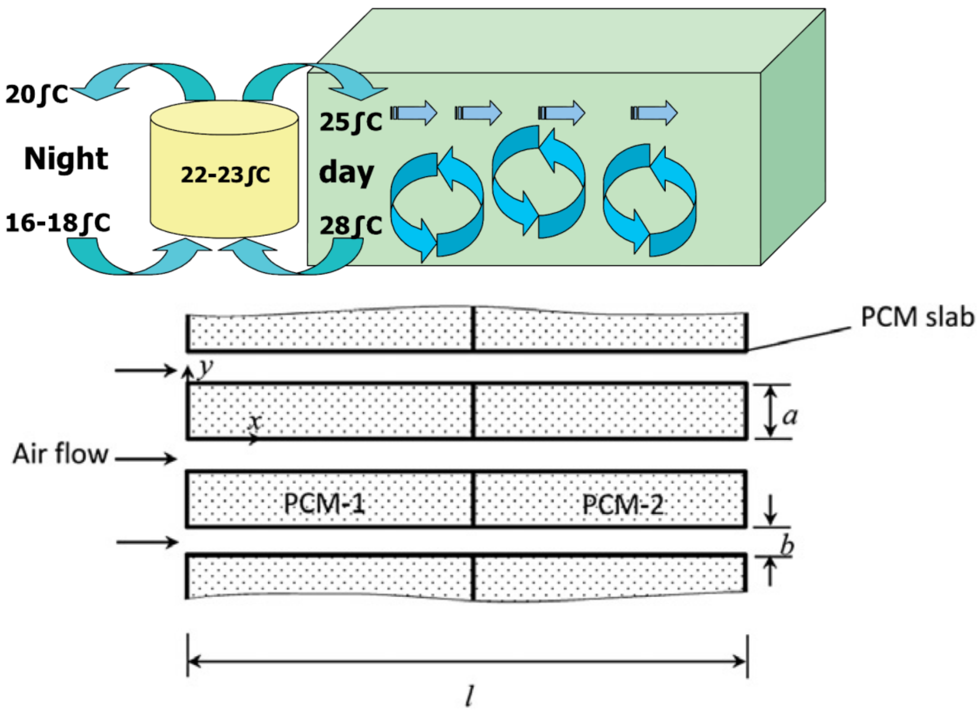


Figure 6 Schematic of a free cooling air conditioning system according to Zalba et al. [125] (top) and Mosaffa et al. [80] (bottom).

4.1.2 Peak load shifting

Peak loads that hit during the day put pressure on the electrical grid and also lead to the need for heating, ventilation and air conditioning (HVAC) systems being dimensioned for higher heating or cooling loads. Ultimately, this could lead to a need for more power generation facilities being built. By shifting the peak load away from the peak hours of electrical demand using PCMs, the peak load may be divided throughout the day reducing the highest peaks (Halford and Boehm [33]). Figure 7 illustrates how the peak may be both reduced and shifted by the use of PCMs.

Sun et al. [114] reviewed strategies involving PCMs for peak load shifting and control that have been tested so far. From the studies reviewed, peak cooling load reductions ranging from 10% to 57% with no or simple control strategies were found. The greatest reductions were found in cases where the PCM was compared against an insulated lightweight construction, while the lowest reduction was found when comparing against structures containing more mass, e.g. concrete. However, the cost saving potential of these systems could be further improved if more sophisticated load shifting control strategies were developed.

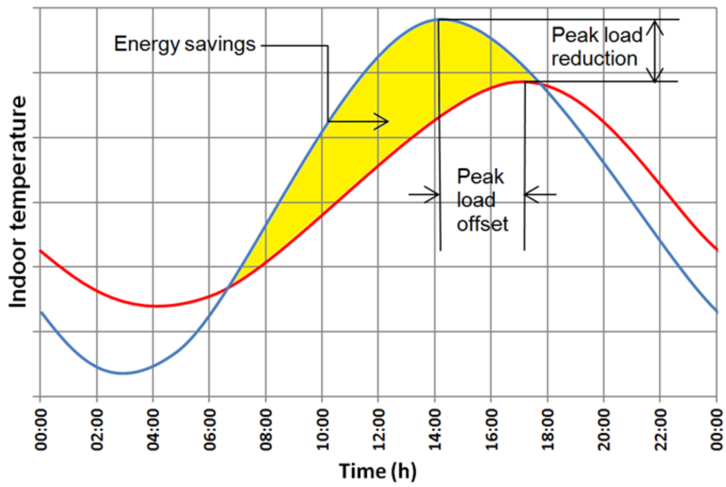


Figure 7 Illustration of peak load offset and peak load reduction (Redrawn from Tate [116]).

4.1.3 Active building systems

The storage capability of PCMs can be integrated into systems such as e.g. solar heat pump systems, heat recovery systems and floor heating systems. Such systems can be combined to attain a peak load reduction as described in the previous chapter. However, if they are made even more effective they can achieve further savings through reduced electrical demand for HVAC systems.

An example of a radiant floor incorporating PCMs in an active system has been described by Ansuini et al. [6]. The system investigated consists of a lightweight piped radiant floor system with an integrated PCM layer aimed at buffering internal gains during the summer season without affecting the winter warming capacity.

4.1.4 Passive building systems

Passive building systems is the use which has attained the most interest as of yet. For passive applications, PCMs are integrated into the building envelopes to increase the thermal mass. This is especially beneficial in lightweight constructions, which suffer from low thermal

inertia. A known issue for these buildings are large temperature fluctuations in the summer due to excessive overheating caused by a lack of thermal mass. This is especially the case in cold climates where buildings have been built according to passive house standards, often involving large amounts of insulation to reduce heating loads in the winter.
The materials incorporating PCMs will melt during the daytime and solidify during nighttime. This will help rooms from overheating during the daytime in warm months and may also reduce the need for heating during nighttime in the winter.

An issue that has been brought up is the importance of getting passive PCM systems to completely discharge during nighttime in warm periods. If the PCM is not able to completely solidify, the effectiveness of the system may be considerably reduced. This point makes PCMs more effective in climates with large daily variation in temperatures. For areas where the discharge does not happen naturally, cool air has to be supplied during nighttime to reset the PCMs completely.

4.1.5 Thermal comfort control

Though PCMs show potential for energy savings, another important factor to highlight is the benefits PCMs may have towards increasing the overall indoor thermal comfort. Lan et al. [69] showed a correlation between workers' performance and productivity compared to the sensation of thermal comfort due to shifting temperatures. Seppänen and Fisk [102] showed that elevated air temperatures had a negative effect on performance and productivity. When temperatures increased up to 20 ^{o}C there was an increase in working performance. However, when temperatures increased above 23 ^{o}C there was a decrease in productivity. Maintaining a steady temperature around the comfort zone for longer periods without relying on HVAC systems may be possible with PCMs.

With PCMs installed temperature fluctuations are reduced. The focus should be placed on selecting a PCM within the desired melting/freezing point so temperatures stay stable around the comfort temperature. This will benefit the indoor climate in two ways. First, the temperature will be held more stable, reducing the feelings of thermal discomfort due to temperature fluctuations throughout the day. Second, the peak temperature will be reduced and should not reach a temperature which leads to increasing thermal discomfort. Another possible benefit of PCMs can be that they lead to a more uniform temperature between surfaces and air temperature, reducing thermal discomfort from radiative heat.

4.2 Solar energy storage

PCMs hold the ability to store energy given off by the sun. Where solar cell panels can produce energy during hours of solar radiation, PCMs can store some of the excess energy and release it at a more needed time of the day. This can be combined with different energy distribution systems such as a heat pump.

For PCMs to best utilize the solar energy it is important that the surfaces are positioned in areas where they can fully absorb the energy coming from the sun, e.g. wallboards or PCM windows. PCM incorporated into concrete floors is an example of a position which poorly utilizes the possible energy gains from the sun as such floors are covered with other materials in most traditional structures.

4.3 Examples of integration of phase change materials for passive systems

Though there have been few detailed studies on the overall effect of PCMs in real life constructions, commercial PCM products have already been used in several projects. In the following, examples from some of these constructions, reasoning for the use of PCMs as well as general thoughts around possible areas and materials where PCMs can be incorporated beneficially, will be explored. The solutions treated in this chapter are all seen as part of a passive system.

When used in buildings, PCMs can be integrated into other building materials. This has attracted a lot of interest as it will enable buildings to be built fairly similar to the way they are built today, but with materials that have an increased thermal energy storage capacity.

In the reviewed literature it is obvious that wall systems integrating PCMs have received the most attention. Studies on floor and roof systems are limited.

4.3.1 Walls

The most common solution for implementing PCMs into buildings so far is by installing PCM enhanced wallboards towards the interior side of the building envelope. For lightweight structures, which have low thermal inertia, PCMs can provide a significant increase in thermal storage capacity. When facing the interior rooms of a building or being used in partition walls, wallboards will be able to absorb and release heat throughout the room for large parts of the day. Several investigations, both experimental and practical, have been conducted to see how this affects overall indoor climate and energy usage.

Experimental hot box tests have shown that PCM wallboards give an obvious reduction in temperature fluctuations as demonstrated in Figure 8 (Sunliang et al. [115]).

A full-scale investigation was performed on a lightweight building's inner partition walls. In this study, several positive effects could be seen when a room with PCM wallboards was compared to one without PCMs added. Air temperature fluctuations were reduced, the overheating effect was lower and the PCM wall was shown to release energy when temperatures fell. The tests also showed reduced fluctuations of the surface temperature of the wall, i.e. lower surface temperatures during the day and higher surface temperatures during the night. Hence, the thermal comfort by radiative effects could be increased during daytime (Kuznik et al. [65]).

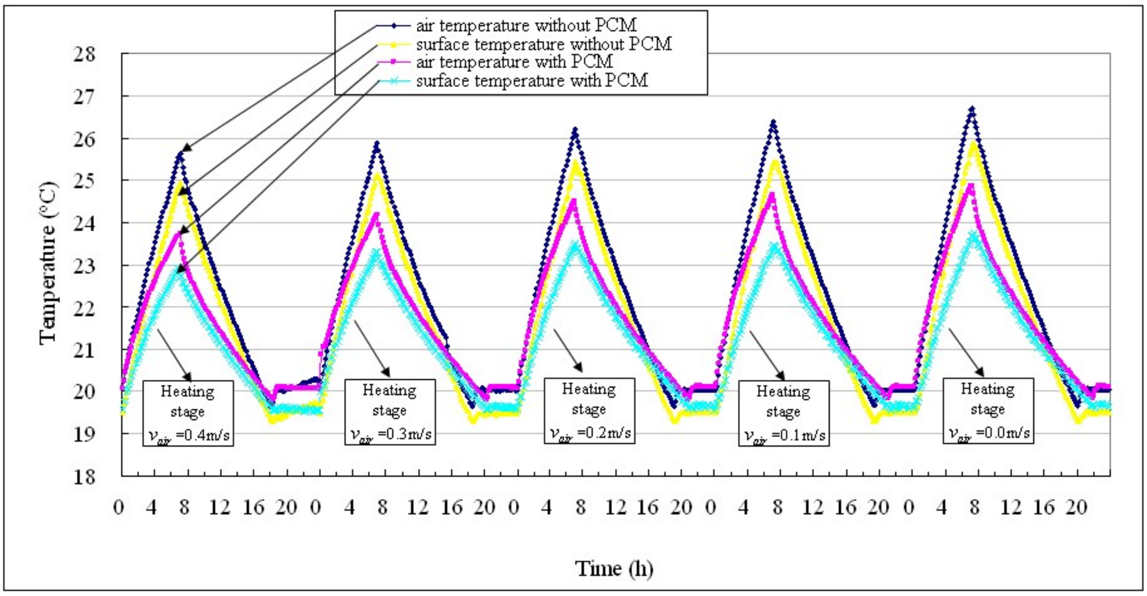


Figure 8 Indoor air and surface temperatures of a test wall with and without PCM panels versus elapsed time, demonstrating the ability of the PCM panels to decrease the indoor temperature variations with about 2 °C. Redrawn from Sunliang et al. [115].

Kuznik and Virgone [66] performed an experimental investigation in a full-scale test room for a typical day in the winter, summer and mid-season with PCM enhanced wallboards. The PCM wallboards were created by adding 60% microencapsulated paraffins in a flexible sheet of 5 mm thickness. The PCMs were shown to reduce overheating effects, reduce the surface temperature on the walls and enhance the natural convection mixing of the air.

Evola et al. [27] performed a simulated case study of an office building refurbished with PCM enhanced wallboards during summer conditions. The wallboards were made of an aluminium honeycomb matrix and filled with 60% microencapsulated PCMs with paraffin as the core material. This simulation showed that even if the PCMs are frequently activated, on average they only utilized 45% of their total latent heat storage potential, meaning that the entirety of the PCM will not melt or solidify within each cycle. The utilization of total latent heat storage potential is affected by factors such as e.g. convective heat transfer across the wall surface, whether it is placed in areas of a room which receives low amounts of direct solar radiation and climate conditions such as cloudy weather or extreme temperatures that are outside the expected normal temperatures. The study also discussed the importance of evaluating the PCM over a longer period of time, such as a few months rather than a few days, to be able to better evaluate the activation rate and the utilization rate of total latent heat storage potential of a PCM under a given climate.

Diaconu [24] studied the influence of the occupancy pattern and ventilation may be affected by PCM enhanced envelopes. Through numerical simulations the potential for thermal energy savings for heating was investigated. It was clear that occupancy patterns and ventilation must be considered when attempting to select the optimal PCM melting temperature.

Ascione et al. [7] investigated the possibility of refurbishing a building with PCM plaster on the inner side of the exterior building envelope and the effect it would have on energy savings and indoor comfort in the cooling season. The results were simulated while varying the phase change temperature, thickness of the wallboard and the location of the PCM layer. Phase change temperatures ranging from 26 ^{o}C to 29 ^{o}C were tested. With a melting temperature of 29 ^{o}C the highest energy saving potential and increase in comfort hours were seen. However, the achievable benefit for energy savings in climates simulating Seville and Naples were no more than 3%, while Marseille and Athens received a benefit of 4.1 and 3.5% respectively. The highest energy saving effect was reached in Ankara, with energy savings of 7.2%. The comfort hours during the occupied hours increased by 15.5% (Seville), 22.9% (Naples), 19.8% (Marseille), 15.8% (Athens) and 20.6% (Ankara).

The experiments conducted by Ascione et al. [7] also highlight another important factor for PCMs. They found that during the summer, the period with temperatures lower than the phase change temperature, i.e. the period where the PCM solidifies, would not always be sufficient for the PCM to fully solidify. The same would also occur during the winter time, where the heat available during the day would not be enough to completely melt the PCM. This indicates that the optimal phase change temperature is seasonal, and complete discharge, or complete absorbance of heat, is difficult to obtain for a single PCM.

Shilei et al. [106] tested the impact of PCM incorporated gypsum boards at winter climate conditions in the northeast of China. The experiment was performed on two similar rooms, one with PCM and one without PCMs. The PCM room showed that it could reduce the heat transfer to outdoor air and improve the thermal comfort. Furthermore, the possibility to reduce the scale of the heating equipment was shown.

A renovation project in the south of Lyon using PCM enhanced wallboards was monitored over a one year period by Kuznik et al. [68]. The room was compared to a room in the same building that was renovated without PCMs. The effect of the PCM showed through increased thermal comfort of the occupants due to air temperature and radiative effects. However, the PCMs seemed to be unable to utilize its latent heat storage capacity over several periods over the year due to excessive temperatures and the lack of a complete discharge overnight.

Becker [16] investigated how thermal and energy performance of a building would be affected by placing PCMs on the inner surface of the walls during summer conditions. By using EnergyPlus and a simplified model the thickness of the PCMs needed to store heat gains from solar radiation and occupancy patterns occurring during the day, and ventilation needed by night to discharge they system were studied for lightweight buildings, semi-lightweight buildings and heavyweight buildings in a Mediterranean climate. In heavyweight constructions, PCMs could improve thermal conditions, but had a marginal effect on energy savings. For lightweight dwellings and offices and semi-lightweight schools the analyses showed positive effects on both thermal and energy performance. The greatest effect was seen in lightweight office buildings, where energy savings up to 57% were found. However, this study also pointed out the importance of occupancy patterns and the focus on including night ventilation needed for discharging when studying PCMs. It is still important to get full-scale validation in occupied buildings under normal working and climate conditions.

4.3.2 Floors

Areas which are in direct contact with solar radiation hold large potential for storage of thermal heat energy. Floor solutions incorporating PCMs in areas of a building where the sun shines for large parts of the day may benefit from incorporating PCMs. Figure 9 shows flat profiles filled with PCMs that were used in the floor in North House, a competitor in the US Department of Energy's solar decathlon.

Figure 9 Flat profiles which can be installed under floor to store and release latent thermal heat energy (Cosella-Dörken [22]).

Xu et al. [122] performed a simulation on the thermal performance of PCMs used in a passive floor system during the winter season. The performance on the systems was influenced by the choice of covering material, the air gap between the PCM and covering material and the thickness of the PCM. For the simulations performed, the thickness should not exceed 20 mm as this would not increase the influence of the thermal storage significantly.

4.3.3 Roofs

Implementing PCMs into roof systems does not seem to have received much attention. Only a few studies on the possible effects of PCMs in passive roof systems have been found. The thought is that PCMs placed on the roof will be able to absorb the incoming solar energy and the thermal energy from the surroundings to reduce temperature fluctuations on the inside.

Pasupathy and Velraj [83] studied the effects of a double layer of PCM for year round thermal management in Chennai, India. An experiment was performed with a PCM roof panel compared to a reference room without the PCM panel. The PCM used was an inorganic eutectic of hydrated salts. The experiment showed that the PCM panel on the roof narrowed the indoor air temperature swings, and that such a system could perform during all seasons when the top panel had a melting temperature 6-7 ^{o}C higher than the ambient temperature in the early morning during the peak summer month, and the bottom panel had a melting temperature near the suggested indoor temperature.

Kosny et al. [62] set up a naturally ventilated roof with a PV module and PCMs to work as a heat sink (Fig.10). The goal was that the PCM would absorb heat during the day in winter and release it in the night to reduce heating loads. In the summer the PCM would absorb heat to reduce the cooling loads in the attic beneath. A full scale experiment was performed over a whole year from November 2009 until October 2010 in Oak Ridge, Tennessee. The data from the tests were compared with a conventional asphalt shingle roof. The PV-PCM attic showed a 30% reduction in heating loads during the winter and a 55% reduction in cooling loads. Furthermore, 90% reduction in peak daytime roof heat fluxes were observed.

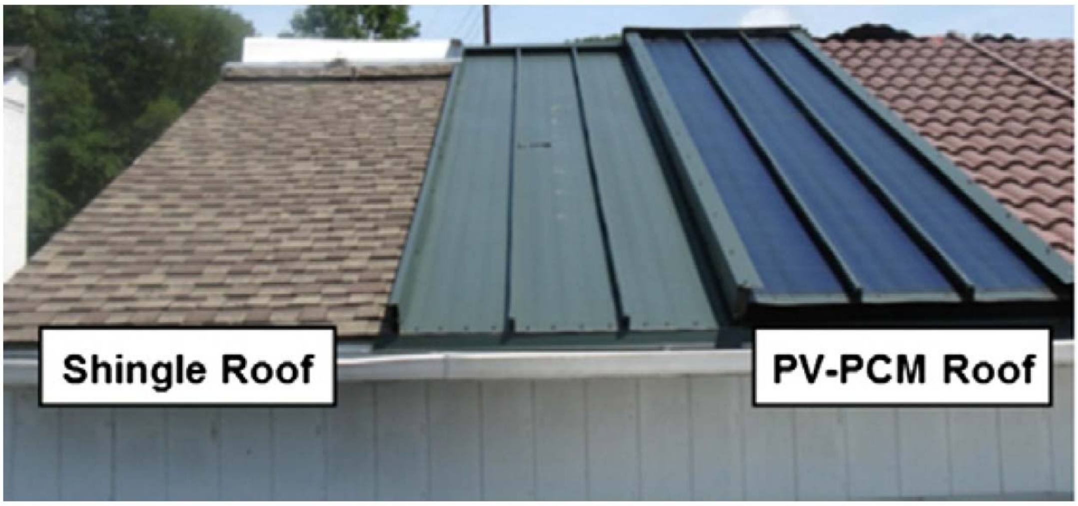
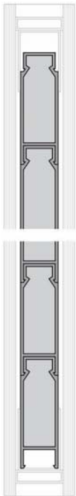


Figure 10 PV-PCM roof (Kosny et al. [62]).

4.3.4 Windows and shutters

Windows represent a part of the building that is considered to lead to a higher energy consumption. In warm climates dominated by cooling loads, excessive solar heat gain lead to an increased need for mechanical cooling. In cold climates, large parts of the energy escapes through glazed facades, leading to a need for mechanical heating (Ismail et al. [35]). Several new advanced window technologies such as electrochromic windows, low-e glazing, evacuated glazing, self-cleaning glazing, building integrated photovoltaics (BIPV) as solar glazing, etc., have been explored to counter these issues (Baetens et al. [12], Jelle et al. [37], Jelle et al. [38], Jelle and Hagen [39], Jelle et al. [40], Jelle and Hagen [41], Jelle et al. [42], Jelle et al. [45], Jelle et al. [46], Jelle and Breivik [47], Jelle and Breivik [48], Jelle [50], Jelle [51], Midtdal and Jelle [79]). However, glazed facades still suffer from low thermal inertia, and has no way of storing excess heat. Transparent PCMs for use in windows is an opportunity that has been explored for this purpose.

The first issue to overcome is the desire to have sufficiently transparent windows. Figure 11 shows a commercialized glazing filled with a PCM, also depicting the visibility in its liquid state. As of today, only translucent PCMs have been used for PCM windows, though they enable relatively high amounts of visible light to pass through, they do not offer the same visibility as regular windows.



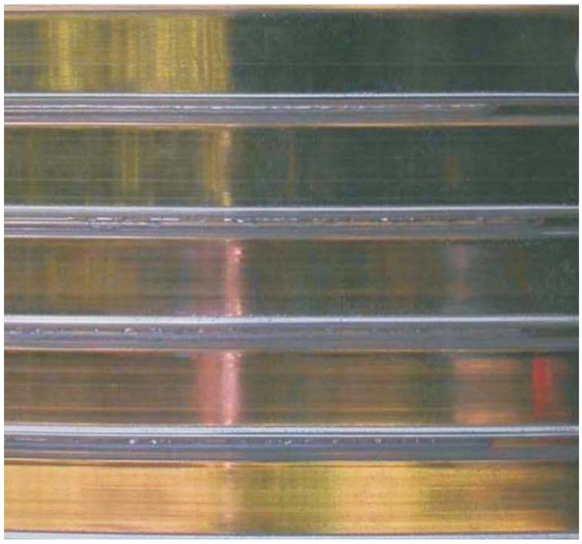


Figure 11 Illustration of a PCM filled window (left) and commercialized PCM window in its liquid state (right) (GlassX [131]).

The solar transmittance of a commercial grade PCM was tested by Jain and Sharma [36]. For a pure PCM with a thickness of 4 to 30 mm the solar transmittance was found to be 90.7 to 80.3% respectively. Due to the fact that PCMs have low thermal conductivity, they concluded that PCMs may be interesting as a transparent thermal insulating medium.

Goia et al. [30] compared a prototype PCM glazing system with a traditional double glazed insulating unit with regard to the effect on thermal comfort in the winter, summer and mid season. The two glazing systems were measured over a six-month experimental campaign, and this data was used to numerically evaluate an indoor office room. The thermal conditions were considerably improved for most parts of the year with the PCM prototype compared to the regular double glazing. However, on cloudy days, the two systems showed similar properties on thermal comfort. The study also highlighted the importance of selecting the correct melting temperature for the PCM as this could affect the system negatively if not optimized.

A similar study was performed by Weinläder et al. [121], comparing a double glazing unit combined with PCM compared to a regular double glazing unit. The test specimens were studied experimentally in an outdoor test facility and the data gained from the experiment was used for further simulations. The light transmittance from this solution was found to be 0.4, giving them the ability to be used as daylighting elements. Compared to regular double glazing they gave a more equalised energy balance, achieving moderate heat gains with very low heat losses. During the winter season, PCM windows improved the thermal comfort considerably and in the summer they shifted heat gains to later in the evening. However, the PCM windows can not be used where visual contact to the environment is desired.

Goia et al. [31] performed a full-scale test on a PCM glazing prototype. The test was performed on a south facing wall during summer, mid-season and winter days in a sub-continental climate and compared to a conventional double glazing for reference. The experiment showed that PCM glazing can reduce the energy gain in the summer by more than 50%. In the winter, heat loss reduction during the day was observed, however this technology might not be effective if the purpose is to achieve solar heat gains. The experiment also pointed out the importance of removing the stored heat during the night via, e.g. night cooling, and selecting the correct phase change temperature, if the system is to function optimally.

Grynning et al. [32] performed measurements on a state-of-the-art commercial glazing including a PCM in a large scale climate simulator. The tested glazing was a 4-layer glazing with a prismatic glass in the outer pane and a PCM fill in the cavity between the inner panes. The study showed that characterization of static components (e.g. U-value, solar heat gain coefficient, thermal transmittance) is insufficient for describing the performance of PCMs due to its dynamic nature.

A zero energy office building using translucent PCMs in the window construction has been built in Kempen, Switzerland (Fig.12). In this project, each second window panel has been equipped with PCM windows. The aim for the windows is to effectively store solar energy during the warmer parts of the day, and release thermal energy throughout the colder periods of the day to reduce the total energy required for space heating.

Figure 12 Zero energy office building from Kempen, Switzerland (Cosella-Dörken [23]).

Alawadhi [3] investigated the possibility to implement PCM in window shutters, where the goal was to see of the solar heat could be absorbed before it reached the indoor space. When compared to foam shutters, the shutters containing a PCM could lead to a reduction in heat gain through the windows by as much as 23.29%.

4.3.5 Concrete

Adding PCMs directly into concrete has shown some promising results through lower thermal conductivity and an increase in thermal mass at specific temperatures. However, PCM concrete has shown some undesirable properties such as lower strength, uncertain long-term stability and lower fire resistance (Ling et al. 2013). Several studies have been conducted on PCM-concrete and have shown positive effect through reduced indoor temperatures in warm climates (Cabeza et al. [17]).

Combining concrete structures with PCMs have been tried in several various ways. One studied solution is to drill holes in the concrete which may then be filled with a PCM (Alqallaf and Alawadhi [5]).

Royon et al. [92] tested the possibility of filling the already hollow areas in a hollow concrete floor with PCMs. The concrete was filled with a paraffin PCM with a melting temperature of 27.5 ^{o}C. This test showed that the temperature on the other side of the hollow concrete was lower during summer conditions. Hence, such floors can be used as a passive thermal conditioner during the summer. However, more tests are needed with real life climate conditions to validate the effects.

4.3.6 Thermal insulation materials

Recently, incorporation of PCMs into fibrous thermal insulation materials has received considerable attention. Kosny et al. [61] performed an experimental and numerical analysis of a wood-frame wall containing PCM enhanced fibre insulation. The wall assembly had an R-value of 4.14 (m^2K)/W (U-value of 0.241 W/(m^2K)). For fibre insulation filled with 30wt% PCM in summer conditions, results showed a reduced peak hour heat gain of 23-37% in Marseille and 21-25% in Cairo and Warsaw.

4.3.7 Furniture and indoor appliances

A point that has not been investigated for this study, but should be mentioned, is the possibility of using PCMs in furniture and other indoor appliances. The benefit of PCMs is as mentioned its ability to store heat in periods where there is a surplus, and release it when there is a deficit. It would be interesting to study how incorporation of PCMs into other components in a building besides the structural components, could benefit energy savings and thermal comfort. PCMs have already been widely studied for textile applications (Sarier and Onder [98]), showing that there is a possibility of adding PCMs to various forms of materials.

4.4 Retrofitting

Building retrofitting is an important measure to reduce the total energy usage worldwide. PCMs may offer an increase in a building's overall energy efficiency with little or no additional space required (Rodriguez-Ubinas et al. [91]). The impacts on the design of the building can be minimalised through solutions such as PCM enhanced wallboards, PCM shutters etc.

4.5 Safety requirements

The safety requirements for materials used in buildings is a crucial point for the PCMs to fulfil. As mentioned earlier, PCMs should not be toxic or flammable. However, for many organic PCMs flammability and possible release of toxic fumes during combustion have been an issue. Solutions have been made to counter this issue, such as ignition resistant microcapsules for PCMs and the adding of fire retardants.

Hence, it is of significance that manufacturers of PCMs for building applications are required to give reliable information about the fire performance of their products. Nguyen et al. [81] reviewed the work that has been carried out to improve fire safety of PCMs. This work investigates the use of fire retardants to increase fire resistance of composite PCMs.

5 Future research opportunities

5.1 Improving the current technologies

5.1.1 Increasing thermal storage capacity

A desirable trait for PCMs is a high thermal storage per unit volume and unit weight. Hence, there is always a focus on finding new materials and solutions that may increase the thermal storage capacity for a given volume or weight of a PCM. However, as mentioned earlier, this should not come at the cost of using potentially environmental harmful materials and chemicals.

Microencapsulation reduces the risk of PCMs leaking from the material in their liquid state. Unfortunately, the encapsulation leads to a lower latent heat storage capacity. The method is a promising way for integrating PCMs with building materials, so finding new methods or materials to encapsulate with, which will give a better thermal storage capacity, is desirable. Possibilities to achieve this may include developing a thinner shell for the capsules, which will increase the weight percent of PCMs in the final products.

5.1.2 Enhancing heat transfer

A problem that has been addressed throughout the literature is the low thermal conductivity for many promising PCMs (around 0.15 - 0.2 W/(mK) for organic PCMs and around 0.5 W/(mK) for inorganic salts). Low thermal conductivity reduces the rate of heat absorption or heat release throughout the PCM, i.e. reducing the effectiveness at which it can store and release thermal energy. This may lead to a system which does not fully utilize the full latent heat storage of PCM materials. In the study conducted on wallboards under summer conditions by Evola et al. [27] they found that the wallboards tested only took advantage of about 45% of the possible latent heat storage. Note that this is affected by several other factors than thermal conductivity alone, such as local climate conditions and the way the system is installed.

Fan and Khodadadi [28] reviewed methods that have been used to enhance the thermal conductivity for the last few decades. Recently, graphite based PCM systems and metal foams have been getting increased attention.

One solution that has been investigated includes adding of a material with a high thermal conductivity to the PCM. A material that has been investigated for this purpose is various carbon-based nano-fillers (Babaei et al. [8], Ji et al. [53], Yu et al. [123]). Though the results are varying, the increase in thermal conductivity has increased between 65 and 336% in these studies.

Another solution is to add the PCM to a material with a porous structure and a high thermal conductivity (Fig.13). Investigations on graphite foam composites (Sedeh and Khodadadi [101], Zhong et al. [127], Song et al. [113]) and metal foams based on aluminium (Jiang et al. [54]) have been conducted. Graphite foam composites have shown potential for creating a structure with high thermal conductivity (ranging from 230-570 times higher than the original PCM).

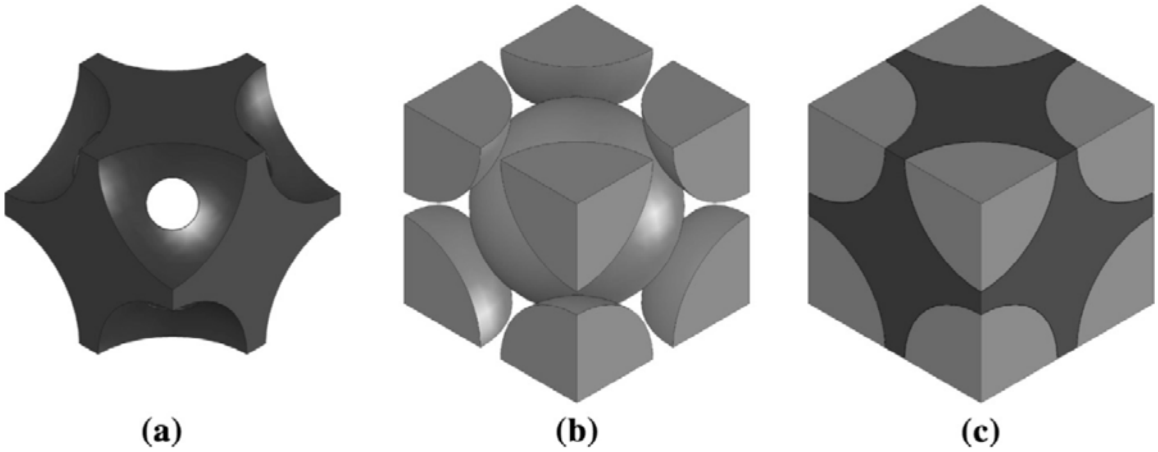


Figure 13 Illustration of (a) graphite foam, (b) PCM material, (c) graphite foam and PCM composite (Sedeh and Khodadadi [101]).

Note that adding a new material to the PCM and creating a composite material reduces the total latent heat storage ability per unit weight due to the adding of new particles. The energy uptake and release of the system may improve, but as of yet, this comes at the cost of less thermal heat storage per unit weight.

5.2 New technologies

5.2.1 Nanoencapsulated PCMs

Though it has not yet been used in commercial products, nanoencapsulation of PCMs may have a potential to improve PCM materials. The idea is similar to that of microencapsulation, but with even smaller capsules ranging in the size of nanometres. A smaller size of the capsules could be interesting due to a higher heat transfer area, leading to a higher heat transfer speed. Several studies have been performed and given functional nanocapsules with PCMs.

Chen et al. [20] prepared nanocapsules containing *n*-dodecanol by miniemuslion polymerization. These capsules reached a latent heat capacity of 98.8 J/g.

Rao et al. [87] performed a simulation on nanocapsules by using *n*-octadecane as the core material and SiO_2 as the shell material. This study pointed out that the possibilities of creating excessive thick or thin shells might be problematic for the current nanocapsules.

Latibari et al. [71] created nanocapsules containing palmitic acid as the core material and SiO_2 as the shell material by a sol-gel method. The latent heat was measured by a differential scanning calorimeter (DSC) analysis and was found to be 180.91 kJ/kg when melting and 181.22 kJ/kg when freezing.

Nanoencapsulation is still a novel technology. However, it would be interesting to see how the nanocapsules perform in comparison to microcapsules when integrated into building materials. Both with regards to energy usage and structural stability in materials such as concrete. An issue that has not been discussed in the studies found is how nanocapsules will compare with respect to overall cost.

5.2.2 Adjustable phase change temperature

Through most of the studies investigated in this review it is clear that the phase change temperature is one of the most important criteria for optimising a PCM system. It is also clear that the optimal phase change temperature for summer conditions will not be optimal for winter conditions and vice versa. Some systems have been described where PCMs of different phase change temperatures are used to partly counter this issue. These systems work by adding different layers of PCMs with different phase change temperatures that can work optimally at different temperatures (Jin and Zhang [55], Pasupathy and Velraj [83]). However, if this could be taken a step further, and a system with an adjustable phase change temperature could be created, the efficiency could be significantly improved. This could either be performed through a controllable or adaptive system and would enable a dynamic change of the phase change temperature in response to user preferences, different climates and different seasons.

5.3 Further reflections

5.3.1 Developing a standard test scheme

With more and more commercial PCM products reaching the market, properties relevant for their use in constructions have to be identified and tested. Mehling et al. [76] showed that PCMs cannot be measured accurately enough by using standards that have been developed for other materials. These tests do not fully map all relevant effects around the phase change process due to PCMs' low thermal conductivity and large melting enthalpy. This leads to an error in the stored heat as a function of temperature and may give errors that can not be tolerated when evaluating the application of PCMs.

It has been pointed out that there is a lack of common test methods to compare and model the results of various PCMs (Agyenim et al. [1], Shrestha et al. [108]). This makes it difficult to assess the suitability for each individual application. Accurate knowledge of a PCM's enthalpy as a function of temperature or storage capacity at each temperature is important for design purposes (Lázaro et al. [72]).

Kousksou et al. [64] reviewed the applications and challenges for energy storage systems, including PCMs. From this study it was found that there were still discrepancies between the literature and actual measurements of thermophysical properties of technical grade PCMs. Thus, further proving that a uniform test standard is needed.

It is important to note that the values measured for pure PCM compounds will not be representative when they are integrated into buildings. Encapsulation materials and combination with building materials will alter the response of the PCMs. It is therefore of importance that finished products aimed for the use in buildings are tested properly. Having a standard test scheme will also be beneficial for future work within field testing of PCMs as all values can be compared with respect to the same conditions.

There are still many issues regarding correct modelling of PCM behaviour. Some of these issues include:

- Properly representing PCM subcooling.
- Incorrect DSC data for whole building simulations.
- Non-uniform PCMs can not be tested in DSC.
- Need for development of Δ-enthalpy charts for PCM-enhanced materials.

Subcooling, which is a common problem for PCMs based on salt hydrates, is still an effect which can not be treated analytically or numerically. If salt hydrate PCMs become widespread, this is an effect that can have major effect on a system's performance, even at just 1 or 2 ^{o}C of subcooling (Mehling et al. [77]).

The most common test methods used for evaluating the performance of PCMs to date are mentioned in the following. Further research into these methods may give a method that can be used as a common standard for testing PCMs in the future.

5.3.2 Differential scanning calorimeter (DSC)

Currently, DSC is the most used method to determine a PCMs thermophysical properties (Barreneche et al. [14]). DSC can only be used for testing small samples of PCMs. Through DSC it is possible to obtain melting temperatures and the heat of fusion. For this purpose, DSC is the most used method. However, for small samples, the degree of supercooling may be increased while the degree of phase segregation may be decreased, giving a different results from actual use of the bulk materials used in practical systems (Zhang and Jiang [126]). DSC can only be performed on relatively uniform test specimens, which is not very realistic when testing building envelope products (Kosny et al. [61]).

5.3.3 T-history

The T-history method allows for testing of the melting temperature, degree of supercooling, heat of fusion, specific heat and thermal conductivity of several PCMs simultaneously (Zhang and Jiang [126]).

Solé et al. [112] wrote a review on the T-history method as it has been used to test PCMs up until recently. The aim of their study was to increase the consensus around the use of this method as it has several advantages when measuring PCMs. The T-history method is efficient at determining fusion enthalpy, specific heat and thermal conductivity for large PCM samples. Nevertheless, there is still no commercial T-history equipment available yet.

5.3.4 Dynamic heat flow apparatus method

The dynamic heat flow apparatus method is based on the traditional heat flow meter apparatus method, which is used to determine steady-state heat transfer properties, thermal conductivity and thermal resistance of flat slab specimens. The traditional heat flow apparatus method is already used in accordance with standards such as EN 12667, ISO 8301 and ASTM C518 to determine these properties for traditional insulation materials. When performing a dynamic heat flow test, the plates on each side of the specimen to be tested are held at the same temperature, and both plates are changed to a different temperature, whereas different temperatures are used in normal heat flow tests. By using the dynamic method, results were found to be more accurate when testing PCMs. Dynamic properties such as heat capacity profiles, peaks of melting and solidification cycles and amount of sub-cooling were found to be relatively similar to those measured by DSC (Shukla et al. [110]).

5.3.5 Dynamic hot box method

The dynamic hot box method can be used to simulate changes in temperature on the climate side of a test specimen. From this, the dynamic thermal characteristics of a building component can be found. When testing PCMs it is important to get as correct picture as possible of their dynamic properties. With the dynamic hot box, the temperature is held constant until a steady-state is reached, then the temperature on one side is changed and results are measured until a new steady-state has been reached.

5.3.6 Dynamic guarded hot plate method

A study recently performed by Pomianowski et al. [86] investigated the possibility of using a dynamic guarded hot plate apparatus to determine the specific heat capacity as a function of the temperature for PCM incorporated concrete. The study describes the experimental set-up and proposes various methods to calculate the specific heat capacity of PCM concrete. The advantage of this method is the possibility to attain a very small heating rate, which can imitate the temperature increase in real building constructions. Thus, simulating realistic thermal conditions of the PCM in actual use. Though the study focuses on PCM concrete, it is also pointed out that this experimental set-up could also be used on various other PCM composites.

5.3.7 M-value

Phase change materials are added to structures and lead to an increase in thermal mass. As PCMs have a specific temperature range, they have also been referred to as "smart thermal mass". However, the phase change temperature of a PCM is not always absolute. It may happen over a small temperature interval and differ between melting and freezing (Fig.14). This is a cause for confusion as there is no standard which specifies in which part of the phase change process this value should be stated. A new energy performance label for PCMs has been mentioned. The M-value, which should express the phase transition related enthalpy change of the PCM within a standardised range so that all values given for a PCM can be evaluated on an equal basis.

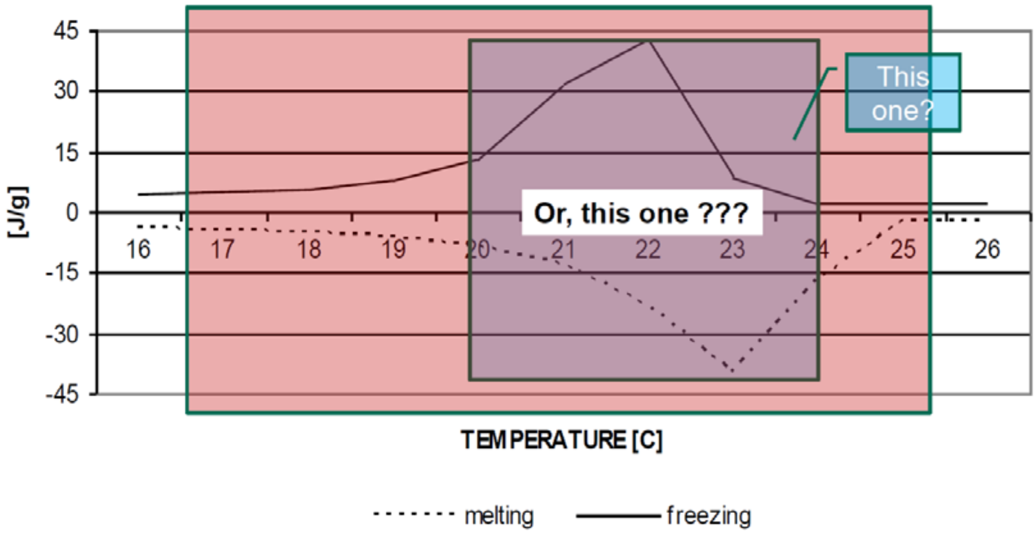


Figure 14 The current confusion around the correct enthalpy value for phase change (Kosny [60]).

5.3.8 Environmental impact assessments

New materials that may be suitable for use as PCMs are continuously being investigated. As mentioned earlier, it is critical that PCMs for use in buildings are not hazardous or poisonous in any ways. This also includes during production and handling after a PCM's useful lifetime. It is important that possible new materials are evaluated with regards to waste from the production and necessary treatment when they are to be disposed. As there may be many different chemicals in use in PCMs, environmental assessments could be conducted to avoid unknown pollutants of any kind.

5.3.9 Expected lifetime predicament of phase change materials

As a thawing/freezing cycle may happen thousands of times, some phase change materials may be prone to deterioration over time. Gradual breakdown of the material will end up reducing the amount of latent heat storage per phase transition and may also affect the phase change temperature. Thus, reducing the overall energy performance. Such deterioration is particularly common in inorganic PCMs, and to some extent in less pure organic PCMs. It is important that future possible PCMs are tested with regard to their ageing over time. As of today there is no standard method to do this. An aim for the future should be to develop a standard testing scheme which all commercial grade PCMs will have to follow when stating the lifetime of their products.

5.3.10 Quantifying the effect of PCMs in real life buildings

Though the theory behind PCMs shows that they have the ability to reduce temperature fluctuations in buildings, there has been no studies to prove an increase in overall thermal comfort or productivity. Some way of measuring the effect and number of full cycles in different environments is needed.

To fully utilize the effect of PCMs an overview of how they perform in different climates are needed. Ideally, a PCM should undergo a full phase change cycle once a day. However, the lack of guidelines for selecting PCMs for various climates is a source for uncertainty when used for building applications. It would be preferable, if a detailed overview of the effect that could be expected for various PCMs in various climates was developed. It has been pointed out that it is difficult to select a PCM that functions optimally for every season and location.

From all the experiments and simulations reviewed in this study, one of the most important factors for implementing PCM enhanced materials is found to be selecting the correct phase change temperature. They also highlight the difficulty of selecting the correct PCM for specific climates and that the effect of PCMs will vary with varying climate conditions over the year.

The selection of a PCM based on a specific phase change temperature in one climate region will not be appropriate for another. Important factors that govern the selection of a PCM includes phase change temperature, local climate, type of PCM and design and orientation of the building (Pasupathy and Velraj [83]). Several other authors have also highlighted the need for guidelines to select PCMs for specific and different climates (Kosny et al. [63], Ascione et al. [7]).

From the various manufacturers that have been investigated in this study a large amount of reference projects have been found. However, to the authors knowledge, there has been no studies to evaluate and quantify the effect of PCMs in these projects. Although every project has been deemed to increase energy efficiency and thermal comfort, monitoring projects from real life buildings should be conducted and evaluated so the beneficial effects of PCMs can be documented and shared.

5.3.11 Investigating payback times for various systems

As PCMs offer a decrease in overall energy usage, in many cases through minimal interference with the original structure, it is highly relevant to know what the payback of the initial investment can be expected to be. To the authors' knowledge, little research has been carried out on this topic. This may come from several factors. The most important being that there is still a lack of knowledge on how PCMs actually perform in real life constructions in all sorts of various climates.

There is still much uncertainty regarding the overall effect of PCMs. Showing the long-term economical benefits of selecting PCMs may help to increase the interest among customers to use PCMs. Should the results of such analyses show unfavourable payback times, it may also help to drive the research and development forward towards more cost-efficient solutions.

Conclusions

Incorporating phase change materials (PCM) into a building enables a more dynamic use of energy. Due to the storage capabilities of PCMs, excess heat can be stored during warm periods and released during cold periods. It may also work the other way around, storing cold energy and using it for free cooling systems in warm periods. The benefits of using PCMs in buildings mainly revolve around a decrease in energy usage along with a peak load shifting of energy required for heating or cooling and an increase in thermal comfort by decreasing temperature fluctuations.

Commercial products have been developed and released on the market with some success. What makes PCMs particularly interesting is the fact that many PCM solutions, e.g. wallboards and floor tiles, can be added to the construction with fairly little alterations to the current way of building. However, there are a wide range of materials which can be used as PCMs and identifying the correct PCM for the specific application and for the specific climate conditions is an area which need further research. Calculations of payback periods for PCM installations are also needed to further validate the use of PCM technology.

Though solutions have been tested to increase thermal conductivity for more effective absorbance and discharge cycles, this has come at the cost of a lower latent heat storage per unit weight and unit volume i.e. and hence giving the PCMs less storage potential. Fire safety is still an issue for organic PCMs, though here as well, solutions which show promise have been introduced.

The PCM technology seems promising, however there are still some hurdles which need to be overcome for a large-scale application of this technology. Standards which state test methods and can help identify the correct PCMs for various climates to enable proper cycling and optimisation of PCM systems are needed. Research into new PCM technologies is also of major importance, e.g. the possibility of having a dynamically adjustable and even controllable phase change temperature.

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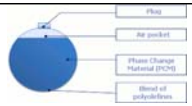
Appendix

Table A1 Manufacturers of PCM compounds.

Manufacturer	Product	Illustration	Phase change temperature Melting/freezing (^oC)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
BASF Tel: +49 (0)621 60-0 Fax: +49 (0)621 60-42525 www.basf.com/group/corporate/en/	DS 5000		21/n.a.	45				Dispersed wax mixture	Organic	http://www.micronal.de/portal/basf/ien/dt.jsp?setCursor=1_290798 (Accessed 10.12.2013)
	DS5007		23/n.a.	41				Dispersed wax mixture	Organic	
	DS 5030		26/n.a.	37				Dispersed wax mixture	Organic	
	DS 5001		21/n.a.	110				Wax mixture in powder form	Organic	
	DS 5008		23/n.a.	100				Wax mixture in powder form	Organic	
	DS 5029		26/n.a.	90				Wax mixture in powder form	Organic	
RGEES North America 1465 Sand Hill Road, Suite #2016, Candler, NC – 28715 Tel: +1 828 708 7178 info@rgees.com http://rgees.com/	PCM-OM21P		n.a./21	120				Organic chemicals	Organic	http://rgees.com/products.php (Accessed 10.12.2013)
	PCM-HS22P		23/22	185		0.54 liquid 1.09 solid		Inorganic salts	Inorganic	
	PCM-HS24P		24/25	185		0.54 liquid 1.09 solid		Inorganic salts	Inorganic	
	PCM-HS29P		29/29	190		0.54 liquid 1.09 solid		Mixture of $CaCl_2$ and other salts	Inorganic	
	PCM-OM32P		n.a./32	235				Organic chemicals	Organic	

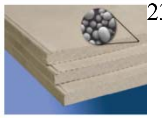
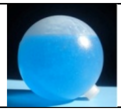
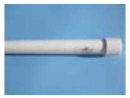
Manufacturer	Product	Illustration	Phase change temperature Melting/freezing (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Phase change products Ground Floor 57 Havelock Street West Perth Western Australia 6005 Tel: +61 8 9324 8520 Fax: + 61 8 9324 8560 keith.coakley@pcpaustralia.com.au http://pcpaustralia.com.au/	PC14		14/n.a.	145		0.010 "J/sec/cmK"		Hydrated calcium chloride and calcium bromide	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc14/ (Accessed 10.12.2013)
	PC17		17/n.a.	145		0.010 "J/sec/cmK"		Hydrated calcium chloride and calcium bromide	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc17/ (Accessed 10.12.2013)
	PC25		25/n.a.	150		0.011 "J/sec/cmK"		Hydrated calcium and magnesium and chlorides	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc25/ (Accessed 10.12.2013)
	PC29		29/n.a.	188		0.011 "J/sec/cmK"		Hydrated calcium chloride	Inorganic	http://pcpaustralia.com.au/pcm-range-products/pc29/ (Accessed 10.12.2013)
Entropy Solutions Inc. 151 Cheshire Lane, Suite 400, Plymouth MN 55441 Tel: +1 952-941-0306 Fax: +1 952-944-6893 info@puretemp.com www.puretemp.com	PureTemp 15		15/n.a.	165				Vegetable based	Organic	http://www.puretemp.com/technology.html (Accessed 10.12.2013)
	PureTemp 18		18/n.a.	189				Vegetable based	Organic	
	PureTemp 20		20/n.a.	180				Vegetable based	Organic	
	PureTemp 23		23/n.a.	203				Vegetable based	Organic	
	PureTemp 24		24/n.a.	185				Vegetable based	Organic	
	PureTemp 25		25/n.a.	185				Vegetable based	Organic	
	PureTemp 27		27/n.a.	200				Vegetable based	Organic	
	PureTemp 28		29/n.a.	205				Vegetable based	Organic	
	PureTemp 29		29/n.a.	189				Vegetable based	Organic	
	PureTemp 31		31/n.a.					Vegetable based	Organic	

Manufacturer	Product	Illustration	Phase change temperature Melting/freezing (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Salca www.salcabv.nl	Thermusol HD26		26/n.a.					Salt-crystals	Inorganic	http://www.salcabv.nl/index.asp?CategorieID=2&Taal=EN (Accessed 10.12.2013)
	Thermusol HD32		32/n.a.	150				Salt hydrate	Inorganic	
Climator Sweden AB Norregårdsvägen 18 SE-541 34 Skövde Tel: +46 (0)500 48 23 50 climator@climator.com www.climator.com	ClimSel C21		21/n.a.		43 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	http://www.climator.com/en/climsel/ (Accessed 10.12.2013)
	ClimSel C24		24/n.a.		58 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
	ClimSel C28		28/n.a.		64 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
	ClimSel C32		32/n.a.		64 Wh/Litre	0.5-0.7		Sodium sulphate	Inorganic	
Phase Change Material Products Limited Unit 32, Mere View Industrial Estate, Yaxley, Cambridgeshire PE7 3HS United Kingdom Tel: +44 -(0)-1733-245511 Fax: +44 -(0)-1733-243344 info@pcmproducts.net www.pcmproducts.net	S15		15	160		0.43		Salt hydrate	Inorganic	http://www.pcmproducts.net/Salt_Hydrate_PCMs.htm (Accessed 10.12.2013)
	S17		17	160		0.43		Salt hydrate	Inorganic	
	S19		19	160		0.43		Salt hydrate	Inorganic	
	S21		22	170		0.54		Salt hydrate	Inorganic	
	S23		23	175		0.54		Salt hydrate	Inorganic	
	S25		25	180		0.54		Salt hydrate	Inorganic	
	S27		27	183		0.54		Salt hydrate	Inorganic	
	S30		30	190		0.48		Salt hydrate	Inorganic	
	S32		32	200		0.51		Salt hydrate	Inorganic	
	A15		15	130		0.18			Organic	http://www.pcmproducts.net/Organic_Positive_Temperature_PCMs.htm (Accessed 10.12.2013)
	A16		16	213		0.18			Organic	
	A17		17	150		0.18			Organic	
	A22		22	145		0.18			Organic	
	A22H		22	216		0.18			Organic	
	A23		23	145		0.18			Organic	
	A24		24	145		0.18			Organic	
	A25		25	150		0.18			Organic	
	A25H		25	226		0.18			Organic	
	A26		26	150		0.21			Organic	
	A28		28	155		0.21			Organic	
	A29		29	226		0.18			Organic	
	A32		32	130		0.21			Organic	
	X25		25	110		0.36				http://www.pcmproducts.net/Solid_Solid_PCMs.htm Solid-solid (Accessed 10.12.2013)
	X30		30	105		0.36				

Manufacturer	Product	Illustration	Phase change temperature Melting/freezing (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
PCM Energy P. Ltd Mazgaon, Mumbai 400 010, India Tel: +91-22-23770100 Fax: +91-22-23728264 anmol@pcmenergy.com http://pcmenergy.com	Latest 18T		17-19	175		1		Inorganic salts	Inorganic	http://pcmenergy.com/products.htm (Accessed 10.12.2013)
	Latest 20T		19-20	175		1		Inorganic salts	Inorganic	
	Latest 25T		24-26	175		1		Inorganic salts	Inorganic	
	Latest 29T		28-30	175		1		Inorganic salts	Inorganic	
	Latest 32S		31-32	>200		0.6		Inorganic salts		
Microtek Laboratories, Inc. 2400 E. River Rd. Dayton, OH 45439 Tel: +1 937.236.2213 Fax: +1 937.236.2217 microtek@microteklabs.com www.microteklabs.com	MPCM 18		18/n.a.	163-173				n-Hexadecane	Organic	http://www.microteklabs.com/micropcm_products.html (Accessed 10.12.2013)
	MPCM 18D		18/n.a.	163-173				n-Hexadecane	Organic	
	MPCM 24		24/n.a.					Special blend		
	MPCM 24D		24/n.a.					Special blend		
	MPCM 28		28/n.a.	180-195				n-Octadecane	Organic	
	MPCM 28D		28/n.a.	180-195				n-Octadecane	Organic	
	MPCM28D-IR		25-32/n.a.	160-180				Special blend		
	MPCM 32		32/n.a.					Special blend		
	MPCM 32D		32/n.a.					Special blend		
Cristopia Energy Systems info@cristopia.com www.cristopia.com	AC.27		27							http://www.cristopia.com/cristopia/english/products/indproducts.html (Accessed 10.12.2013)
Rubitherm Technologies GmbH Sperenberger Str. 5a D-12277 Berlin Tel: +49 30 720 004 62 Fax: +49 30 720 004 99 info@runitherm.com http://rubitherm.com	RT 18 HC		17-19/19-17	250		0.2	12.5			http://rubitherm.com/english/index.htm (Accessed 10.12.2013)
	RT 21		18-23/22-19	160		0.2	12.5			
	RT 21 HC		20-23/21-19	190		0.2	14			
	RT 22 HC		20-23/23-20	200		0.2	12.5			
	RT 24		21-25/25-21	150		0.2	12.5			
	RT 25		22-26/26-22	148		0.2	14			
	RT 25 HC		22-26/26-22	230		0.2	12.5			
	RT 27		25-28/28-25	179		0.2	12.5			
	RT 28 HC		27-29/29-27	245		0.2	12.5			
	RT 31		27-33/33-27	170		0.2	12.5			

Manufacturer	Product	Illustration	Phase change temperature Melting/freezing (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Rubitherm Technologies GmbH Sperenberger Str. 5a D-12277 Berlin Tel: +49 30 720 004 62 Fax: +49 30 720 004 99 info@runitherm.com http://rubitherm.com	SP 21 E		22-23/21-19	160		0.6	3-4	Inorganic components		http://rubitherm.com/english/pages/02f_latent_heat_blend.htm (Accessed 10.12.2013)
	SP 22 E		22-23	180		0.6	3-4	Inorganic components		
	SP 24 E		24-25/23-21	222		0.6	3-4	Inorganic components		
	SP 25 E		24-26/24-23	200		0.6	3-4	Inorganic components		
	SP 26 E		25-27/25-24	200		0.6	3-4	Inorganic components		
	SP 31		31-33/30-28	240		0.6	3-4	Inorganic components		
	PX 15		10-17/17-10	85		0.2				http://rubitherm.com/english/index.htm (Accessed 10.12.2013)
	PX 25		22-25/25-22	96		0.1				
	PX 27		25-28/28-25	102		0.2				
	PX 31		27-31/33-27	110		0.1				

Table A2 Manufacturers of PCM enhanced products for building applications.

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Dupont Tel: + 352 3666 5772 www.dupont.com	Energain		18-24		515			Paraffin wax	Organic	http://energain.co.uk/Energain/en_GB/index.html (Accessed 10.12.2013)
Knauf AG Kägenstrasse 17 CH- 4153 Reinach Tel: +41 58 77 58 800 Fax: +41 58 77 58 801 info@knauf.ch www.knauf.ch	Comfort board		23		200	0.23		BASF micronal	Organic	http://www.knauf.ch/files/produkts/K763_ch_0213_ger_screen.pdf (Accessed 10.12.2013)
	Smartboard 23		23		330	0.20				http://vanoncinicommerciale.it/schede_tecniche/Knauf/Lastre%20ok/Smartboard%20PCM%20K764_10_2008_EN.pdf (Accessed 10.12.2013)
	Smartboard 26		26		330	0.20				
RGEES North America 1465 Sand Hill Road, Suite #2016, Candler, NC – 28715 Tel: +1.828.708.7178 info@rgees.com http://rgees.com/	PB29P		29		33 kWh/cbm				Organic	http://rgees.com/products_pcm-ball.php (Accessed 10.12.2013)
	PB22P		22		0.1 kWh/(ft^2)				Inorganic	http://rgees.com/products_pcm-pipe.php (Accessed 10.12.2013)
	PB24P		24		0.1 kWh/(ft^2)				Inorganic	
	PB29P		29		0.1 kWh/(ft^2)				Inorganic	
Phase Change Energy Soutions 120 E Pritchard St., Asheboro, North Carolina, 27203 USA Tel: +1 800 283-7887 info@phasechange.com www.phasechange.com	BioPCmat M27		23					Bio-based	Organic	http://www.phasechange.com/index.php/en/standard-products/biopcmat (Accessed 10.12.2013)
	BioPCmat M51		25					Bio-based	Organic	
	BioPCmat M91		27					Bio-based	Organic	
	ThermaStix							Bio-based	Organic	http://www.phasechange.com/index.php/en/standard-products/therma-stix (Accessed 10.12.2013)

Manufacturer	Product	Illustration	Phase change temperature (^{o}C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Dörken GmbH & Co. KG Wetterstraße 58 D-58313 Herdecke Tel: +49 23 30/63-0 Fax: +49 23 30/63-355 bvf@doerken.de www.doerken.de	Delta-cool 24									No longer available on the market? http://www.doerken.de/bvf-en/system/error.php (Accessed 17.01.2014)
	Delta-cool 28									
Salca BV Koggelsteeg 2, NL-7631 AH Ootmarsum Tel: +31 (0)541 291143 Fax: +31 (0)541 291175 infor@salcabv.nl www.salcabv.nl	K-Block				590			Salt hydrate	Inorganic	http://www.salcabv.nl/index.asp?CategorieID=5&Taal=EN (Accessed 10.12.2013)
SGL Group www.ecophit.com	Ecophit GC20		22	85		2-5	5-10			http://www.sglgroup.com/cms/_common/downloads/products/product-groups/eg/construction-materials-ecophit/ECOPHIT_GC_LC_e.pdf (Acessed 19.12.2013)
	Ecophit LC20		22	140		5-20	5-10			
Phase Change Material Products Limited Unit 32, Mere View Industrial Estate, Yaxley, Cambridgeshire PE7 3HS United Kingdom Tel: +44 -(0)-1733-245511 Fax: +44 -(0)-1733-243344 info@pcmproducts.net www.pcmproducts.net	FlatICE									Filled with various of their own PCMs listed in Table A1. http://www.pcmproducts.net/Encapsulated_PCMs.htm (Accessed 19.12.2013)
	TubeICE									
	BallICE									
National gypsum 2001 Rexford Road, Charlotte, NC 28211 Tel: +1 704-365-7300 ng@nationalgypsum.com www.thermalcore.info/	ThermalCORE		73^{o} F		22 Btu/(ft^2)			BASF micronal		http://www.thermalcore.info/tech-specifications.htm (Accessed 10.12.2013)

Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
H+H Deutschland GmbH Industriestr. 3 23829 Wittenborn Tel: +49 4554 7000 Fax: +49 4554 700223 www.hplush.de/home	CelBloc Plus							BASF micronal		No longer available on the market?
Maxit Deutschland GmbH	Maxit clima							BASF micronal		No longer available on the market?
Ilkazell Isoliertechnik GmbH Talstraße 17 08066 Zwickau/Germany PF 20 05 34 08005 Zwickau/Germany Tel: +49 03 75 / 43034 -0 Fax: +49 03 75 /43034 -33 mail@ilkazell.de www.ilkazell.de	Ilkatherm air conditioning systems							BASF micronal		http://www.ilkazell.de/en/climate-systems/ilkatherm-ceiling-and-wall.html (Accessed 08.01.2014)
Emco Bau- und Klimatechnik GmbH & Co. KG Post box: 1860 49803 Lingen (Ems) Germany Tel: +49 (0) 591 9140-0 Fax: +49 (0) 591 9140-851 klima(at)emco.de www.emco-klima.com	Emcovent									http://www.emco-klima.com/de-en/products/emcovent/pcm-systems.html (Accessed 05.01.2014)
Monodraught Ltd Halifax House Cressex Business Park High Wycombe Bucks HP12 3SE United Kingdom +44 (0)1494 897700 info@monodraught.com www.cool-phase.net/	Coolphase									http://www.cool-phase.net/ (Accessed 05.01.2014)

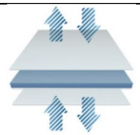
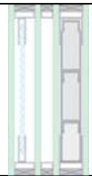
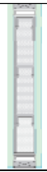
Manufacturer	Product	Illustration	Phase change temperature (°C)	Latent heat capacity (kJ/kg)	Latent heat capacity (kJ/m^2)	Thermal conductivity (W/(mK))	Volume expansion (%)	Materials	Type	More info
Tate 7510 Montevideo Road Jessup, MD 20794 Tel: +1 (800) 231-7788 Fax: +1 (410) 799-4207 tateinfo@tateinc.com www.tateinc.com	EcoCore 60cm		75.2 °F	147 Btu				Vegetable bio based	Organic	http://www.tateinc.com/products/ecocore.aspx (Accessed 08.01.2014)
Autarkis BV Ondernemersweg 2 7451 PK HOLTEN (NL) Tel: +31 (0)548 - 374 374 Fax: +31 (0)548 - 364 165 info@autarkis.nl http://www.autarkis.nl/en										Offers various systems incorporating PCMs, however no specific product information can be found on the website http://www.autarkis.nl/en (Accessed 07.01.2014)
Armstrong World Industries Ltd. Armstrong House, 38 Market Square, Uxbridge, UB8 1NG, United Kingdom Tel: +44 0800 371849 Fax: +44 1895 274287 www.armstrong.co.uk	CoolZone				136.2 Wh/m^2			BASF micronal	Organic	http://www.armstrong.co.uk/content2/commclgeu/files/71629.pdf (Accessed 06.01.2014)
Trox GmbH Heinrich-Trox-Platz D-47504 Neukirchen-Vluyn Germany Tel: +49(0)28 45 / 202-0 Fax: +49(0)28 45 / 202-265 e-mail trox@trox.de www.troxtechnik.com	FSL-B-PCM									http://www.troxtechnik.com/en/products/air_water_systems/facade_ventilation_units/under_sill_units/fsl-b-pcm/index.html (Accessed 10.01.2014)

Table A3 Manufacturers of PCM windows.

Manufacturer	Product	Illustration	Phase change temperature (^oC)	Latent heat capacity (kJ/kg)	Heat storage capacity (Wh/m^2)	Light transmission of PCM solid/liquid (%)	Solar heat gain coefficient solid/liquid	Materials	Type	More info
GLASSX Tel: 778.285.8530 Fax: 778.285.8520 www.glassxpcm.com	GLASSX crystal		26-30		1185	0-28/4-45		Salt hydrate	Inorganic	http://www.glassxpcm.com/products/ (Accessed 15.12.2013)
	GLASSX comfort		26-30		1185	0-38/4-55		Salt hydrate	Inorganic	
	GLASSX comfort "slim"		26-30		1185	0-38/4-45		Salt hydrate	Inorganic	
	GLASSX comfort "store"		26-30		1185	0-38/4-55		Salt hydrate	Inorganic	