DIPLOMARBEIT

Phase Change Materials as Variable Heat Storage in the Built Environment

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Technischen Universität Wien

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0548258

Wien, 3. November 2020

ABSTRACT

Phase change materials (PCM) have long been shown to notably improve the thermal mass of buildings, thereby significantly reducing thermal loads required to maintain comfortable indoor conditions. The application of phase change materials, however, requires a solid understanding of buildings as thermodynamic systems. To increase such intuitions and encourage planers to creatively incorporate PCM based application into their architectural concepts, a concise introduction into matters of heat transfer and storage at the level of abstraction relevant for architectural and building engineering purpose is presented. An emphasis on passive systems was set. This introduction is followed by an exposition into the function and use of PCM, followed by a review of past and current research into PCM applications in the building sector. A selection of built examples was also given. The presented research was further categorized and presented in a summarized overview for easy referencing.

KURZFASSUNG

Latentwärmespeicher (Engl.: Phase Change Materials, PCM) können wesentlich dazu beitragen die thermische Masse von Gebäuden zu verbessern. Der Energieverbrauch zur Erhaltung eines angenehmen Innenklimas kann somit nennenswert gesenkt werden. Die Anwendung von Latentwärmespeicher setzt jedoch ein solides Grundverständnis thermodynamischer Abläufe voraus. Um dem Planer das kreative Implementieren von Latentwärmespeicher zu erleichtern wurde eine knappe Einführung in die Materie des Wärmetransfers und der Wärmespeicher zusammengestellt. Aufbauend auf diese Einleitung folgt eine Darlegung der Wirkungsweisen und Anwendungsbereiche unterschiedlicher Latentwärmespeicher, gefolgt von einer Review vergangener und gegenwärtiger Forschung verschiedener Anwendungen von Latentwärmespeicher im Bausektor. Der Schwerpunkt wurde dabei auf passive Anwendungen gelegt. Eine Auswahl gebauter Beispiele wurde ebenfalls präsentiert. Des Weiteren wurden die angeführten Publikationen in einer zusammenfassenden Übersicht kategorisiert.

CONTENTS

1 INTRODUCTION

The key to using many forms of renewable energy effectively, lies in solving the problem of time difference that frequently spans between supply and demand. Solar energy, for example, follows an obvious diurnal supply cycle. Looking at the energy demand for space heating in winter climates, which is commonly highest in the colder evenings we can easily understand these disparities. What is true for solar, applies similarly for wind and other energy sources that occur in abundance, though often erratically and largely outside our ability to control. Thermal energy storage can play an essential role in bridging these gaps for space-heating and cooling. Traditionally, these mechanisms have been well understood and applied with the use of high thermal mass materials like brick and stone. Today, phase change materials (PCM), which rely on the phenomenon of latent, rather than sensible heat storage, are growing to be recognized increasingly as highly efficient heat storage devices, able to store up to 5-14 times more energy per unit volume than conventional materials (Sharma et al. 2009). First scientifically conceptualized by Joseph Black at the University of Glasgow in the mid-eighteenth century, latent heat refers to the energy involved in the process of phase change that most materials go through with changing temperature or pressure. In practice however, humans have been using one such phase changing material at least since antiquity. Greeks as well as Romans were known to transport and store ice to use for refrigeration much like we still do today whenever we drop an ice cube into a glass in order to chill a refreshing drink. Igloos are another ingenious example of a pre-scientific application that depends on latent heat. The Igloo allows the energy put out by the human body to be conserved within, thereby maintaining temperatures that allow the occupant to survive extreme, sub-zero temperatures during arctic winters (Kośny 2015). The first documented scientific application of PCM to heat an indoor space was studied at MIT by Dr. Maria Telkes in 1948. However, it wouldn't attract much attention until the energy crises of the 1970s and 80s. PCMs have generated ever growing attention as thermal storage in buildings and a multitude of other domains like food preservation, electronics cooling and even textiles ever since (Rathod and Banerjee 2013).

1.1 Overview

If we are to reduce the extensive energy demands of the building sector, planners need to be enabled and thus encouraged to think creatively about energy flow. This, it seems, can only be achieved by building up stronger intuitions that would allow such considerations to arise effortlessly with the initial conception of any design. The opening chapters of this paper are therefore formulated as a concise introduction into matters of heat transfer and storage at the level of abstraction relevant for architectural and building engineering purposes. Building on this strengthened understanding, chapter three specifically addresses the topic of phase change materials, their function, classification, implementation methods, and other aspects of their use. Chapter four reviews the relevant primary literature on various methods of application in the context of architectural planning, with an emphasis on passive applications. A selection of fully operational buildings using PCM storage elements is presented in chapter five. The discussion in chapter six is a summary of the methods of application presented in form of a guide that may allow planners to develop better intuitions on implementing PCMs intelligently into their design. A categorization and overview of the research reviewed in chapter four was also given for easy referencing. The paper ends with conclusions in chapter seven.

1.2 Motivation

Energy is a scarce resource. This statement has been made intuitively obvious to most, either by immediate circumstance or exposure to ardent public discourse around the geopolitics of fossil fuel acquisition, not to mention the increasingly dire forecasts of human made climate change, due in large parts to the combustion of these fuels (Romm 2016). Unrelenting population growth and massively increasing standards of living around the world (Pinker 2018) have consequently begun to shed a bright spotlight on consumption habits in the developed world. Though vigorously advertised as universally desirable on the stages of global media, these habits and lifestyles, it seems, could not possibly be experienced in any ecologically sustainable way by ever growing numbers of individuals (O'Neill et al. 2018). In this sense energy is truly and unequivocally scarce.

However, most processes we rely on in our daily lives and in the industries are remarkably inefficient. Considering for example a car engine that gives off 55-80% of the energy derived from its toxic combustion right back to its surroundings in the form of exhaust heat (Orr et al. 2016). Similar ratios may be found for many industrial processes whose bulky cooling towers must, in some sense, be seen as shadowing monuments to their inefficiency (Cot-Gores et al. 2012). The building sector, which consumes approximately 40% of total global energy demands is no exception (International Energy Agency 2019). In residential buildings, over half of this energy is used for heating and cooling spaces as well as heating water (Ürge-Vorsatz et al. 2015). Applying smarter architectural design methods, making use of well-understood thermodynamic phenomena, such as sensible heat storage in high thermal mass materials, has long been shown to reduce these energy demands (Balaras 1996; J. Zhou et al. 2008).

In practice, however, design choices are usually confined if not determined by seemingly unavoidable, short-term financial consideration that often tend to select for lightweight low volume constructions as opposed to the heavy large volume structures, usually associated with more favorable thermal properties. Nonetheless, much progress has been made in research on improving the thermal mass of built environments without significantly increasing neither the mass nor the volume of their structures. Phase change materials can play a central role in these strategies. Their proper implementation, however, necessitates a solid understanding of buildings as thermodynamic systems, which is not always what comes natural and therefore cheap to architects that may not have been adequately educated on these issues. In a world driven forward by the economic rather than ethical realities of the day, we may find it futile to expect the morally appropriate decision regarding the long-term to be made on a regular basis whenever it comes attached to voluntary financial sacrifices. Still, this mustn't be a source of frustration, in fact considering the evolutionary origins of human nature, it shouldn't even be a cause for confusion. Encouraged by this understanding, efforts should converge on setting up systems in which every player may be allowed to act according to his or her own, sometimes selfish fancies within the confines of a well-tuned set of rules, informed by sober collective foresight and arranged in such a manner that the aggregate outcome of individually self-interested actions may translate into a common good. We thus rely on elected officials to set up these well-structured laws and incentives that would protect us from our own natural tendencies to satisfy short-term needs and wants. We rely on informed civic discourse to generate that public opinion and collective passion which compels politicians as well as planers to appear in line with, if only to advertise their businesses and election campaigns. And finally, we rely on the informed researcher to aid politicians, planers and public opinion alike, to effortlessly choose those solution that appear wholesome in the long term, simply by making them known.

It is in this spirit that this paper aims to inform about the underlying principles and applications of phase change materials and their role in heating and cooling load reduction. Thereby empowering architectural planners to design buildings that function in harmony with the forces of thermodynamics and not futilely against them, ultimately enabling them to acknowledge with confidence that energy, in many ways, is not all that scarce, that it is, in fact, everywhere, though not necessarily in the right form, at the right place or at the right time – until knowledge is applied.

1.3 Objective

Heat storage is a remarkably powerful concept. The ability to harness naturally occurring heat or cold where and when there is abundance to release it at a point of scarcity could truly reduce and even eliminate our reliance on fossil fuels to heat and cool indoor spaces in certain climates. In theory, any diurnal, outdoor temperature variation could be equalized to our advantage indoors. In plain words, colder nights would cool down warm days and warm days warm up colder nights. We could imagine this by illustrating a rather unrealistically idealized diurnal temperature variation, conveniently oscillating sinus-like around a comfortable 23°. By shifting the curve by exactly half a phase or half a day, we can see how excess would equalize deficiency resulting in a constant indoor temperature of 23°C as seen in figure 1-1.

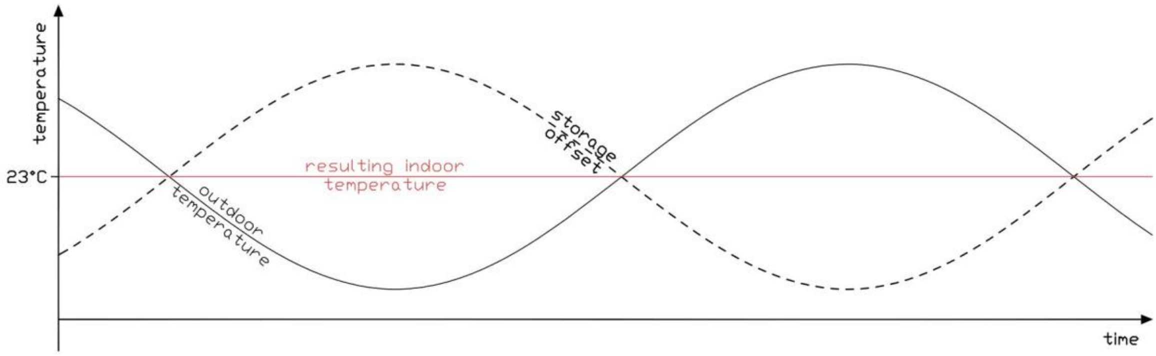


Figure 1-1: *idealized outdoor temperature fluctuation and storage offset resulting in constant indoor temperature*

Given perfectly ideal storage devices, we may even imagine working towards equalizing annual temperature variations, heating cold winter with excess heat and solar radiation harnessed during the summers, while cooling warmer seasons to comfortable levels releasing the cold stored during the winter. This latter scenario could hardly be achieved by using phase change materials or other regular heat storage but would most likely require the development of sophisticated thermochemical heat storage devices which will be discussed briefly in chapter 2.2.2. However unrealistic or unreachable, it is useful to keep such objectives in mind when discussing what part, any particular method or technology, like phase change materials might play towards approaching them.

2 HEAT TRANSFER AND STORAGE

To competently discuss questions of temperature regulation in the context of heat transfer and storage which are the subject of this paper, we may have to replace our more intuitive understanding of some of these notions by more refined descriptions derived from observations at the molecular level. Regardless of how static, uniform and solid an object may appear to us at the scale of our senses, all matter consists of ceaselessly moving particles. *Absolute Temperature* as described by physics, is an emergent property held by a set of particles, that we may arbitrarily call a substance and is expressed as a function of the average kinetic energy of its constituents.

$$T = \frac{1}{k} \cdot \frac{2}{3} \cdot \frac{1}{2} m \overline{v^2} \qquad (1)$$

The low end of the physical temperature scale, referred to as 0 Kelvin or *absolute zero*, accordingly describes a theoretical state of total absence of particle movement. According to the 2nd law of thermodynamics any such particle movement naturally dissipates from areas of high kinetic energy (high temperatures) to areas of lower kinetic energy (low temperatures) until a state of thermal equilibrium is reached. The resulting transfer of energy may be called *heat flow* (Demtröder 2017).

2.1 Heat Transfer

Wherever there is a temperature differential, there will be heat flow running from hot to cold. This occurs either when kinetic energy is transferred as particles come into contact with one another[1] or through electro-magnetic radiation. We generally distinguish three modes of heat transfer, they are referred to as *convection, conduction* and *radiation*.

2.1.1 Conduction

Heat flow that occurs with direct transfer of kinetic energy between particles is referred to as *conduction*. In ideal gases[2] we can imagine this process much like billiard balls in chaotic translational motion, smashing into each other in frictionless space. If one region of space is populated with slow moving balls and another with faster ones, the kinetic energy will spread by means of collision from the latter region to the other until

[1] Note that particles do not actually *touch* in the common sense of the word but get close enough to repel each other via electromagnetic forces.

[2] Ideal gases are theoretical models in which particles are understood as homogenous balls that solely interact in idealized elastic collisions and whose radii are negligible compared to the average distance between them.

an equilibrium is reached, in other words when the average velocities of the balls contained in any region of space have converged (fig. 2-1).

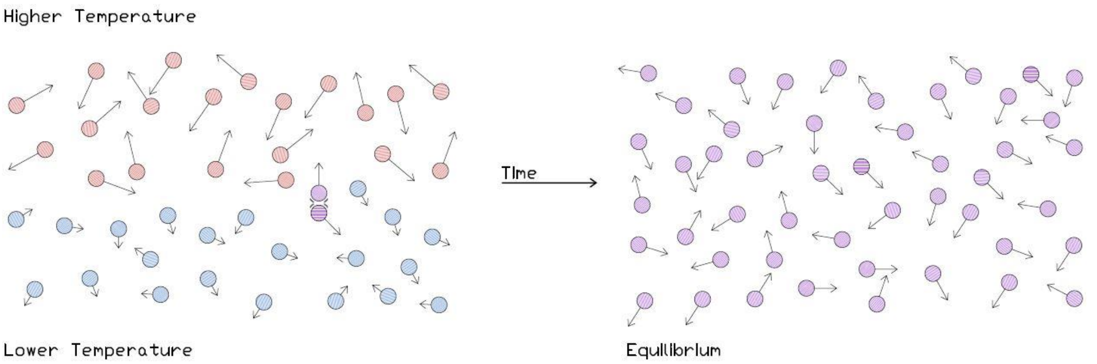


Figure 2-1: *schematic representation of ideal gas molecules reaching thermal equilibrium*

The analogy to billiard balls, however, can only be used as a rough abstraction when contemplating ideal gases. When we consider actual particle motion more closely, we find that molecules may also vibrate and rotate depending on what is referred to as their *degrees of freedom.*[3]

The defining property of a solid, in fact, is that particles are restricted in their translational and rotational motion by being bound up in rigid arrangements or *lattices* resulting in what we may call the stiffness or solidity of a substance. In solids therefore, the translational motion of the particle is restricted to what is referred to as *lattice vibration*. This motion occurs as particles are packed against each other, vibrating in constant electromagnetic interaction. An instance of higher relative excitation will therefore spread in a wave-like manner from one particle to its neighbors and so forth (fig. 2-2). Thus, energy dissipates through the substance via conduction until an equilibrium is reached. The equation governing heat conduction is known as *Fourier's Law*.

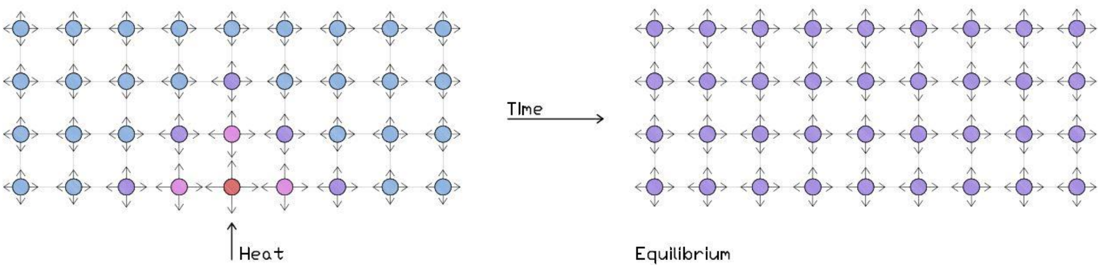


Figure 2-2: *schematic representation of heat conduction through a solid*

[3] Note that consequently this means that not all the translational kinetic energy may be conserved as such after a particle collision as some of that energy may be transformed into rotational and vibrational kinetic energy which do not have an immediate influence on what we refer to as the temperature of a substance.

$$\ddot{q} = -k \frac{\Delta T}{\Delta x} \qquad (2)$$

The equation shows the temperature gradient $\frac{\Delta T}{\Delta x}$ to be directly proportional to the *heat flux density* $\ddot{q}$ where the proportionality factor k refers to the *thermal conductivity* of the medium. Accordingly, the thermal conductivity is that property which indicates how much heat a substance will transfer under given circumstances. It may vary significantly not just for different materials but also with temperature-, pressure-, and phase. In solids, the conductivity can be expressed as a function of the lattice vibration and the *specific heat capacity* c.[4]

$$k = \frac{1}{3} c\, \bar{c} \lambda_{mfp} \qquad (3)$$

The *specific heat capacity* describes how readily a substance will increase its temperature under given circumstances. It is defined by the amount of energy needed to raise the temperature of 1kg of a substance by 1K. It consequently refers to the proportion of input energy that will not affect the temperature of a substance and its value depends largely on the structure of its particles and their resulting degrees of freedom. The product of the specific heat capacity c and the density ρ is often referred to as its *volumetric heat capacity* $c\rho$. The ratio of thermal conductivity and volumetric heat capacity yields an additional relevant property, known as the *thermal diffusivity* α.

$$\alpha = \frac{k}{\rho c} \qquad (4)$$

The thermal diffusivity describes the inertia a substance will initially manifest before a steady heat flow is established and like the heat capacity is a significant property in the context of heat transfer and storage.

As discussed with the billiard ball analogy, conduction also occurs in fluids, because of their free-flowing constituents however it is usually accompanied by at least some macroscopic bulk motion of particles which is the case we will consider next.

2.1.2 Convection

Owing to the internal dynamics associated with fluids, free-flowing particles tend to move collectively in what we may call a stream (fig. 2-3). When such streams flow across temperature differentials, heat will be transferred not only within the bulk

[4] Some materials with high thermal conductivity, like metals, can be understood to contain a significant number of free-flowing electrons moving through a positively charged ion grid, thus notably increasing the thermal (as well as electrical) conductivity of the substance. In these cases, the total conductivity can be expressed as the sum of both regular and electron conductivity.

motion of matter itself but also via particle interaction (conduction) at the boundary layers of the current. The superposition of these two mechanisms is generally referred to as *convection*.[5]

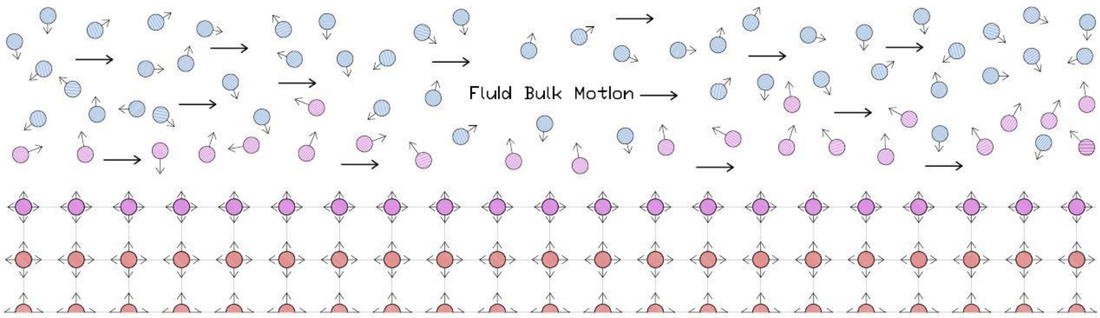


Figure 2-3: *schematic representation of a solid surface experiencing convective heat loss in contact with a fluid in motion.*

Newton's law of cooling states that "[…] *the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings while under the effect of a breeze.".*

Accordingly, the convection heat flux density q" can be expressed as a function of the *convection heat transfer coefficient* h and the temperature differential $T_s - T_\infty$ where T_∞ stands for the temperature of the fluid stream and T_s for the surface temperature of the substance in contact with the boundary layer of the stream.

$$\ddot{q} = h\ (T_s - T_{\infty)} \qquad (5)$$

The convection heat transfer coefficient refers to the conditions at the boundary layer and is therefore highly influenced by the geometry of the border environment as well as the thermodynamic properties of the fluid stream.

In addition to the general case it is worth noting a very common case of convection which occurs as colder fluids naturally expand with rising temperatures in contact with a hotter surfaces and get displaced by colder ones under the effect of gravity, thus establishing a particle stream (Demtröder 2017; Incropera and Dewitt 1985).

2.1.3 Radiation

All matter emits electro-magnetic radiation as a function of its temperature. As a particle emits radiation it loses kinetic energy, this emission will radiate through space at the speed of light until it hits another particle that will absorb it and thereby increase its kinetic energy. Thus, heat is transferred by *thermal radiation*. Consequently, unlike

[5] Note that the relative motion is decisive here, a hot object moving through a colder still fluid would suffer heat loss by convection just as much as a still solid in an equivalent stream.

conduction or convection, this mechanism does not involve direct kinetic interaction between constituent particles of the substance. Hence, it is the only form of heat transfer that occurs in a vacuum (fig. 2-4). As a result of high particle density most of the radiation emitted inside a solid or liquid substance is being absorbed by adjoining particles. Thermal energy, therefore, spreads through solids and liquids by radiation not entirely unlike by thermal conduction up to the point where it reaches proximity to a surface in contact with a gas or exposed to a vacuum.

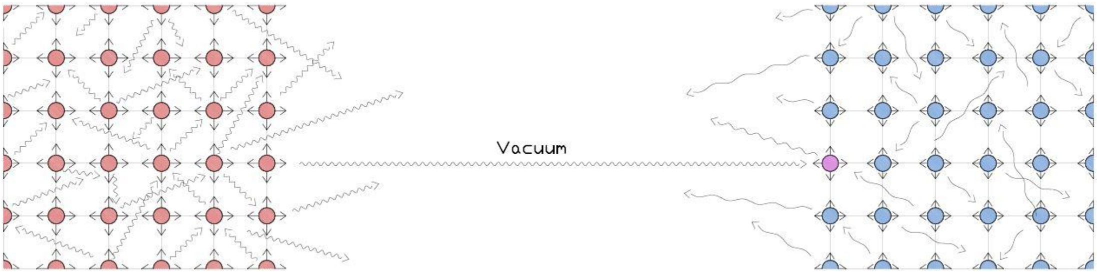


Figure 2-4: *schematic representation of particles within two solids emitting and absorbing radiation across a vacuum*

In fact, practically all radiation that is emitted from such a surface originates from within a depth of about 1 µm (Incropera et al. 1985). Thermal radiation emitted from solids and liquids is therefore often considered as a surface phenomenon in most practical applications.[6] Consequently, the structure of the surface, including its smoothness and what we phenomenologically refer to as its color at the level of our senses, has a defining impact on the capacity for thermal emission as well as absorption of a surface. Using the *Stefan-Boltzmann law*, the *emissive power* E of a surface can be described as proportionate to its temperature T to the fourth power and its *emissivity* ε.

$$E = \varepsilon \sigma T_s^4 \qquad (6)$$

The *emissivity* is determined by the structure of a surface and refers to the percentage of radiation a surface may emit compared to an ideal radiator also referred to as a *blackbody.* Analogously, the percentage of irradiation a surface will absorb from its surroundings is referred to as its *absorptivity* α. As a surface will constantly emit as well as absorb radiation to and from its surroundings, the radiation heat flow is defined by the net differential of both processes. Finally, the *transmissivity* refers to that amount of energy, which is neither reflected nor absorbed, but passes right through the substance.

[6] This may not apply at microscales or for substances that become transmissive to thermal radiation at certain temperatures.

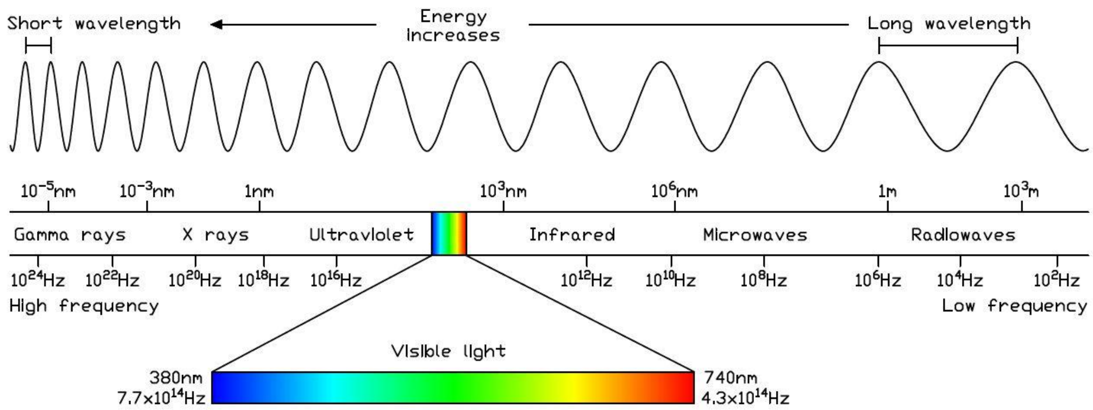


Figure 2-5: *the electromagnetic spectrum* *(source: miniphysics.com)*

It is important to recall, at this point, that what we perceive as visible light is merely a slim slice of the total spectrum of electromagnetic radiation that occurs in nature (fig. 2-5)[7]. When we talk of reflectivity, absorptivity and transmissivity, we have to remember that different substances in different energetic states will vary greatly in their capacity to reflect, absorb or transmit different wavelengths.

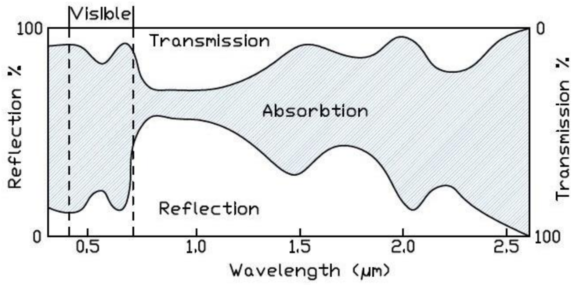


Figure 2-6: *Idealized relation between the spectral reflectivity, transmissivity and absorptivity of a green leaf* *(Monteith et al. 2013)*

Figure 2-6 shows the relationship between these properties in the example of a leaf. The high transmittance range of water, to use another example, matches our visible spectrum close to perfectly (Manz 1997). This is no coincidence as the human eye appears to have evolved as an adaptation to life under water, not to mention the fact that the gel-like liquid inside the eyeball consists almost entirely of water. That a substance appears opaque to our senses, merely indicates its low transmissivity within the range of the visible spectrum, it may be entirely *transparent* to other wavelengths.

[7]The distribution of emitted wavelengths depends on the composition and temperature of the emitting body and can vary substantially along with the energy that it carries. The energy transmitted via radiation from our sun, spikes around the range of visible light. This results in the fact that about 50% of incident radiation energy on earth falls into the slim visible range even though the total radiation spectrum of the sun is much larger.

2.2 Heat Storage

Having reviewed the various modes of heat transfer and their underlying causes we now understand in theory, as we previously knew from experience, that heat transfer is a transient process, in other words it occurs continuously over time. Along with this thermal latency comes a phenomenon that we may describe as *heat storage.* A substance that cools down can hence be described conceptually as gradually releasing the heat it has previously *stored*. This concept is technically referred to as *physical heat storage* to set it apart from *thermo-chemical heat storage* which will only be discussed briefly here.

When speaking of physical *heat* storage however, so as to protect our understanding from the ineptness of language, it seems useful to point out, that the identical substance which, in a relatively colder environment will be said to contain stored *heat* has to be said to contain stored *cold* in an equivalent, hotter environment. In this sense it must be understood that the concept of physical heat storage really refers to a potential for thermal energy transfer out of or into the substance that is entirely relative to circumstance (fig. 2-7). As we will see this is not true for thermochemical heat storage, for these systems will always either add to or absorb energy from a system, somewhat independent of circumstance and depending on their set up.

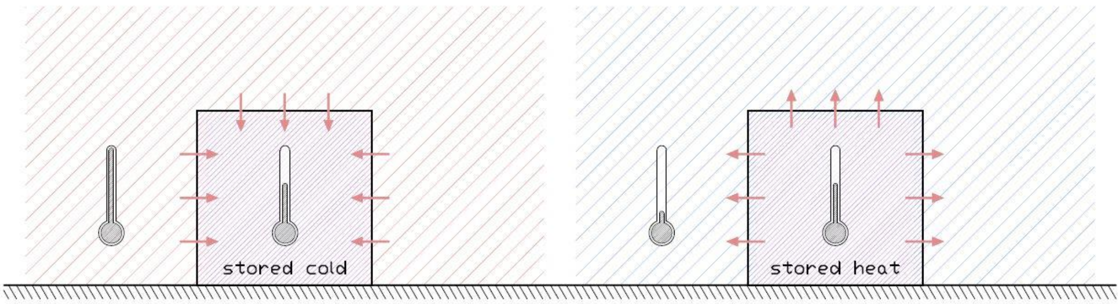


Figure 2-7: *the relative nature of heat and cold storage for equal temperature*

2.2.1 Physical Heat Storage

- #### Sensible Heat Storage

To better illustrate the concept of physical heat storage, consider a graph representing the relationship of internal energy and temperature of a substance, using water as an example (fig. 2-8). Recalling the previous chapter on conduction we understand that the internal energy per unit mass must be equal to the product of the temperature and the specific heat capacity that will consequently determine the slope of the graph which will be linear, assuming for sake of simplicity that c remains constant with temperature. The equation thus allows us to determine how much extra energy per unit mass ΔE will be *stored* within a substance when its temperature has been raised by ΔT. We refer to this concept as *sensible heat storage.*

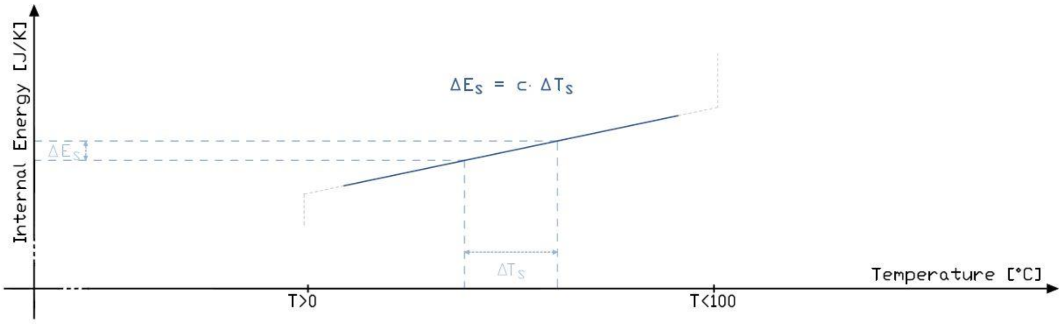


Figure 2-8: *Internal energy of water as a function of Temperature (simplified)*

Latent Heat Storage

As we extend the range of our graph to include the freezing and boiling point of the material, we discover that as a substance reaches a temperature at which it will naturally undergo a change in phase, the temperature remains about constant with rising internal energy levels until the phase change is completed at which point the function becomes linear again[8] (fig 2-9).

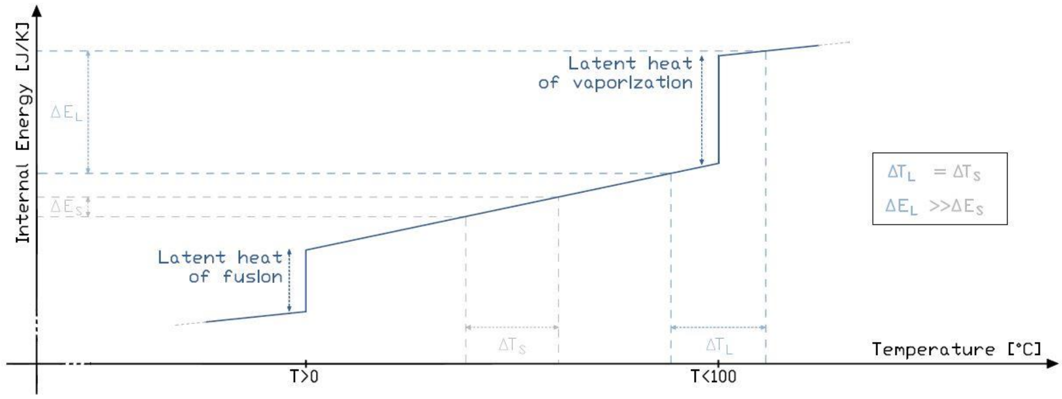


Figure 2-9: *Internal energy of water across phases as a function of Temperature (simplified)*

We thus find that the energy that is put into the system as melting or vaporization occurs will be consumed entirely by the intermolecular process of the phase change. Analogously, the opposite is true for the reverse case as a substance will release internal energy without lowering its temperature, as it condensates or freezes. The total energy stored within a substance around a phase change will therefore not only

[8] Note that while the specific heat capacity usually remains roughly constant within phases, it may vary significantly across the phases. Also note that phase change isn't a perfectly symmetrical process, meaning that melting and freezing may occur over a range of temperatures and at slightly different peak values.

include the sensibly stored energy but also those quantities of energy consumed or released by the process of the phase transition itself. These measures of energy are referred to respectively as the *latent heat of fusion* and *latent heat of vaporization* (Demtröder 2017; Incropera et al. 1985). We thus refer to this concept as *latent heat storage* and recognize it as the central mechanism that allows for what engineers have termed *phase change materials*.

2.2.2 Thermochemical Heat Storage

The process of chemical reaction, in other words, the disassociation or synthesis of molecular compounds, generally either absorbs or releases energy. We speak of endothermic and exothermic reactions respectively. Those reactions that may be fully reversed can be used to engineer *thermochemical heat storage systems*. Such systems operate in cycles of charge, storage and discharge, not at all unlike an electric battery. A chemical compound that is synthesized in a fully reversable endothermic reaction, for example, can thus be understood to contain stored heat. This potential, unlike *physically stored energy,* does not relate to the actual thermodynamic energy state of the substance but firmly resides within the molecular bonds of the compound. The stored energy is released only as the exothermic reverse reaction that separates the compound into its initial substances is triggered (Cot-Gores et al. 2012). Once more, analogous processes can be used for heating just as much as for cooling as shown in figure 2-10.

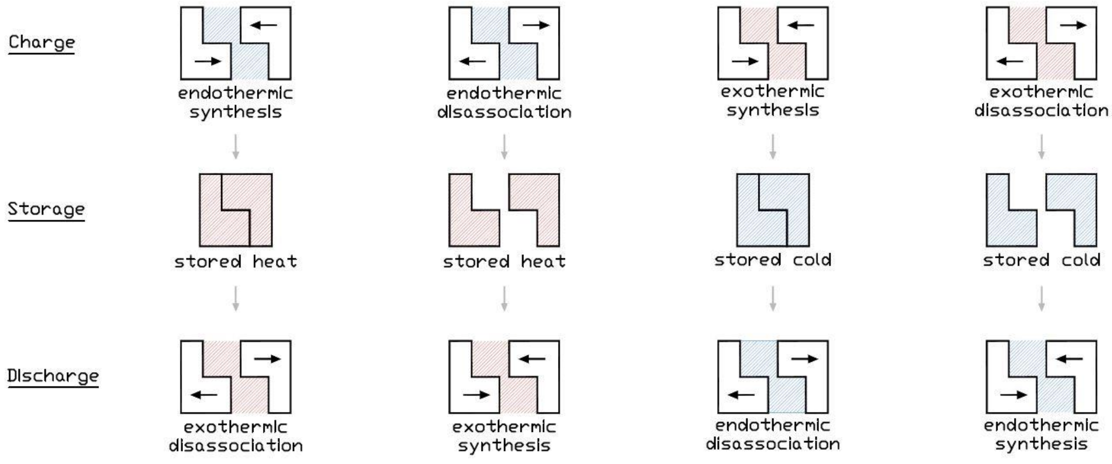


Figure 2-10: *thermochemical storage*

These technologies seem to hold a great deal of potential for countless applications from storing and re-using some of the immense amounts of industrial waste heat to storing energy in building systems to achieve year-long cycles, using the excesses of summers to heat the winters and vice versa. However, despite showing great promise, these technologies remain in their infancies and have yet to emerge from the realm of research into that of general commercial availability (Nazir et al. 2019).

2.2.3 Thermal Mass

Applied to the realm of built environments, our acquaintance with the workings of heat transfer and heat storage allows us to better understand how heat will naturally flow through a structure. When aiming to create a comfortable indoor climate for humans while keeping the energetic requirements to a minimum, this knowledge must be viewed as entirely indispensable, particularly so when considering climatic environments with significant diurnal temperature differences (Balaras 1996).

The box model: To better understand how this is true let us briefly consider a simplified building in form of a mere box with openings on opposite sides allowing for cross ventilation, situated in a hot summer climate with pronounced diurnal temperature differences. In a first version of this set up we consider a box made of thin low heat capacity materials (fig. 2-11). We may therefore describe it as being of low *thermal mass*. Based on our understanding gained in the previous chapters we can plausibly predict that peak indoor temperatures will coincide rather perfectly with peak outdoor temperatures with limited use for ventilation as the hottest indoor air of the day is bound to be replaced by nothing but the hottest outdoor air. In many circumstances therefore, air conditioning will be the only solution to assure functionality and comfort, introducing significant energetic costs (Al-Sanea et al. 2012).

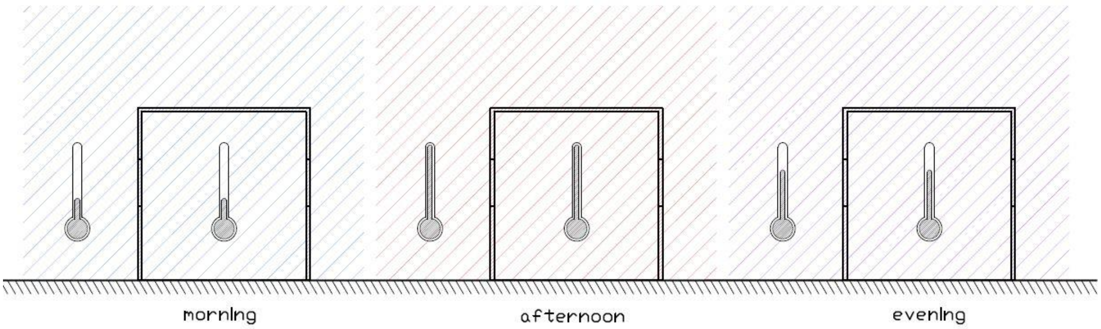


Figure 2-11: *the box model: low thermal mass*

Let us now consider a contrasting example and imagine a box of high *thermal mass*, made of thick walls of high heat capacity materials (fig. 2-12). While indoor surface temperatures in our first scenario corresponded rather directly to the outdoor conditions, indoor surface temperatures in the second scenario will initially not increase at all with rising outdoor temperatures and then only do so gradually as the walls slowly take up energy, allowing for a potentially significant time shift between peak outdoor temperatures and peak indoor temperatures at which point ventilation may be used to evacuate excess heat gains, capping the peak and thus reducing or eliminating energetic costs of artificial cooling (J. Zhou et al. 2008).

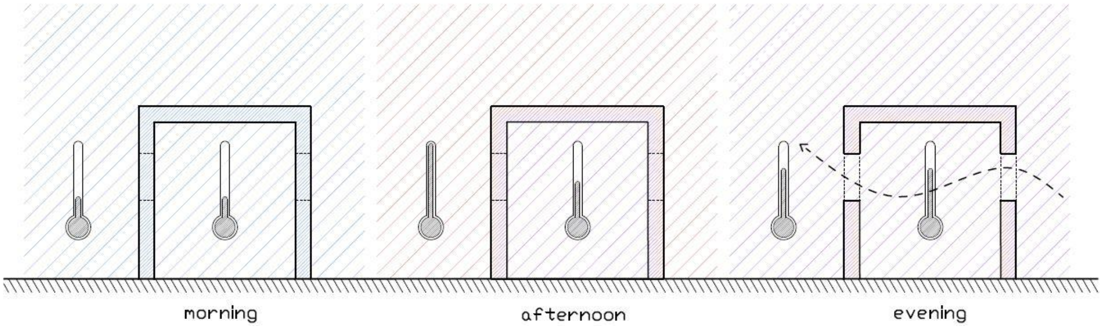


Figure 2-12: *the box model: high thermal mass*

As depicted in figure 2-13, similar effect can be expected in winter climates as gains from solar radiation would be shifted into the cold evenings where heating demands are usually highest thus reducing the peak energy demand for heating significantly (Balaras 1996).

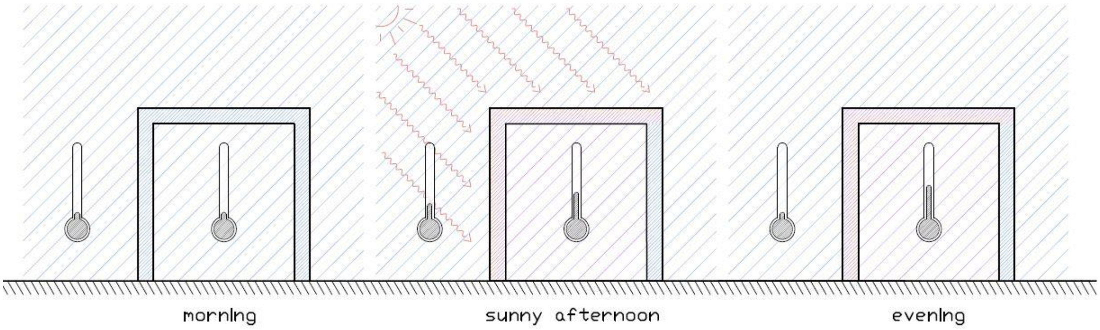


Figure 2-13: *the box model: high thermal mass with solar radiation in winter*

Adequate thermal mass does not only reduce energy demands in the extremes but may also generally increases indoor thermal comfort by reducing temperature fluctuations during the day as well as reducing the difference between air and surface temperatures, thus reducing the thermal discomfort caused by radiative heat (Kalnæs and Jelle 2015). Traditionally the effects of thermal mass could only be achieved with sensible heat storage within high heat capacity materials that generally come with large masses and volumes. In recent decades however, researchers have focused their attention on the moment of phase change and sought to unlock the storage potential held by the latent heat bound up in the process, thus developing those technologies we now look to as phase change materials.

3 PHASE CHANGE MATERIALS

Phase change, as we have seen, occurs naturally with changing temperatures (and/or pressure) and results of the interplay of electromagnetic repulsion and attraction between particles as a function of their constituents, their kinetic energies, their interparticle distances, and therefore the pressure of the substance. Phase change occurs in all elements and numerous other compound substances. What we technologically refer to as *phase change materials* are a subset of these substances, characterized by their physical properties in regard to their ability to regulate thermodynamic flows, through latent energy storage in a given application (Sharma et al. 2009). As this paper specifically discusses the benefits and workings of latent energy storage for architectural building applications, we will first need to identify the relevant functional confines for this context.

3.1 Conceptual Function of PCMs

Like sensible heat storage, PCMs can be used to increase the thermal latency of a building to distribute daytime-gains in winter and night-time cooling in summer more evenly across the diurnal cycle, thus levelling out unwanted indoor temperature fluctuations and reducing overall energy demands. However, unlike sensible storage that operates in a relatively uniform manner across the relevant temperature spectrum, the charge and discharge cycle of latent heat storage is centered around a discrete temperature value specific to the given substance.

To ensure that PCMs retain their position and shape when transitioning across these temperature thresholds, structural stability must be considered across all relevant states. For most application this means that PCMs need to be enclosed, encapsulated or otherwise stabilized.

The box model: Returning to the simplified box model of the previous chapter, let's consider a massive concrete wall structure laid out with tightly wrapped panels of a PCM that liquefies at 21°C. As cool morning temperatures start to rise, the walls will take up heat and eventually transfer it to the inside in familiar manner. The moment, however, temperatures on the inside of the structure reach 21°C, the PCM will start to liquify absorbing energy that would otherwise have been passed on to the room, therefore creating a sort of anchor point, further delaying the moment of peak indoor temperature. As outdoor temperatures drop in the later part of the day, proper ventilation can be applied in order to cap indoor peak temperatures as well as to allow the PCM to re-solidify completely, once outdoor temperature drop below 21°C (fig. 3-1).

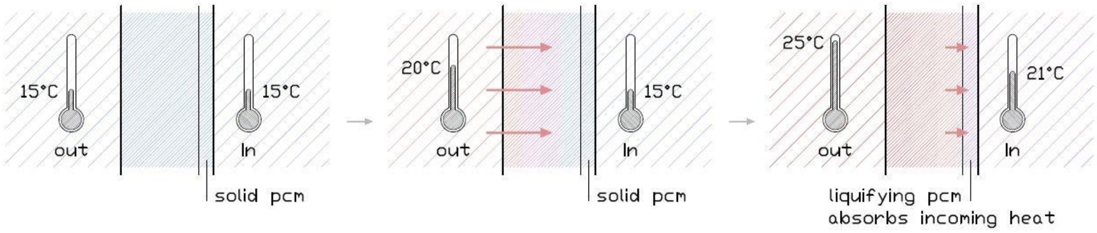


Figure 3-1: *the box model wall with pcm layer on inner surface*

In addition to lowering overall energy demands, energy storage materials like PCMs could also help solve problems that arise when electricity supply and demand are out of phase which, for example, is one of the major issues in solar energy applications (Hasnain 1998). Moreover, less accentuated power demand patterns would put less strain on power grids and notably benefit the overall efficiency of the system as well as the consumer as electricity is often cheaper in off-peak hours (Khudhair and Farid 2004).

3.2 Relevant Criteria

When considering PCMs, several criteria need to be examined to guarantee their functionality, safety and longevity in the context of a given application. Issues of longevity in particular have been a limiting factor in the spread of PCM technology as many materials tend to experience property changes with passage of time and increasing numbers of undergone cycles. (Rathod et al. 2013).

Functionality, safety and longevity, in general, depend on a number of criteria that Abhat classified into thermodynamic, kinetic, chemical and economic criteria. (Abhat 1983). The following list and figure 3-2 show an updated variation of Abhat's criteria:

- ### Thermodynamic Criteria

  The PCM should possess:

  - a melting point in the desired operating temperature range. In building applications, this will often be close to the desired room temperature (Khudhair and Farid have suggested an optimal effect at about 1-3K above room temperature (Khudhair et al. 2004)) but must be chosen with regards to the location, type and layout of the structure as well as the climatic context in which it is anticipated to function in.

- high latent heat of fusion per unit mass, to allow for maximum heat storage effect in relation to minimal volume and mass.
- high specific heat to provide for additional significant sensible heat storage effects.
- high thermal conductivity, to ensure rapid and complete phase transitions throughout the PCM-element.
- congruent melting: the material should melt completely so that the liquid and solid phases are identical in composition, otherwise, the difference in densities between solid and liquid cause segregation resulting in changes in the chemical composition of the material which will negatively affects the cyclical stability of the PCM.
- small volume changes during phase change transition, to ensure the integrity of the containment.

Kinetic Criteria

The PCM should exhibit:

- little or no supercooling[9] during freezing, the melt should crystalize at its thermodynamic freezing point. This is achieved through a high rate of nucleation and growth rate of crystals.

Chemical Criteria

The PCM should show:

- chemical stability, no chemical decomposition, to ensure long cyclical stability.
- non-corrosiveness to construction materials.
- The material should be non-poisonous,
- non-flammable and non-explosive.

Economic Criteria

The PCM should be:

- available in large quantities
- inexpensive

[9] Supercooling describes a phenomenon in which substances retain their liquid state beneath the natural freezing point due to the lack of nucleation in the process of crystallization.

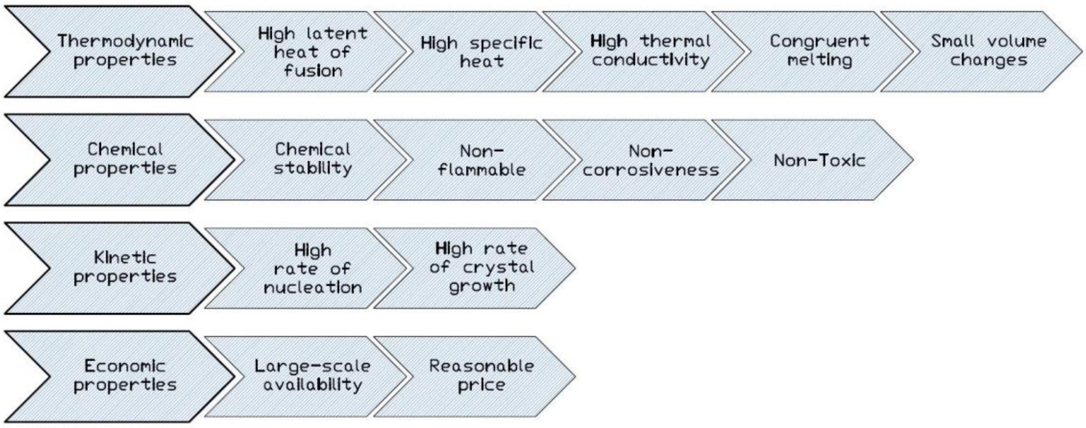


Figure 3-2: *selection criteria* (Akeiber et al. 2016)

- ### Ecological Criteria

In addition to these considerations, PCMs need to be examined with regard to their ecological cost across their entire lifecycle. Energy saving approaches that conceal substantial environmental harms in the shadows of their up and or downstream processes may be superficially understood and advertised as eco-efficient and sustainable but naturally miss the point entirely. Assessing the lifecycle impact of any product, however, is a complex and an inherently incompletable task, that must nonetheless lie at the core of any discussion or thought towards truly sustainable systems. We will therefore discuss this topic in more detail in chapter 3.7 of this paper.

3.3 Classification by Phase Change Type

Phase changes, in this context, occur between gaseous and liquid, liquid and solid and gaseous and solid. Latent energy is absorbed and released in all these transitions. Phases changes involving gaseous states are associated with high latent energy, however, since substances generally expand significantly as they transition into gases, exploiting these phase changes is impractical and therefore irrelevant for most applications (Nazir et al. 2019). PCMs that make use of liquid to solid transitions are the most relevant to the architectural context and, therefore, the main focus of this paper. Nevertheless, certain solids undergo a crystalline restructuring with changing temperature (and/or pressure) which can be understood as a solid to solid phase change. While these changes generally involve relatively low storage densities, they naturally do not require any consideration with regard to enclosure (Chandra et al. 2005).

3.4 Classification by Substance

The classification by substance is remarkably useful as similar molecules retain a significant degree of similarity at the level of substances in the process of phase transition (Mehling and Cabeza 2007). We distinguish three main categories, organic PCMs, in-organic PCMs and eutectic PCMs. The list of substances that have been reviewed in the context of PCMs is quite large and is constantly growing. This chapter, therefore, does not attempt to present a comprehensive inventory but rather to give a solid overview of categories and the properties that define them (fig. 3-3). Extensive lists can be found in Cabeza et al. (2011). Individual materials are presented in chapter 3.8 in a listing of specific commercial products.

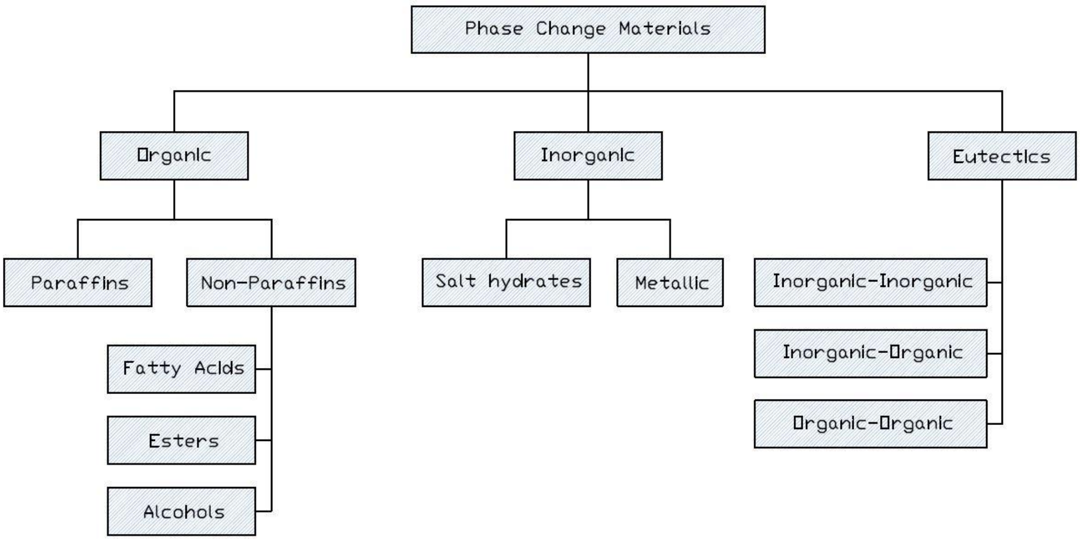


Figure 3-3: *PCM classification (Rathod et al. 2013)*

3.4.1 Organics

Organic PCMs are further divided into paraffins and non-paraffins. They are mostly non-corrosive and have been shown to exhibit little or no supercooling and no phase segregation effects and show little consequent degradation of latent heat of fusion (Rathod et al. 2013). Common disadvantages include low thermal conductivity, incompatibility with plastic containers and moderate flammability (Sharma et al. 2009).

- #### Paraffins

Paraffins are a group of saturated hydrocarbons. They can be represented as C_nH_{2n+2} and consist of mixtures of straight hydrocarbon chains. The longer the molecular chains or the greater the molecular mass, the higher the melting point (Koschenz and Lehmann 2004). Paraffins are available in a considerable range as their melting temperature is proportional to the number of carbon atoms n. Paraffins do not show any significant degradation in their thermal properties after repeated numbers of cycles and are, therefore, regarded as reliable and predictable (Rathod et al. 2013). They have relatively high heat of fusion (~120-210 kJ/kg) as well as low vapor pressure and are reasonably inexpensive (Zeinelabdein et al. 2018). They do, however, show all the aforementioned disadvantages of organic PCMs as well as comparatively high volume changes between the phases (Su et al. 2015).

- **Non-paraffins**

Non-paraffins are the largest sub-group of PCM including a large variety of organic materials such as esters, fatty acids, alcohols and glycols (Su et al. 2015). Among them, fatty acids are the most commonly used. Easily derived from common vegetable and animal oils, the continuous supply of fatty acids does not experience the same shortages and fluctuation as those PCMs relying on fossil fuels, and other non-renewable materials. (Rathod et al. 2013). Other superior properties include melting temperatures close to human comfort levels (~16-65°C) comparatively high heat of fusion (~155 and 180 kJ/kg), high heat capacity, congruent melting, little or no supercooling, lower vapor pressure, good chemical and thermal stability, low cost and small volume change. (Yuan et al. 2014; Zeinelabdein et al. 2018). However non-paraffins are approximately two to three times more expensive than paraffins and like many organic materials some are considered moderately flammable. Some are mildly corrosive and have varying toxicity. These drawbacks need to be addressed when considering the containment of these materials in building contexts (Zeinelabdein et al. 2018)

3.4.2 Inorganics

Widespread inorganic PCMs include salt hydrates, and metallic alloys. They tend to show significantly higher latent heat of fusion relative to their volume than their organic counterparts (fig. 3-4) as well as higher thermal conductivity (~0,5 W/mK) and lower costs. Common drawbacks however include, supercooling, phase separation and corrosion leading to poor long-term thermal stability (Zeinelabdein et al. 2018) .

- **Salt Hydrates**

Mixtures of inorganic salts and water are among the oldest and most studied PCMs. These salt hydrates can be described by the general Formula $A \cdot nH_2O$ where A represents the salt component. The transition from liquid to solid states in salt hydrates essentially occurs with the disassociation of salt and water. The process, however, resembles a phase change thermodynamically even though technically they are distinct processes (Su et al. 2015). As they *melt,* salt hydrates generally disassociate either fully into anhydrous salts and water or lower grade salt hydrates and water. Due to the resulting difference in densities of the substances, heavier salt and salt hydrate particles tend to gather towards the bottom of the container where the level of disproportion of salt to water may be sufficient to cause an effective reduction of the amount of salt available for rehydration. The result is an increasing segregation of the compound over time, weakening the thermal storage effect of the PCM with every cycle. This degradation can be reduced by adding thickening mixtures to the compound; however, these additives influence the heat storage characteristics of the PCM and they too degrade with time (Rathod et al. 2013). Supercooling due to poor nucleating properties of many salt hydrates is also a problem and leads to PCMs unpredictably solidifying at lower than expected temperatures (Kalnæs et al. 2015). Salt hydrates tend to show high latent heat per volume, high thermal conductivity, small volume changes but low specific heat. They are considered inflammable, compatible with plastic and slightly toxic as well as widely available and also relatively cheap compared to organic compounds. Many salt hydrate compounds have a melting temperature that is much higher than human comfort levels which make them more suitable for storage of solar energy and waste heat recovery (Zeinelabdein et al. 2018).

- **Metals**

Metals have not been widely considered as PCMs in building applications. This is mostly due their unsuitably high melting temperatures, however, there are some metals and alloys that fall into the required temperature range for human comfort levels as well as for solar energy applications.

Due to their unique molecular structure, metals have high thermal conductivity and large latent heat of fusion per unit volume. They have been shown to have low vapor pressure and only small volume expansion during liquid to solid transition. However, they generally do experience supercooling and corrosion in contact with certain materials. They are furthermore quite expensive and heavy which makes them more suitable for use in combination with non-metallic PCMs or in any application that requires compactness (Ge et al. 2013).

3.4.3 Eutectics

Eutectics are PCM composites, made of two or more components, that melt and solidify congruently forming mixtures of crystals during solidification. Eutectics provide a distinct advantage in terms of flexibility over regular PCMs since varying thermal properties can be engineered not only by choice of component materials but also by the proportions between them. Eutectic PCMs can be made from organic-organic, inorganic-organic, and inorganic-inorganic mixtures which creates a wide spectrum of possibilities for all sorts of applications. However, thermophysical data on eutectics is limited (Kalnæs et al. 2015).

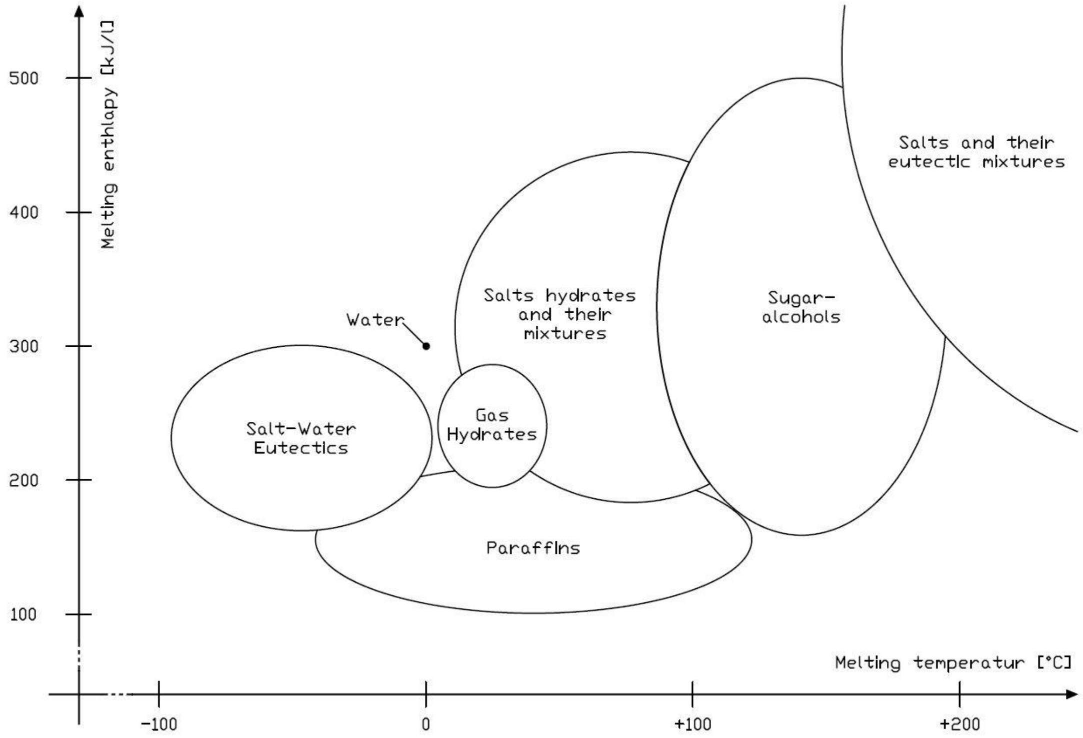


Figure 3-4: *Classes of materials that can be used as PCM with regard to their typical range of melting temperature and melting enthalpy*

3.5 Classification by Enclosure

Enclosure is a central issue in PCM technology. For one, enclosure is usually necessary to contain the liquid phase of the material but also to avoid contact between the PCM and its surrounding to ensure that neither is negatively affected in its function (Mehling and Cabeza 2008). Furthermore, encapsulation can also provide significant enhancements to avoid some previously discussed drawbacks like flammability or low thermal conductivity (Zeinelabdein et al. 2018). The enclosing material needs to be functionally compatible with both the PCM and the environment.

3.5.1 Macro-Encapsulation

Macroencapsulation generally refers to containers of around 1cm in diameter up to several liters. Common configurations include aluminum or plastic panels, spheres, tubes and pouches that serve as heat changers themselves. They suit application within walls and partitions of the building (Zeinelabdein et al. 2018). They are available in a large variety of different containers and are therefore a simple technique to contain comparatively large quantities of PCM and apply them onto a structure or as part of the structure itself (Mehling et al. 2008). However, a major drawback of most macroencapsulated PCM is slow heat transfer due to their size and subsequent low surface to volume ratio which may prevent the system form completely discharging overnight. Furthermore, macroencapsulated PCM may be susceptible to physical damage such as perforation especially during construction (Kalnæs et al. 2015). Figure 3-5 shows several examples of macroencapsulated PCM elements.

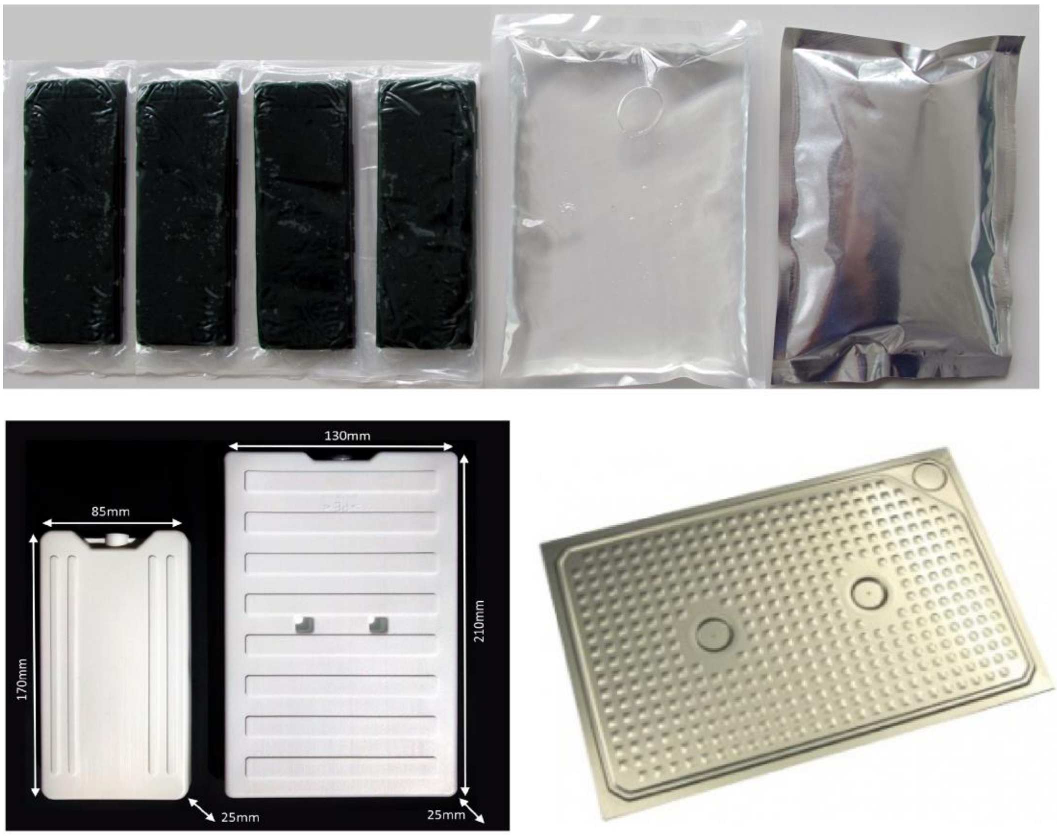


Figure 3-5: *several examples of macro-encapsulations by Rubitherm*

3.5.2 Micro-Encapsulation

Microencapsulated PCMs are thinly coated particles that are generally smaller than 1mm (fig. 3-6). They combine into a sand or powder-like materials made up of minuscule spheres or rods that can be incorporated directly into any compatible construction material like concrete or plaster, as an additive, which makes them particularly flexible and simple in their application. Large surface to volume ratio also increases the heat transfer, facilitating complete charges and discharges. Microencapsulation also improves cyclical stability for PCMs that suffer from phase segregation as the effect is reduced to microscopic distances due to the overall size of the container (Cabeza et al. 2011). Techniques for microencapsulation include so-called physical methods like spray cooling, spray drying and fluidized bed processes, as well as chemical methods that can produce even smaller containers often referred to as nanoencapsulation. A useful description of these methods was published by W. Su et al as well as by Y. Konuklu (Konuklu et al. 2015; Su et al. 2015). A drawback of these methods, however, is that the materials used for this type of encapsulation generally have low thermal conductivity. Furthermore, when these PCMs are mixed directly into materials like concrete or plaster, the amount of PCM that can be added is limited by its effect on the mechanical properties of the structural material, thus often limiting the sum total heat storage capacity of the application (Konuklu et al. 2015).

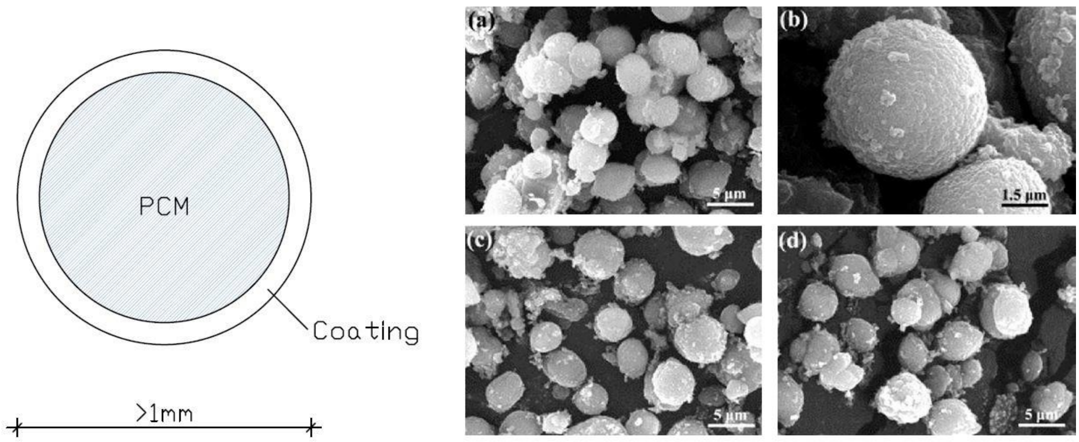


Figure 3-6: *micro-encapsulated PCM (Konuklu et al. 2015)*

3.5.3 PCM Incorporation, Impregnation and Shape-Stabilization

Different methods have been considered that do not require any complete enclosure. In these methods the liquid material is restrained by adhesive forces resulting in the capillary effect occurring at the molecular level between compatible materials. This may occur directly by incorporating PCM-additives into a subsequently hardening mass or by impregnating mechanically stable porous, materials with liquid PCM, often with the use of vacuum pumps. Depending on the PCM, this is possible with different types of ceramics, concrete and wood fiberboards as well as with high density polyethylene structures to achieve what have been called shape-stabilized PCMs (Mehling et al. 2008). However, while these methods appear comparatively low-tech, cheap and application friendly, some studies have put into question their long term usability due to leakage and direct contact of the PCM to its environment (Zeinelabdein et al. 2018).

3.6 Enhancement Strategies

Low thermal conductivity (typically around 0.2-0.5 W/mK) is a common problem of most PCMs relevant for the architectural context. Composite materials of PCM and high conductivity materials like metals and graphite have been shown to be viable solution to this problem (Zhou et al. 2012). Graphite seems especially advantageous due to its stability to high temperatures as well as its non-corrosiveness when applied in combination with salts, salt hydrates, water or water-salt solutions. A highly effective method to produce such a composite is to create a thin graphite matrix, into which the liquid PCM is injected, making up about 80-85% of the total volume. This method typically results in an increase in conductivity by a factor of 50 to 100 depending on the PCM. Due to the minimal size of the matrix, this method can only be applied to macroencapsulated elements, and is not suitable for all common PCMs. Mixing PCM with granular graphite is another method to produce PCM graphite composites. The thermal conductivity of the PCM, in this case, can only be increased by a factor of about 5 to 20 (at around 80% PCM) due to the lack of connected carbon network. However, it can be brought into any shape and used with any PCM (Mehling et al. 2008).

3.7 Environmental Impact Assessment

As the earth's ecosystem itself is essentially sealed, any notion of a truly sustainable, large-scale civilization must include an adequate ability to assess the long-term impact of its internal dynamics on its environment. A scientific, data driven approach seems indispensable when considering that most of our day to day consumption choices are now usually the final elements in long chains of processes, intricately woven into a global web of production, marketing and commerce that, by design or circumstance, has become increasingly opaque to most and certainly to the end user.

It must be noted however, that such assessments suffer from inherent epistemological limitations that need to be considered whenever discussing models of such complex systems. Leaning on an observation made by the French mathematician Henri Poincaré, we must recognize that even models with the finest resolution and the widest scope will fail to register occurrences that may very well trigger unpredictably significant consequences (Poincaré 1914). Not recognizing such limitations may be highly problematic according to the risk analyst Nassim Taleb, since resulting models may, at a certain point, only inflate our subjective impression of understanding rather than actually increase it (Taleb 2007).

Furthermore, we must recognize that certain aspects of collecting the necessary data stands in conflict with presently established economical systems. For no business would be naturally inclined to share information voluntarily, that may in any way reflect negatively on the image of their product or service, in absence of laws that would oblige them to do so. All the while, manufacturers may be objectively justified in their reluctance to disclose data in so far that it may expose confidential information that would jeopardize any competitive advantages which, after all, represent the core value of any capitalist entity (Kylili and Fokaides 2016; Reap et al. 2008).

Whenever we talk about environmental impact assessment, it is important to be aware of these inherent and political limitations while remembering, that a bad partial solution to an unsolvable problem is arguably better than no data driven discourse on these issues at all.

The most effective approach to measure environmental impact is called life cycle assessment (LCA). It considers energy and materials consumed for the extraction of raw materials, transportation, maintenance and disposal of a product. LCA is a standardized methodology that allows for data driven comparisons between products and scenarios. It is described in the international standards ISO 14040 and ISO 14044 and contains four phases:

1. Goal and scope definition phase
2. Inventory analysis phase
3. Impact assessment phase
4. Interpretation phase

Research on the life cycle of phase change materials is limited. A number of papers have been published, studying specific scenarios, making varying abstracting assumptions. Kylili et al and Kyriaki et al each published review papers on the subject of LCA of PCM in 2016 and 2018 respectively. Kylili et al concluded that the research demonstrated that the use of PCM lead to an overall improvement of the environmental impact, however several reviewed papers pointed out that this impact offset significantly depends on the operational life time of the system. Garcia et al for example studied Ventilated double skin facade systems and found that the environmental impact balance is only tipped in favor of the use of PCM after 31 years of operation (de Gracia et al. 2014). Kylili et al furthermore pointed out that the accuracy of the LCA result was very dependent on the goal and scope definition, which led the authors to express the need for the introduction of a common framework for implementing LCA studies for assessing the sustainability of building materials (Kylili et al. 2016). The following review published by Kyriaki et al drew more nuanced conclusions from the papers they reviewed. They made sure to point out that, naturally, the addition of PCMs has a greater environmental impact compared to most conventional forms of construction. This impact varies depending on the type of PCM. Therefore, different applications require different minimal operational time frames to reach the point of offset making them more environmentally sustainable than traditional construction methods, specifically, about 25 years for hydrated salts and 61 years for alkanes. They thus concluded that building life span should to be maximized while new PCMs with lesser environmental impact should be developed. Further, most PCMs, according to Kyriaki et al. can be recycled, organic PCMs are biodegradable and inorganic ones are innocuous. The authors also pointed out the need for standards of testing thermal energy storage products and further research to reduce the high price of PCM products (Kyriaki et al. 2018).

3.8 Commercial Products

PCM products have been commercialized for many years and a number of companies are now offering a wide spectrum of products ranging from raw PCM compounds to ready to implement building elements like wallboards, mats, containers or floor tiles. One problem when comparing commercial products is that there is no unifying labeling norm. Most manufacturers for example choose to state a single phase change temperature, while some distinguish melting and freezing temperatures and others give a temperature range. The resulting vagueness also results in uncertainty of describing the enthalpy curve which only allows a limited ability to properly represent the phase change reaction (Kalnæs et al. 2015). The following table gives a list of commercially available raw PCM suitable for human comfort applications within the range of 14-33°C. This list is intended to give a sample of manufacturers and products and should not be seen as comprehensive. Further listings of commercial PCM products can be found in Cabeza et al. (2011), Kalnæs et al. (2015), Zeinelabdein et al. (2018), Nazir et al. (2019) as well as a whole chapter in Kośny (2015) dedicated to commercial PCM enhanced building elements. Also note that many of the companies listed here, offer products with transition temperatures well beneath or above the ones presented in this list.

Table 1: commercial PCM products

Manufacturer	Product	PC-Temperature (°C) melting/freezing	Latent heat (kJ/kg)	Type	Material	Encapsulation
Mirotek microteklabs.com	nextek 18	18	190			micro
	nextek 24	24	170			micro
	nextek 28	28	155			micro
	nextek 32	32	170			micro
	Micronal 24	24	105		acrylic-based	micro
	Micronal 28	28	150		acrylic-based	micro
	PCM 18	18	205-215			bulk/macro
	PCM 24	24	165-175			bulk/macro
	PCM 28	28	195-205			bulk/macro
	PCM 32	32	180-190			bulk/macro
	vivtek 29	29	170	organic	agricultural biomass	micro
savENRG rgees.com	PCM-OM18P	18	233	organic		macro
	PCM-HS22P	22	185	inorganic		macro
Phase Change Products Pty Ltd. pcpaustralia.com.au	PC14	14	145	inorganic	hydrated $CaCl_2$ and $CaBr_2$	bulk/macro
	PC17	17	145	inorganic	hydrated $CaCl_2$ and $CaBr_2$	bulk/macro
	PC25	25	150	inorganic	hydrated $CaCl_2$ and $MgCl_2$	bulk/macro
	PC29	29	188	inorganic	hydrated $CaCl_2$	bulk/macro
PureTemp LCC puretemp.com	PureTemp15	15	165	organic	bio-based	micro and macro
	PureTemp18	18	189	organic	bio-based	micro and macro
	PureTemp20	20	180	organic	bio-based	micro and macro
	PureTemp23	23	203	organic	bio-based	micro and macro
	PureTemp24	24	185	organic	bio-based	micro and macro
	PureTemp25	25	185	organic	bio-based	micro and macro
	PureTemp27	27	200	organic	bio-based	micro and macro
	PureTemp28	28	205	organic	bio-based	micro and macro
	PureTemp29	29	189	organic	bio-based	micro and macro
	PureTemp33	33		organic	bio-based	micro and macro
Salca salcabv.nl	Thermusol HD26	26		inorganic	salt hydrate	micro
	Thermusol HD32	32	150	inorganic	salt hydrate	micro
Climator Sweden AB climator.com	ClimSel C21	21-26	134	inorganic	sodium sulfate	macro
	ClimSel C24	24-27	140	inorganic	sodium sulfate	macro

Manufacturer	Product	PC-Temperature (°C) melting/freezing	Latent heat (kJ/kg)	Type	Material	Encapsulation
	ClimSel C28	27-31	170	inorganic	sodium sulfate	macro
	ClimSel C32	29-32	160	inorganic	sodium sulfate	macro
PCM Products Ltd. pcmproducts.net	Plus ICE S15	15	180	inorganic	salt hydrate	macro
	Plus ICE S17	17	155	inorganic	salt hydrate	macro
	Plus ICE S19	19	175	inorganic	salt hydrate	macro
	Plus ICE S21	21	220	inorganic	salt hydrate	macro
	Plus ICE S23	23	215	inorganic	salt hydrate	macro
	Plus ICE S25	25	175	inorganic	salt hydrate	macro
	Plus ICE S27	27	185	inorganic	salt hydrate	macro
	Plus ICE S32	32	220	inorganic	salt hydrate	macro
	Plus ICE A15	15	205	inorganic	aliphatic compounds	macro
	Plus ICE A17	17	235	inorganic	aliphatic compounds	macro
	Plus ICE A19	19	150	inorganic	aliphatic compounds	macro
	Plus ICE A21	21	160	inorganic	aliphatic compounds	macro
	Plus ICE A23	23	155	inorganic	aliphatic compounds	macro
	Plus ICE A25	25	150	inorganic	aliphatic compounds	macro
	Plus ICE A27	27	250	inorganic	aliphatic compounds	macro
	Plus ICE A29	29	225	inorganic	aliphatic compounds	macro
	Plus ICE A32	32	120	inorganic	aliphatic compounds	macro
Rubitherm rubitherm.eu	RT 15	15	155	organic		micro and macro
	RT 18 HC	18	260	organic		micro and macro
	RT 21	21	155	organic		micro and macro
	RT 21 HC	21	190	organic		micro and macro
	RT 22 HC	22	190	organic		micro and macro
	RT 24	24	160	organic		micro and macro
	RT 25 HC	25	210	organic		micro and macro
	RT 26	26	180	organic		micro and macro
	RT 28 HC	28	250	organic		micro and macro
	RT 31	31	165	organic		micro and macro
	SP 15	15-17	180	inorganic	salt hydrates	macro
	SP 21 EK	21-23	170	inorganic	salt hydrates	macro
	SP 24 E	24-25	180	inorganic	salt hydrates	macro
	SP 25 E2	24-26	180	inorganic	salt hydrates	macro

Manufacturer	Product	PC-Temperature (°C) melting/freezing	Latent heat (kJ/kg)	Type	Material	Encapsulation
	SP 26 E	26-27	180	inorganic	salt hydrates	macro
	SP 29 Eu	29-31	200	inorganic	salt hydrates	macro
	SP 31	31-33	210	inorganic	salt hydrates	macro
CrodaTherm crodatherm.com	CrodaTherm 15	15/9.5	177	organic	plant-based	micro and macro
	CrodaTherm 19	19.3/17.9	175	organic	plant-based	micro and macro
	CrodaTherm 21	21/19	190	organic	plant-based	micro and macro
	CrodaTherm 24	24.1/20.1	183	organic	plant-based	micro and macro
	CrodaTherm 24W	23.8/22.8	184	organic	plant-based	micro and macro
	CrodaTherm 29	29/26	207	organic	plant-based	micro and macro
	CrodaTherm 32	32/29.5	190	organic	plant-based	micro and macro
Phase Changer Energy Solutions phasechange.com	BioPCM Q15	15	210-250	organic	bio-based	macro
	BioPCM Q18	18	210-250	organic	bio-based	macro
	BioPCM Q20	20	210-250	organic	bio-based	macro
	BioPCM Q23	23	210-250	organic	bio-based	macro
	BioPCM Q25	25	210-250	organic	bio-based	macro
	BioPCM Q27	27	210-250	organic	bio-based	macro
	BioPCM Q29	29	210-250	organic	bio-based	macro

4 PCM BUILDING APPLICATIONS REVIEW

Phase change materials have been studied and upheld as suitable for a wide range of thermoregulatory applications in buildings. They include, among other, free cooling, free heating and peak load shifting. These applications can be distinguished further into passive and active systems. *Passive* refers here to purely static, systems usually as part of the building envelope or internal building substance (as described previously, in this paper's chapter 3.1 on the conceptual function of PCMs). However, there are also numerous applications, referred to as *active,* in which PCMs are coupled with mechanical and/or electrical systems. These systems range from simple ventilation devices, to ensure complete phase change cycles, to highly complex HVAC systems (Zhu et al. 2009). Figure 4-1 shows a diagram of possible applications within the building envelope. The application studies presented in sections 4.1-4.7 are focused on more passive solutions, while section 4.8 offers an overview of active systems.

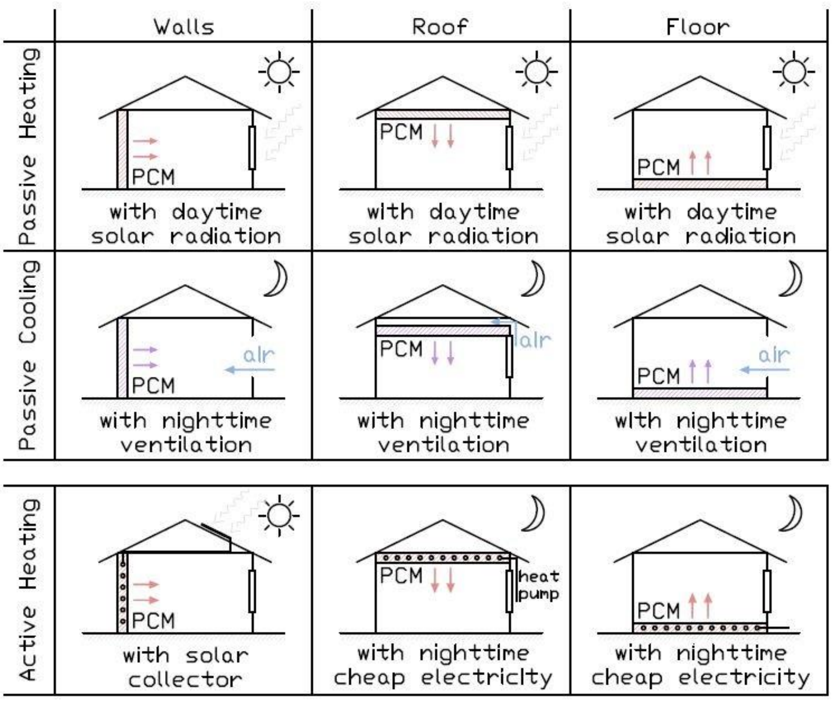


Figure 4-1: *PCM envelope applications for heating and cooling* (Zhang et al. 2007)

○ Free Cooling

In climates with significant diurnal temperature fluctuations, free cooling can be achieved when PCMs are applied in such a way, that cool nighttime air evacuates daytime heat, stored within the liquid phase of the PCM by causing it to freeze. During the day, the frozen PCM acts as a sort of buffer by absorbing incoming heat in its melting process which would otherwise have gone toward increasing the temperature of the structure and the indoor air. This can be achieved in a great number of arrangements, however, factors like ventilation air flow rates, transition temperatures of the PCM as well as its thermal conductivity in interplay with its geometry and link to the ventilation system, play cardinal roles in setting up effective systems aimed at full charge and discharge cycles. Air ventilation is the most straight forward means of evacuating heat in most cases, however other media like water pipes can be used (Kalnæs et al. 2015). Such systems are functional as long as the diurnal temperature extremes lay on either side of the chosen PCM's transition temperatures, thus allowing the PCM to cycle through its phases (Zalba et al. 2004).

- ### Free Heating

Free heating, to a certain degree, functions analogously to free cooling. As temperatures drop in the evenings and nights, liquid PCM solidifies, releasing the energy that would otherwise have been drawn from the structure and indoor air thus decreasing its temperature and acting, again, as a sort of buffer against the loss of heat. The recharging, re-liquefying process however is not mainly achieved by convection as is the case in free cooling but by solar radiation during the day. In colder climates that have high incident solar radiation a good deal of heating can be achieved by absorbing the incoming radiation. These systems rely in some sense on trapping the fleeting heat generated by solar radiation and storing it for release during the evening and night (Kalnæs et al. 2015).

- ### Peak load shifting

The effect of peak load shifting can be achieved in a heating and a cooling scenario and refers to the time delay of peak energy consumption caused by the buffering effect of storage systems like thermal mass (fig. 4-2). Energy demand patterns of buildings in relevant proximity to each other are far from random, they follow not only the same diurnal temperature curves but also roughly similar occupancy patterns. As a result, the energy supply grid experiences significantly disproportionate stresses during what is referred to as on-peak period and lower to very low demands during off-peak hours. From the side of the supplier this seems loosely analogous to building, operating and maintaining a fleet of large cargo vessels that run close to empty most of the time. Unlike most cargo, however, electricity is not at all easy or cheap to store in the relevant quantities. An efficient supply and demand system is, therefore, absolutely essential for keeping total energy consumption to a minimum. In 2003 the international Energy Agency reported that the wholesale price of electricity could be reduced by 50% with a mere 5% reduction of peak demand (International Energy Agency 2003). To incentives consumers to shift their demands away from peak hours, many suppliers have introduced a bracketed pricing system, charging more for on-peak consumption and less during off-peak hours. Peak load shifting thus works towards enabling consumers and suppliers to create cheaper and more efficient electricity consumption patterns (Sun et al. 2013).

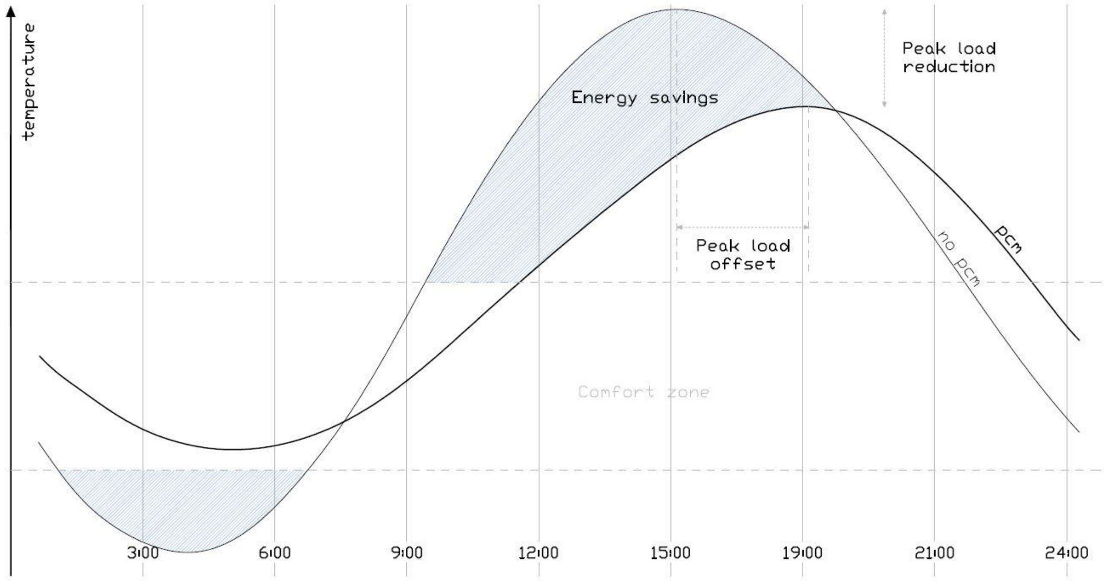


Figure 4-2: *simplified representation of PCM energy saving and peak load offset effects*

4.1 Wallboards and Interior Plaster Applications

Due to their widespread use in numerous building applications, drywall products, like gypsum wallboards and other mineral or synthetic, non-structural wall elements have been studied most extensively, both numerically and experimentally, for applications of PCM. This has resulted in a large body of research discussing the usability of PCM within interior wallboards and other similar applications.

The 1980s have shown several attempts to implement and market different forms of macroencapsulated PCM into wall structures. Most bulk encapsulated PCM elements however have an unfavorable surface area which significantly reduces the regulatory potential which makes them impractical to implement into passive applications. In an attempt to overcome the shortcomings of bulk encapsulation, researchers turned their attention to implementing PCM directly into walls which offer a very large exposed surface area (Tyagi and Buddhi 2007).

Neeper conducted several studies and concluded that PCM impregnated gypsum wallboard could be installed in place of ordinary wallboard during new construction or rehabilitation of a building at little or no higher cost while adding thermal storage

(Neeper 1986). He furthermore found that the thermal storage provided by PCM wallboard would be sufficient to enable a large solar heating fraction with direct gain (Neeper 1989). Kedl and Stovall presented a concept of octadecane wax impregnated wallboard for passive solar applications. Their process successfully scaled up from small samples to full size sheets and was shown to achieve higher storage capacities than adding wax filled pellets to wallboards during manufacture (Kedl and Stovall 1989).

Using direct incorporation and immersion techniques, Hawes et al. investigated gypsum wallboards in combination with different PCMs (Capric-lauric acid, Butyl stearate, propyl palmitate, dodecanol). They successfully impregnated 25-30wt% PCM in gypsum wallboards. They found an elevon-fold increase in energy storage capacity through a 4°C rise and comparable flexural strength. Depending on the type and content of PCM, thermal conductivity was found to be within the range of +- 15%. Fire resistance was excellent and compatibility with paints and wallpapers was good. They further found a 22% weight increase which remains within the weight limits accepted by the industry. Finally, they concluded that the elements were more durable in moist environments (Hawes et al. 1993). The same team then went on to conduct a full scale experimental study which concluded that PCM wallboards may be considered a suitable candidate for thermal energy storage application (Scalat et al. 1996).

Athienitis et al. built a full-scale outdoor test room to examine gypsum wallboards with 25wt% incorporated butyl stearate. They found that the wallboards may reduce the maximum temperature by 4 °C during the daytime and can significantly reduce the heating load at night (Athienitis et al. 1997).

Neeper examined the thermal performance of PCM boards, looking at three parameters, namely, melting temperature of the PCM, the temperature range over which melting occurred and the latent capacity per unit area of wallboard. He concluded that the diurnal storage achieved in practice may be limited to about 300-400 kJ/m². Furthermore, he found that maximum diurnal energy storage occurs when the PCM is chosen such that the melting temperature equals the average wallboard temperature (Neeper 2000).

Koschenz et al. developed a gypsum PCM panel, designed to serve as ceiling board in lightweight and retrofitted office buildings. As seen in figure 4-3, the panel is inlayed with aluminum fins and capillary tubing to enhance conductivity throughout the gypsum. To reach their projected 320Wh/m² a day that would allow for maintaining a comfortable room temperature in standard office buildings, they calculated that the thickness of the panel would have to be at least 5cm and the needed weight proportion of the encapsulated paraffin PCM (melting point: 22°C; latent heat: 110 kJ/kg) to gypsum needs to be at least 25%. Using this set up as a ceiling panel allows for easy addition of an air cavity layer above the panel to ensure good heat transfer rates, however, they noted that the panel could just as readily be implemented as a wallboard (Koschenz et al. 2004).

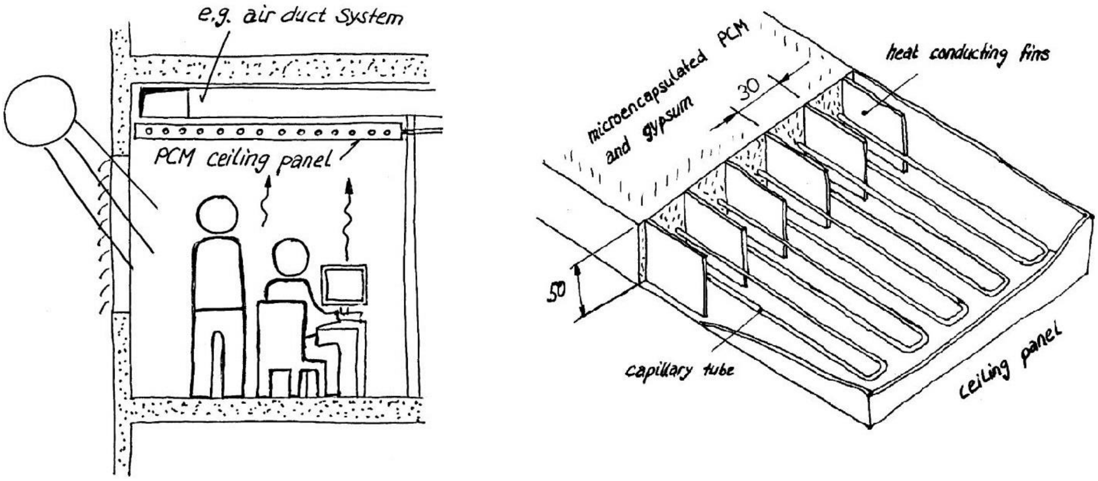


Figure 4-3: *schematic sketches microencapsulated PCM gypsum ceiling panel (Koschenz et al. 2004)*

Schossig et al. reviewed the findings of a large-scale study on incorporating PCM into gypsum board, conducted at Fraunhofer Institut over a period of several years. They discuss two different PCM wallboards. One 6mm dispersion-based plasterboard with 40wt% of PCM and a 15mm gypsum plasterboard with 20wt% of PCM. Test results showed that microencapsulated PCM were effective in reducing the cooling demand and increased the comfort of lightweight buildings. During a summer period of three weeks, the reference room was warmer than 28°C for 50h while the PCM room was only 5h above 28 °C. The Authors added that microencapsulated PCM has the advantage of easy application, good heat transfer and no need for protection against destruction. Furthermore, added the reminder that adequate ventilation is essential for a successful application of PCM technology (Schossig et al. 2005).

Shilei et al. investigated the performance of gypsum wallboard impregnated with 26wt% PCM (capric mixed with lauric acid). They built two full size test rooms (5x3.3x2.8m) and monitored them over three consecutive days. Compared to the control room, the PCM test room showed a 1.15°C reduction in maximal temperature fluctuation. They thus concluded that PCM wallboard can be used to increase room thermal comfort and reduce the scale of heating equipment (Shilei et al. 2006)

Sari et al prepared PCM gypsum by impregnating the wallboard with 25wt% of a eutectic mixture of capric and stearic acid (melting point: 24.68°C; latent heat: 48.32J/g). The wallboard did not show any sign of leakage after 5000 cycles. The results from their scaled test room showed that the indoor temperature was reduced by 1.3°C (Sarı et al. 2008).

Sunliang et al. conducted an experimental hotbox study using 5.26mm thick Dupont Energain PCM panels (melting point: 21.7°C; latent heat: >70J/g) and showed a clear reduction in temperature fluctuations (Sunliang et al. 2010).

Kuznik et al. studied wallboards that included 60% microencapsulated paraffin. They built a test cell and looked at three controlled cases for a summer day, a winter day and a mid-season day. The results showed that air temperature and wall surface temperature fluctuations were reduced. The air temperature in the room with PCM was reduced up to 4.2°C in summer conditions. In addition, the room with PCM showed less uncomfortable thermal stratifications (Kuznik and Virgone 2009). They then went on to include the studied wallboard into a renovated office building and monitored the rooms over the period of one year which showed that the PCM wallboards enhanced the thermal comfort of residents due to reduced air temperature fluctuations and a reduction of negative radiative effects that result from differences in air and surface temperatures (Kuznik et al. 2011).

Chan simulated the energy and environmental performance of a typical residential flat in Hong Kong. Using typical weather data representing a summer day, it was found that the living room of a residential flat with west-facing integrated with PCM showed a decrease in surface temperatures of up to 4.14% which would lead to an annual energy saving of 2.9% which would correspond to a cost buyback time of 91 years. This makes the investment infeasible economically for a building with an expected lifespan of 60 years on average. In terms of environmental impact, however, the authors showed an energy payback period of 23.4 years. Therefore, the energy saved can recover the embodied energy of the PCM wallboard and contribute to mitigation of greenhouse gases emission over the life span of the building (Chan 2011).

Oliver investigated gypsum wallboards containing 45wt% of PCM reinforced with additives. She found that 1.5 cm thick gypsum board with PCM stores five times the thermal energy of a laminated gypsum board which amounts to the same energy stored in a 12cm thick brick wall within the comfort temperature range (Oliver 2012).

Evola et al. conducted a simulated case study of an office building refurbished with PCM enhanced wallboards during summer conditions. Their wallboards consisted of a honeycomb aluminum matrix filled with a 60% mixture of microencapsulated paraffin, Micronal T23, produced by BASF (melting point: 22-28.5°C). They proposed and discussed indicators such as *intensity of thermal discomfort, frequency of thermal comfort, frequency of activation* and *storage efficiency.* Their simulations showed a reduction of peak operative temperature of about 1°C and remarkable reduction in surface temperature fluctuations as well as a time shift of about 1.5-2h for surface temperatures (fig. 4-4). They pointed out however that even with frequent activation, only about 45% of the total latent heat was exploited, showing that the entire PCM would not melt or solidify each cycle (Evola et al. 2013).

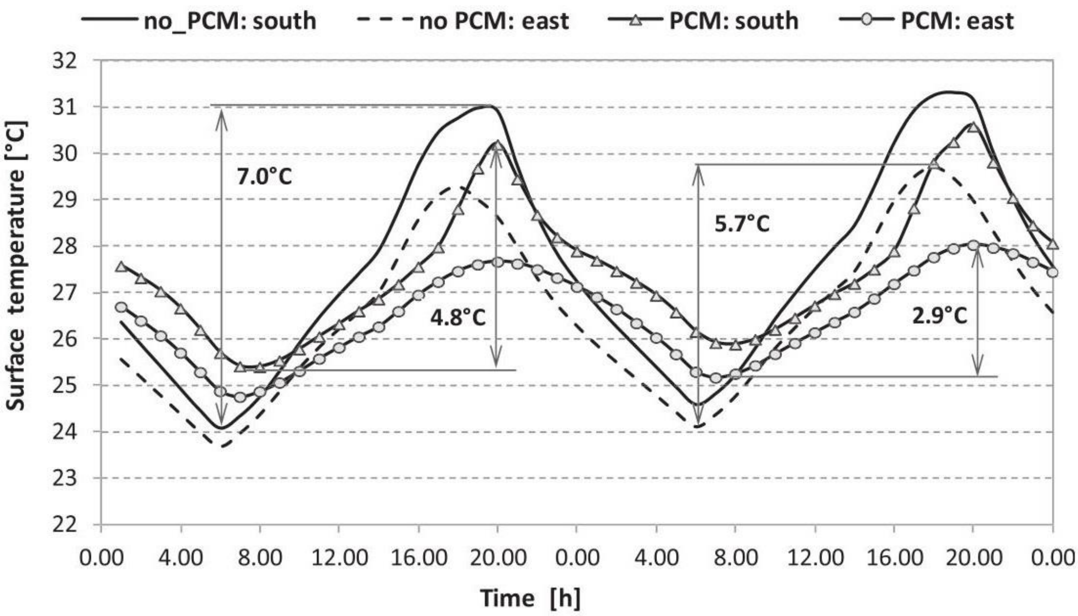


Figure 4-4: *surface temperature in a 48h period* (Evola et al. 2013)

Diaconu studied the influence of occupancy patterns on thermal energy savings for heating with PCM enhanced walls. He conducted a numerical investigation and clearly showed that occupancy patterns must be considered when selecting a suitable PCM (Diaconu 2011).

Becker developed a simplified model to analyse how the application of PCM to inner walls may substitute insufficient thermal mass in lightweight constructions in warm Mediterranean climates. Her simulation rendered the effective thickness of PCM that can be fully discharged via night ventilation as well as the respective surface are required for storing the internal heat gains occurring during the day. Furthermore, she analysed energy performances for three building types (light, semi-light and heavy). Results showed that night ventilation is essential and that during the hottest summer periods, only a thin layer of several millimetres can be fully discharged overnight. However minimal thicknesses were shown to be very effective in reducing cooling energy demands in lightweight offices though much less effective in semi-lightweight classrooms and practically irrelevant in heavy weight constructions. Thermal comfort however was increased by reducing surface temperature fluctuations in all scenarios (Becker 2013).

Ascione et al. investigated methods for refurbishing buildings with PCM plaster on the inner side of the building envelope in terms of the effect it would have on energy savings and indoor comfort for in the cooling season in Mediterranean climates. The simulations varied melting point ranging from 26 to 20°C, thickness of the wallboard and location of the PCM layer. The achievable benefit for energy savings in climates simulating Seville and Naples were about 3%. The benefits for Marseille and Naples were about 4.1% and 3.5% respectively, while the results for Ankara showed a 7.2% benefit. The comfort hours during the occupied time increased by 15.5% (Seville), 22.9% (Naples), 19.8% (Marseille), 15.8% (Athens) and 20.6% (Ankara). They further indicated that the optimal phase change temperature is seasonal, meaning that complete charge and discharge cycles may be difficult to obtain year-round with a single PCM (Ascione et al. 2014).

Using a remarkable experimental set up, called plug-and-play walls, in which different wall modules can be mounted and exchanged with very little effort, lee et al. studied the effect of 5mm thick PCM wallboards (melting point: 20.6°C; latent heat: 73.4J/K). Their results showed that the average daily heat transfer reductions were 27.4% and 10.5% for south and west facing walls, respectively, and the average heat flux reductions when the heat fluxes of the control walls were at their peaks were 67.0% and 80.2%. The delay of peak heat transfer rate per unit of wall area was two to three hours on average (Lee et al. 2015).

Zhou and Eames conducted simulations to analyze PCM wallboard in a lightweight building using weather data for UK summer months. They found the optimal melting temperature to be 23.4°C. Their results further showed that energy savings can be as high as 40% compared to the control and that the period in which temperatures are maintained within the thermal comfort range can be extended by up to 7.2% (Zhou 2019).

Wang et al. looked at incorporating PCM-Wallboards into light-weight high-rise structures in shanghai. While the effect was shown to be higher in winter, their simulations found that PCM Wallboards improve indoor comfort in both seasonal extremes while the optimal PCM melting points varied between 22°C and 26°C depending on orientation and season. Economically, the PCM integrated into walls on the south side of the building showed the greatest benefit and was deemed economically viable by the researchers with a payback time of 5 years. (H. Wang et al. 2020).

4.2 Structural Concrete

Ling and Poon gave a comprehensive overview on the feasibility of incorporating PCM into concrete elements. They concluded that incorporating PCM into concrete brings significant improvement to the thermal performance of the concrete by substantially increasing its thermal mass and reducing its thermal conductivity. However, it must be noted that a reduction in thermal conductivity, while granting benefits in terms of insultation, may also negatively affect the integrity of charge and discharge cycles. We must, therefore, expect there to be an effective limit to the amount of PCM that can be added to concrete without additional additives to increase conductivity. Furthermore, the compressive strength and density may be affected negatively by the addition of PCM. This is especially the case with microencapsulated PCM mixed directly into the fresh concrete and significantly less so for immersed or vacuum impregnated concrete. According to the research, care must be taken in the choice of PCM and of the method of incorporation when considering, cement hydration time, long term stability and fire resistance. They also found that paraffins seemed most suitable in combination with concrete for their general chemical stability and inactivity in the alkaline environment of concrete (Ling and Poon 2013).

Hunger et al. investigated the behavior of self-compacting concrete containing micro-encapsulated PCM. Using different amounts of PCM, ranging from 0-5% (by weight) as a substitute for marble powder incorporated directly into the concrete mix. Their measurements show a significant increase of thermal mass and consequent reduction in temperature fluctuations. They estimated possible energy savings up to 12% for a 5% PCM mix. They also observed a significant loss of compressive strength (21,36N/mm² for the 5%mix compared to 74,05N/mm²), they mentioned, however, that these values would still satisfy the demands of most structural applications (Hunger et al. 2009).

Cabeza et al studied two full size concrete cubicles in Lleida, Spain. One cubicle was made of regular concrete, the other included 5% (by weight) of microencapsulated PCM with a melting point of 26°C. They found the compressive strength of the PCM-enhanced concrete to be about 25N/mm² and thus retained its suitability for structural purposes. Their results as seen in (fig. 4-5) show a considerable reduction in indoor peak temperature and temperature fluctuation in a closed window scenario. They closed by mentioning that no difference in the effects of the PCM was seen after 6 months and that the set-up was to be refitted for further research on winter heating which will be discussed in chapter 4.4 on Trombe walls (Cabeza et al. 2007).

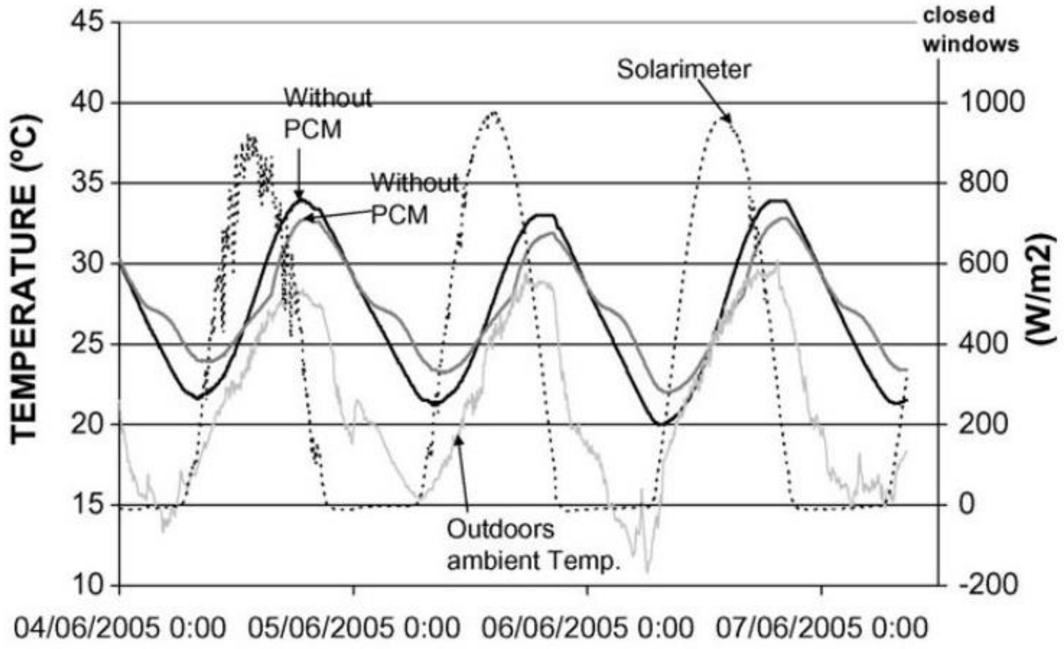


Figure 4-5: *comparison between south wall temperature in both cubicles, outdoor ambient temperature and solarimeter signal (Cabeza et al. 2007)*

Cui et al. investigated concrete adding a macro-encapsulated paraffin using hollow steel balls with 22mm diameters (fig. 4-6). They prepared 4 test room models replacing 0%, 25%, 50% and 100% of the coarse additives weight (corresponding to 0%, 11%, 23%, 34% and 44% of the total weight)[10] by PCM filled HSB fitted into metal clamps to increase mechanical bonding between the smooth steel ball and the mortar matrix. The reduction in compressive strength compared to the 0% mix was found to be 16%, 17%, 20% and 40% respectively. The authors results, as displayed in figure 4-6 show a remarkable increase in thermal mass and suggest a significant decrease in heating and cooling loads. In consideration of the mechanical properties, thermal performance and economic factors, the authors recommend the 50% and 75% PCM-HSB-c replacement ratios (Cui et al. 2017).

[10] No information was given concerning the weight of the clamps, however, it was stated in a previous paper by the authors that the PCM made up 80,3% of the total mass of the filled balls without the clamps (Dong et al. 2016).

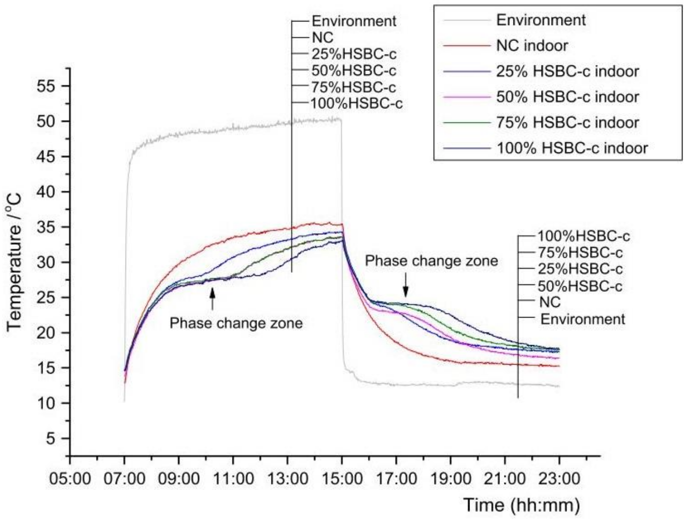


Figure 4-6: *left: measured PCM effect; right: macroencapsulation HSB with metal clamp* *(Cui et al. 2017)*

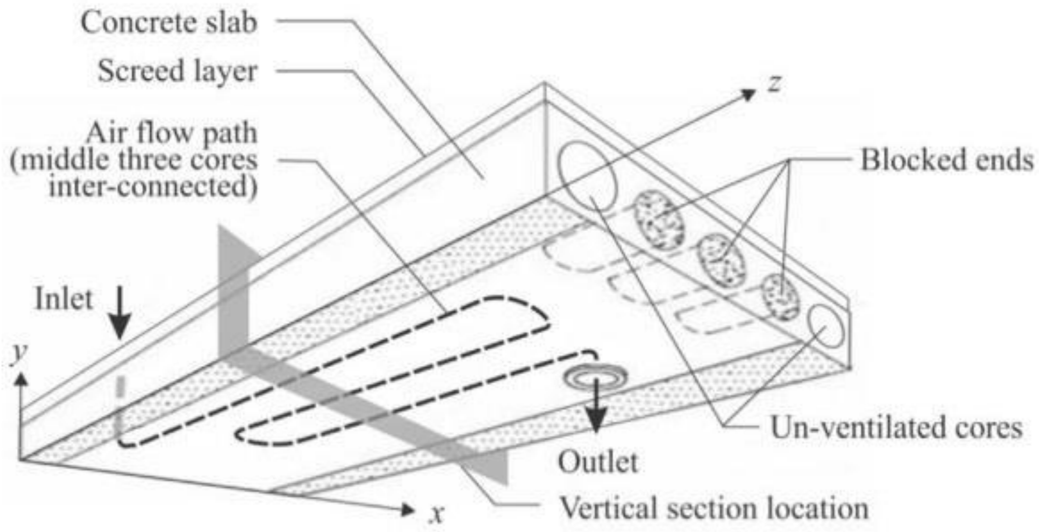


Figure 4-7: *Schematic of a ventilated hollow core slab (VHCS)* (Faheem et al. 2016)

Faheem et al. presented a numerical model for a ventilated hollow core slab (VHCS) and studied the effects of incorporating micro-encapsulated PCM for cooling of office buildings (fig. 4-7). They analyzed the impact of different PCM, different melting points and different air flow rates for on a high thermal mass building in one case and on a low thermal mass building in a second. They found that the highest performance occurred with a 20°C PCM melting point in the high thermal mass environment and a 19°C melting point in the low thermal mass environment, noting that the VHCS had much higher cooling potentials when placed in the latter. Their results also showed the importance of high flow rates, especially in high thermal mass environments. They furthermore concluded, that no significant improvement occurs with PCM contents beyond 10%, regardless of the ventilation rate (Faheem et al. 2016).

Rayon et al. studied a hollow structural concrete floor panel with cylindrical holes filled with a paraffin that was shape stabilized and brought into cylindrical shape in a polymeric matrix. Their experimental set-up consisted of a scaled model of 280x280x71mm containing eight horizontal holes with a diameter of 25mm. The outer boundary conditions were set to a cyclical linear variation of temperatures between 20 and 35°C while the inner temperature was set at 20°C. Their results as shown in figure 4-8 show a substantial decrease in fluctuation of the surface temperature and an increased time lag. They subsequently investigated reduced annular rather than full cylindrical PCM elements and concluded that a 50% reduction seemed most efficient (Royon et al. 2014).

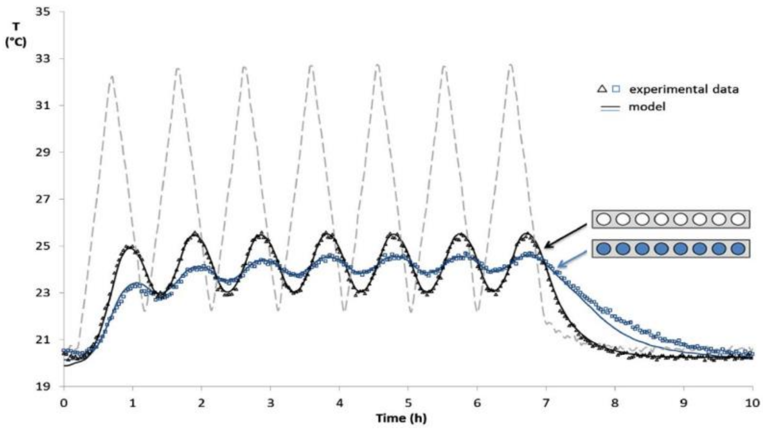


Figure 4-8: *Variation of temperature at the surface of the floor panel. (Royon et al. 2014)8*

4.3 Floors

Ansuini et al. developed and analyzed a lightweight piped radiant floor with an integrated PCM layer, designed both for summer and winter use in Mediterranean climates. The set up consisted of a 40mm insulation layer on which they spread 40mm of large micro-encapsulated paraffin PCM granulate (1-3mm diameter) around a water bearing pipe system. Lastly the floor prototype was sealed with unspecified tiles (10mm) on a mortar bed (5mm). As early measurements showed a significant reduction of efficiency as a function of depth, they added a steel matrix (a commercial product initially developed to increase structural strength in thin concrete floors, (fig 4-9) to act as a highly conductive diffusor which lead to a reduction in stratified melting behavior of the PCM. Their results showed an approximate 25% saving of cooling water. In mid-season, they reported, the PCM was able to buffer radiant and internal gains for about 2-3 day in typical living conditions which improves the integration of the floor into intermittent renewable energy systems. Furthermore, they noted that using PCM in combination with radiant floors for cooling also reduces the occurrence of condensation typical in such applications (Ansuini et al. 2011)

Figure 4-9: *steel matrix for increased structural strength and conductivity* (Ansuini et al. 2011)

A group around Kunping Lin at Tsinghua University of Beijing conducted a series of simulations and experiments on increasing the thermal performance of floors using PCM. They initially looked at combining under-floor electric heating systems with PCM that would charge during off-peak hours and discharge during peak hours. They developed a floor system made up of an electrical heater positioned between a layer of insulation and a 20mm thick layer of shape stabilized PCM followed by a 10mm layer covered with 12mm wood flooring as seen in figure 4-10. Their numerical models showed that the system is able to keep indoor temperatures within the comfort range throughout winter for different sorts of heat loads as long as phase transition temperature and thickness of air layer are appropriately chosen (Lin et al. 2004). Their subsequent experimental study suggested that more than half of the total electric heat energy can be shifted from peak periods to off-peak periods and thus provides significant economic benefits in regions with differential energy pricing (Lin et al. 2005).

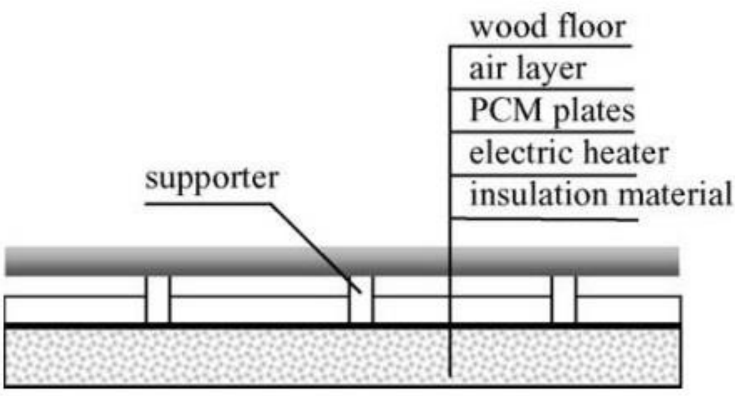


Figure 4-10: *schematic of electric heating system with shape stabilized PCM plates* *(Lin et al. 2005)*

The same group then looked at passive systems in which their previous PCM enhanced floor set up would take up and store solar gains during day providing free heating during cold winter evenings and nights. Using numerical modeling they studied the influence of various factors like PCM thickness, melting temperature, heat of fusion and thermal conductivity. They found that for any given climate, the suitable melting temperature of the PCM should be roughly equal to the average indoor air temperature on sunny winter days. They further determined that the heat of fusion and thermal conductivity should be greater than 120 kJ/kg and 0.5 W/(m K), respectively. The thickness of the PCM layer should not exceed 20mm and the air gap between PCM and floor needs to be minimized. Furthermore, they determined that wood floors are less suitable than metal and tile floors due to their weak conductivity (Xu et al. 2005; Zhang et al. 2006). In a recent study, they also explored and demonstrated the benefits of adding expanded graphite to the shape stabilized PCM to increase its conductivity (Cheng et al. 2015).

Jeong et al. studied PCM for wood-based flooring application. Aiming at creating a suitable PCM enhanced adhesive layer to lay out underneath wooden floors, they analyzed epoxy resin mixtures filled with varying amounts of micro-encapsulated PCM ranging from 0-10wt%. Their results indicated that the addition of PCM decrease the adhesive strength of the resin but still falls into suitable values at 10wt%. They furthermore confirmed that the heat storage capacity of the floor system was increased (Jeong et al. 2012).

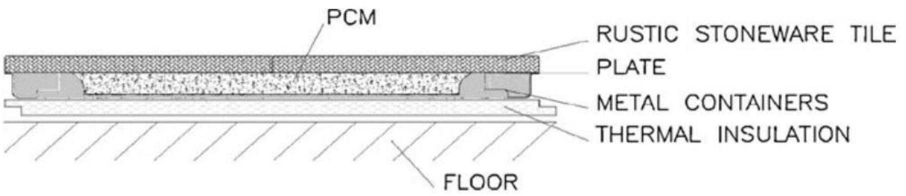
- ### Concrete Floors

Entrop et al. examined PCM enhanced concrete floors for thermoregulatory purposes in moderate climates. To study the effect of PCM floors they set up four scaled living room box models with large south oriented windows, on the campus of the University of Twente. In two of them, they installed concrete floors containing 5% micro-encapsulated PCM. They also experimecnted with different kinds of insulation and glazing. Their results showed a reduction of maximum floor temperatures up to 16 ± 2% and an increase of minimum temperatures up to 7 ± 3% (Entrop et al. 2011).

- ### Ceramic Tiles

Despite their widespread use, ceramic tiles have been studied little in combination with PCM. In a topical report D. Hittle suggested to use microencapsulated octadecane in 3/4inch floor tiles and thereby increase annual energy savings by 24% referring to an analysis on the basis of a static model. Furthermore he states that the ideal tile would substitute all quartz powder for PCM expecting at least some deterioration in mechanical properties (Hittle 2002).

Cerón et al. developed a prototype of PCM enhanced ceramic tile and tested it over a winter period of 60 days in a house in Madrid, Spain. The prototype consisted of a metal casing containing a 32mm layer of paraffin PCM sandwiched in between a layer of thermal insulation and an array of 2x2 stoneware ceramic tiles, as seen in figure 4-11. Compared to the control their results show significantly lower surface temperatures during peak hours and slightly higher surface temperatures during evening and night. The researchers found that the effect was most pronounced in those parts of the floor directly exposed to solar radiation and concluded that it would be efficient to limit the application to those areas only. Furthermore, they inferred that the porotype could also serve as a heat sink in the summer season though noted that it would be necessary to raise the melting point of the PCM (Cerón et al. 2011).



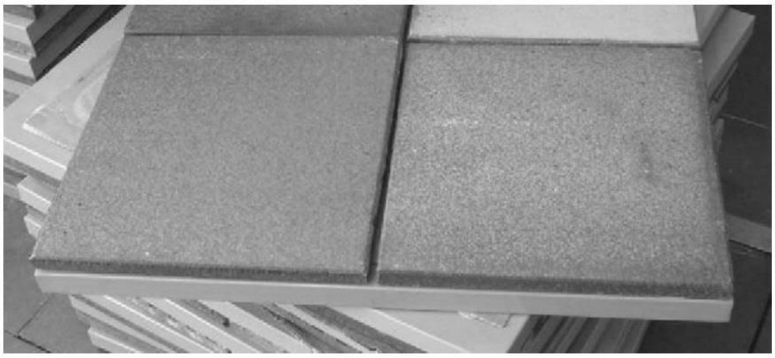


Figure 4-11: *PCM-tile protorype (Cerón et al. 2011)*

Novais et al. developed a method to directly incorporate PCM into lightweight tiles. To ensure that the porous ceramic would soak up a maximum amount of PCM, they kept the tile resting in a bath of liquid PCM for 2 hours under a vacuum. The saturated tile was then taken out of the vacuum and placed in an oven at 50° to remove the excess PCM from the surface before being coated with an epoxy resin to prevent further leakage. They went on to compare tiles with varying proportions of PCM (0-8.1%). As a higher proportion of PCM effected a decrease of conductivity they established the optimal percentage to be of about 5.4%. They concluded a decrease in temperature variation of up to 22% as well as a decrease in energy demand. If combined with under-floor heating, they added, energy consumption would be shifted into cheaper off-peak hours providing additional benefits (Novais et al. 2015).

4.4 Trombe Walls

A classical Trombe wall is a passive solar heating system usually consisting of a high storage capacity wall with high absorptivity placed behind a south facing glass front[11] at a small distance to allow for air circulation between the two layers. The heat gains are thus trapped by the system and absorbed by the wall during sunshine hours and subsequently released to the space behind it. As seen in figure 4-12, air flow in the gap is controlled by means of openings in the upper and lower part of the wall to heat the indoor space behind it, as well as openings in the upper and lower parts of the glass front to evacuate unwanted excess heat in the warmer seasons. The system was first patented by Edward Morse in 1881 and later made famous by Félix Trombe in the 1950s (Jaber and Ajib 2011). Over the years, all sorts of modified Trombe walls have been suggested for heating as well as cooling applications. Theses variations have been usefully reviewed by Hu et al. (Hu et al. 2017).

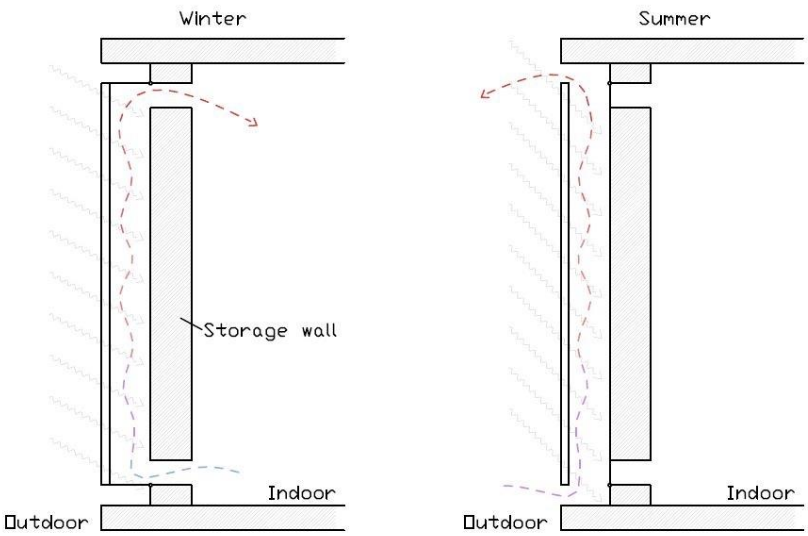


Figure 4-12: *schematic function of Trombe walls*

In recent years considerable research has been focused on implementing PCM as storage medium to increase the thermal efficiency and compactness of Trombe walls. Bourdeau and Jaffrin were one of the first to simulated and test a PCM-enhanced Trombe wall using salt-hydrates. Their numerical model showed that a 3.5cm thick board of PCM could replace a 15cm thick concrete wall (Bourdeau and Jaffrin 1979). Bourdeau subsequently conducted experiments placing PCM filled plastic containers

[11] Naturally, the north side is used in the southern hemisphere.

on a wooden shelf behind a glass front and thus validated that latent heat storage was more efficient than conventional concrete walls. In terms of wall thickness, he concluded that such PCM elements outperform their conventional concrete equivalents by roughly a factor of four (Bourdeau 1982).

Benson et al. conducted simulations for a Trombe wall using PCM, comparing it to conventional concrete elements. Their parametric studies showed that the optimal melting temperature for their set-up was 27°C. Their calculation predicted that adding about 2wt% of graphite or similarly conductive materials would increase the thermal diffusivity of the PCM by a factor of 5, which would increase the overall performance of the Trombe wall by roughly 30%. They concluded that their set-up performed as well as a conventional concrete Trombe wall that is four times thicker and nine times heavier, suggesting significant design advantages (Benson et al. 1985).

Stritih and Novak presented a Trombe style solar wall using PCM and transparent insulation material (TIM). The interesting advantage of such insulation materials is that they are largely transparent to short-waved solar radiation, allowing for adequate insulation without fencing out solar heat gains. Their system as seen in figure 4-13 consisted of a glass front, a layer of translucent insulation, a layer of black paraffin wax, and air gap, a layer of regular insulation followed by a plaster wall. They found the efficiency of the absorption to be at 79% and an optimal PCM- thickness of 50mm. Their analysis furthermore revealed an optimum melting point a few degrees above room temperature (Stritih and Novak 1996). Heim conducted a whole year analysis on a similar system and found thermal conditions on internal surfaces highly improved (Heim 2016).

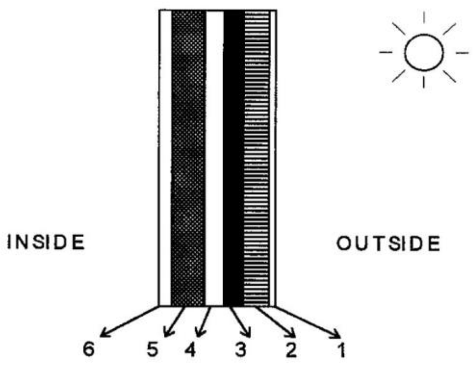


Figure 4-13: *1. glass; 2. translucent insulation; 3. black paraffin wax 4. air gap; 5. regular insulation; 6. plaster (Stritih et al. 1996)*

Sun and Wang proposed a new type of passive solar collector-storage in form of a Trombe wall with PCM storage. They investigated transfer performance and energy saving characteristics by numerical approach. An Experimental room was used to examine performance in winter. They used a 6mm thick synthetic polymer sunlight board as a front, followed by a 100mm air gap. 15mm of specialized collector mortar was then applied to a 40mm extruded board mounted on a 190mm concrete wall. Finally, they applied a 15mm thick phase change mortar layer on the indoor facing surface of the concrete. 200x200mm openings were located in the upper as well as lower part of the wall. The melting temperature of the PCM was 19.45°C and its latent heat 128J/g. Their experimental results, as shown in figure 4-14, show significantly higher temperatures in the test room compared to the control room indicating that the solar collector wall has distinct potential for improving indoor comfort and energy saving (Sun and Wang 2016).

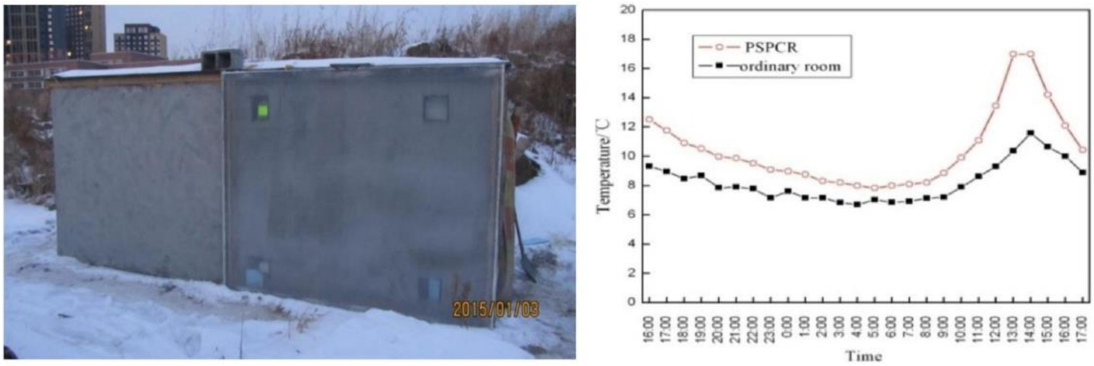


Figure 4-14: *left: external view of the set-up; right: indoor temperature* (Sun and Wang 2016)

In an experimental set-up, Li and Liu aimed at extending the duration of utilization of solar chimneys[12], to achieve an offset of solar gains into night-time. They used a 1000x1600x40mm stainless-steel container filled with 50kg RT42 paraffin wax produced by Rubitherm (melting point: 38-43°C; latent heat: 174J/g). The inside of the container was laid out with 30 straight 1mm steel fins to increase thermal conductivity. The radiation-facing outer side of the container was painted black to increase absorptivity and the four lateral sides as well as the back side were insulated to keep heat loss negligible. Thermocouples for measurement were arrayed throughout the air gap as seen in figure 4-15. Using an artificial light source, they went on to investigate optimal heat flow rates for different radiation intensity levels (700,600 and 500W/m²). Their observations showed that the ventilation period can be extended for 13 h 50 min for all investigated cases. They found that 700W/m² requires slightly higher air flow rates and that the chimney operates at higher efficiency for the lower intensity levels (Li and Liu 2014).

[12] The basic solar chimney is somewhat less specific than a Trombe wall but operates on very much the same principles.

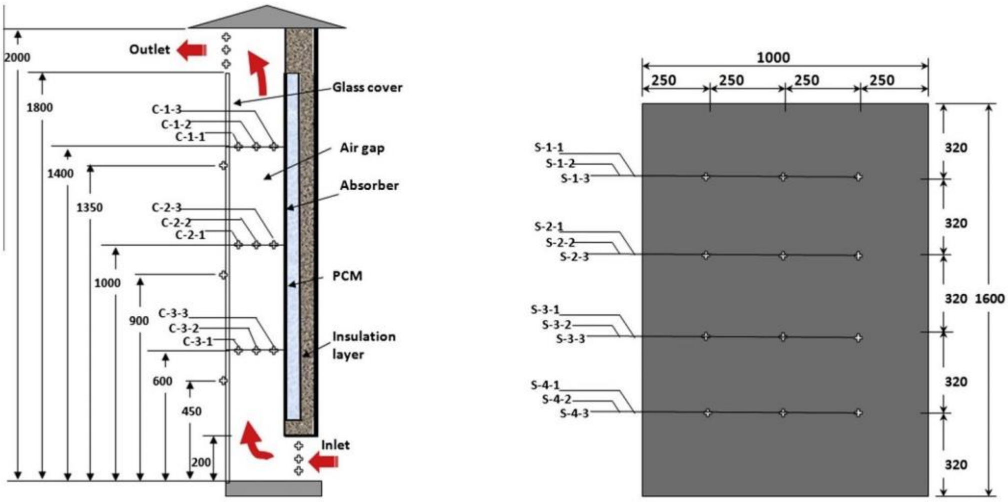


Figure 4-15: *schematic view of the solar chimney experimental system* (Li et al. 2014)

Zhou and Pang performed experiments on the thermal behavior of a Trombe style collector-storage wall system using PCM in a lab set-up. Their tests were carried out over 24-hour periods with charge and discharge periods of 6.5 and 17.5 hours respectively. Figure 4-16 shows their lab set-up as well as the resulting distribution of energy flow. They found the indoor temperature of the test chamber to be above 22°C during the whole discharging period which suggests that the latent heat released by the PCM wall could provide indoor thermal comfort for a long time (Zhou and Pang 2015).

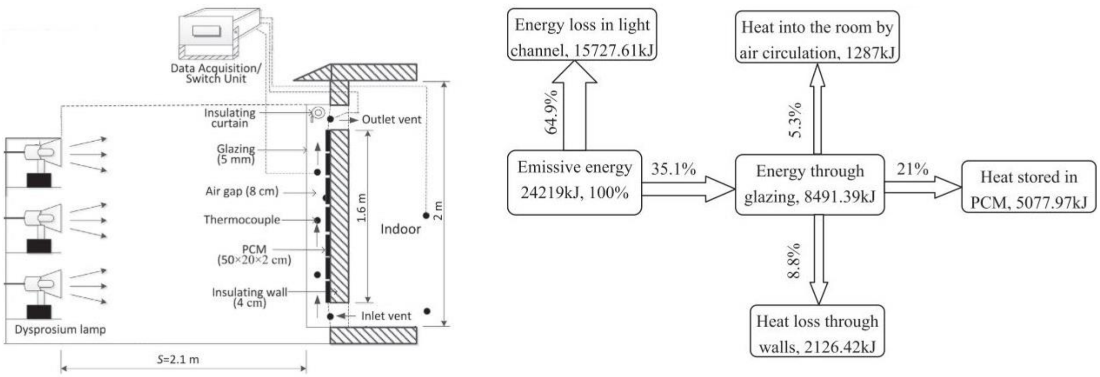


Figure 4-16: *left: schematic sketch of experimental set up; right: energy flow diagram during charging process* (Zhou et al. 2015)

Kara and Kurnuc, investigated Trombe walls with the aim to overcome two typical disadvantages of the classical set-up. For one they used PCM to reduce the bulk of the heat storage wall and secondly, they used a novel triple glazing (NTG) technology to reduce overheating problems in summer. They set up two adjacent, south facing test rooms which varied only in the melting temperature of the PCM (34°C and 45°C). The NTG system, as seem in figure 4-18, consisted of 4mm of ordinary glass on the outer side, followed by a 9mm air gap, followed by a 6mm prismatic glass structure presented by Christoffers in 1996 to deflect summer radiation coming in at steep angles (fig. 4-17), followed by another 9mm air gap and a final 4mm low-e glass. They found that the NTG met its goals by greatly reducing the solar transmittance in summer compared to winter. Furthermore, their results showed that in both cases the winter indoor temperatures tended to overreach thermal comfort levels, suggesting that adding more PCM to the inner side of the wall would be advisable to stretch the peak temperature further towards nighttime to even out temperature fluctuations further. They finally concluded that the PCM with a melting point at 34°C degrees operated more efficiently than the one at 45°C (Kara and Kurnuç 2012).

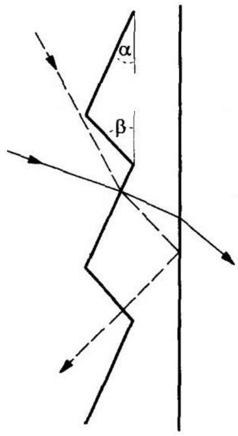


Figure 4-17: *prismatic glass (Christoffers 1996)*

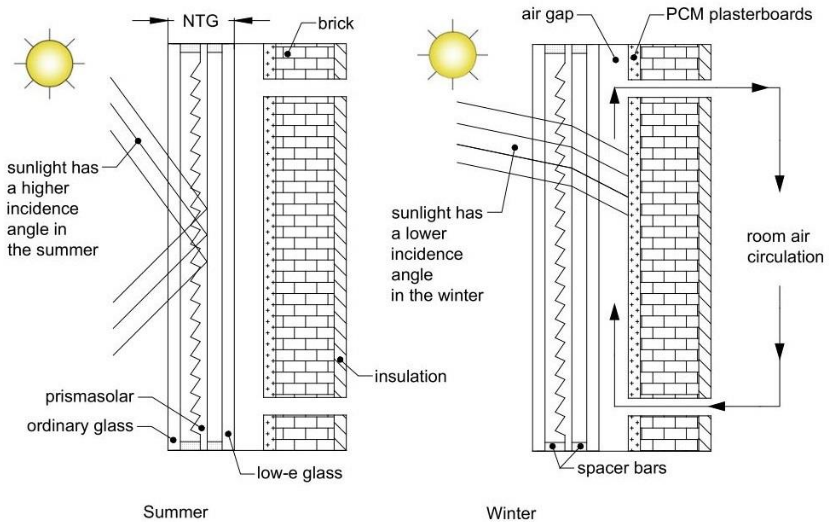


Figure 4-18: *cross-section of the PCM wall (Kara et al. 2012)*

Zhou and you investigated the year-round thermal performance of a new ventilated Trombe wall with integrated PCM in the hot summer and cold winter region of China. Aiming to achieve a system that works for hot and cold seasons alike, they developed an elaborate multi-layered system as seen in figure 4-19. For summer condition, they added a highly reflective automatic shutter in the air gap to reflect radiation outward and provided air in- and outlets to evacuate excess heat directly. A lower melting temperature PCM layer (22°C), inlayed with water cooling pipes, was designed on the inward facing side of the wall to shift the peak heat gains into the afternoon. For winter conditions they provided a high absorptivity PCM layer (28°C) on the outward facing side of the wall and air in- and outlets towards the room. Their results showed a 14.8% contribution in cooling load and a 12.7% contribution in heating load reduction and a considerable improvement of indoor thermal comfort (Zhou and Wah Yu 2018).

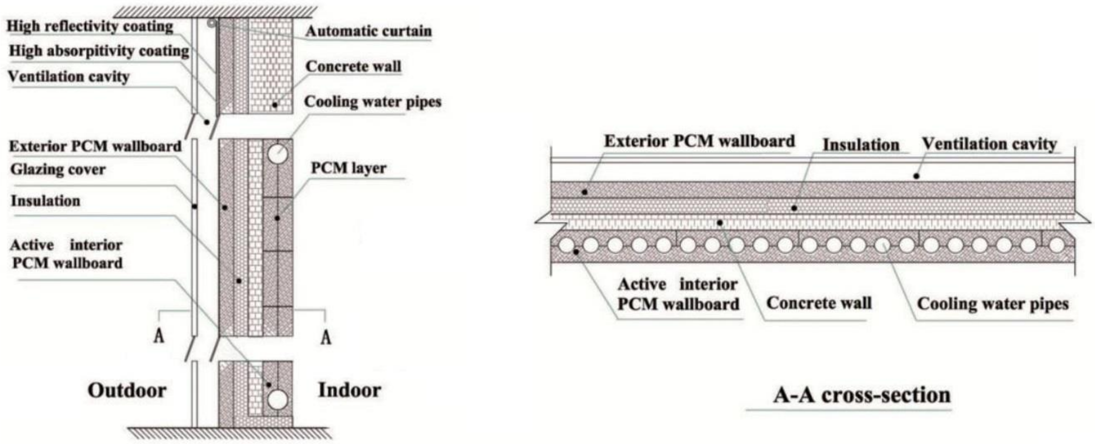


Figure 4-19: *schematic sketch of the trombe wall set-up* (Zhou et al. 2018)

In their 2017 review on PCM Trombe walls Hu et al. stated seven conclusions on their research. (1) Increased Trombe wall area translates into greater efficiency. However, at a ratio of 37% Trombe area to total south wall area, the effects have been found to become negligible (Jaber et al. 2011). (2) Classic Trombe walls with 30 to 40cm concrete or brick storage walls have been found to perform well in many geographical locations. PCM have been shown to be useful for significantly reducing the weight and thickness of the storage walls. Adding insulation to the classical Trombe wall set-up has been shown to mitigate further deficiencies. (3) Glazing properties as in the materials and number of layers affect the performance significantly and should be chosen according to climatic context. However, they suggest that in most cases, low-e double glazing is recommended. (4) Channel depth affects the air flow resistance. The depth should be chosen not only according to the height but also according to the inlet and outlet dimensions. In addition to insulation mentioned in point 2, adding roller shutters, overhangs, ventilation blinds or other shading devices to the air gap can further help to address the two major shortcomings of classic Trombe walls: overheating in summer and heat loss in winter. (5) Heat gains can also be absorbed and stored by indoor floors and walls. This should be kept in mind when designing the size and location of Trombe walls and windows. (6) The performance of Trombe walls is mainly influenced by solar radiation. In the northern hemisphere, south facing Trombe walls with variations of up to 45° have been shown to be most effective. (7) Wind speed and direction have been shown to relate to the heat loss coefficient. Trombe walls tend to perform better if the wind speed is small, however more investigation is needed in this domain (Hu et al. 2017).

4.5 Translucent Structures, Windows and Shutters

Windows are still considered problematic parts of the building envelope in terms of unwanted solar gains in summer and heat loss in winter, both resulting in a reduction in thermal comfort levels or the need for additional cooling and heating systems (Ismail et al. 2008). Several solutions have been proposed for these problems over the years, ranging from external shading to vacuum isolated composite glass panes. However, glazed surfaces still suffer from low thermal inertia and therefor hold significant potential for improvements. Introducing PCMs into glazing and other translucent structures has, therefore, attracted significant attention in recent years. A useful review into this field was published by Fokaides et al. (2015).

The main challenges of such applications lie in selecting PCMs and containers, that not only comply with the aforementioned desired properties but also meets the need for adequate translucence. As previously discussed in the introductory chapter on radiation, different substances at different energetic states vary significantly in their ability to reflect, absorb and transmit different wavelengths. The PCM needs to be selected such that an appropriate amount of visible light is transmitted, while a suitable amount of invisible radiation can be absorbed and stored. Since, as we have seen, the transmission range of water coincides with the sensitivity of the human eye, water based PCMs such as salt hydrates are predominantly used in these applications (Fokaides et al. 2015).

In one of the first studies to research translucent PCM applications, Sedrick proposed a modular, translucent PCM storage system developed for use behind south-facing windows and roofs in a somewhat Trombe like manner. Based on test room data and thermal network analysis he showed that the system is superior to a 34cm thick masonry wall for thermal storage. Accelerated and real-time testing, furthermore showed, that the lifetime of the system exceeds 10 years (Sedrick 1980).

Manz et al. developed a TIM-PCM external wall system for solar space heating and daylighting. Their set up as seen in figure 4-20 consisted of a glass front, a small air gap, a layer of honeycomb-type transparent insulation material and a structure of commercially available glass blocks, filled with a salt hydrate PCM (melting point: 24-29°C; melting enthalpy: 192 J/g). Between glass front and insulation, a high reflectance roller blind was designed to prevent overheating and summer and also reduce nighttime losses in the heating season. They reported promising energy gains but discussed disadvantages due to reflection of the radiation off the PCM's solid surface, leading to a reduction in heat and light gains. They furthermore discussed possible advantages of reducing the melting point of the PCM to about 21°C and noted that they did not observe any segregation within the PCM over a period of five months (Manz et al. 1997).

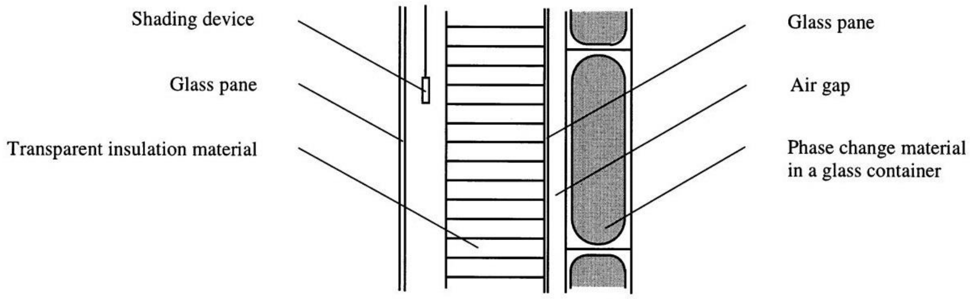


Figure 4-20: *prototype of a TIM-PCM external wall system for solar space heating and daylighting* (Manz et al. 1997)

Weinländer et al. investigated PCM-facade panels for daylighting and room heating and found that light transmittances in the range of 0.4 could be achieved. Compared to standard double-glazed panels, they found that PCM panels suffer about 30% less heat loss in south oriented windows. And that solar heat gains are reduced by 50%. They further stated that PCM-Facades would improve thermal comfort considerably in winter, especially in the evenings. Due to the peak load shift occurring in summer they indicated that this technology might be especially relevant in lightweight glazed office buildings and further suggested that concealment methods like screen-print glazing could be used to provide a homogenous appearance. They also acknowledged that leakage, especially using salt-hydrates was still a problem (Weinläder et al. 2005).

Ismail et al. conducted a comparison between models of PCM filled and absorbing gas filled double glazed windows as options for reducing excessive heat gains in warm summer climates. They used a numerical model to analyze double glazing set-ups filled with multiple gas mixtures as well as a PCM and calculated heat transfer through the window and compared the total heat gain coefficients. Their results showed that the PCM filled glass performed worse, producing a heat gain coefficient of about 0.65-0.80 while the absorbing gas windows produced coefficients of about 0.55-0.65. However, they used a reflective glass in the latter case which, they admitted, influenced the heat gain coefficient (Ismail et al. 2008).

Jain and Sharma looked PCMs for day lighting and glazed insulation in buildings by conducting solar transmittance measurements of commercial grad PCMs. They studied the effects of temperature, solar radiation and thickness. While neglecting to specify which PCM precisely they used, they stated that they chose a suitable one with a melting point around the average ambient temperature (31.98°C) it furthermore had a heat of fusion of 236,17J/g and a density of 777kg/m³ which suggests a paraffin wax. They concluded that the transmittance of the liquid phase of the PCM was slightly higher than water while showing low thermal conductivity suggesting it to be a suitable transparent insulating medium (Jain and Sharma 2009).

Bontemps et al. presented an experimental and modelling study of twin cells separated by a latent heat storage glass brick wall. The investigated fatty acids, paraffin, and salt hydrate. Their results shows a peak temperature reduction of 3-5°C. They also pointed out the essential need for night ventilation (Bontemps et al. 2011).

Weinländer et al. looked at vertical shading elements filled with PCM and compared them to conventional interior sun protection elements that often heat up to 40°C or more. They showed that the interior surface of the PCM filled slats hardly ever exceeded the PCMs melting temperature of 28°C and reduced the maximum temperature of the office by 2K significantly increasing thermal comfort and reducing potential cooling loads. They noted that night time ventilation is absolutely essential in order to discharge the PCM (Weinlaeder et al. 2011).

Soares et al. presented Numerical simulation of a PCM inside shutter for buildings space heating during the winter. The shutters are charged when they are open during the day as the dark high absorption side faces outward, and discharged when they are closed protected by the now outward facing insulation layer. They showed the optimal melting point of the PCM (thickness: 30mm) to be 20°C for their location in Coimbra and that the total energy stored and released by the optimal system can reach 2501.3kJ over a 24-hour cycle. However they concluded that their system can be used to define optimal system configurations, with optimal PCM melting temperatures for any given location and climate characteristic (Soares et al. 2011).

Based on his preliminary research on PCM glazing (Goia 2012) Goia et al. looked at improving thermal comfort conditions by means of PCM glazing systems and compared a paraffin filled double glazed unit to a conventional reference. They built a simple test cell as seen in figure 4-21 and recorded surface temperatures as well as transmitted irradiances over a six-months period. They concluded that the PCM glazing

Figure 4-21: *test cell with two glazing systems (Goia et al. 2013)*

provided considerable improvement of the thermal conditions of the indoor environment for most of the time during the various seasons. The higher the solar irradiance the greater the benefit offered by the PCM which is due to the shading as well as the buffering effect. On cloudy days the performance of the two windows are similar (Goia et al. 2013, 2014).

Gowreesunker et al, investigated the thermal an optical characteristic of the PCM RT27. They found that the transmittance spectra from the PCM are unstable, during rapid phase change while observing transmittance values of 90% and 40% respectively for the liquid and the melted phase. They furthermore found that radiation scattering effects were dominant in the solid phase while radiation absorption was dominant in the liquid phase. They state that the addition of PCM improves the thermal mass of the unit during phase change but note that the risk of overheating may be significant after the PCM has melted. However, they added that while numerical day-lighting aspects were shown to be favorable, the change of appearance as the phase changes may pose limitation on the aesthetical value of such systems (Gowreesunker et al. 2013).

Using a large-scale climate simulator Grynning et al. looked at a four-pane glazing unit equipped with prismatic glass in the outer and transparent PCM-containers in the innermost cavity (fig. 4-22). They ran several test cycles and found that even for temperatures similar to a warm day in Nordic climate, the potential latent heat storage capacity of the PCM was fully activated. However, they added that long periods of sunshine with high exterior temperatures were needed to fully melt the PCM. This system gained a significant amount of attention as it was implemented in several realized projects, primarily in Switzerland, among other by Schwarz Architekten, Zürich (fig 4-22), showing that PCM glazing systems can be designed to achieve high aesthetic standards (Grynning et al. 2013).

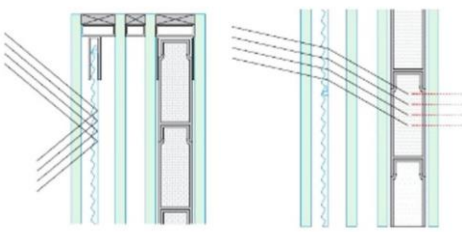


Figure 4-22: *left: PCM wall by Schwarz Architekten; topt: PCM wall cross section with summer and winter radiation (Grynning et al. 2013)*

Liu et al. conducted experimental investigation of optical and thermal performance of a paraffin filled glazing unit. They concluded that solar irradiance has an effect on the optical performance of the double-glazed unit containing PCM during its melting process. The thickness, therefore, should not exceed 16mm, by their estimate, in order to retain adequate optical. performance (Liu et al. 2018).

D. Li et al. investigated double glazed windows filled with paraffin wax. To increase thermal conductivity, they added nanoparticles. Using a numerical as well as experimental model, they went on to study the effect of varying volumetric proportions and diameters of nanoparticles. They concluded that the higher the nanoparticle volume fraction, the higher the energy consumption, and the larger the particle diameter, the smaller the energy consumption. The minimal energy consumption was obtained with nanoparticle concentration of 1% and nanoparticle diameter of 100 nm. They furthermore pointed out that the impact of the studied parameters was more significant during winter and that overall energy consumption could be reduced by up to 4%. The temperature differences between interior glass surface and the indoor environment were found to be about 1–4 °C in summer, 5–10 °C in autumn and 14–16 °C in winter (Li et al. 2018).

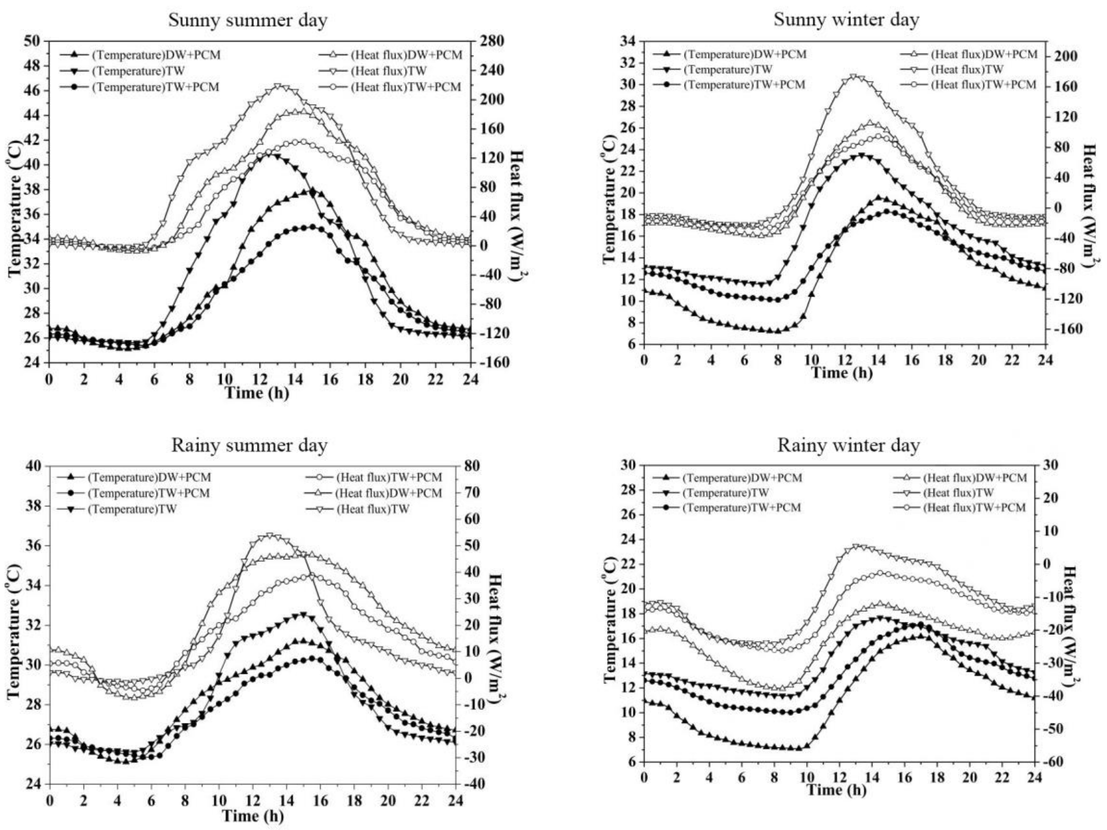


Figure 4-23: *results for three glazing units in four different weather conditions (Li et al. 2018)*

S. Li et al compared three glazing units. First a triple-glazing unit with two air filled cavities (TW), a triple-glazing unit with one air filled and one outward facing PCM filled cavity (TW+PCM) and finally a PCM-filled double glazing unit (DW+PCM). Figure 4-23 show their resulting heat flux measurements for typical sunny and rainy, summer and winter days. They concluded that TW+PCM windows can help avoid overheating, as well as improve thermal insulation in winter. It can effectively reduce indoor temperature fluctuations and thus reduce energy consumption (Li et al. 2018).

4.6 Roofs

While buildings are conventionally designed based on steady state heat transfer criteria reduced into a single reference value, the R-value, most of the relevant building components are subject to a complex dynamic blend of convective, radiative and conductive heat transfer processes. While this is true for most components of the envelope, according to Kosny, this seems especially true for roofs and attics due to their increased exposure to dynamic stresses making them particularly suitable for PCM enhancement (Kośny 2015).

In 1997, Petrie et al. proposed a novel attic configuration containing hydrated calcium chloride PCM, dispersed in perlite filled test cells and sandwiched between two layers of conventional XPS insulation. The PCM/perlite weight ratio was 2:1 and 6:1. Their results showed a 22% thermal load reduction, a 42% peak heat flux reduction in addition to a four-hour time delay for the 2:1 ratio. The 6:1 system showed a 32% reduction in cooling loads (Petrie et al. 1997).

Ismail and Castro conducted a theoretical and experimental study of PCM enhanced roofing insulation using a setup consisting of a small room with movable roof and side walls. The roof was built in a traditional way using attic floor insulation with added PCM. The results showed that the PCM-enhanced envelope can help in keeping the indoor climate within the desired thermal comfort zone in the context of a Brazilian climate (Ismail and Castro 1997).

Kissock and Limas investigated a paraffin PCM added to a standard commercial steel roof to reduce peak diurnal cooling and heating loads. The PCM used was octadecane (melting point: 25,6°C). The roof was insulated by two 2,5cm layers of polyisocyanurate foam. The bottom layer of foam was enhanced with the PCM. Their results showed a close to 14% cooling load reduction for the climate of Dayton, Ohio, USA (Kissock and Limas 2006).

In an effort to study year-round efficiency of PCM roof structures in Chennai, India, Pasupathy and Velraj, looked at incorporating a double layer of eutectic salt hydrate PCM to a roof structure. Their results indicated that the system narrowed indoor temperature swings and that year-round efficiency would be significantly increased when the top panel had a melting point 6-7K higher than the early morning ambient temperature during the hottest summer month and the bottom panel had a melting temperature close to the desired indoor temperature (Pasupathy and Velraj 2008).

Kosny et al. produced a significant body of research on enhancing residential roof constructions using natural sub-venting (10cm) and PCM heat sinks. The developed a multilayer insulation configuration of PCM-enhanced polyurethane foams, PCM-impregnated fabrics, and highly reflective aluminum foil. They used about 0.39kg per m² roof surface of two different types of PCM with melting points around 26 and 32°C. The total storage capacity of the heat sink was about 54kJ/m². Their results as shown in figure 4-24 show a 90% summertime peak heat flow reduction through the roof compared to the conventional roof (Kośny et al. 2008).

Another team around Kosny used a similar configuration of a roof consisting of metal roof panels with integrated amorphous silicon PV laminates, a ventilated air cavity, dense fiberglass over-the-deck insulation with reflective surface, and arrays of bio-based PCM cells. It was compared to a conventional asphalt shingle roof. Their results showed a 30% reduction in roof-generating heating loads in winter (without PCM-contribution). During the cooling season, the roof generated cooling loads were about 55% lower than those generated by the control. Peak roof heat flows were reduced by 90% for the PV-PCM roof (Kośny et al. 2012).

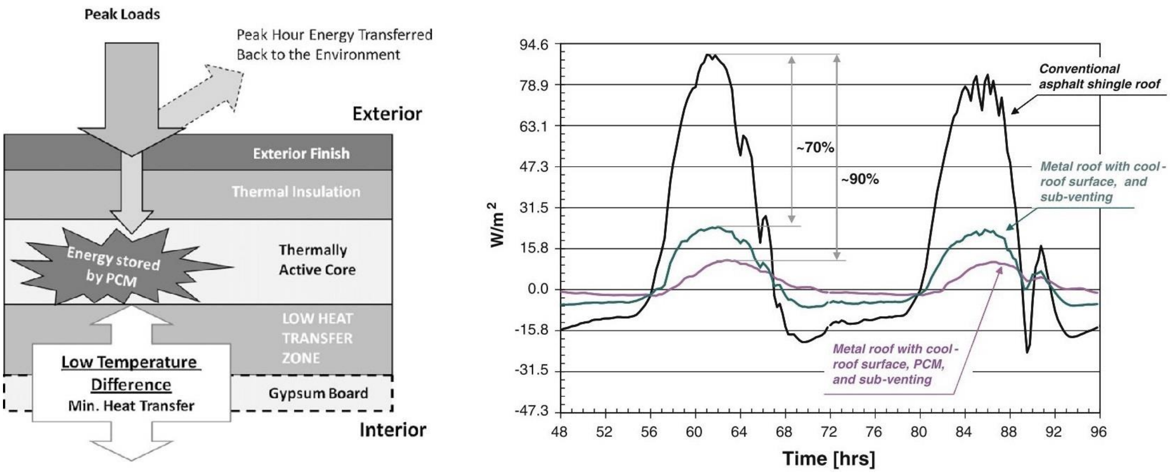


Figure 4-24: *left: roof schematic; right: results* (Kośny et al. 2012)

Based on an earlier study, Alqallaf and Alawadhi looked at filling cylindrical holes on concrete roofs with PCM for free cooling in Kuwaiti September climate. Numerical methods were used extensively and subsequently validated by experiments. Their set up, as shown in figure 4-25 consisted of a 150x150x15cm concrete slab, containing an array of holes with diameters of 14.14cm and depths of 7.5cm, placed on top of an insulated 150x150x150 chamber. The slab was protected from the

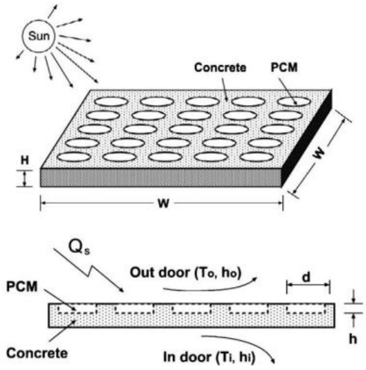
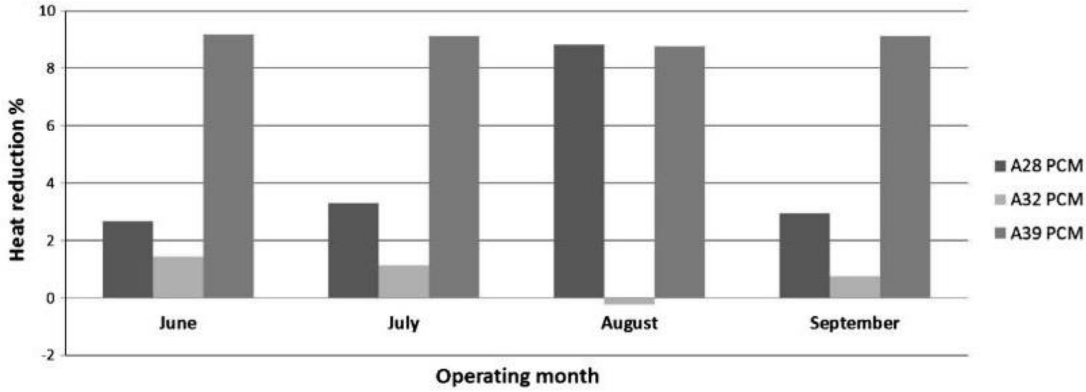


Figure 4-25: *PCM roof schematic* (H. Alqallaf et al. 2013)



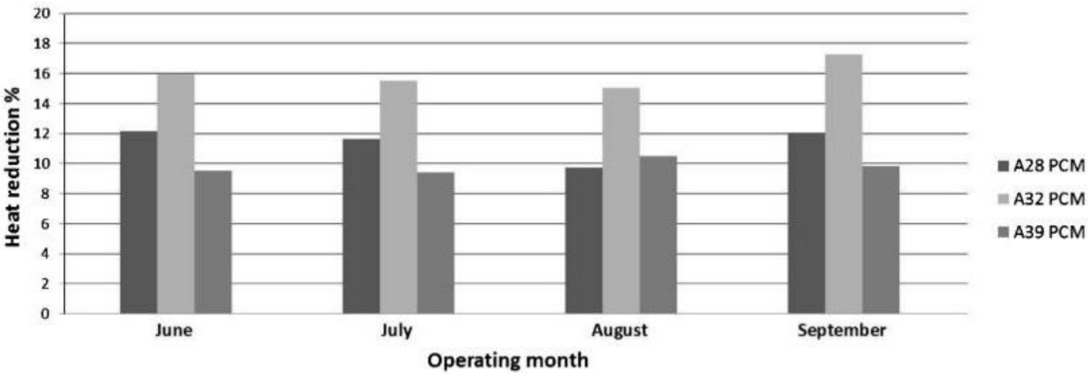


Figure 4-26: *heat reduction relative to phase change temperature and operating month* (H. Alqallaf et al. 2013)

elements by a thin wooden roof. They observed that the heat gain is strongly affected by the value of the PCM melting point. Their results suggest that the heat flux at the indoor surface of the roof can be reduced by 12.04-17.26% depending on the operating month (fig. 4-26). They noted that adding insulation to the PCM-concrete roof could further enhance its benefits (H. Alqallaf and Alawadhi 2013; H. J. Alqallaf and Alawadhi 2011).

Chou et al. proposed a novel roof construction method for single story houses covered by metal sheet roofing. Their aim was to reduce downward heat flow generated by incident solar radiation. Their set up as seen in figure 4-27 consisted of PCM elements (melting point: 46.3°C) molded into a polyurethane insulation layer underneath to sheets of traditional corrugated metal roof sheets. Their results show that their set up can effectively reduce the downward thermal flow through the roof, adding that, as a consequence, the cooling load of the house could be reduced and thus electricity otherwise used for cooling saved (Chou et al. 2013).

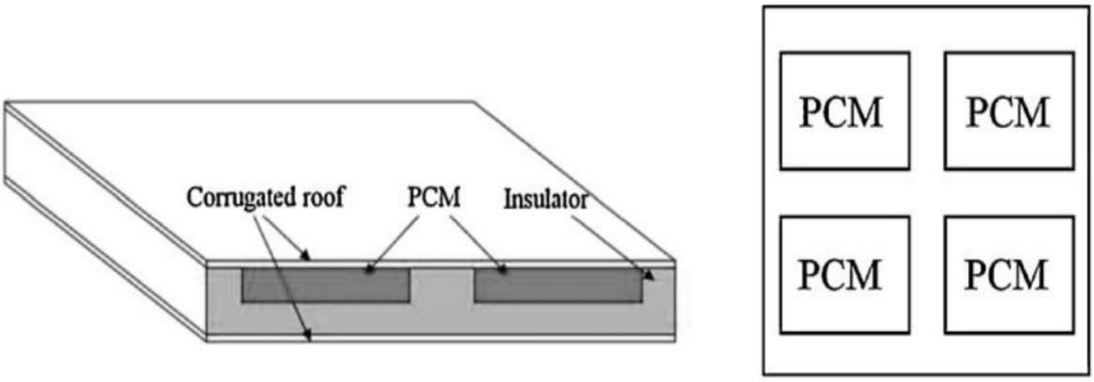


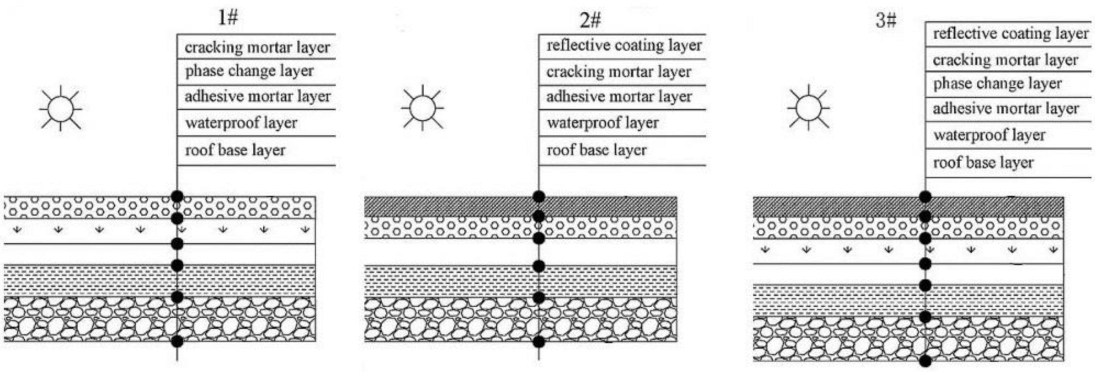
Figure 4-27: *PCM roof schematic (Chou et al. 2013)*

Ravikumar and Srinivasan investigated heat transmission across a concrete roof structure containing PCM in the context of an Indian climate. On a yearly basis, their results showed a 56% reduction in heat transmission in comparison with the conventional Indian concrete roof design (Ravikumar and Srinivasan 2012, 2014).

Li et al investigated PCM roofs in the northeast cold region of China. They explored the influencing factors on thermal behavior such as solar radiation intensity, melting point and latent heat of PCM, roof slope, PCM layer thickness, and absorption coefficients of external roof surface. Their results showed that the PCM roof produce a significant time delay of temperature peaks (>3h). They also found that the choice of slope and absorption coefficient of the outer roof surface, as well as PCM layer thickness have a significant effect on the overall performance of the roof (Li et al. 2015).

Jayalath et al. looked at improving energetic efficiency in a typical, fully airconditioned single-story, three-bedroom residential building in Melbourne, Australia by implementing a 12.1mm layer of BioPCM M182 (melting point: 23°C; latent heat: 182kJ/kg) underneath a 47mm layer of insulation set underneath a steel outer roof cover. They reported a 39% reduction in cooling loads when using a transition temperature of 23°C as well as a 12% reduction in heating loads. The heating load could be reduced further by using a transition temperature of 21°C, however, considering heating and cooling, the PCM with a 23°C transition temperature produced the lowest consumption (Jayalath et al. 2016).

Lu et al. conducted a field test for a novel PCM roof in Tianjin, China. They used a eutectic PCM mix, encapsulated in PE-RT pipes, located beneath a cracking mortar layer which was either exposed as outer layer (#1) or topped off with a reflective cool roof coating layer (#3) as shown in figure x. #2 served as control without PCM but with reflective coating. The results as seen in figure 4-28 show a significant heat flux reduction for set up #1 and #3, across the cycles (Lu et al. 2016).



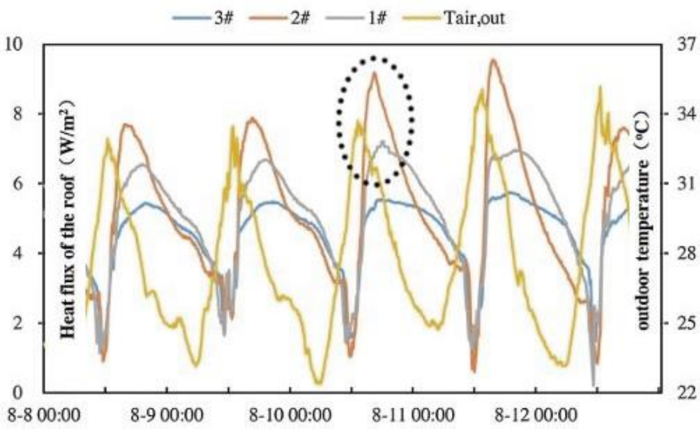


Figure 4-28: *top: PCM roof schematic; left:: heat flux (Lu et al. 2016)*

Saffari et al. also looked at combining PCM technology with reflective cool roof concepts to not only increase thermal efficiency and indoor comfort, but also mitigate urban heat island (UHI) effects as part of a more large-scale attempt to reduce over heating in summer cityscapes. They used a straightforward roof structure consisting of Polyurethane cool roof membrane, 20mm of PCM (varying melting points; latent heat: 160 kJ/kg) followed by insulation and gypsum board. They ran simulations, for different climate locations and with two distinct optimization objectives. Scenario 1 was optimized for a maximum reduction in roof surface temperatures that would mitigate UHI effects. Scenario 2 was optimized to minimize the total annual electricity consumption. A control roof structure without PCM was used to demonstrate the effect. Their results showed that the application of PCM with melting temperatures ranging from 10 to 30°C, depending on the climate conditions, can considerably decrease the annual thermal stress of the cool roof membrane (18-30%). The other scenario rendered maximum energy savings of 1 to 6% by using slightly lower melting temperatures ranging from 10 to 20°C. They therefore pointed out that the objective to optimize the structure for energy consumption across the year may be in slight conflict with the objective of the cool roof in summer. These reductions to the functionality of the cool roof membrane are, however, acceptable according to the authors. The complete tables of their results for both scenarios and different climate locations was added to the appendix of this paper (Saffari et al. 2018).

4.7 Insulation

Kosny et al. conducted a set of experiments looking at what they call dynamic reflective insulation containing different kinds of PCM. They concluded by giving the following list of results: (1) Hot-box test demonstrated that DRI, installed in wood frame walls, can effectively reduce heat flow generated by dynamic thermal excitations. (2) In a field-tested residential attic with a cool-painted metal roof using reflective insulations and subventing air channels, summertime peak heat flow crossing the roof deck was reduced by about 70% compared with the heat flow penetrating a conventional shingle roof. (3) In a similar cool-roof attic containing DRI (with PCM), an additional 20% reduction of the peak-hour heat flow was observed. (4) In a tested prototype attic design, the total summertime peak heat flow crossing the roof deck was reduced by about 90% compared with the heat flow penetrating a conventional shingle roof. (5) In the prototype attic, the PCM energy storage eliminated the overnight subcooling effect. (6) A dynamic hot-box test that included a 20°C thermal ramp, performed on a 2×6 wood frame wall, demonstrated about 40% reduction of the surface heat flow as a result of the use of PCM. This finding was confirmed by the field tests. (7) A dynamic hot-box test performed on the attic containing PCM-enhanced cellulose insulation proved that PCM can be fully discharged without the use of additional forced ventilation of the attic. This finding has to be confirmed under full-scale field conditions (Kośny et al. 2008). Further theoretical analysis showed the PCM effectiveness during peak summer conditions could be increased further by using higher melting points, however, the authors noted that this can reduce the number of active days for May and September, which shows that numerical analysis is usually necessary to optimize PCM design for a specific climate (Kośny and Kossecka 2013).

Fateh et al. conducted a numerical and experimental study of PCM layers within the insulation layer of a lightweight wall. They considered different positions of the PCM within the insulation layers (fig. 4-29) and different orientations of the wall. The PCM layer used was a 5mm Energain PCM board. Their results showed that PCM integrated insulation layers could provide major reductions of heat loads when their intensity is fluctuating and variable especially around the phase change temperature of the PCM, which can lead to energy savings up to 75% of the heat load through opaque walls (Fateh et al. 2017). Using very similar parameters, Fateh et al. conducted another numerical study, concluding that the PCM layer is more active when placed in the middle of the insulation layer. However, they noted that its capability of smoothing the thermal oscillations and the heat waves is very sensitive to the combination of the range of the oscillations of the external temperature with the PCM layer position inside the wall. Their test results indicated a reduction of peak heat load around 15% but restated that the proper design of PCM integrated walls requires multiple considerations about the crosslinks between climate, wall orientation, PCM melting point and period of the year (Fateh et al. 2018).

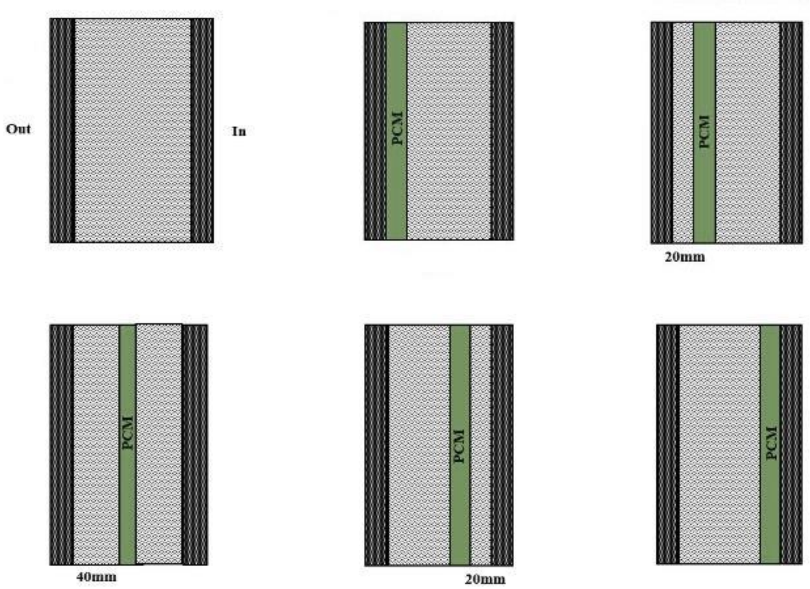


Figure 4-29: *PCM layer at different positions within the wall (Fateh et al. 2017)*

In 2012, another group around Kosny conducted an experimental and theoretical analysis on the performance of a wood-framed wall assembly with PCM-enhanced fiber insulation in different climatic conditions. The PCM used was a micro-encapsulated paraffin (melting point: 22-23°C; latent heat: 115kJ/kg). They concluded that for south oriented vertical frame walls, filled with PCM-enhanced insulation with 30wt% PCM content, a time shift of the heat flow rate oscillations is about three hours. Furthermore their results indicated that for summer days about 20–35% peak-hour load reduction can be expected (Kosny et al. 2012).

Lee et al. also looked at adding PCM directly into the mix during the manufacturing process of cellulose insulation. Using two identical test houses under full weather conditions, they evaluated the thermal performance of north, east, south, and west facing residential walls with and without PCM. The results showed that the daily average peak heat flux reduction for individual walls was 25.4%, while the hourly average peak heat flux reduction for the sum of all four walls was 20.1% (Lee et al. 2018).

4.8 Active Systems

4.8.1 HVAC components

Using PCM components in HVAC systems to harvest the heat storage potential of diurnal temperature differences can significantly increase the energetic efficiency of a building. Such applications are especially advantageous for summer cooling as the cold night air can easily be sucked into the system to charge PCM components that will subsequently discharge by cooling the warmer air during the day. It is thus possible to reduce or even eliminate the use of conventional active air-cooling systems. A number of studies have been published on this subject, laying out different heat exchanger configurations with integrated PCM components (Zeinelabdein et al. 2018).

Arkar and Medved for example proposed a system for lowering the use of conventional air conditioning in buildings using a cylindrical latent heat energy storage unit filled with 50mm diameter spherical balls of paraffin PCM (Rubiterm RT20) (Arkar and Medved 2005). The device was integrated into a mechanical ventilation system of an existing house in Slovenia. They concluded that summer thermal comfort in the tested house could be achieved with 6.4kg of the PCM per square meter of floor area. The authors further mentioned that the device could be used for winter heating when deploying it in combination with an air solar collector or a ventilated facade (Arkar and Medved 2007).

Zalba et al presented a prototype involving arrays of PCM components arranged in sequence. They used commercially available flat plate PCM packs with a melting temperature range of 20-25°C. A parametric study and statistical analysis showed that lower thickness of encapsulation, higher flow rate and large variation between inlet air temperature and phase chance temperature had a positive impact on solidification efficiency. Based on these results they designed a free cooling system with a mean loading capacity of 3000W using 8 PCM components (4xC22 and 4xRT25). Figure 4-30 shows their set up as well as the temperature gradient across the modules during the tests. A feasibility evaluation proved the system to be technically feasible as well as economically beneficial compared to conventional cooling systems (Zalba et al. 2004).

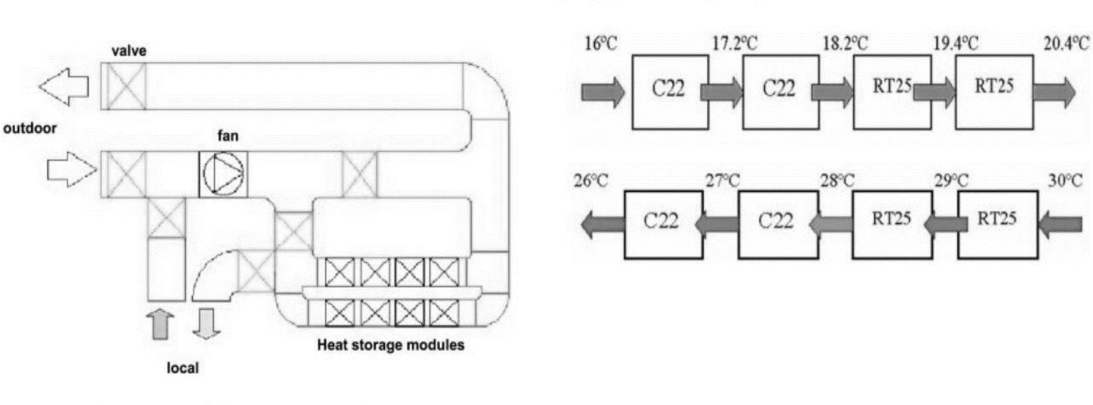


Figure 4-30: *left: Set up schematic; right: heat storage module layout (Zalba et al. 2004)*

Marín et al further optimized the set up proposed by Zalba et al. by embedding the PCM components into a graphite matrix. Using the solidification time without graphite matrix as a set reference point, they were able to reduce the power consumption of the fans by 50% and use 70% thicker PCM plates which resulted in lower costs. Using the PCM plate thickness as a set point, the graphite matrix reduced the solidification response time by 50% while causing only a slight reduction (12-20%). of the heat storage capacity (Marín et al. 2005).

4.8.2 Activated Building Components

Active PCM applications are not limited to components within conventional HVAC systems. In an attempt to reduce summer daytime energy demand peaks in Japanese metropolitan areas, Nagano et al. proposed a ventilated PCM office floor system that is being charged with an air conditioning unit during the nights. The PCM they used for their small-scale experimental model was made of foamed glass beads and paraffin wax with a phase change temperature of about 20°C and was positioned right on top of the underfloor space underneath a porous floorboard and carpet as seen in figure 4-31. During the night the system can store about 1.79MJ/m² cooling energy that is subsequently released to the space the following day. The use of conventional air conditioning is thus reduced to about three hours during the daytime translating into a night shift ratio of 89%. They further noted that such systems could be further optimized with increasing the amount of PCM. They admitted that the regions near the floor surfaces may be perceived as too cold in the mornings however they also pointed out that this form of air conditioning does not produce the kind of drafts that tend to cause comfort issues with conventional air conditioning (Nagano et al. 2006).

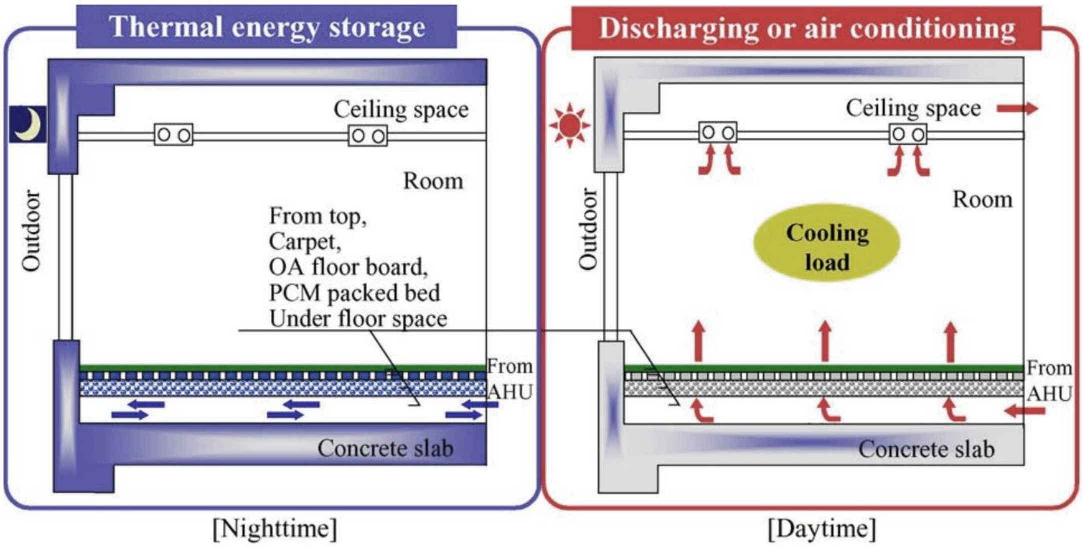


Figure 4-31: *schematic set up sketch* (Nagano et al. 2006).

Other researchers have looked at incorporating PCM elements into a ventilated suspended ceiling. An early contribution to this idea was made by a team around Turnpenny in 2000. They envisaged circular arrays of heat pipes attached to PCM Units with the heat pipes facing the center of the set-up underneath which a large ceiling fan controlled the flow of air. In- and outflow of air was regulated by two openings as seen in figure 4-32. During the night the fan would rotate such that the cold outside air would be sucked in from the lower opening to charge the PCM units. The resulting warmer air would then be expulsed through the top opening. During the day the fan rotation would be reversed sucking in the warm room air over the sides to be cooled by the discharging PCM and blown back into the room through the ceiling fan (Turnpenny et al. 2000).

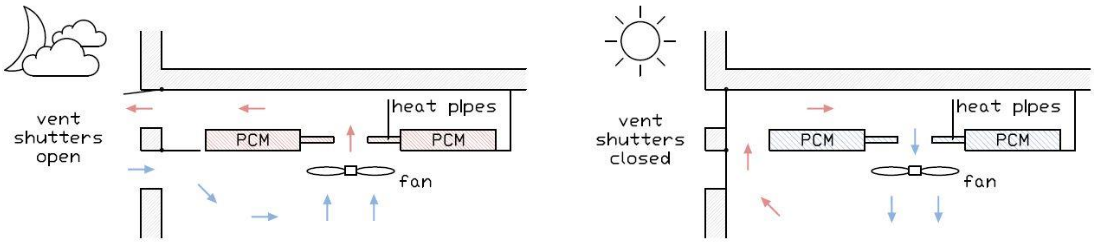


Figure 4-32: *Schematic set up sketch, redrawn from* (Turnpenny et al. 2000)

In a subsequent experiment, Turnpenny et al. tested a slightly altered version of this concepts, arranging the openings a little different and adding more elaborate addons, such as fins, to the heat pipes to increase the conductivity to the PCM units. Their results indicated that a combination of their prototype system and night cooling could provide heat storage rates adequate to prevent a room from overheating in normal

UK summer conditions. They further noted that equipping 2000 offices with this system instead of conventional air conditioning would reduce CO_2 emissions by approximately 430 tons (Turnpenny et al. 2001).

4.8.3 Solar Water Heater

Solar water heaters have been gaining in popularity recently as they are a relatively simple and inexpensive way to reduce the amount of energy that is required to heat water. Adding PCM to increase the efficiency of solar water heaters has been suggested by a number of studies. They generally work by exposing cold-water conduits to solar radiation to heat up water during sunshine hours. The warm water is then collected in a storage tank equipped with PCM units that melt by absorbing the required amount of thermal energy from the water. During off sunshine hours, withdrawn warm water is replaced by cold water, in turn absorbing energy from the PCM units which solidifies, ready to be recharged during the next. The energy needed to supply warm water is thus greatly reduced, depending on the intensity of the radiation and the efficiency of the system cycle (Sharma et al. 2009). Several studies have shown that incorporating PCM at different points inside the collector unit can also be beneficial. Furthermore, a setup of mirrors to enhance the amount of incident radiation has been discussed in the literature (Sharif et al. 2015). The function of a solar water heater connected to a PCM enhanced storage tank in support of a conventional water heater is sketched in figure 4-33.

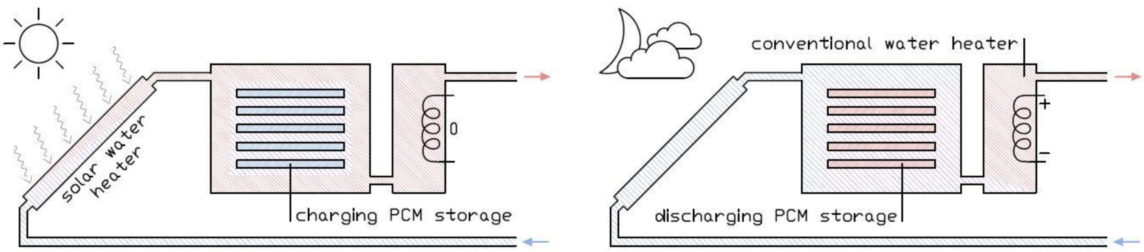


Figure 4-33: *Schematic function of a solar water heater supporting a conventional water heater*

Recent reviews on this specific topic have been published by Shukla et al. (2009), Khot et al. (2012), Sadhishkumar and Balusamy (2014), Z. Wang et al. (2015), Seddegh et al. (2015) and Kee et al. (2018).

4.8.4 Photovoltaic

Just like passive solar heating, where thermal energy generated by solar radiation is stored when available and subsequently released as temperatures drop, PCMs can be used to store thermal energy generated by solar collectors to make it available during off-hours, thereby increasing the reliability of such systems (Ge et al. 2013).

PCMs can also be incorporated directly into the photovoltaic panel to regulate its operating temperature. Conversion efficiency is one of the central issues in the development of photovoltaic systems. Currently only around 15-20% of the incident solar radiation can be converted into electricity while the rest is transformed into heat. High operating temperatures, however, directly impact that efficiency negatively. Keeping the operating temperature of the panels as low as possible, therefore, becomes a pressing concern especially in building integrated photovoltaic systems (BIPV) where convective heat loss is generally limited to the top face of the panel (Hasan et al. 2010). A large body of research has therefore emerged on what are commonly called PV-PCM systems. Hasan et al., for example, conducted a study on PV-PCM achieving an 7.3% increase in electric yield (Hasan et al. 2016). Recent reviews on this specific topic have been published by Chandel and Agarwal (2017), Preet (2018), Waqas et al. (2018) and Ma et al. (2019).

5 BUILT PROJECT EXAMPLES

○ BASF 3-L – Ludwigshafen, Germany

Launched in 2001 by BASF, the 3-Liter House is a model for retrofitting mid-century concrete structures to meet modern low-energy demands using less than 3 litres of heating oil per m² per year. Using a wide range of applications like high R-value exterior sheathing, triple-glazed windows, enlarged glazed surfaces to increase solar gains, an 85% efficient heat recovery system as well as PCM-enhanced internal plaster on the walls and ceilings. The energy consumption was subsequently monitored for a 3-year period showing and average consumption of 2.6 litres per m² per year, which represents an 80% reduction in heating fuel consumption (Kośny 2015). A house implementing analogous concepts was planned and built by BASF and partnering construction companies in Kyonggi, South Korea.

Figure 5-1: BASF 3L House, Ludwigshafen www.luwoge.de

○ Haus der Gegenwart – München, Germany

Planned by Allmann, Sattler, Wappner Architekten in 2001, Haus der Gegenwart is a 200m² housing project proposing a novel living space sharing approach. It provides three individually accessed private living spaces, individually connected to a shared living room and kitchen on top. All four boxes were designed as post and beam wood constructions. The lower three boxes were insulated with 15cm mineral wool for the walls and 20 for the roofs. The upper living space box was insulated with 20cm mineral wool for the walls and floors and 40cm for the roof. Windows had a U-value of around 1.1 W/m²K. A total of 600m² PCM enhanced gypsum board (phase change temperature: 23°C; phase chance enthalpy: 110 J/g) was used for the walls and ceilings. This is equivalent to 1800kg of PCM that yields a total PCM heat storage capacity of 198 MJ (Kośny 2015).

Figure 5-2: *Haus der Gegenwart www.allmannsattlerwappner.de*

○ BASF House – Nottingham, UK

Built in 2008 on the university campus in Nottingham, it was designed using the PassivHaus standard to have near-zero carbon emissions while remaining within the budget of a first-time home buyer's market. It is a 82m² single family house with a measured energy consumption of 12.5 kWh/m² per year which is equivalent to about 1.5 litres of heating oil per square meter per year. Along with low U-value materials resulting in an overall R-value of about 6.7 m²K/W for the walls and roof. The heart of the passive heating concept consists of a fully glazed south-facing two-layer sunspace combined with ventilation hatches to allow the warm air to circulate into the living spaces in winter or back to the outdoor environment in

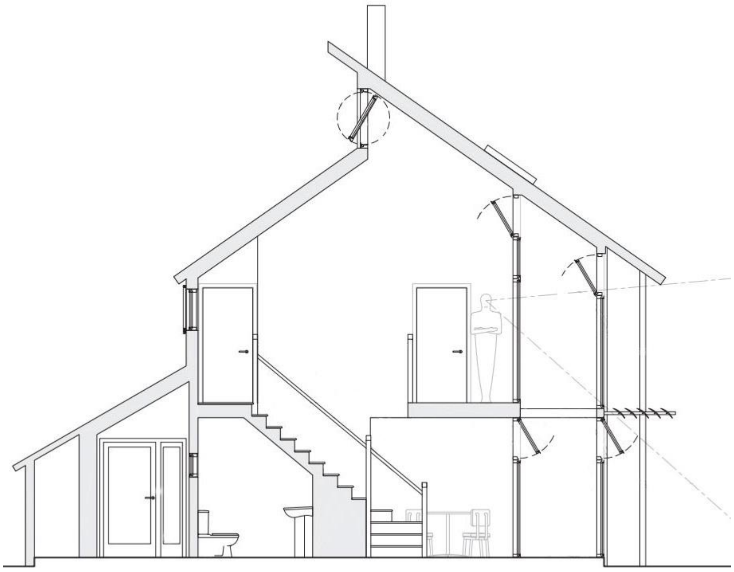


Figure 5-3: BASF House
www.nottingham.ac.uk/creative-energy-homes/documents/basfhousebrochure.pdf

summer. High thermal heat storage is provided by PCM enhanced gypsum wallboards with a melting temperature of 23°C and a phase change enthalpy of 110kJ/k (Kośny 2015)

○ Kingspan Lighthouse – Watford, UK

Designed by Sheppard Robson and completed in 2007 the Kingspan Lighthouse is a 100m² single-family net zero carbon emission home. The walls were made of 2 layers of structural insulated panels and the windows were wood frame gas filled triple glazing. Thermal inertia was increased by including PCM enhanced wallboards for and suspended ceilings and south facing walls. Like in both previous example, the melting temperature of the microencapsulated PCM was 23°C and its transition enthalpy 110kJ/kg.

Figure 5-4: *Kingspan Lighthouse www.sheppardrobson.com*

○ Crossway Eco-House – Staplehurst, UK

Designed by Architects Richard Hawkes for his family, Crossway Eco-House was built in 2008. Thermal inertia is provided by the iconic red brick vault arch as well as around 127m² shape-stabilised PCM boards (melting point: 21.7°C) manufactured by DuPont. A Photovoltaic system provides the house with 5500kWh of electricity per year. To buffer the solar generated thermal energy to help bridge cloudy days the PV-system is linked to an experimental 580 litre PCM heat storage unit. The PV-system is further supported by an 11kW wood pellet boiler. A four-year-long monitoring performed by the University of Cambridge has shown that the application of PCM boards helped in reducing the summer peak temperatures by 4°C on average. Furthermore, they recorded the average primary energy consumption to be 54.59 kWh/m² per year with an annual heating load of 14.82kWh/m² (Kośny et al. 2013).

Figure 5-5: *Crossway Eco-House* www.hawkesarchitecture.co.uk

○ Academic Office Building – Albury, Australia

Planned by Wayne McPhee Architects in association with BASF this office building of the Charles Stuart University has operating temperatures between 21 and 23°C in winter and 23-26°C in summer. These temperatures are achieved without the use of active cooling but with an integrated evaporative cooling system working mostly during the night to maximize efficiency. In order to reach the required thermal inertia for the system to operate, microencapsulated PCM was integrated into the concrete floors throughout and PCM boards were used for the ceilings, effectively doubling the buildings thermal storage capacity. Ceilings and floors were integrated with a

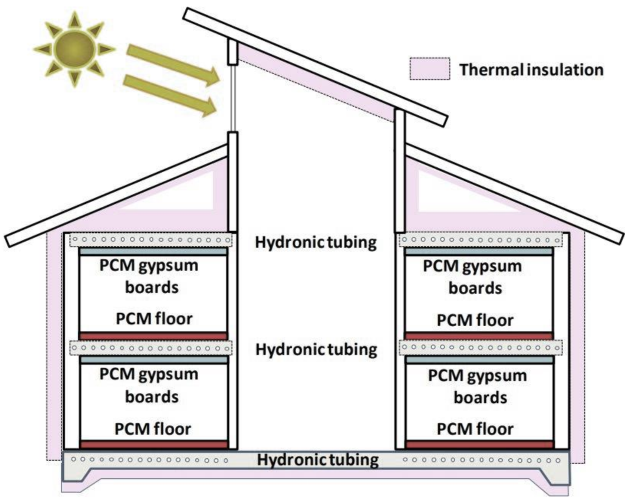


***Figure 5-6:** Academic Office Building, Albury, Australia*

hydronic tubing system imbedded into the concrete slabs to help the re-solidification process during the nights. Building component surface temperatures remained relatively constant around the phase change temperature value which was 23°C. Lightweight steel frame construction was used for the structure other than the massive concrete slabs. Heat loss through the envelope is kept to a minimum with R_{si}-values of 5.6m²K/W for the roof and 3.5m²K/W for the walls. A network of sensors was installed to monitor the buildings actual performance and long-term behaviour. They showed a reduction of carbon dioxide production and energy consumption by about 65 %, compared to similar conventional office buildings in Australia.

○ SARL Busipolis Company Building – Metz, France

SARL Busipolis is a 1950m² office building that was rewarded several awards for its excellent energy performance. It was completed in 2010 and has a total energy consumption of 38 kWh/m² per year. More than 500m² of shape-stabilised PCM-boards with a melting point of 21.7°C were used. The PCM was installed behind the gypsum wallboards and within the suspended ceilings. The PCM was produced by DuPont, had a phase change temperature between 18-24°C and a latent heat storage capacity of 515 kJ/m². A special ventilation system was used to ensure the discharging of the panels.

Figure 5-7: *SARL Busipolis Company Building* *www.wiconafinder.com*

○ Oak Ridge PCM House – Oak Ridge, USA

Oak Ridge PCM House was one out of four full scale test homes that were completed in 2010 as part of a large study on high performance envelopes conducted at Oak Ridge National Laboratory. The 243m², two-story wood frame house was designed to demonstrate the thermal performance of high R-value walls and attic containing PCM-enhanced thermal insulation. The otherwise conventional frame attic is equipped with a dynamic solar-powered ventilation to reduce attic generated cooling loads and PCM-insulation was installed on the attic floor and gable walls. They used 10.2cm thick PCM enhanced cellulose insulation on top of 25.4cm regular cellulose insulation for the attic floors. The attic gable walls as well as the interior partitions were enhanced with approximately 9cm of PCM-enhanced cellulose. For wall construction, they used the US-typical 2x4 inch wood frames with normal insulation and doubled it up with a second offset frame structure using PCM-enhanced cellulose insulation as seen in figure 5-8.

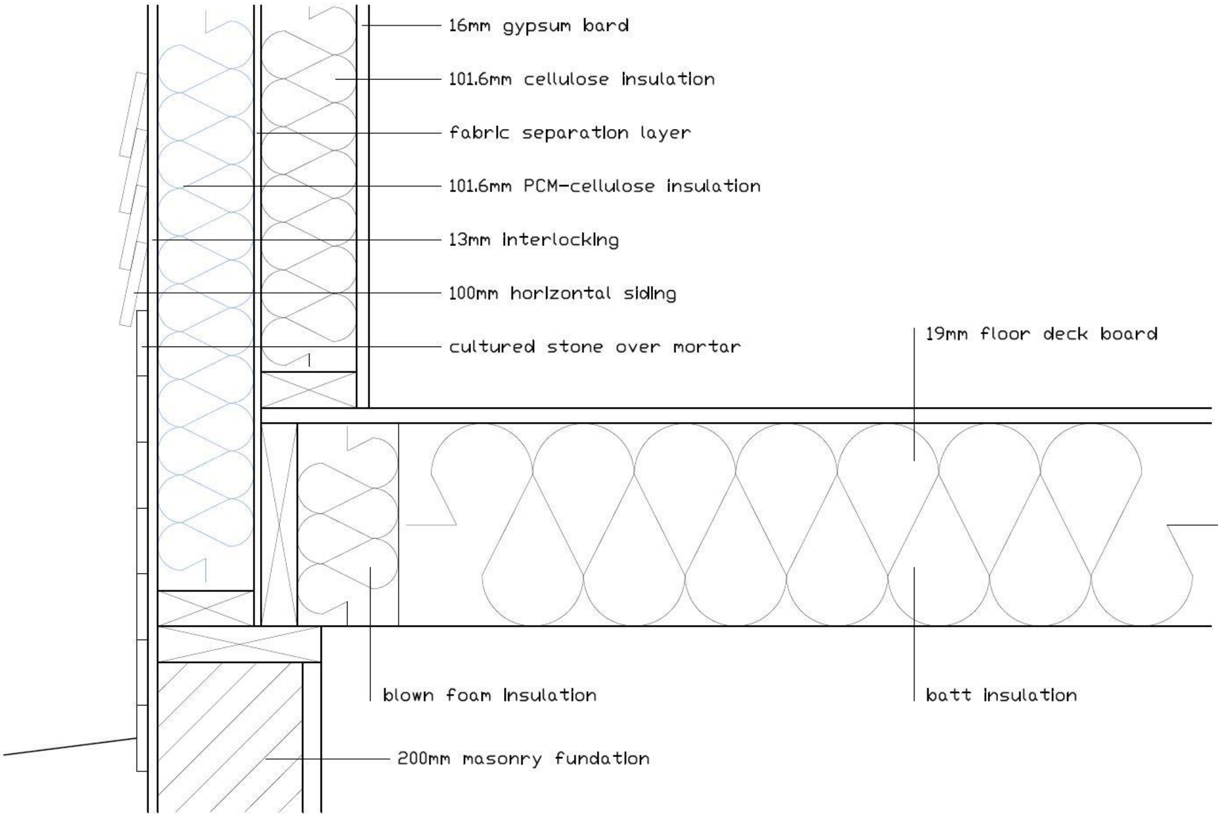


Figure 5-8: *Oak Ridge PCM-House, outer wall section detail* (Kośny 2015)

○ TrekHaus – Portland, USA

Completed in 2012 by a team around architect Robert Hawthorne, TrekHaus consist of two adjacent family homes of 155m² each. Heat losses were minimized by using high thermal resistance envelope with R_{si}-values of 6.7m²K/W for the floor slab, 8.6m²K/W for the exterior walls and 14.6 m²K/W for the roof. They used a heat-pump water heater a mini-split heat-pump for space conditioning and a heat recovery ventilation system. With three people in each unit, the TrekHaus is expected to work at net-zero carbon emissions with the help of two independent 4.14kW roof-mounted photovoltaic-systems. To increase thermal inertia, a soy-based bioPCM, manufactured by Phase Change Energy Solutions, was installed in plastic foil pouches in the drywalls and second floor ceiling. Construction costs, excluding the plot and the PV-system came to about 1500$ per m².

Figure 5-9: *TrekHaus www.pdxlivingllc.com*

6 DISCUSSION / PCM GUIDE FOR PLANNERS

6.1 Choice of Application

An efficient choice of PCM-application will always depend on many variables, starting with the prevailing climate of the location and the intended use of the spaces. Furthermore, most passive applications are inextricably linked to the type of structure, its geometry and its orientation, while most active HVAC PCM-components may be added with fewer considerations.

Along with an assessment of circumstances, a first step in planning with phase change materials is a formulation of the desired goals. PCM-applications can be optimized towards achieving multiple objectives which may not necessarily align. Depending on the prevailing climate for example, the optimal melting point for a specific application may be higher when optimized for passive cooling then for heating. Thus, a compromise or multiple PCM may be required if both objectives are to be met.

For cooling purposes, adequate night ventilation is essential to a proper function. Without it, the PCM will not fully discharge the energy it stored during the day and won't function to its full capacity. Discharge time and/or air flow rate can be reduced by increasing the overall heat transfer rate of the PCM element. This can be attained in various ways depending on the set-up of the PCM. When microencapsulated PCM is incorporated directly into a building material, highly conductive supplements can be added to the mix to increase overall conductivity. In any case it is important to maximise the relevant surface area of the storage element. This is especially clear when looking at macroencapsulated PCM. Much like a thin pane of ice will melt incomparably faster than a chunky ice cube of equal mass, a thin, well-considered container of highly conductive material will achieve much greater heat transfer efficiency than a bulkier one. Thicker elements, however, can be enhanced, for example by embedding the storage medium in highly conductive matrices or by laying out the container with internal heat fins. Outer heat fins can also be applied to increase the effective surface area.

Passive heating applications rely primarily on harvesting the energy coming from the sun via radiation, during daylight hours. Orientation and geometry are therefore key factors, along with the properties of the outer layer. The higher the absorptivity, the more energy will be taken up by the storage element and less will be reflected back to the environment. Ideally the storage layer should be insulated from the outside cold.

This can be achieved with conventional insulation; however, some solar gains may be lost before reaching the storage layer. A more efficient set-up can include a transparent or highly translucent insulation layer that lets through a maximum of short-wave radiation but traps the heat from exiting the system to be lost to the environment. This can be achieved by various forms of translucent insulation materials (TIM) as well as regular insulated glazing in a Trombe wall set-up. Passive Heating applications however, need not be restricted to the building's envelope. Any interior surface, furniture or object that is hit by direct sunlight during the day can, in theory, be enhanced with PCM to store excess energy during sunny winter days in order to release it as the sun drops along with the temperatures. When integrated into solar water heaters, PCM can also significantly reduce the energy needed for warm water.

Combining PCM storage mass with active heating and cooling systems can represent a smart way to reduce peak loads and shift parts or all loads into off peak hours. Floors and HVAC systems have been shown to achieve this effectively, though most other PCM applications reviewed in this paper have also shown some favourable peak load shift. Reducing peak demands on the power grid can notably increase efficiency thus reducing the grids ecological footprint. Electricity is often cheaper during off-peak hours, to incentivize the implementations of such systems.

PCM applications have been shown to significantly improve certain construction types that commonly require considerable amounts of energy to achieve indoor comfort levels. Most notably lightweight, low thermal mass, frame constructions and traditional non-ventilated shingle or metal roofs. However, PCM can also be added to increase the thermal mass of standard concrete structures and gypsum wallboards.

6.2 Classification of Application

Figure 6.1 shows an attempt to categorize applications. They were separated into two major categories, passive and active applications. Passive applications can be further distinguished between those that are merely PCM enhanced traditional building materials and those that are part of a larger more elaborate component, while active applications are always part of larger mechanical systems. The resulting classification code can be used to easily distinguish applications and their research.

The following list represents a summary of the original research reviewed in chapter 4. For better orientation, the publications have been presented in the table in the same order as in chapter 4, furthermore the application code introduced in figure 6-1 was added to allow quick access of information.

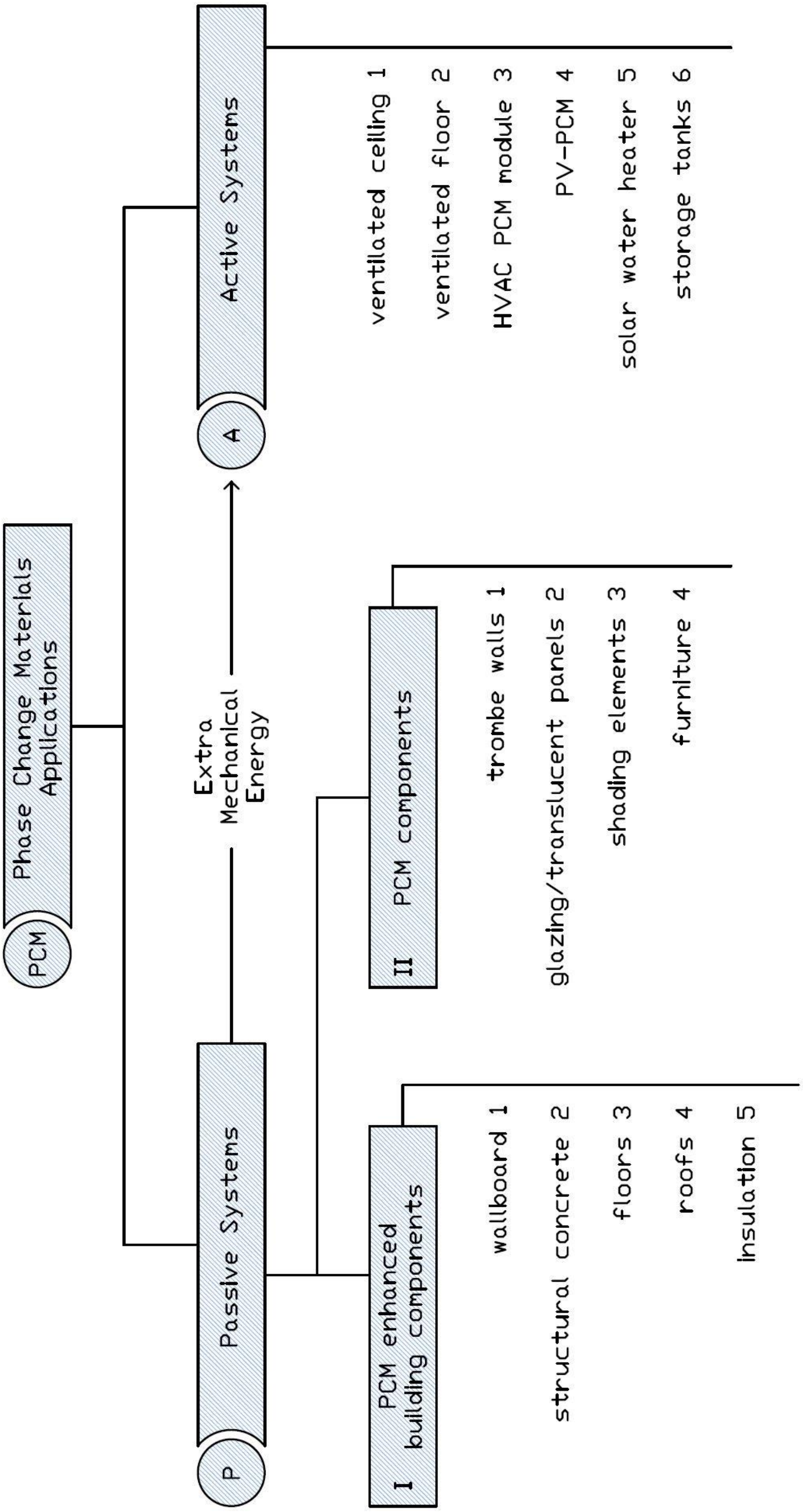


Figure 63: classification of architectural PCM application

Table 2: architectural PCM application research

Publication	Application Type	Research topic	Main Finding
Neeper 1986, 1989, 2000	PI_1	impregnated gypsum boards	starage is maximised when meltingpoint (mp) is about equal to the average temperature of the wallboard
Kendl Stovall 1989	PI_1	impregnated gypsum boards	successful impregnation of octadecane wax into wallboards
Hawes et al. 1993	PI_1	gypsum boards	11-fold storage increase
Scalat et al. 1996	PI_1	gypsum boards	PCM wallboard shown to be suitable for thermal energy applications
Athienitis et al. 1997	PI_1	gypsum boards	maximum temperature was reduced by 4°C; heat load reduction at night
Koschenz 2004	PI_1	ceiling panels / wallboards (offices)	projected capacity of 320Wh/m² to maintain comfortable office temperature was reached
Schossig et al. 2005	PI_1	gypsum boards	during a summer period of three weeks, control room was warmer than 28°C for 50 days, test room only for 5 fays; ventilation is essential
Shilei et al. 2005	PI_1	impregnated gypsum boards	1.15°C reduction in maximal temperature fluctuation scale of heating equipment can be reduced
Sarı et al. 2008	PI_1	impregnated gypsum boards	indoor temperature reduced by 1.3°C no sign of leakage after 5000 cycles
Sunliang et al. 2010	PI_1	energain PCM panels	clear reduction in termperature fluctuations
Kuznik and Virgone 2009	PI_1	gypsum boards	indoor temperature reduced up to 4.2°C in summer condition and less uncomfrotable thermal stratification
Kuznik et al. 2011	PI_1	gypsum boards (office)	enhanced thermal comfort, reduced air temperature fluctuation, reduction of negatice radiative effects associated with air-/surface temperature differences
Chan 2011	PI_1	energain PCM panels	anual savings of 3-7.2%
Oliver 2012	PI_1	gypsum boards	1.5cm thick gypsum board with PCM stores five times the thermal energy of laminated gypsum board and the same energy as 12cm Brick wall within the comfort temp. range
Evola et al. 2013	PI_1	aluminum honeycomb matrix filled with microencaspulated PCM	peak indoor temp. was reduced by ~1°; remarkable reduction in surface temp. fluctuations with 1.5-2h time shift; only ~45% of latent heat was exploited - PCM did not fully melt or solidify
Diaconu 2011	PI_1	impregnated gypsum boards occupancy patterns	occupancy patterns must be considered
Becker 2013	PI_1	panel thickness (mediteranean)	only minimal thickness of several mm could be discharged during the night, but thin layers were still effective in light-weight constructions; surface temperature fluctuations were reduced
Ascione et al. 2014	PI_1	refurbishing with PCM-plaster on inner side of the envelope (mediteranean)	comfort hours increased by 15.5% in Sevilla, 22.9% in Naples, 19.8% in Marseilles, 15.8% in Athens and 20.6% in Ankara
Lee et al. 2015	PI_1	plug and play PCM wallboard experiments	2-3h delay of peak heat transfer rate
Zhou et al. 2019	PI_1	PCM wallboard (UK summer)	optimal melting temp. foudn to be 23.4°C; energy savings can be as high as 40%; period in which temp. are maintained within comfort range can be extended by up to 7.2%

Publication	Application Type	Research topic	Main Finding
Wang et al. 2020	PI_1	PCM wallboard (light-weight high-rise in Shanghai)	favorable effects higher in winter but improve both seasonal extremes; PCM integrated in south side envelope showed greatest benefit with payback time of 5 years.
Ling and Poon 2013	PI_2	PCM-Concrete Overview	substantially increase in thermal mass and decrease in conductivity; effective limit of PCM addition to be expected; reduction in compressive strenght; paraffin seems most suitable
Hunger et al. 2009	PI_2	concrete with 0-5% microencapsulated PCM	energy savings of 12% for a 5% mix, acceptable strength reduction
Cabeza et al. 2007	PI_2	concrete with 5% microencapsulated PCM (spain)	considerable reduction in indoor peak temp. and temp. fluctuation
Cui et al. 2017	PI_2	concrete with 0-44% macroencapsulated PCM balls	remarkable increase in thermal mass suggests significant decrease in heating and cooling loads
Faheem et al. 2016	PI_2	concrete with microencapsulated PCM in ventilated hollow core slab	no significant efficiency increase beyond 10% PCM; optimal melting point found to be 20°C; high air flow rates are essential.
Royon et al. 2014	PI_2	slab with paraffin filled holes	substantial decrease in fluctuations: ring elements more efficient than full cylindrical holes
Ansuini et al. 2011	PI_3	piped radiant floor with steel matrix (mediteranian)	25% reduction in cooling water; buffered radiant/internal gains for 2-3 days during midseason; reduces condensation usually asociated with such systems
Lin et al. 2004, 2005	PI_3	heated PCM floor	more than half of the total heating energy can be shifted to off-peak hours
Xu et al. 2005	PI_3	passive PCM floor	most suitable melting point = average air temperature on sunny winter days
Zhang et al. 2006	PI_3	passive PCM floor	wood floors not as good as tiles or metals
Cheng et al. 2015	PI_3	passive PCM floor with added graphite	enhanced conductivity for cleaner cycles
Jeong et al. 2012	PI_3	PCM for wooden floors	heat storage capacity of the floor was increased
Entrop et al. 2011	PI_3	concrete floors with microencapsulated PCM	~16°C reduction of max floor temperature; ~ 7°C increase of minimum floor temperature
Hittle 2002	PI_3	ceramic tiles	projecting 24% annual energy savings
Cerón et al. 2011	PI_3	ceramic tiles for solar heating	PCM tiles should be limited to areas with direct sun in winter
Novais et al. 2015	PI_3	ceramic tiles impregnated with 0-8.1% PCM	optimal percentage found to be around 5.4% temperature fluctuations decreased by about 22%
Hu et al. 2017	PII_2	trombe wall overview	
Bourdeau and Jaffrin 1979	PII_1	trombe wall (numerical analysis)	3.5 cm thick PCM found to be equivalent to 15cm of concrete
Bourdeau 1982	PII_1	trombe wall (experimental validation)	PCM outperforms conventional concrete in Trombe walls by a factor of 4

Publication	Application Type	Research topic	Main Finding
Benson et al. 1985	PII_1	trombe wall	optimal melting point was found to be about 27°C; as efficient as a 4x thicker concrete wall; adding 2wt% of graphite would increase performance by 30%
Stritih and Novak 1996	PII_1	trombe wall with TIM	optimal melting point found to be a few degrees over room temperature; optimal thickness 50mm; absorption rate reached 79%
Heim 2016	PII_1	trombe wall with TIM	thermal conditions on internal surfaces highly improved
Sun and Wang 2016	PII_1	trombe wall	significantly higher indoor temperatures in winter conditions
Li and Liu 2014	PII_1	solar chimney for gain shift	ventilation period extended for 13h50min
Zhou and Pang 2015	PII_1	trombe wall	test room air temperature remained above 22°C
Kara and Kurnuc 2012	PII_1	trombe wall with NTGlazing	NTG reduces transmittance in summer; melting point of 34°C showed better results than 45°C
Zhou and Yu 2018	PII_1	trombe wall (heating and cooling)	14.8% contribution to cooling 12.7% contribution to heating
Fokaides et al. 2015		translucent PCM overview	
Sedrick 1980	PII_1	trombe wall with translucent PCM	superior to 34cm brick; lieftime exceeds 10 years
Mainz et al. 1997	PII_2	TIM/PCM	promising energy gains, reflectivity issues
Weinländer et al. 2005	PII_2	translucent PCM panels	compared to conventional double glazing, PCM panels suffer 30% less heat loss (south oriented), heat gains reduced by 50% and transmittance reduced by 60%
Ismail et al. 2008	PII_2	PCM filled glass to reduce heat gains (summer)	heat gain coefficient 0.65-0.80
Jain and Sharma 2009	PII_2	translucent PCM insulation	transmittance of liquid phase found to be higher than water; low conductivity
Bontemps et al. 2011	PII_2	PCM filled glass bricks	peak temperature reduction by 3-5°C; night ventilation was found to be essential
Weinländer et al. 2011	PII_3	PCM filled shading elements	reduces maximum indoor temperature by 2°C; night ventilation was found to be essential
Soares et al. 2011	PII_3	PCM filled shutters (Portugal; heating)	melting point of 20°C was found to be suitable for the location; optimal system can reach 2501kJ in 24h
Goia 2012, 2013 Goia et al. 2013, 2014	PII_3	paraffin filled double glazing	the greater the solar irradiance the greater the benefit through shading and buffering
Gowreesunker et al. 2013		optical characteristics of RT27	risk of overheating after PCM has melted; limited aesthetic value
Grynning et al. 2013	PII_3	4-panel glazing with PCM and prism glass (nordic climate)	extend periods of sunshine needed to fully melt the PCM

Publication	Application Type	Research topic	Main Finding
Liu et al. 2018	PII_3	paraffin filled glazing	not thicker than 15mm to retain optical perfromance
D. Li et al. 2018	PII_3	paraffin filled double glazing	overall energy consumption reduced by up to 4%
S. Li et al. 2018	PII_3	triple glazing with air and PCM cavities	reduction in temperature fluctuation and energy consumption
Kosny 2015		PCM roofs overview	
Petrie et al. 1997	PI_4	PCM roof insulation sandwich	up to 32% cooling load reduction; 42% peak heat flux reduction; 4h offset
Ismail and Castro 1997	PI_4	attic floor PCM insulation (brazil)	can help keeping indoor climate within desired comfort zone
Kissock and Limas 2006	PI_4	steel roofs with PCM (Ohio, USA)	up to 14% cooling load reduction
Pasupathy and Verlaj 2008	PI_4	roof with double layer of salt hydrate	top panel melting point should be 6-7K higher than early morning ambient temp. in summer bottom panel melting point should be close to desired indoor room temperature.
Kosny et al. 2008	PI_4	multilayer roof insulation with PCM and reflective foil	90% summertime peak heat flow reduction
Kosny et al. 2012	PI_4	PV-laminates with PCM cells	30% load reduction in winter 55% load reduction in summer
Alqallaf and Alawadhi 2011, 2013	PI_4	concrete roof with cylindrical holes fill with PCM with varying melting points	heat flux can be reduced by ~12-17%
Chou et al. 2013	PI_4	corrucated metal roof with PCM	set up effectively reduces downward heat flux
Ravikumar and Srinivasan 2012, 2014	PI_4	concrete PCM roof (India)	56% reduction in heat transmission on a yearly basis
D. Li et al. 2015	PI_4	PCM roofs with varying parameters	peak delay up to 3h; melting point, slope, PCM thickness and absorbtivity affect outcome
Jayalath et al. 2016	PI_4	steel roofs with PCM (Melbourne)	39% cooling load reduction; 12% heating load reduction; melting temperature 23°C resulted in best year round performance
Lu et al. 2016	PI_4	PCM in PE-RT pipes with/without reflective outer layer	significant heat flux reduction
Saffari et al. 2018	PI_4	PCM with reflective cool roof	18-30% decreased annual thermal stress
Kosny et al. 2008	PI_5	dynamic reflective PCM insulation	40% decrease in wall heat flow 90% decrease in roof heat flow
Kosny and Kossecka 2013	PI_5	dynamic reflective PCM insulation	higher melting points showed more peak effect in summer but less activation in spring and summer
Fateh et al. 2017, 2018	PI_5	layered PCM insulation	reduction in peak heat load around 15%

Publication	Application Type	Research topic	Main Finding
Kosny et al. 2012	PI_5	PCM enhanced fiber insulation	3h peak time shift; 20-35% peak load reduction in summer
Lee et al. 2018 2018	PI_5	PCM enhanced cellulose insulation	daily average peak heat flux reduction 25.4%
Zeinelabdein et al. 2018		active systems overview	
Arkar and Medved 2005, 2007	A_3	PCM module with mechanical vent	summer comfort can be achieved with 6.4kg/m2 PCM; winter system requires a kind of sun collector unit
Zalba et al. 2004	A_3	HVAC with PCM array	reached a loading capacity of 3000W; system was deemed feasible and economically beneficial
Marin et al. 2005	A_3	HVAC with PCM array and graphite matrix	reduction in fan power by 50% translates to 70% thicker PCM or 50% response time reduction
Nagano et al. 2006	A_2	ventilated PCM floor with air conditioning	89% night shift ratio; less draft than conventional air conditioning operation though colder floors could be perceived as uncomfortable
Turnpenny et al. 2000, 2001	A_1	ventilated PCM ceiling (UK)	heat storage adequate to prevent overheating in normal summer conditions
Ahmad et al. 2016	A_4	PV-PCM	7.3% increased electric yield

7 CONCLUSION

The literature concerning the use of PCM in building is extensive and growing rapidly. It is therefore impossible to present a comprehensive review of the research. This paper remains an attempted to present a relevant selection in order to give a concise overview of the topic. In summary, the research has shown that PCM can be an efficient tool in increasing the thermal mass of buildings. To function properly however PCM need to operate in conditions that allow for clean melting and solidification cycles. This requires an understanding of many parameters to adapt any application to the unique prevailing climatic and functional circumstances of any project. These parameters include phase change temperature, latent heat capacity, ventilation, overall conductivity of the storage medium, solar irradiation, absorptivity of the relevant surface, among others. To efficiently harness the full storage capacity of the PCM, these parameters need to be somewhat carefully balanced. While an architectural planer without the means to calculate and simulate the interaction of these parameters, would not be able to plan an intricate system and evaluate its output, the data presented in this paper should certainly provide the information necessary to adequately apply simple methods to increase thermal mass and appreciate the value of investing in more complex applications.

As unrelenting digital process, however, has already dramatically increased the efficiency and flexibility of many aspects of architectural planning, we can expect an equivalent progress in energy efficient planning. As simulation tools become increasingly powerful and user friendly, as more CAD programs used on a daily basis in main stream architecture start to include simple and accurate means to quickly asses how tweaks and changes in their designs may impact thermodynamic processes in real time, the more we can expect planers to develop intuitions of buildings as thermodynamic rather than merely spatial environments.

8 INDEX

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9 LITERATURE

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10 APPENDIX

A. Tables

Optimum PCM melting temperatures to reduce the thermal stress of the cool roof membrane (Scenario 1).

Köppen Geiger climate zone	City	$\overline{\Delta T}_{annual}$ (°C) Reference	CR+PCM	$\overline{\Delta T}_{annual}$ reduction(%)	T_{peak} PCM (°C)	Eh savings (kWh)	Ec savings (kWh)	Etot savings (kWh)
BSk	Albuquerque	17.7	13.8	22.2	17.5	14.7	8.2	23.9
BSk	Midland	17.6	14.3	18.5	11.3	54.5	2.6	57.8
BSk	Ceduna	15.7	11.4	27.2	13.8	43.3	1.6	45.7
BSk	Del Rio	12.4	10.0	19.9	23.8	7.0	−1.4	6.3
BSh	Abu Dhabi	17.1	12.6	26.2	30.0	0.1	−2.4	−2.5
BWh	Phoenix	18.0	14.0	22.3	17.5	11.0	13.7	25.2
BWh	Las Vegas	16.4	13.4	18.2	10.0	29.9	4.9	35.6
BWh	Brisbane	14.0	9.9	29.1	20.0	10.8	6.9	17.8
BWk	Madrid	16.2	12.1	25.1	15.0	29.4	7.1	37.3
Cfa	Tokyo	13.6	10.7	21.0	15.0	39.6	1.3	41.8
Cfa	Perugia	10.7	7.6	28.6	17.5	−3.0	4.7	2.8
Cfa	Milan	14.4	10.7	25.8	16.3	21.0	5.9	28.2
Cfa	Berlin	9.4	7.1	24.3	13.8	18.0	1.5	20.9
Cfa	Johannesburg	15.5	10.3	33.6	16.3	35.3	0.8	36.7
Cfb	Paris	10.3	7.6	25.5	15.0	28.6	2.5	31.8
Cfb	Ankara	15.7	11.6	26.2	12.5	−23.2	3.1	−17.4
Cfb	Tehran	14.3	10.9	23.8	26.3	4.0	2.6	6.8
Csb	Seville	17.3	12.7	27.0	17.5	15.1	9.1	24.7
Csa	Barcelona	11.6	8.8	23.9	10.0	28.2	−0.1	28.6
Csa	Cagliari	11.6	8.7	25.0	20.0	7.6	4.8	12.7
Csa	Palermo	8.9	6.8	24.0	21.3	7.2	2.0	9.4
Csa	Nice	9.7	7.7	20.7	20.0	12.0	4.6	17.1
Csa	Adelaide	12.9	9.3	28.3	15.0	33.0	2.3	36.0
Cwa	Hong Kong	7.5	5.4	28.4	26.3	1.3	−3.3	−4.8

(Saffari et al. 2018)

Optimum PCM melting temperatures to reduce the annual heat pump energy use.

Köppen Geiger climate zone	City	$\overline{\Delta T}_{annual}$ (°C) Reference	CR + PCM	$\overline{\Delta T}_{annual}$ reduction (%)	T_{peak} PCM (°C)	Eh savings (kWh)	Ec savings (kWh)	Etot savings
BSk	Albuquerque	18	14.3	19.4	10.0	30.6	4.1	35.6
BSk	Midland	18	14.3	18.5	10.0	57.0	2.4	60.1
BSk	Ceduna	16	11.4	27.2	13.8	43.3	1.6	45.7
BSh	Del Rio	12	10.4	16.7	11.3	23.6	0.0	24.1
BWh	Abu Dhabi	17	13.5	21.1	20.0	0.1	12.0	12.3
BWh	Phoenix	18	14.8	17.4	10.0	23.3	6.7	30.6
BWk	Las Vegas	16	13.4	18.2	10.0	29.9	4.9	35.6
Cfa	Brisbane	14	10.3	26.2	13.8	26.7	1.5	28.5
Cfa	Madrid	16	12.4	23.2	10.0	39.1	5.0	44.9
Cfa	Tokyo	14	10.8	20.5	10.0	47.8	0.7	49.4
Cfa	Perugia	11	8.1	24.0	12.5	2.7	2.6	6.3
Cfa	Milan	14	10.9	24.0	10.0	34.8	3.0	39.3
Cfb	Berlin	9	7.1	24.3	13.8	18.0	1.5	20.9
Cfb	Johannesburg	15	10.3	33.4	15.0	38.3	0.5	39.4
Cfb	Paris	10	7.8	24.3	12.5	30.6	1.3	32.6
Csb	Ankara	16	12.4	20.5	20.0	51.5	5.5	57.2
Csa	Tehran	14	11.8	17.4	10.0	21.7	2.3	24.5
Csa	Seville	17	13.4	22.8	10.0	31.9	4.3	36.8
Csa	Barcelona	12	8.8	23.9	10.0	28.2	−0.1	28.6
Csa	Cagliari	12	9.0	22.3	10.0	22.8	1.6	24.7
Csa	Palermo	9	7.0	21.2	12.5	15.5	−0.4	15.4
Csa	Nice	10	7.7	20.4	11.3	20.6	−0.3	20.8
Csa	Adelaide	13	9.3	28.2	13.8	34.9	1.5	37.1
Cwa	Hong Kong	7	6.0	19.8	15.0	9.9	−2.5	7.5

(Saffari et al. 2018)