

# **REVIEW ON THERMAL ENERGY STORAGE WITH PCM: APPLICATIONS FOR BUILDING MATERIALS**

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*“Now this is not the end  
It is not even the beginning of the end  
But it is, perhaps, the end of the beginning”.*  
*Winston Churchill*



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## **ABSTRACT**

Thermal energy storage with phase change materials (PCMs) offers a high thermal storage density with a moderate temperature variation. Building materials with incorporated phase change materials (PCMs) has been found to reduce significantly indoor temperature fluctuations whilst maintaining desirable thermal comfort sensation.

This review dissertation provides an update on various methods that have been investigated by previous researchers to incorporate PCMs into the building structures.

The main objective is to optimize this methods by integrating PCM at surrounding wall (gypsum board and interior plaster products), trombe walls, ceramic floor tiles, concrete elements (walls and pavements), windows, concrete or brick masonry, underfloor heating, ceilings, thermal insulation and furniture and indoor appliances.

Based on phase change state, PCMs fall into three groups: solid–solid PCMs, solid–liquid PCMs and liquid–gas PCMs. Among them the solid–liquid PCMs are proper for thermal energy storage. The solid–liquid PCMs include organic PCMs, inorganic PCMs and eutectics.

The process of selecting an appropriate PCM is very complicated but crucial for thermal energy storage. The potential PCM should have a suitable melting temperature, desirable heat of fusion and thermal conductivity specified by the practical application. Thus, the methods of measuring the thermal properties of PCMs are very important.

Suitable PCMs and a right incorporation method with building material, latent heat thermal energy storage (LHTES) can be economically efficient for heating and cooling buildings. However, several problems need to be tackled before LHTES can reliably and practically be applied.

**KEYWORDS:** Thermal energy storage, Phase Change Materials (PCM), Building applications, Thermal comfort, Thermal performance.





## **RESUMO**

O armazenamento de energia térmica nos materiais de mudança de fase (PCMs) oferece uma alta densidade de armazenamento térmico com uma variação de temperatura moderada. Os materiais de mudança de fase incorporados (PCM) em materiais de construção foram descobertos para reduzir flutuações de temperatura internas, mantendo uma sensação de conforto térmico.

Esta dissertação proporciona uma atualização sobre os vários métodos de incorporação de PCMs em materiais de construção investigados por vários autores.

O principal objetivo é otimizar esses métodos integrando PCM na parede (painéis de gesso cartonado), paredes de trombe, ladrilhos cerâmicos, elementos de betão (paredes e pavimentos), janelas, blocos de betão ou tijolo, pavimentos radiantes, tetos falsos, isolamento térmico e mobília.

De acordo com a sua mudança de fase, os PCMs dividem-se em três grupos: PCM sólido-sólido, PCM sólido-líquido e PCM líquido-gás. Entre eles, os PCM sólidos-líquidos são adequados para o armazenamento de energia térmica. Os PCMs sólido-líquido incluem PCMs orgânicos, PCMs inorgânicos e eutéticos.

O processo de seleção de um PCM é complexo, mas crucial para o armazenamento de energia térmica. O PCM para ser considerado adequado deve ter uma temperatura de fusão adequada, um calor de fusão desejável e condutividade térmica específica para uma determinada aplicação. Os métodos de medição das propriedades térmicas dos PCMs são bastante importantes.

A escolha de um PCM adequado, um método de incorporação correto no material de construção e com armazenamento de energia térmica latente (LHTES) podem ser economicamente fatores eficazes para edifícios com aquecimento e arrefecimento. No entanto, existem alguns problemas que precisam de ser tratados antes que o LHTES possa ser aplicado de forma confiável e prática.

**PALAVRAS-CHAVE:** materiais de mudança de fase (PCM), conforto térmico, calor latente, eficiência energética, capacidade de armazenamento.



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## NOMENCLATURE

$\lambda$  - Thermal Conductivity [W/(m.K)]

$c_p$  - Specific Heat [J/(kg.K)]

$C$  - Specific Volumetric Heat [J/(m<sup>3</sup>.K)]

$\alpha_T$  - Thermal Diffusivity [m<sup>2</sup>/s]

$\rho$  - Density [kg/m<sup>3</sup>]

$H$  - Enthalpy [J/kg]

$h(T)$  - Enthalpy–Temperature Relationship

$t_m$  - Melting Temperature (°C)

$I_{win}$  - Integrated Discomfort Level for Indoor Temperature in Winter (°C)

$I_{sum}$  - Integrated Discomfort Level for Indoor Temperature in Summer (°C)

$T_{nuc}$  - Nucleation Temperature (°C)

EU - European Union

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

PCM - Phase Change Material

PCMs - Phase Change Materials

LHS - Latent Heat Storage

LHTS - Latent Heat Thermal Storage

LHTES - Latent Heat Thermal Energy Storage

TES - Thermal Energy Storage

SHS - Sensible Heat Storage

DSC - Differential Scanning Calorimetry

DTA - Differential Thermal Analysis

TA - Thermal Analyses

BS - Butyl Stearate

CSM - Compact storage module

SSPCM - Shape-Stabilized Phase Change Material

HDPE - High-Density Polyethylene

PVC - Polyvinyl Chloride

SEM - Scanning Electric Microscope

XPS - Extruded polystyrene

EPS - Expanded Polystyrene

ICB - Expanded Cork

PPD - Predicted Percentage Dissatisfied

CFD - Computational Fluid Dynamics

xGnP - Exfoliated Graphite Nanoplatelets

GmbH - Gesellschaft mit beschränkter Haftung

RT - Organic PCM

SP - Inorganic PCM

Fig - Figure

# 1

## INTRODUCTION

### 1.1. GENERAL INTRODUCTION

Due to European Union (EU) and worldwide high energy consumption of the buildings stock, it is important to take measures to reduce these needs and, consequently, reduce the EU energy dependency. To improve the behaviour of the buildings, regarding thermal comfort of the occupants and energy performance, it is necessary to use thermal insulation and the buildings thermal inertia, to reduce the thermal amplitudes, the winter heat losses, the summer heat gains and to store the energy from solar gains [2].

Today's constructive quality standards have been more demanding not only in the way that we are designing but also in the incorporation of new and better materials, more ecological and with a more durability facing the changes of weather, with more comfort and less expenses. It's very important that the construction's design could create less energy dependence building. In the past years, the word comfort has been a very demanding challenge for companies and especially for the engineers involved. Do we want a beautiful house just because is aesthetically beautiful or a beautiful house which is practical and comfortable? The challenge begins with the new forms of construction, exploring different materials and in what way they can improve comfort.

Part of the thermal building envelope, not considering thermal insulation material in itself, is the promising technology of phase change materials (PCM) which has received considerable attention over the last decade. PCMs utilize the principle of latent heat thermal storage (LHTS) to absorb energy in large quantities when there is a surplus and releasing it when there is a deficit. Correct use of PCMs can reduce peak heating and cooling loads, i.e. reduce energy usage, and may also allow for smaller dimensions of technical equipment for heating and cooling. An added benefit is the ability to maintain a more comfortable indoor environment due to smaller temperature fluctuations. Over the past few years there have been written several reviews on the use of PCMs in buildings for thermal energy storage systems and indoor climate comfort purposes [60].

The use of PCM as thermal storage systems for buildings has been of interest throughout the second half of the twentieth century. Most often latent heat storage materials are used to stabilize interior building temperatures. In building envelope applications, PCM stores latent heat as the ambient temperature rises to the melting point (most PCMs change from a solid to a liquid state). As the temperature cools down, the PCM returns to a solid phase and the latent heat is released. This absorption and release of heat takes place at a constant temperature, which is ideal to smooth external temperature fluctuations [81].

In the Mediterranean countries the thermal behaviour of buildings is declining, due to the current trend of using large windows and of reducing the buildings weight and, consequently, their thermal inertia [3]. The selection of the type and amount of PCM to be used is a challenge owing to the different characteristics needed to accomplish an adequate behaviour of the buildings during winter and summer periods.

The use of PCM in buildings began in the mid-1940s and this passive solar system with thermal storage capability was one of the first applications studied at that time [81]. When phase changing heat storage materials are incorporated into the building envelope or internal building structural components, during the day they absorb heat from the glazing and opaque enclosure. As the PCM melts, they stabilize the indoor temperature. At night, when the interior space temperatures decrease, in passive cooling scenarios, the PCM releases the stored energy, thus preventing the temperature in the room from getting excessively cold.

In short, the integration of PCM in building envelope and building service equipment, is a way to enhance the energy storage capacity of enclosures and then to rationalize the use of renewable and non-renewable energies. Consequently, not only the building energy performance could be optimized, but also indoor thermal comfort improvement is expected because of its thermal environment regulated at the “thermal comfort zone” [140].

## **1.2. OBJECTIVES**

This paper summarizes previous works on latent thermal energy storage in building applications, covering PCMs, reviews commercial state-of-the-art products found on the market and shows some of the potential areas of use for PCMs in building applications, the impregnation methods, current building applications and their thermal performance analyses and furthermore building materials and projects using PCMs that have already been realized. There seems to be a scarcity of data published on actual performance in real life applications so far. However, many laboratory and full scale experiments have shown positive results on energy savings. Furthermore, future research opportunities have been explored and challenges with the technology as of today have been discussed.

## **1.3. THESIS STRUCTURE**

The structure of this dissertation is divided into five chapters in order to achieve the main objective of evaluating the use of building elements with incorporated phase change materials (PCM) in order to increase the thermal efficiency of buildings. The content of the thesis was then organized in the following chapters:

- Chapter 1 – presents the objectives of the dissertation and a brief description of each chapter;
- Chapter 2 – corresponds to the bibliography collected on the phase change materials (PCM), first the concept of PCM and then other general concepts associated with the absorption of latent heat are explained;
- Chapter 3 – in this chapter the properties of the various PCM groups are listed, highlighting the advantages of each, and some techniques for improving their main limitations are presented, then a description is made of the various forms of incorporation of PCM into materials and constructive elements;
- Chapter 4 – this chapter presents current building applications and their performance analyses, sustained by experimental campaigns carried out by different authors.

- Chapters 5 – summarizes the main conclusions of the work developed and discuss possible perspectives of future developments/works to give continuity to the study presented in this dissertation.

Fig. 1.1. shows a schematic overview of the work methodology to be developed.

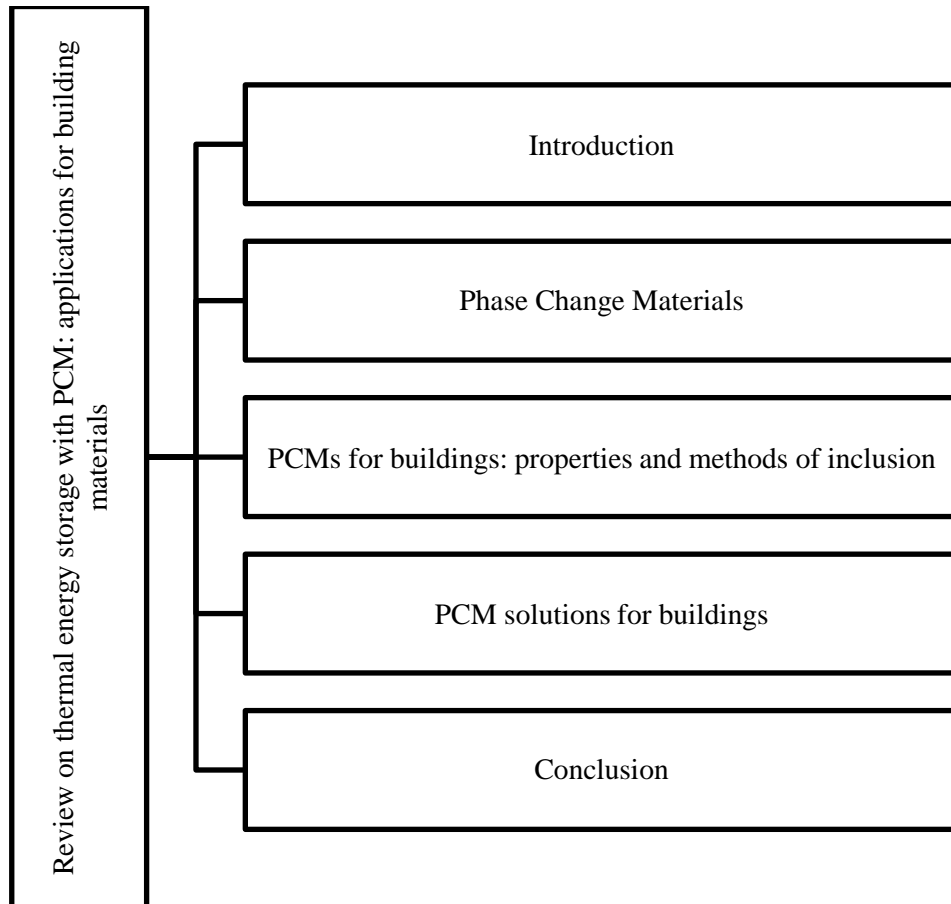


Fig. 1.1 – Schematic overview of the work methodology





## 2

## PHASE CHANGE MATERIALS

## 2.1. DEFINITION

What is a Phase Change Material? A PCM is a substance composed by molecules. The principle of the PCM is simple. As the temperature increases, the material change phase from solid to liquid. The reaction being endothermic, the PCM absorbs the heat. Similarly, when the temperature decreases, the material changes phase from liquid to solid. The reaction being exothermic the PCM desorbs the heat (Fig. 2.1.).

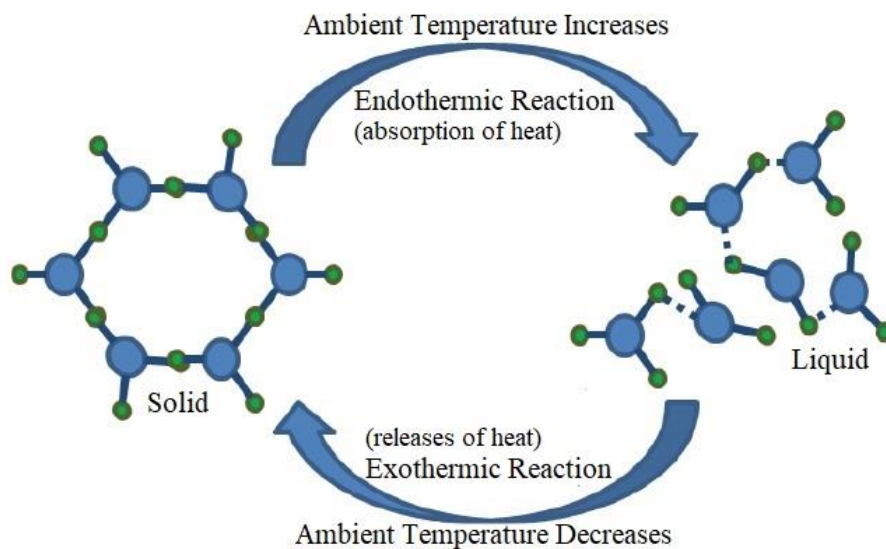


Fig. 2.1. - Water melting cycle, adp. [1]

This kind of material has the capacity of storing and releasing energy in the form of latent heat; latent heat storage can be achieved through the transition from solid to liquid and vice-versa. The PCM uses the latent heat of phase change to control temperatures within a specific range.

The energy used to alter the phase of the material, once the phase change temperature is around the desired comfort room temperature, will lead to a more stable and comfortable indoor climate as well as cut-peak cooling and heating loads [198].

In this chapter we can find references to some concepts, definitions and a survey of the different types of PCM.

## 2.2. PROPERTIES

Material properties in general depend on boundary conditions, like pressure, temperature, relative humidity. The common materials used in construction, like concrete, brick, stone, glass, wood, ceramic, have a set of properties that give them greater or lesser heat storage capability and heat storage restitution to the surroundings.

Thermophysical properties are those which give information about the amount of energy that such materials and composites can store. But the characterization of the thermophysical properties is not always easy and for composites many times cannot be carried out with conventional laboratory equipment, mostly due to the sample size [70]. The main criteria that oversee the selection of PCMs are [199]:

- Possess a melting point in the desired operating temperature range (temperature range of application) to assure useful heat storage and extraction. Building application temperatures range from 15°C (cold storage) to 70°C (heat storage);
- Possess high latent heat of fusion per unit mass, so that a smaller amount of material stores a given amount of energy;
- High specific heat to provide additional significant sensible heat storage effects;
- High thermal conductivity, so that the temperature gradients for charging and discharging the storage material are small;
- Small volume changes during phase transition, so that a simple container and heat exchanger geometry can be used (less than 10%);
- Exhibit little or no subcooling during freezing/melting cycle;
- Possess chemical stability, no chemical decomposition and corrosion resistance to construction materials;
- Contain non-poisonous, non-flammable and non-explosive elements/compounds;
- Available in large quantities at low cost.

It's now time to introduce some important concepts related to calorimetry, the part of science that studies energy exchanges in the form of heat between bodies or systems. The concepts of thermal conductivity, specific heat and specific volumetric heat, thermal diffusivity, latent heat or phase change and enthalpy will be addressed.

Thermal conductivity,  $\lambda$  in W(m.K), describes the transport of energy, in form of heat, through a body of mass as the result of a temperature gradient. According to the second law of thermodynamics, heat always flows in the direction of the lower temperature. For example, let's focus on two very different materials needed to build a wall, concrete and thermal insulation. The coexistence of these materials provides strength and stability to the building skeleton and at the same time makes it less vulnerable to thermal amplitudes occurring during the day. The amount of heat, per unit time, passes through a thickness unit of material (m), when a temperature unit difference is established between two flat and parallel faces (1°C or 1K). Consulting the ITE50 (Coeficientes de transmissão térmica de elementos da envolvente dos edifícios) [205] it was found that for concrete  $\lambda=2\text{W(m.K)}$  and for thermal insulation is  $\lambda=0,04\text{W(m.K)}$  so the difference in conductivity values between this materials indicates that the heat flow through the thermal insulation is fifty times lower than the heat flow that crosses the concrete element for the same superficial area [200].

The specific heat,  $c_p$  in units J/(kg.K), is the amount of heat per unit mass (constant pressure) required to raise the temperature by one degree Celsius (1°C).

The capacity of the material to storage energy is usually represented by the specific volumetric heat –  $C$ , which results from the product of the density by the material's specific heat,  $p \cdot c_p$  and the units in which it is expressed are  $J/(m^3.K)$  [1].

Thermal diffusivity,  $\alpha_T$  express in  $(m^2/s)$ , is a material-specific property for characterizing unsteady heat conduction. This value describes how quickly a material reacts to a change in temperature, ( $\alpha_T = \frac{\lambda}{p \cdot c_p}$ ). The metals are materials with a high thermal diffusivity and they have a fast response to surroundings thermic changes, for example against materials such as XPS (extruded polystyrene), cork and others, which, because of low  $\alpha_T$ , can be used as a thermal insulation.

Below there is a table (Table 2.1) where some common materials used in building construction are represented according to their thermic conductivity, density, specific heat and specific volumetric heat [1].

Table 2.1 - Thermal conductivity, density, specific heat, specific volumetric heat of some building materials [1]

Material	Thermal conductivity ( $\lambda$ ) [W/(m.K)]	Density ( $\rho$ ) [kg/m <sup>3</sup> ]	Specific heat ( $c_p$ ) [kJ/(kg.K)]	Specific volumetric heat ( $p \cdot c_p$ ) [kJ/(m <sup>3</sup> .K)]
Water (T=10°C)	0,600	1000	4,181	4181
Air (T=20°C)	0,025	1,230	1,012	1,245
Concrete	1,650	2000-2300	0,880	1760-2024
	2,000	2300-2600	1,040	2392-2704
Ceramic (roof tiles, bricks, tiles)	0,600	1400-1600	0,840	1176-1344
Mortar (traditional plasters)	1,300	1800-2000	1,000	1800-2000
	1,800	>2000	1,046	>2092
Metals (steel)	50,00	7800	0,450-0,512	3510-3994
Wood (dense woods)	0,230	750,0-820,0	1,500-2,500	1125-2050
Calcareous stones	1,400	1800-1990	0,810	1458-1612
Granite	2,800	2500-2700	0,790	1975-2133
Thermal insulation:				
EPS	0,040	15,00-20,00	1,550	15,83-21,10
XPS	0,037	25,00-40,00	1,045	26,13-41,80
ICB	0,045	90,00-140,00	0,170	15,30-23,80
Glass (Quartz glass)	1,400	2200	0,840	1848

It's important to take into account that although heat storage capacity (that results from the product,  $p \cdot c_p$ ) and restitution to stored heat, that is thermic diffusivity, are intrinsic characteristics of the materials but their properties are not constant. In the presence of water, temperature fluctuations or the simply the physical state in which the materials are found can change their properties.

It is known that all materials interact with the environment. However, most of them lack the capability to alter its own properties according to the environment characteristics in which they are applied. Phase change materials (PCM), as the name itself advocates, possesses the capability to alter its own state as function of the environmental temperature the same does not occur in other traditional building materials [201].

So PCMs are latent heat storage materials, they use chemical bonds to store and release the heat. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change state or phase. PCMs, having melting temperature between 20°C and 32°C, were used/recommended for thermal storage in conjunction with both active solar storage for heating and cooling in buildings and passive storage, where the heat or cold stored is automatically released when indoor or outdoor temperature rises [7].

Changing of material phase can be classified into four states: solid-solid, solid-liquid, gas-solid and gas-liquid. For a better understanding of the concepts described above [1], takes the water as an example.

A phase can be defined as an amount of fully homogeneous material (solid, liquid or gaseous). In each phase can exist at various pressures and temperatures or, using the terminology of thermodynamics, in several states. The solid phase (a) is characterized by strong molecular cohesion giving stable shape; the liquid phase (b) is an intermediate state; and the gaseous phase (c) is characterized by the weak molecular cohesion and, therefore, without form (Fig. 2.2.).

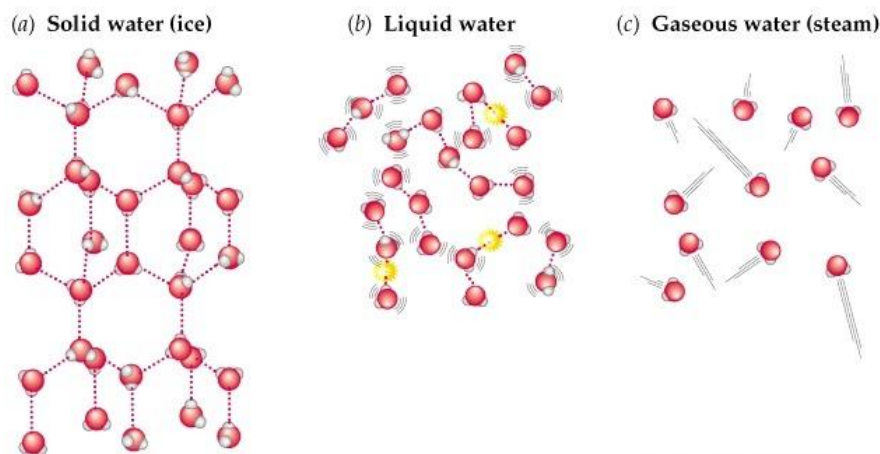


Fig. 2.2. - Material physical phases (water) [160]

If we consider a given body of water we recognize that it can exist in various forms. If it is initially liquid may became steam after heating, or a solid when cooled.

According to Coelho et al. [79] when we supply the heat to the ice at constant pressure, the specific volume increases slightly and the temperature rises to 0°C, at which point ice melts while the temperature remains constant (at 0°C). At this point, by the melting point, all the heat supplied is used to give the change of phase, from solid to liquid. The total amount of heat, or energy, needed to the complete melting fusion of the ice in water is approximately 334kJ/kg. When all ice is melted, any

additional heat transfer causes an increase in the temperature of the liquid (up to 100°C, boiling temperature, in the transition from liquid to gaseous). The energy supplied to the water at 0°C (at the melt temperature) is only restored after the temperature has decreased of water to ice, in an exothermic reaction.

With the illustration of the chart (Fig. 2.3.) below it is intended to synthesize the water phases. It represents the energy (in the form of heat) used by water, in the various states, to increase its temperature, allowing to observe that there is a large heat quantity associated with phase changes. In this process, phase change, the amount of generated energy is called “phase shift enthalpy” or only “enthalpy”.

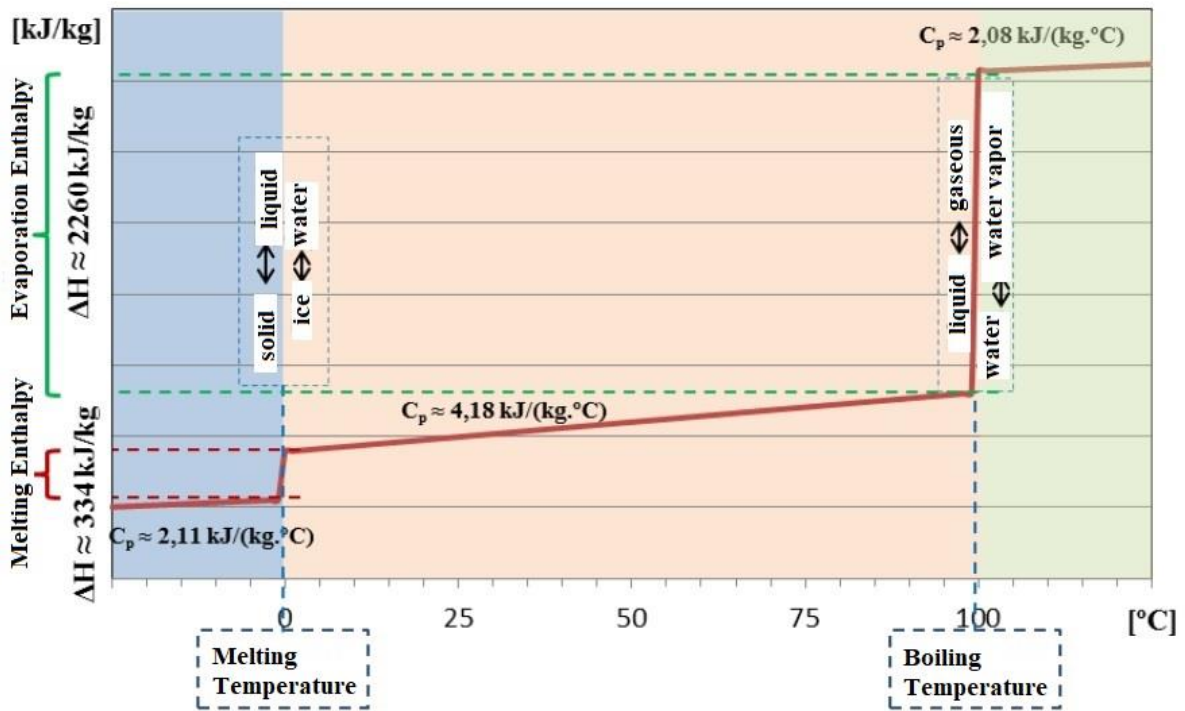


Fig. 2.3. – Water phases, adap. [1]

The amount of energy required to raise the water temperature from 1°C to 80°C is approximately equal to the amount of heat used to melt the ice in water. The amount of heat associated with the phase change and the amount of heat associated with specific heat  $c_p$  of the material are distinguished by latent heat and sensible heat, respectively.

The Fig. 2.4 pretends to illustrate the difference between latent heat and sensible heat using the water as an example.

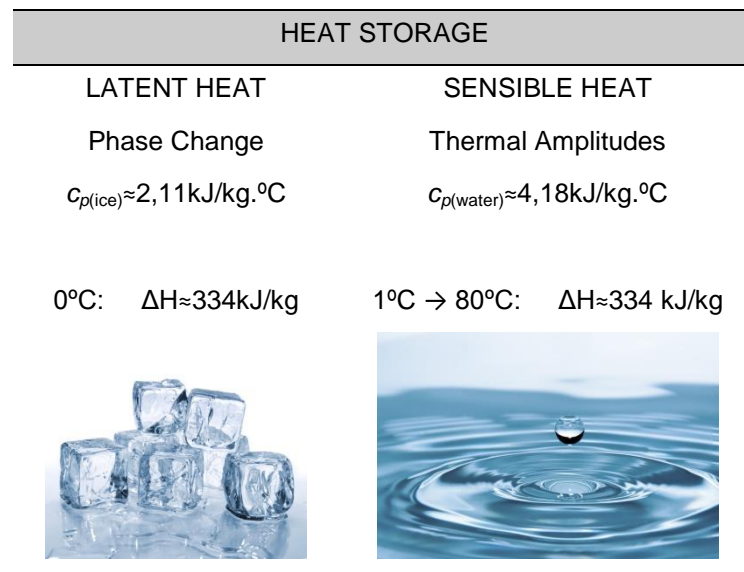


Fig. 2.4. - Latent Heat vs. Sensible Heat, adp. [1]

So one of the most important forms of energy storage is thermal energy storage and its applications are very wide, from heating and cooling using waste or solar energy to high temperature energy storage power production and industrial processes. Thermal energy storage (TES) can be stored as a change in internal energy of a material as thermochemical, latent heat and sensible heat or a combination of these. It's important to refer that, in this thesis, the concepts of latent heat and sensible heat have another distinction besides that of the thermochemical concept, and so, a brief reference is described below.

- Sensible Heat

Sensible heat storage (SHS) method is carried out by adding energy to a material to increase its temperature without changing its phase [112]. In sensible heat storage the quantity of stored heat depends on the temperature change, the heat capacity of the material, and the amount of storing material. In sensible heat storage a solid or a liquid material are used as a storage medium [13]. The storage medium can be water, bricks, sand, rock beds, oil or soil. Together with a container, an input/output device is attached to it to provide thermal energy for any intended application. Most commonly used in dwellings, SHS is used as heat storage to provide hot water for houses and offices. In solar heating systems, water is still used for heat storage in liquid based systems, while a rock bed is used for air based systems [113]. Water as storage material has the advantages of being inexpensive and readily available, of having excellent heat transfer characteristics. For low and high temperature thermal energy storage, solid materials such as metals, rocks, sand, concrete and bricks can also be used [112]. Thousands of materials have been identified as suitable for the use of thermal energy storage. Fernandez et al. [114] have proposed a proper method of selecting the best material to be used for long and short term sensible energy storage in order to minimize cost. By combining multiple objectives and usage restrictions, they are able to identify appropriate materials through evaluation of cost, availability and environmental aspects such as carbon footprint. There are a few advantages and disadvantages of both liquid and solid storage medium. For an example, liquid media such as water is widely available and an inexpensive sensible energy storage medium. It is non-toxic, non-combustible, has a relatively high specific heat and high density characteristics, and is easy to handle. However, at low or high temperature applications, water might freeze or boil and is thus limited by the melting and

freezing point of water. Furthermore, water is highly corrosive and difficult to stratify. To avoid freezing and corrosion problems when using water; chemical additives may be added. Other liquid media such as molten salts, liquid metals and organic oils may be used for applications where water is not suitable [115].

- Latent Heat

Latent heat storage (LHS) is based on the heat release or heat absorption during phase change of a storage material from solid to liquid or liquid to gas or vice versa [111]. The phase change process of the material is adapted to store the latent heat thermal energy. There is a visible advantage of PCMs (paraffin wax, salt hydrates, and fused salts) over sensible heat storage materials [13,116]. LHS, compared to SHS, offers higher density of energy storage with near zero temperature changes. However, difficulties usually arise in real due to the low density change, thermal conductivity, sub cooling of the phase change materials, stability of properties under extended cycling and sometimes phase segregation [113]. Phase change materials are specifically used in latent heat energy storage systems, and thus PCM can also be called latent heat storage material. The thermal energy transfer of PCM occurs during the charging or discharging (melting or solidification) process at which the state or phase of the material changes from liquid to solid or from liquid to solid. At the start of the heating of the material, the PCM temperature rises as it absorbs the thermal energy. When the material reaches a specific temperature range, it will start to melt as the material begins to experience a phase transition from solid to liquid state. However, unlike sensible heat storage materials, during the phase transition process the PCM releases or absorbs heat at a constant or nearly constant temperature. Many authors have experimented with different types of PCMs, subdividing them into organic, inorganic and eutectic types. However, the majority of the phase change material does not possess the recommended properties for an ideal thermal energy medium and thus thermal enhancers are used to improve any disadvantages that the medium may have. Extensive discussions for each class of phase change material properties can be referred from [111,117].

- Thermochemical

In thermochemical energy storage system, the energy is stored after a breaking or dissociation reaction of chemical bonds at the molecular level which releases energy and then recovered in a reversible chemical reaction. Similar to the other type of thermal energy storage systems, thermochemical heat storage system may also undergo charging, storing and discharging processes. Fig. 2.5. illustrates the reversible processes of a thermochemical heat storage system [118]. Additionally, thermochemical heat storage may undergo various processes which include reversible chemical and photochemical reactions, water release from zeolites and hydrates and fuel production. The advantage of this method is the system is more compact due to the higher energy densities compared to SHS and LHS [13]. Furthermore, the system suffers little or no heat loss during the storing period where the two components A and B are stored separately at ambient temperature. Hence, this type of thermal energy storage is more suitable for long-term energy storage i.e. seasonal storage. In order to select the most suitable candidate for thermochemical heat storage material, several key factors may be used as a rough guideline. These key factors are (i) cost, (ii) ability to sustain large number of charging, storing and discharging cycles, (iii) availability of the material, (iv) non-toxic and non-flammable (v) corrosiveness, (vi) reaction rate and temperature range, (vii) energy storage density and (viii) good heat transfer characteristics and flow properties.

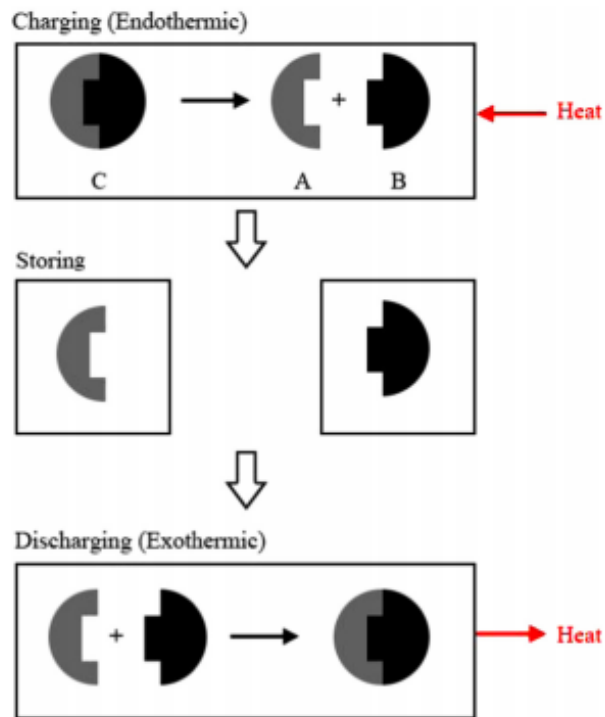


Fig. 2.5. - Charging, discharging and storing processes of a thermochemical heat storage system [118]

When using PCMs for TES the most important material property is the heat storage capability, usually given as the enthalpy as a function of temperature (Fig. 2.6.); PCMs have a strong change in enthalpy in a narrow temperature range [77].

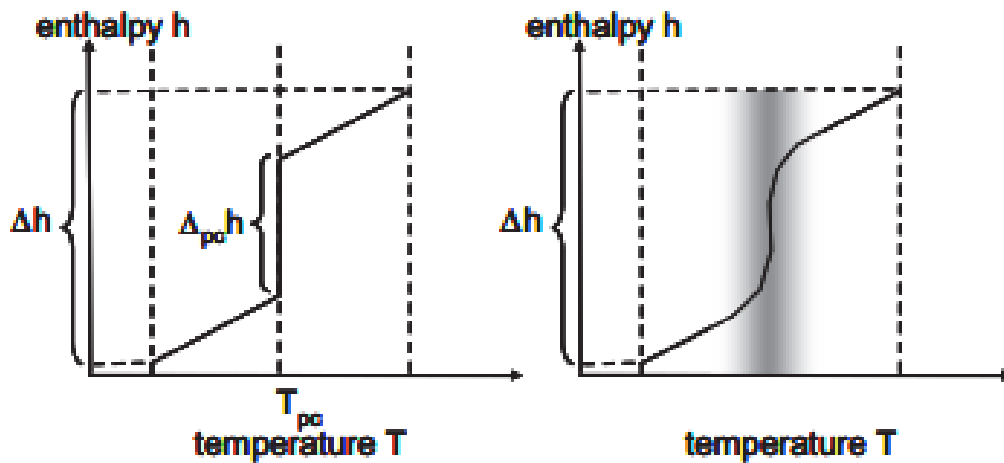


Fig. 2.6. - Enthalpy  $h$  as a function of temperature  $T$  for the case of a phase change [77]



In an idealized case, the enthalpy changes suddenly at a phase change temperature. The heat stored is then called latent heat, while heat stored with a temperature change is called sensible heat. However, many PCM change phase in a temperature range and this must be taken into account when applying such PCM in a real application. In addition, heating and cooling processes often show different thermal behaviour, called hysteresis (Fig. 2.7.). This includes subcooling, which means that for the material to change to the lower temperature phase (in a solid-liquid phase change the solid phase), a certain temperature lower than the phase change temperature has to be reached to start the phase change. At this temperature, the nucleation temperature  $T_{nuc}$ , a small nucleus of the lower temperature phase forms. Subcooling is very common when using the phase change between solid and liquid [77].

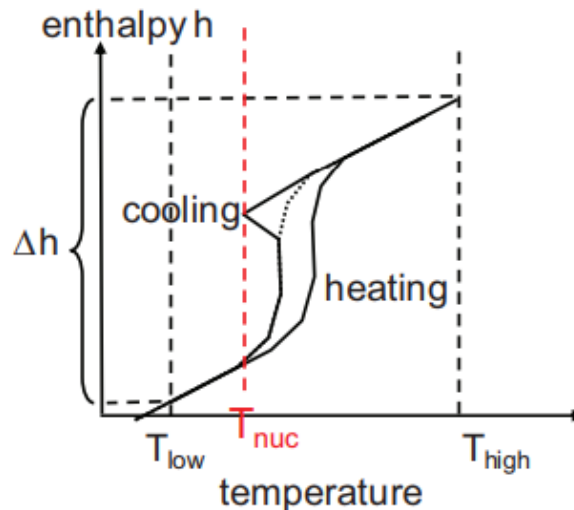


Fig. 2.7. - Enthalpy  $h$  as a function of temperature  $T$  for the case of a phase change [77]

Ice is the best-known PCM used by humans with many and very different types of applications, for generations, inhabitants of northern arctic regions have been using ice for thermal stabilization of their dwellings. Igloos are the first-known application of the phase-change latent heat in building structures. The igloo (Fig.2.8) is an ingenious invention and very effective in keeping arctic people warm. Igloos are relatively easy to construct and made from materials found in abundance, snow and ice which serve simultaneously as building structural components, thermal insulation, thermal radiation shield and energy storage. Blocks of ice are formed into the dome shape, joined together by snow. To prevent excessive amount of snow and cold wind from coming into the igloo, a sunken entrance is constructed, along with a raised sleeping platform covered with fur for comfort and warmth. Internal igloo temperature circulates between  $9^{\circ}\text{C} - 15^{\circ}\text{C}$ , when occupied, even during harsh arctic winters where the outside temperatures can drop to  $-45^{\circ}\text{C}$  [81].

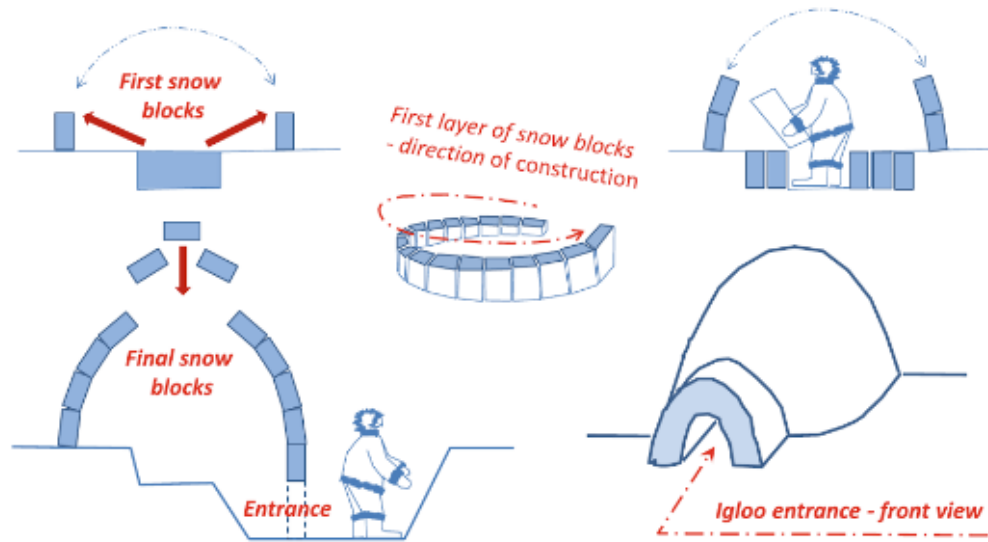


Fig. 2.8. - Igloo construction [81]

### 2.3. CLASSIFICATION OF PCMS

Fig. 2.9. shows the classification of energy storage materials [2].

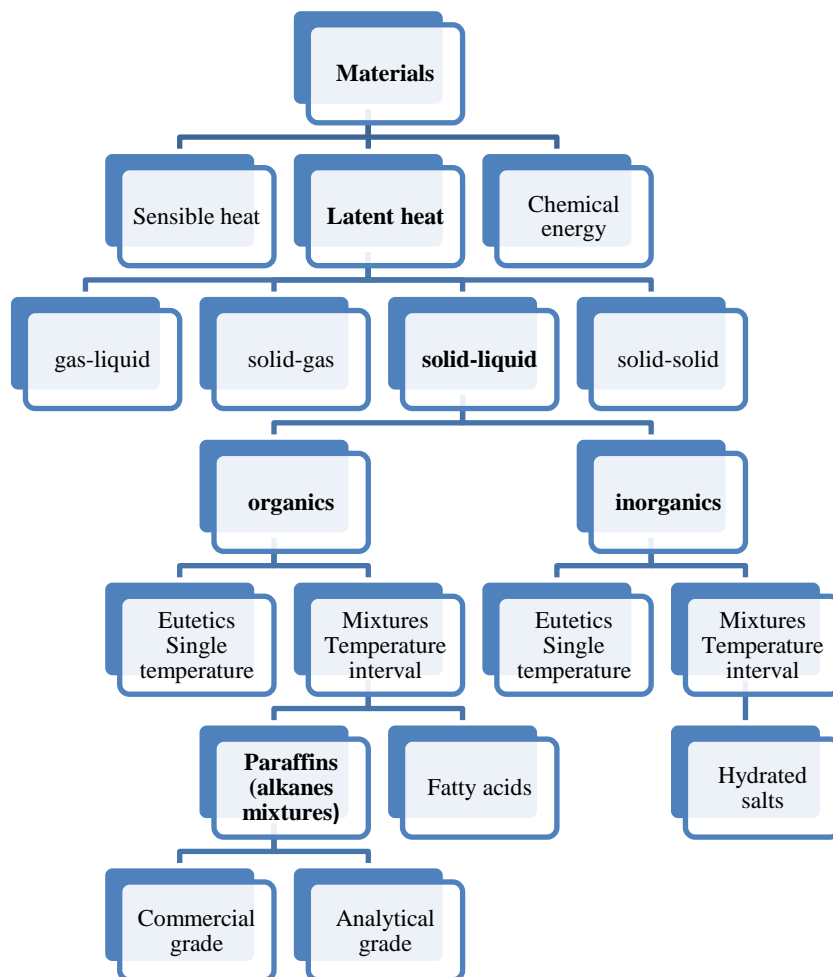


Fig. 2.9. - Classification of energy storage materials [2]

### 2.3.1. NON-COMMERCIAL/COMMERCIAL MATERIALS

The selection of an appropriate PCM for any application requires the PCM to have melting temperature within the practical range of application. Several application areas have been proposed for PCMs studied. Table 2.2 lists the current companies that commercially produce over 100 PCMs. In addition to these, several PCMs have been proposed or studied by different researchers. A detailed list of PCMs studied or proposed for study can be found in [51, 62–65].

Table 2.2 - Commercial PCM manufactures in the world [2]

Manufacturer	PCM temperature range	Number of PCMs listed
RUBITHERM ( <a href="http://www.rubitherm.eu">www.rubitherm.eu</a> )	-3°C to 100°C	29
Cristopia ( <a href="http://www.cristopia.com">http://www.cristopia.com</a> )	-33°C to 27°C	12
TEAP ( <a href="http://www.teappcm.com">www.teappcm.com</a> )	-50°C to 78°C	22
Doerken ( <a href="http://www.doerken.de">www.doerken.de</a> )	-22°C to 28°C	2
Mitsubishi Chemical ( <a href="http://www.m-chemical.co.jp">www.m-chemical.co.jp</a> )	9,5°C to 118°C	6
Climator ( <a href="http://www.climator.com">www.climator.com</a> )	-18°C to 70°C	9
EPS Ltd ( <a href="http://epsLtd.co.uk">epsLtd.co.uk</a> )	-114°C to 164°C	61
Merck		

### 2.3.2. ORGANIC/INORGANIC/EUTECTIC MATERIALS

There are several materials that can be used as PCMs. A common way to distinguish PCMs is by dividing them into organic, inorganic and eutectic PCMs. These categories are further divided based on the various components of the PCMs (Fig. 2.10.).

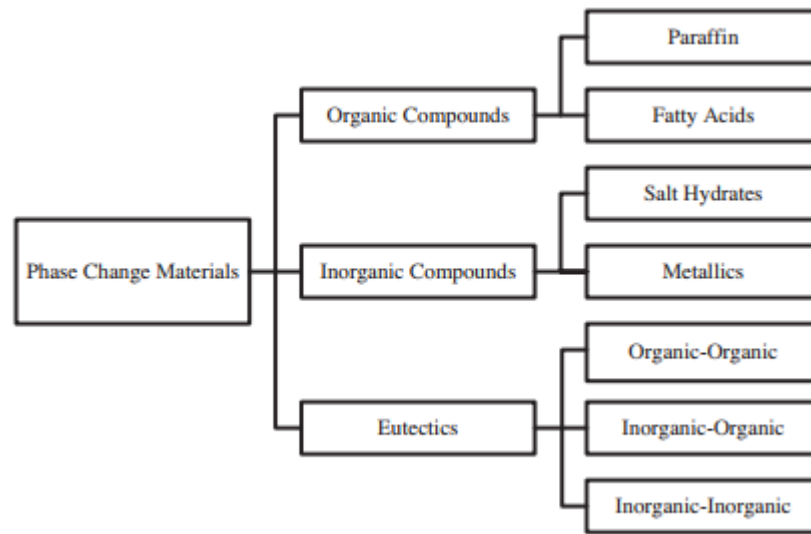


Fig. 2.10 - Phase change materials classification

Fig. 2.11. shows the difference in melting enthalpy and melting temperature for some of the most common materials used as PCMs.

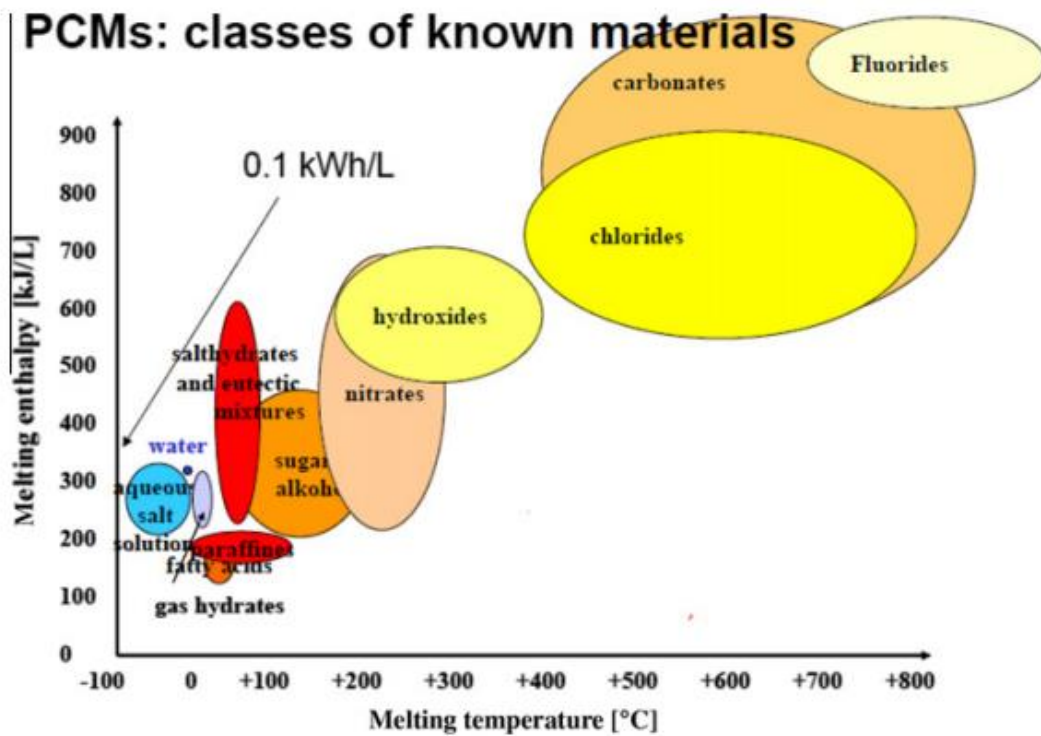


Fig. 2.11. – PCMs classes

From the observation of the Fig. 2.11. it's possible to conclude that there are three main groups whose melting temperature ranges are compatible with the comfort temperature range inside a building. They are the fatty acids, paraffins, hydrated salts and eutectic mixtures, the latter group having a higher enthalpy range of fusion.

For better understanding and a more complex interpretation of this matter the sub groups have been described and developed.

#### 2.3.2.1. Organic

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

Paraffins are available in a large temperature range, with a density around  $900\text{kg/m}^3$ , opening up for use in various other areas besides building related applications. The latent heat is mass based, they show no signs of phase separation after repeated cycling through solid-liquid transitions, and have a low vapor pressure. However, paraffins used as PCMs have some drawbacks. They have low thermal conductivity (around  $0.2\text{W/(mk)}$ ), they are not compatible with plastic containers and they are moderately flammable [27].

Non-paraffins used as PCMs include fatty acids and their fatty acid esters and alcohols, glycols. Fatty acids have received the most attention for use as PCMs in buildings. An extensive review on fatty acids used for PCM purposes has been written by Yuan et al. [72]. Their melting temperatures vary from  $5^\circ\text{C}$  to  $70^\circ\text{C}$ ; possess appreciable latent heat ranging from  $45\text{J/g}$  to  $210\text{J/g}$  but usually around  $150\text{J/g}$  ( $140\text{MJ/m}^3$ ). They have the advantages of congruent melting, low subcooling and vapor pressure, non-toxicity, good thermal and chemical stability, small volume change, self-nucleating behavior and biodegradability. They are also capable of thousands of thermal (melting/freezing) cycles without any notable degradation in thermal properties. Their high surface tension improves their capability of integration in a porous material matrix. However, like paraffins, the major drawback of fatty acids is their low thermal conductivity, ranging from  $0.15\text{W/(mk)}$  to  $0.17\text{W/(mk)}$  [71, 72].

Esterification of fatty acids with alcohols is a common method to shift the phase transition temperature. It enables decreasing the melting point of fatty acids with high thermal capacity. The production of binary and ternary PCMs by mixing fatty acids with fatty alcohols, polyethylene oxide, oleic acid, pentadecane or other products with low melting temperature is another possible tuning technic [72].

According to [73], other organic PCMs have received less attention by researchers such as sugar alcohol. Some of the polyalcohol has latent heat almost double than that of the other organic PCMs but their melting point ranges from  $90^\circ\text{C}$  to  $200^\circ\text{C}$ , which is too high for building applications.

Among them, erythritol is especially noticeable with a latent heat of fusion of  $339.8\text{J/g}$  at  $120^\circ\text{C}$ . Bio-based PCMs are organic materials produced from the biomass: soybean oils, coconut oils, palm oils and beef tallow. Like the other organic product, they have an interesting latent heat with good chemical stability and phase transition temperatures ranging from  $-22.77^\circ\text{C}$  to  $77.83^\circ\text{C}$ . Nevertheless, they suffer from the same problems as other organic materials [71].

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

### 2.3.2.2. Inorganic

Inorganic phase change materials of interest consist of hydrated salts and metallics. For building applications however, metallics are not within the desired temperature range and in addition they have severe weight penalties making them unsuitable. Hydrated salts consist of an alloy of inorganic salts and water and enable a cost-effective PCM due to easy availability and low cost. The phase change transformation involves hydration or dehydration of the salts in a process that resembles typical melting and freezing. The salt hydrate may either melt to a salt hydrate containing less water or to an anhydrous form where salt and water is completely separated [71].

The salt hydrates possess a significant storage capacity and operate phase transition at ambient temperature. Many studies focused on the calcium chloride hexahydrate, sodium sulphate and magnesium chloride hexahydrate because of their availability, moderate costs and non-flammability. Salt hydrates have a density of around  $1700\text{kg/m}^3$ , which is twice higher than for paraffins. With a maximum latent heat of around  $200\text{J/g}$ , their heat storage on a per volume basis is around  $350\text{MJ/m}^3$ , which is much higher than organic products.

Another significant advantage is their thermal conductivity (around  $0.5\text{W/mK}$ ), which is also higher compared to organic materials. However, these products become chemically unstable at high temperature. Heating cycles cause continuous dehydration of the PCM and the heat storage capacity usually degrades over time. Moreover, most salt hydrates melt incongruently with the formation of a lower form product. This irreversible process is an additional drawback for their long term performance. The liquid phase separation and segregation can be prevented by addition of gelling or thickening agents. Subcooling is another problem associated with salt hydrates. The phenomenon is characterized by a solidification of the product below its phase transition temperature. It can be reduced by inducing heterogeneous nucleation in the salt hydrates thanks to nucleators or direct contact with an immiscible heat transfer fluid [70].

### 2.3.2.3. Eutectic mixtures

A eutectic is a minimum melting composition of two or more components, each of which melts and freezes congruently. During the crystallization phase, a mixture of the components is formed, hence acting as a single component. The components freeze to an intimate mixture of crystals and melt simultaneously without separation ([70]). Eutectics can be mixtures of organic and/or inorganic compounds. Hence, eutectics can be made as either organic–organic, inorganic–inorganic or organic–inorganic mixtures ([10]). This gives room for a wide variety of combinations that can be tailored for specific applications. Of organic eutectic mixtures, the most commonly tested consist of fatty acids. Some organic eutectics that have been studied include capric acid/myristic acid ([57]), lauric acid/stearic acid, myristic acid/palmitic acid and palmitic acid/stearic acid ([97]) and capric acid/lauric acid ([107]). The most common inorganic eutectics that have been investigated consist of different salt hydrates. The benefits of eutectic mixtures are their ability to obtain more desired properties such as a specific melting point or a higher heat storage capacity per unit volume. Though it has been given significant interest over the last decade by researchers, the use of eutectic PCMs for use in (LHTS) systems is not as established as pure compound PCMs. Hence, the thermophysical properties of eutectics is still a field for further investigations as many combinations have yet to be tested and proved.

In conclusion, it's possible to see that there is no a perfect product for Latent Heat Thermal Energy Storage (LHTES) in the temperature range  $19^\circ\text{C}$ - $25^\circ\text{C}$ . Fig. 2.12. shows that very few of them present latent heat above  $20\text{J/g}$ . Organic PCMs offer better chemical and thermal stability with congruent

melting and they exhibit little or no subcooling. On the other hand, inorganic products suffer from cycling instability, require nucleating and thickening agents to minimize subcooling and are highly reactive to metal materials. Therefore, the organic PCMs seem to be the most appropriate for low temperature building thermal energy storage (TES) application [73].

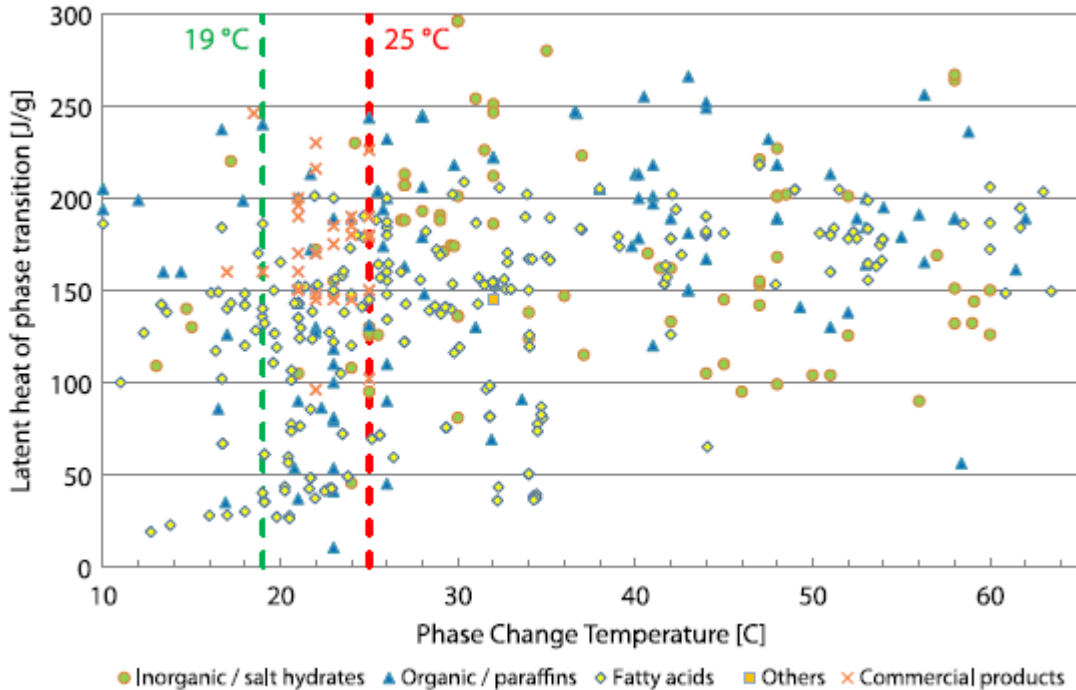


Fig. 2.12. - Compilation of PCM thermal properties [73]

In short, the comparison between different kinds of PCM is synthesized on Table 2.3.

Table 2.3 - Comparison of the different kinds of PCMs

Classification	Advantages	Disadvantages
Organic PCMs	<ol style="list-style-type: none"> <li>1. Availability in a large temperature range</li> <li>2. High heat of fusion</li> <li>3. No supercooling</li> <li>4. Chemically stable and recyclable</li> <li>5. Good compatibility with other materials</li> </ol>	<ol style="list-style-type: none"> <li>1. Low thermal conductivity (around 0.2W/mK)</li> <li>2. Relative large volume change</li> <li>3. Flammability</li> </ol>
Inorganic PCMs	<ol style="list-style-type: none"> <li>1. High heat of fusion</li> <li>2. High thermal conductivity (around 0.5W/mK)</li> <li>3. Low volume change</li> </ol>	<ol style="list-style-type: none"> <li>1. Supercooling</li> <li>2. Corrosion</li> </ol>

4. Availability in low cost		
Eutectics	1. Sharp melting temperature 2. High volumetric thermal storage density	Lack of currently available test data of thermo-physical properties

To be a desirable material used in latent heat storage systems, the following criteria need to be met: thermodynamic, kinetic, chemical and economic properties, which are shown in Table 2.4 [8].

Table 2.4 - Selection criteria [8]

Thermodynamic properties	(1) Melting temperature in desired range (2) High latent heat of fusion per unit volume (3) High thermal conductivity (4) High specific heat and high density (5) Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problems (6) Congruent melting
Kinetic properties	(1) High nucleation rate to avoid super cooling (2) High rate of crystal growth to meet demands of heat recovery from the storage system
Chemical properties	(1) Complete reversible freezing/melting cycle (2) Chemical stability (3) No degradation after a large number of freezing/ melting cycle (4) No corrosiveness (5) No toxic, no flammable and no explosive material
Economic properties	(1) Effective cost (2) Large-scale availabilities

## 2.4. CHAPTER SYNTHESIS

In this chapter we explained the definition of PCM and introduced the various types of existing PCMs, divided, in general, into organic, inorganic and eutectic compounds. Organic compounds are seen as the most stable at thermal level.



It has been demonstrated that the principle of operation of PCMs is simple, but that assessing their effectiveness in contributing to latent heat storage and consequently increasing the energy performance of a building can be a challenge.

The thermal properties are considered as the decisive criterion for choosing the most suitable PCM, highlighting the PCM fusion temperature as the most relevant parameter to make it effective in a given interior environment. Studies argue that the value of the melting temperature should not differ by more than 3°C relative to the average temperature of a given space.



# 3

## PCMs FOR BUILDINGS: PROPERTIES AND METHODS OF INCLUSION

### 3.1. INTRODUCTION

PCMs utilize the principle of latent heat thermal storage (LHTS) to absorb energy in large quantities when there is a surplus and releasing it when there is a deficit. Correct use of PCMs can reduce peak heating and cooling loads, i.e. reduce energy usage, and may also allow for smaller dimensions of technical equipment for heating and cooling. An added benefit is the ability to maintain a more comfortable indoor environment due to smaller temperature fluctuations [60].

Thermal energy storage with phase change materials (PCMs) offers a high thermal storage density with a moderate temperature variation, and has attracted growing attention due to its important role in achievement energy conservation in buildings with thermal comfort [30].

Various methods have been investigated by several researches to incorporate PCMs into building structures, and it has been found that with the help of PCMs the indoor temperature fluctuations can be reduced significantly whilst maintaining desirable thermal comfort.

Using latent heat storage in the buildings can meet the demand for thermal comfort and energy conservation purpose. This chapter mainly focuses on latent thermal energy storage in building applications, impregnation PCMs into conventional construction materials, current building applications and thermal performance, as an introduction to chapter 4.

### 3.2. MEASUREMENT OF THERMAL PROPERTIES OF PCMS

#### 3.2.1. INTRODUCTION

As already mentioned, the process of selecting a suitable PCM is very complicated but crucial for thermal energy storage. The potential PCM should have a suitable melting temperature, desirable heat of fusion and thermal conductivity specified by practical application.

The correct design of the building or storage system with integrated PCMs requires correct knowledge of the thermal properties of the PCMs used. The single data points that the phase change enthalpy at the melting temperature or the heat of fusion do not describe phase change materials properties with accuracy to perform dynamic simulations of a building or a compartment containing PCM [31].

Remembering, the phase change occurs in a temperature range and not at constant temperature level, and therefore specific heat capacity or enthalpy of this type of material has to be known as a function temperature.

There are many existing measurement techniques, among which differential scanning calorimetry (DSC) and differential thermal analysis (DTA) are most commonly used, nevertheless another measurement techniques will be mentioned as the T-history method.

### 3.2.2. DIFFERENTIAL SCANNING CALORIMETRY (DSC)

One of the most important properties is the enthalpy–temperature relationship,  $h(T)$ . When this relationship is determined using conventional differential scanning calorimetry (DSC) with standard methods and procedures, results for PCM are often wrong. The enthalpy values from heating/cooling are systematically shifted to higher/lower temperatures. This temperature shift originates from a temperature gradient inside the PCM and depends on the heating/cooling rate and sample mass [19].

There are different possibilities to use a DSC in thermal analysis of PCM, but the most common used are the dynamic method and the step method [11].

The most widely used scanning mode consists of heating and cooling segments at constant rates (dynamic method). A typical temperature program and corresponding signal are shown in Fig. 3.1.

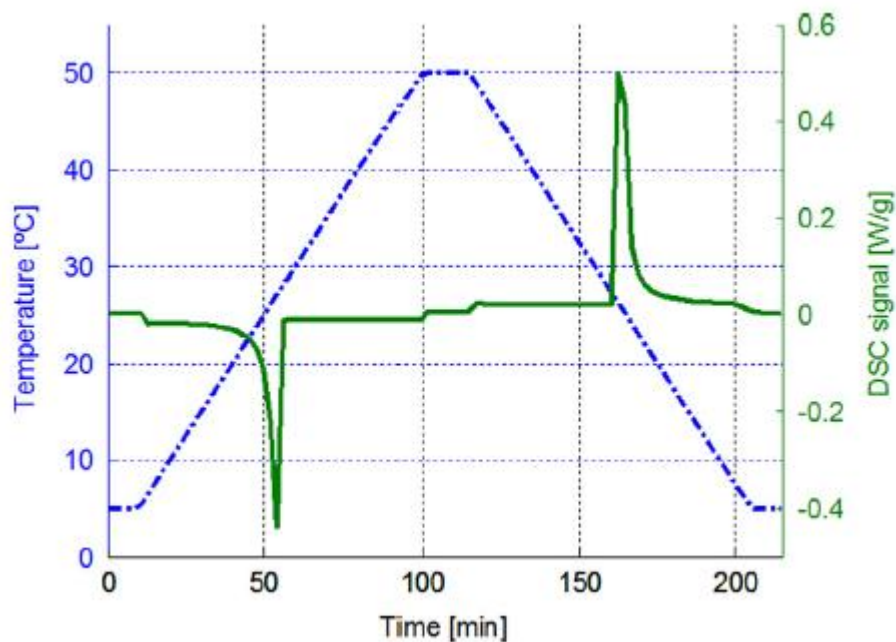


Fig. 3.1. - Typical heat flow and temperature evolution during a dynamic DSC measurement with constant heating rate [11]

So, after a graphic interpretation, the peaks indicate strong thermal effects of the sample at the corresponding temperatures.

According to Luisa F. Cabeza et al. [19], the dynamic method is commonly used for the determination of melting enthalpies. For heat storage applications, the interesting value is the sum of both latent and sensible heat.

In this case, good sensitivity also for small signals is necessary. This is accomplished using the heat flow rate calibration. For the determination of enthalpy, a dynamic program is executed three times:

- First, with the empty crucible to generate the baseline;
- Second, with a standard material (usually sapphire) in the same receptacle to generate the standard line;
- Third, with the sample in the same receptacle to generate the sample line.

From the heat flux, the specific heat as a function of temperature can be obtained with the DSC software using the baseline, the sapphire and the sample heat-flux signal and the enthalpy is determined by integration.

M. Pomianowski et al. [31] point out that measurement with different heating rates and that different sample masses gave results that differ considerably from each other and the dynamic mode is not the proper approach so instead of the dynamic mode an isothermal step mode or T-history method should be used. In the article, it is also mentioned that DSC in general is not suitable for heterogeneous materials, and the shortcomings and some sensitivity analysis of dynamic DSC measurements are discussed and presented in [32].

Another measurement routine is the step method. Here, the heating or cooling is not continuous, but small heating ramps are followed by periods in which the temperature is kept constant to allow the sample to reach thermal equilibrium. The resulting temperature program has small steps, and the signal created is a sequence of different peaks [19].

A typical temperature program and resulting signal is shown in Fig. 3.2. Different peaks indicate different amounts of heat transferred in the respective temperature interval.

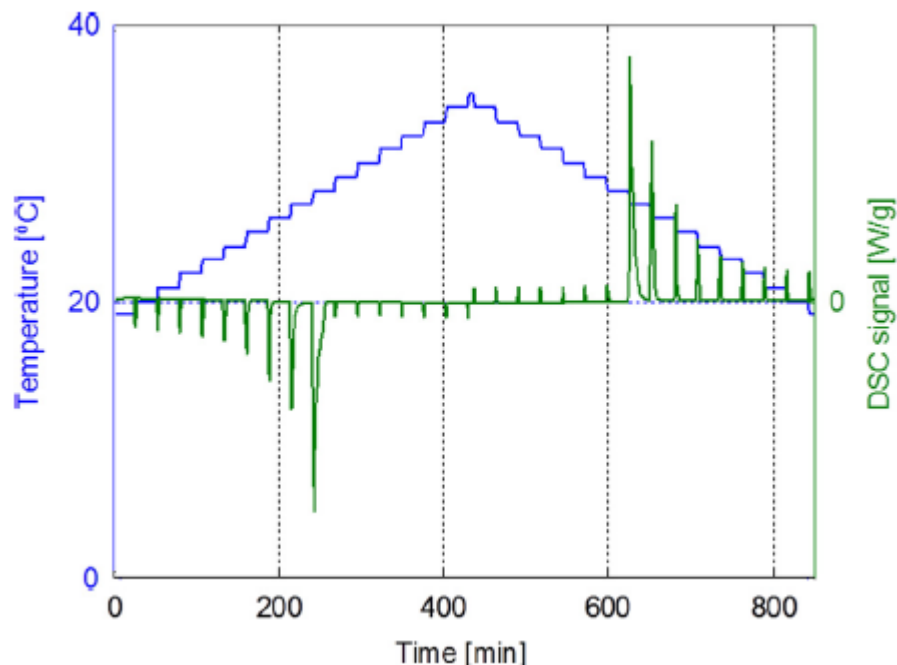


Fig. 3.2. - Typical heat flow and temperature evolution during DSC measurement with the step method, here shown for heating [11]

In the step method, the evaluation considers only peak areas and the exact shape of the baseline has no influence on the resulting enthalpy-temperature relationship.

The main limitation of DSC is the conditions the sample must accomplish: it should be small, pure, and homogeneous. This is an enormous limitation because there are many samples that cannot achieve homogeneous conditions since they are a composite materials or a mixture of different components.

G. Feng et al. [56] summarized the impact of misjudged effective capacity function on the simulated thermal storage and releasing effect of the PCM floor. It was found that for the same PCM, the detected results were significantly distinct. Repeated DSC tests were arranged to discover the influence of heating rate and sample mass on the detected PCM parameters. Errors with 33%- 883% deviation for phase transition range of PCM were discovered for the improperly arranged tests. These parameters were used in the PCM floor simulation and a maximum difference of 20% was observed for the floor surface temperature, which greatly influenced the prediction of the simulation. The research show the importance of setting standard DSC tests and ascertaining right PCM parameters in simulations related to PCM system design.

### 3.2.3. DIFFERENTIAL THERMAL ANALYSIS (DTA)

In DTA test, the heat applied to the sample and the reference remains the same (rather than the temperature in DSC test). The phase change and other thermal properties can then be tested through the temperature difference between the sample and the reference.

Technically, differential thermal analysis (DTA) is a technique which combines the ease of measurement of heating or cooling curves with the quantitative features of calorimetry. Temperature is measured continuously as for heating or cooling curve determinations, and the differential temperature measurement permits the calculation of the heat flow difference between reference and sample, which are kept in almost identical environments. Fig. 3.3. schematically shows a DTA apparatus using thermocouples for measurement [194].

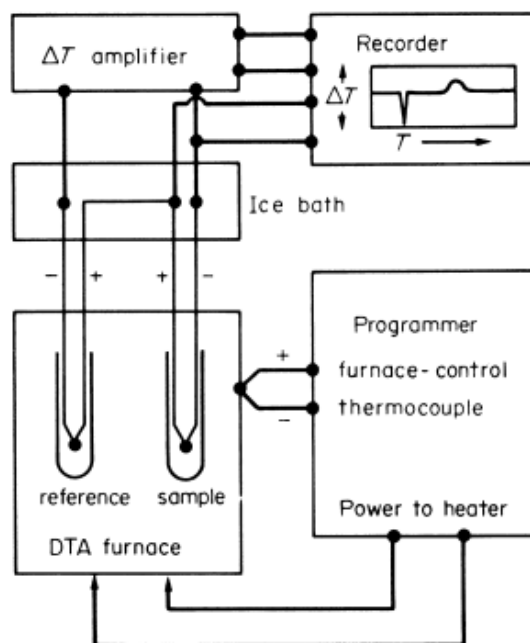


Fig. 3.3. - Schematic diagram of DTA apparatus [194]

### 3.2.4. T-HISTORY METHOD

Zhang and Jiang [22] analysed the limitations of conventional methods including conventional calorimetry, differential scanning calorimetry (DSC) and differential thermal analysis (DTA), and then put forward a new method called T-history method to determine the melting temperature, degree of supercooling, heat of fusion, specific heat and thermal conductivity of PCMs. They made the measurement of some PCMs through this method and found a desirable agreement between their test results and experimental data available in literatures. Hong et al. [23] modified T-history method by improving some improper assumptions in the method by Zhang and Jiang [22]. Peck et al. [24] also improved this measurement method by setting the test tube horizontally which can minimise the temperature difference along the longitudinal direction of the test tube to get more accurate data from T-history method.

T-history method is based on an air enclosure where temperature is constant and two samples are introduced at a different temperature from the temperature in the air enclosure. During the heating or cooling process, three temperatures are registered, that of the ambient (air enclosure), and those of the two samples. The two samples are one reference substance whose thermal properties are known (frequently water) and one PCM whose thermal properties should be determined with the results of the test.

At the University of Zaragoza (Spain), Marín et al. [15] made improvements in order to obtain enthalpy vs. temperature curves. They based their improvements on finite increments method.

Other properties can be studied like subcooling and hysteresis analysing the enthalpy–temperature curves. The set-up developed is seen in Fig. 3.4.

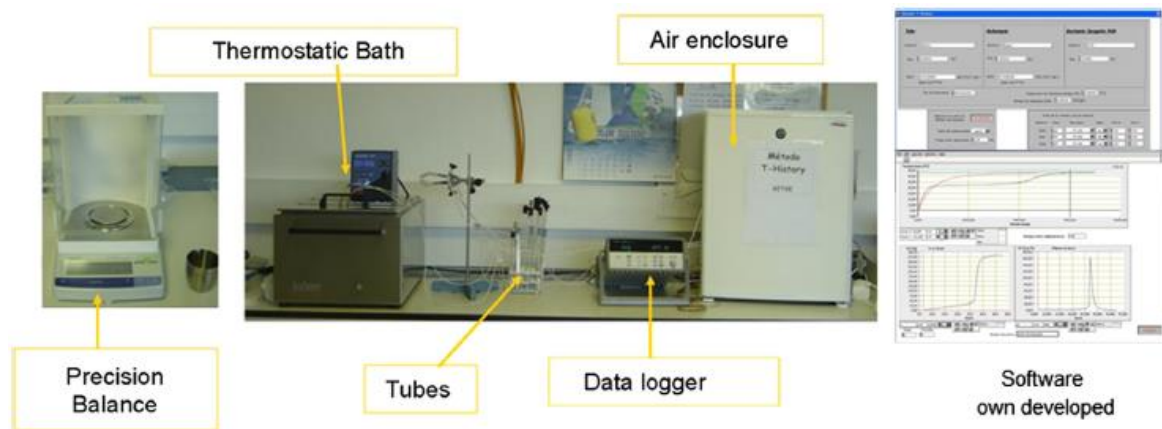


Fig. 3.4. - T-history the set-up available at the University of Zaragoza, Spain [16]

Fig. 3.5. shows an example of  $h$  vs.  $T$  curves obtained in a T-history installation. Detailed information about methodology of verification of a T-History installation proposed by University of Zaragoza in collaboration with ZAE Bayern is given by Lázaro et al.[16].

Updates of this methodology can be found in the review published by Solé et al. [18].

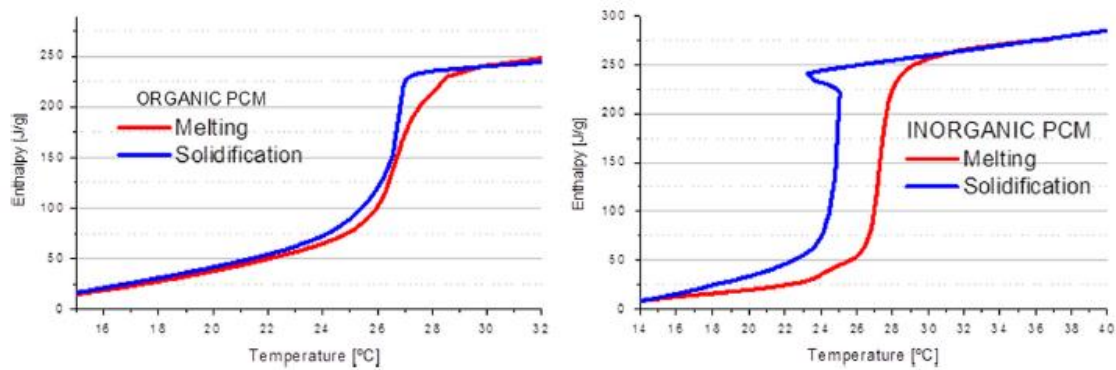


Fig. 3.5. - Enthalpy-temperature curves obtained for an organic and an inorganic PCM with the T-history method [16]

### 3.2.5. METHODS APPRAISAL

The difference between the methods differential scanning calorimetry (DSC) and differential thermal analysis (DTA) is that in the first, the energy supplied to the sample and the reference is always the same, with temperature differences between them (sample and reference) occurring whenever a reaction occurs in the sample [1].

The main advantages of the T-history method compared to differential scanning calorimetry (DSC) are [19]:

- Precision in energy and temperature measurement;
- Sample mass and heating and cooling rate similar to application;
- Other properties can be studied like subcooling and hysteresis analysing the Enthalpy vs. Temperature curves.

Although DSC with isothermal step mode and T-history methods are well-developed, they share the same shortcoming – the sample tested has to be homogeneous. In the recent publication [48], a new experimental set-up and various calculation methods to determine the specific heat capacity of inhomogeneous concrete with microencapsulated-PCM was suggested. In another publication [49], using experimental data from [48] authors go one step further and compare three different optimization algorithms to define which one is the most effective.

### 3.3. THERMAL STABILITY OF PCMS

For successful large scale application of PCMs into the building sector it is crucial that the PCM and PCM-container system can withstand cycling over an extended period of time without showing signs of degradation [60].

There are two main factors which oversee the long-term stability of PCM storage materials: Poor stability of the materials, e.g. supercooling and phase segregation, and corrosion between the PCM and the container system [77,109].

The long term stability of the PCMs is required by the practical applications of latent heat storage, and therefore there should not be major changes in thermal properties of PCMs after undergoing a great number of thermal cycles. Thermal cycling tests to check the stability of PCMs in latent heat storage systems were carried out for organics, salt hydrates and salt hydrates mixtures by many researchers [25–29]. Some potential PCMs were identified to have good stability and thermo-physical properties.



Shukla et al. [109] carried out the thermal cycling tests for some organic and inorganic PCMs selected based on thermal, chemical and kinetic criteria, developed on chapter 2, and their results showed that organic PCMs tend to have better thermal stabilities than inorganic PCMs.

Accelerated ageing tests on stearic acid and paraffin wax, both organic PCMs, have been conducted by Sharma et al. [28]. Both stearic acid and paraffin wax performed well and showed no regular degradation of their melting point over 1500 thermal cycles. However, of the fatty acids, palmitic acid and myristic acid showed to have the best long-term stability [96], which may make them more suited for building applications compared with other fatty acids.

A comprehensive review on the thermal stability of organic, inorganic and eutectic PCMs has recently been given by Rathod and Banerjee [88]. This work covers the investigations on thermal stability of PCMs done over the past few decades. Paraffins have shown good thermal stability. For fatty acids the purity plays an important role. Industrial grade fatty acids may experience changes in its thermal behaviour over time and should be tested by accelerated ageing. Of inorganic PCMs, salt hydrates are the most widely studied. Most studies have shown that the thermal stability of salt hydrates is poor due to phase separation and supercooling. However, the thermal stability may be improved to a certain extent by introducing gelled or thickened mixtures and suitable nucleating materials. In general, new building materials, components and structures should be examined by accelerated climate ageing [50], the PCMs are no exception. Furthermore, a robustness assessment may also be performed [52].

Tyagi and Buddi [51] conducted the thermal cycling test for calcium chloride hexahydrate and found minor changes in the melting temperature and heat of fusion, only about 1°C–1.5°C and 4% average variation respectively during the 1000 thermal cycles. They recommend the calcium chloride hexahydrate to be a promising PCM for applications.

### **3.4. HEAT TRANSFER ENHANCEMENT**

Most PCMs suffer from the common problem of low thermal conductivities, being around 0.2W/m.K for paraffin wax and 0.5W/m.K for hydrated salts and eutectics, which prolong the charging and discharging periods. Various techniques have been proposed to enhance the thermal conductivities of the PCMs, such as filling high-conductivity particles into PCMs [32], incorporating porous matrix materials into PCMs [33–38], inserting fibrous materials [39], as well as macro and micro encapsulating the PCMs [40,41].

Bugaje [32] reported that the phase change time is one of the most important design parameters in latent heat storage systems and found adding aluminium additives into paraffin wax can significantly reduce the phase change time in heating and cooling processes. However, this method results in weight increasing and high cost of the system. Metal foams manufactured by sintering method, have many desirable characteristics such as low density, large specific surface area, high specific strength-to-density ratio as well as high thermal conductivity. All these desirable properties offered by metal foams make them to be promising in heat transfer enhancement for PCMs.

Boomsma et al. [33] found using open-cell metal foams in compact heat exchangers generated thermal resistances twice and three times lower than the best commercially available heat exchanger tested. Thermal transport in high porosity open-cell metal foams was experimentally and numerically investigated in [34, 35], in which it is found that the effective thermal conductivity increases rapidly as temperature increases and porosity decreases.

Tian and Zhao [36] conducted a numerical and experimental investigation of heat transfer in PCMs enhanced by metal foams, and their experiment showed a significant increase of heat transfer rate.

Their numerical simulations employed two-equation non-thermal equilibrium model to account for coupled heat conduction and natural convection, and a good agreement with experimental data was achieved. They reported that metal foams suppress natural convection whilst promoting heat conduction significantly, with the overall heat transfer rate still being higher than the pure PCMs.

Py et al. [38] impregnated paraffin wax in a graphite matrix by employing capillary forces, and a high thermal conductivity and stable power output were observed. Fukai et al. [39] found carbon fibers improved the heat exchange rate during the charge and discharge processes even when the volume fractions of carbon fibers were only about 1%. Zhou et al. [42] carried out relevant experiments to compare the effects of metal foams and graphite materials on heat transfer enhancement, and the results indicate that both metal foams and expanded graphite can enhance heat transfer rate in thermal storage system, with metal foams showing a much better performance than expanded graphite.

### **3.5. INCLUSION OF PCMs INTO CONSTRUCTION MATERIALS**

#### **3.5.1. INTRODUCTION**

Various methods of PCM incorporation have been investigated in the literature. Hawes et al. [20] considered three most promising methods of PCM incorporation: direct incorporation or impregnation, immersion and encapsulation.

D. Zhou et al. [30] refer that the melting and freezing temperatures of PCMs varied slightly when being incorporated in building materials. In addition, PCM can be used in the form of a single laminated board and combined with other envelope components [33, 35].

##### **3.5.1.1. Direct incorporation or Impregnation**

It is the simplest and the most economical method in which liquid or powdered PCM are directly added to building materials such as gypsum, concrete or plaster during production. No extra equipment is required in this method but leakage and incompatible with construction materials may be the biggest problems [30].

An example of this method is a laboratory scale energy storage gypsum wallboard produced by the direct incorporation of 21%-22% commercial grade butyl stearate (BS) at the mixing stage of conventional gypsum board production [21].

The Fig. 3.6. shows H. Ferreira [68], experiment in which the concrete samples were impregnated in paraffin (RT24).



Fig. 3.6 - Impregnation of RT24 [68]

### 3.5.1.2. Immersion

In this method, the porous building material (such as gypsum board, brick, or concrete block) is dipped into the hot melted PCM, which is absorbed into the pores by capillary action (when a porous material, such as a brick or a wick, is brought into contact with a liquid, it will start absorbing the liquid at a rate which decreases over time, when considering evaporation, liquid penetration will reach a limit dependent on parameters of temperature, humidity and permeability) [78].

The porous material is removed from the liquid PCM and allowed to cool and the PCM remains in the pores of the building material [38]. The great advantage of this method is that it enables one to convert ordinary wallboard to PCM wallboard as required, since impregnation can be carried out at practically any time and place [37].

Hawes and Feldman [39] examined the mechanisms of absorption and established a means of developing and using absorption constants for PCM in concrete to achieve diffusion of the desired amount of PCM. However, as Schossig et al. [40] pointed out, leakage may be a problem over a period of many years for this method.

### 3.5.2. ENCAPSULATION

To escape the adverse effects of PCMs on the construction material, phase change materials can be encapsulated before incorporation. There are two principal means of encapsulation: macroencapsulation and microencapsulation [78].

#### 3.5.2.1. Macroencapsulation

The technology with PCMs encapsulated in a container, for example, tubes, spheres or panels, is called macroencapsulation. The RUBITHERM produces a kind of PCM panels called CSM modules which were made from aluminium with an efficient anti-corrosion coating, shown in Fig. 3.7. [44].

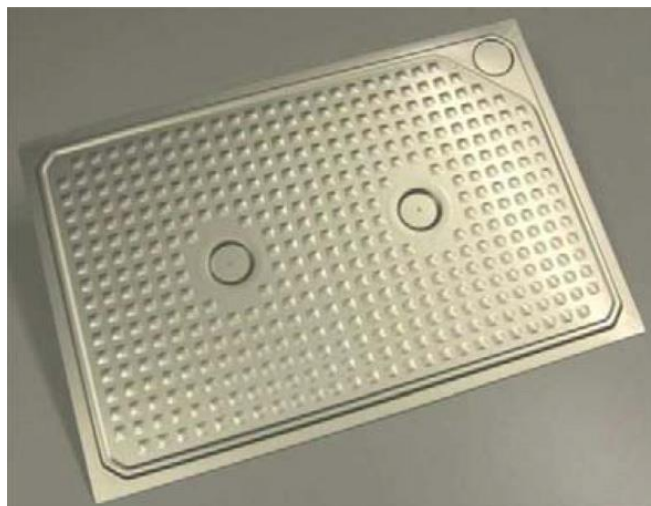


Fig. 3.7. - CSM panel containing the PCM [44]

They can fit many commercial PCMs. With macroencapsulated PCMs, the leakage problem can be avoided and the function of the construction structure can be less affected. It has the disadvantages of poor thermal conductivity, tendency of solidification at the edges and complicated integration to the building materials [78].

Via macroencapsulation, Zhang et al. [47] developed and tested a frame wall that integrated highly crystalline paraffin PCM. Results showed that the wall reduced peak heat fluxes by as much as 38%.

However, macroencapsulation has the disadvantage of needing protection from destruction and requires much more work to be integrated into the building structure, and is thus expensive.

Fig. 3.8. shows more examples of macroencapsulated PCM.



Fig. 3.8. – Macroencapsulated phase change materials (PCM) [1]

### 3.5.2.2. Microencapsulation

Nowadays, microencapsulated PCMs have been used in thermal energy storage of buildings. The Microcapsules may be spherical, continuous-walled (Fig.3.9.), or may be asymmetric, in various forms. The three states of matter (solid, liquid and gaseous) can be microencapsulated. The polymeric film serving as a microcapsule must be compatible with PCM and building materials [1].

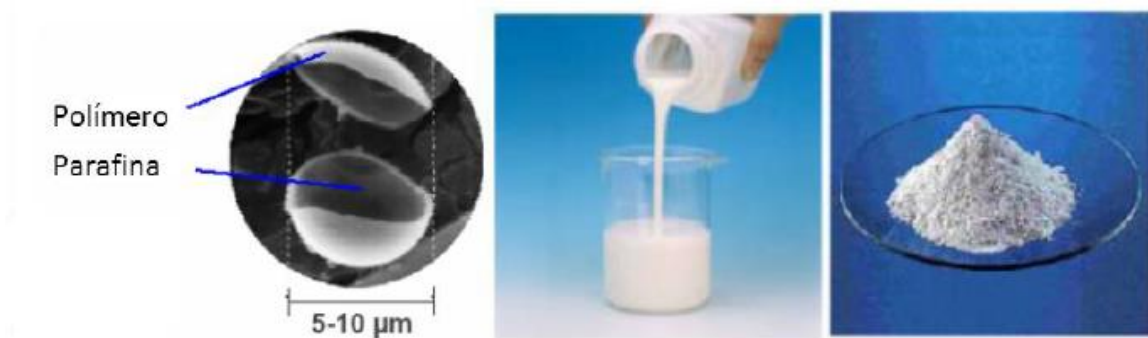


Fig. 3.9. - Microencapsulated phase change materials (PCM) [1]

Microencapsulation is a technology in which PCM particles are enclosed in a thin, sealed and high molecular weight polymeric film maintaining the shape and preventing PCM from leakage during the phase change process (Fig.3.10.). It is much easier and more economic to incorporate the microencapsulated PCMs into construction materials [78].

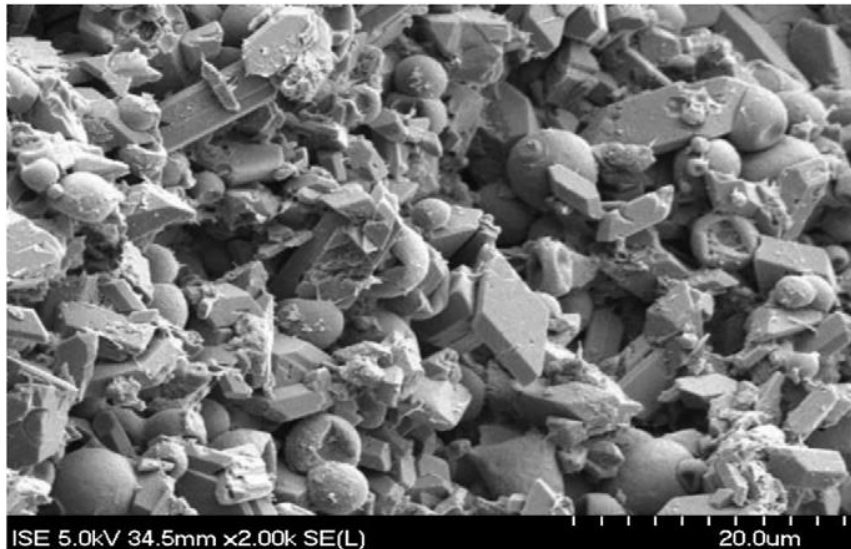


Fig. 3.10. - Image of PCM micro-capsules in gypsum plaster. The PCM micro-capsules with an average diameter of 8 $\mu$ m are homogeneously dispersed between the gypsum crystals [40]

Hawladar et al. [97] conducted thermal analyses and thermal cycle tests on microencapsulated paraffin and found that the microencapsulated paraffin still kept its geometrical profile and heat capacity after 1000 cycles. Their investigation captures the influence of different parameters on the characteristics and performance of a micro-encapsulated PCM in terms of encapsulation efficiency, and energy storage and release capacity. Results obtained from a DSC show that micro-capsules prepared either by coacervation or the spray-drying methods have a thermal energy storage/release capacity of about 145kJ/kg –240kJ/kg. Hence, micro-encapsulated paraffin wax shows a good potential as a solar-energy storage material.

Some researchers think that the microencapsulated PCMs incorporated in the buildings structures may affect the mechanical strength of the structure [89].

Cabeza et al. [46] designed two concrete cubicles with the same shape and size, one with microencapsulated PCMs called Mopcon concrete and the other one without PCMs respectively, in order to find the possibility of using microencapsulated PCMs in construction materials to achieve sizable energy conservation without significantly decreasing the mechanical strength of the concrete structures at the same time. They found Mopcon concrete reached a compressive strength over 25MPa and a tensile splitting strength over 6MPa which had already met the requirements in general structural purpose. However, the applications of microencapsulated PCMs still need further investigation in the aspect of safety, such as fire retardation capability.

Recently, National Gypsum produced a kind of wallboard panels with Mirconal PCM produced by BASF. This kind of panels is called National Gypsum ThermalCORE Panel, shown in Fig. 3.11. The melting point and latent capacity are 23°C and 22 BTU/ft<sup>2</sup>, respectively.

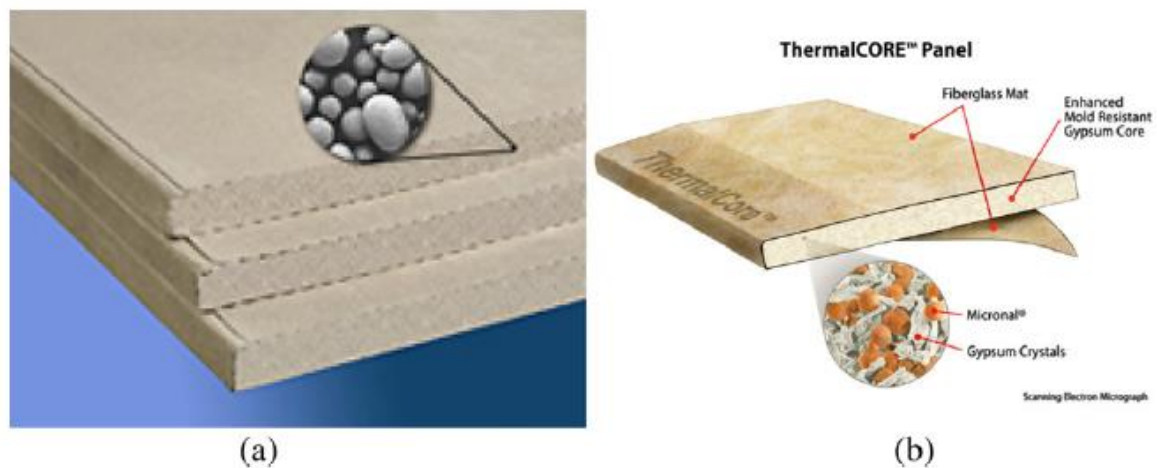


Fig. 3.11. - (a) Gypsum wall board with Micronal PCM (from BASF); (b) thermalCORE phase-change drywall (from National Gypsum) [46]

One of the most widely studied and disclosed constructive solutions are the use of micro-encapsulated PCMs in gypsum plasterboard [1]. This and other constructive solutions with PCM are developed in Chapter 4.

### 3.5.3. SHAPE-STABILISED PCMS

In recent years, a kind of novel compound PCM, the so called shape-stabilized phase change material SSPCM, (Fig. 3.12) has been attracting the interest of researchers [54, 55, 98–102]. It consists of paraffin as dispersed PCM and high-density polyethylene (HDPE) or other material as supporting material.

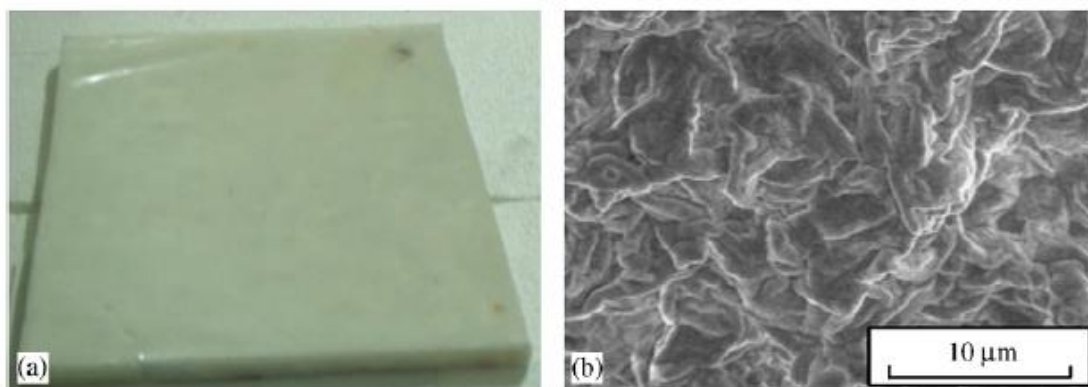


Fig. 3.12. - The photos of the shape-stabilized PCM. (a) Photo of the plate and (b) electronic microscopic picture by scanning electric microscope (SEM) HITACHI S-450 [49]

Since the mass percentage of paraffin can be as much as 80% or so, the total stored energy is comparable with that of traditional PCMs.

So, shape-stabilized PCM are attracting increasing attention due to their large apparent specific heat, suitable thermal conductivity, the ability to keep the shape of PCM stabilised in phase change process, as well as a good performance of multiple thermal cycles over a long period [98–100].

Zhang et al. [54] considered the shape-stabilised PCM, which is shown above in Fig. 3.12., and found that it can make the thermal storage system simpler as it does not need special devices or containers to encapsulate the PCM. Based on the above benefits of this shape-stabilised PCM, they also proposed its potential application in efficient buildings used as inner linings, such as inner wall, ceiling and floor. Zhou et al. [55] simulated the thermal performance of a middle direct gain room with the shape-stabilised PCM plates as inner linings and examined several influencing factors to thermal performance such as melting temperature, heat of fusion, location and board thickness of the shape-stabilised PCM. Their results indicated the PCM plates were advantageous in direct-gain passive solar houses.

#### 3.5.4. CONTAINERS

The conventional construction materials, such as gypsum board, concrete, brick and plaster, can be used to hold PCMs. Some other panels, such as PVC panels, CSM panels, plastic and aluminium foils can also be used to encapsulated PCMs. This subject is developed in chapter 4.

### 3.6. POTENTIAL PCMs FOR BUILDING APPLICATIONS

As we know, many factors influence the indoor air temperature of a building. These include climate conditions (outdoor temperature, wind velocity, solar radiation, and others), building structure and the building material's thermophysical properties (wall thickness, area ratio of window to wall, thermal conductivity and specific heat of wall material), indoor heat source, air change rate per hour and auxiliary heating/cooling installations [78].

Fig. 3.13. indicates that the difference between the indoor temperature and the comfort range determines the heating and cooling load when there is no space heating and cooling. Therefore, the heating and cooling load will decrease with decreasing this temperature difference [6].

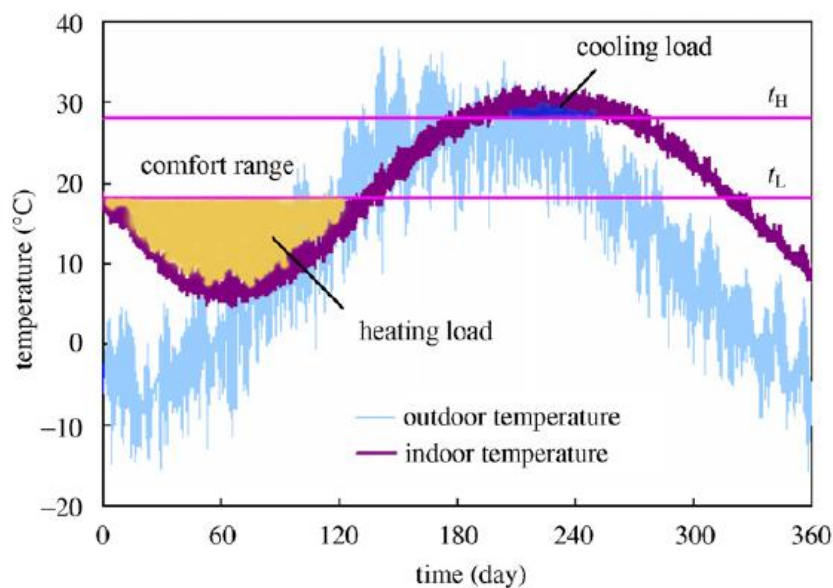


Fig. 3.13. - The indoor/outdoor air temperature and heating/cooling load [6]

For a certain building placed in a specific region, the building structure parameters such as wall thickness, area ratio of window to wall, cubage of the room, are known, however the outdoor temperature and solar energy change with the different hour and day during the entire year. Then, with a certain interior heat source, the natural room temperature (i.e., the room temperature without any active cooling or heating) depends on the material thermophysical properties (thermal conductivity,  $\lambda$ , and specific volumetric heat,  $C$  (the product of the density by the material's specific heat,  $\rho \cdot c_p$ )).

If there are certain building materials whose  $\lambda$  and  $\rho \cdot c_p$  values can make the given room meet the condition  $I_{win} = I_{sum} \approx 0$ , (being  $I_{win}$ , integrated discomfort level for indoor temperature in winter and  $I_{sum}$ , integrated discomfort level for indoor temperature in summer), we can call these materials ideal building materials. This means that the indoor temperature will be in the comfort range all year round without auxiliary heating or cooling. As an example, Fig.3.14 shows the comparison between the ideal material (in reality, it is very difficult to find this kind of material) and concrete buildings [6].

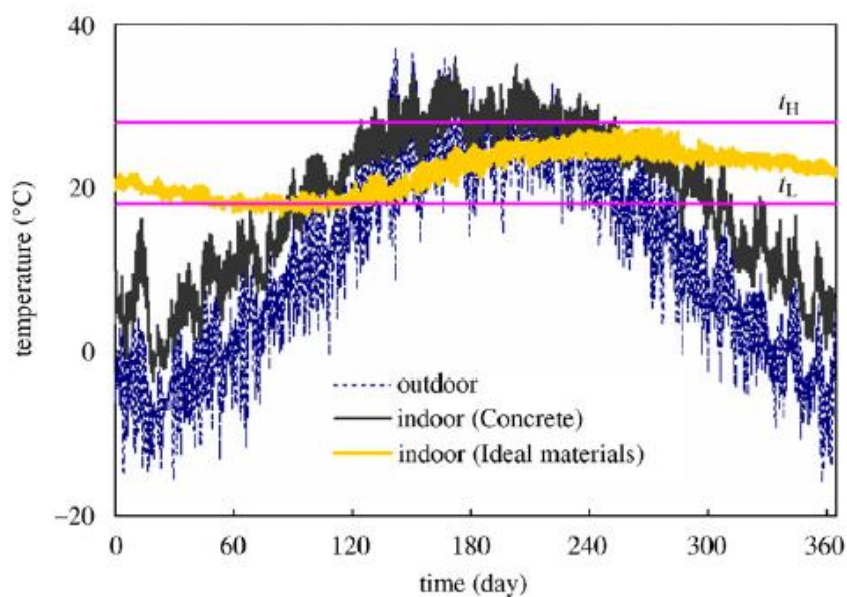


Fig. 3.14 - Indoor temperatures of a room applying concrete and ideal building materials [6]

The application of PCMs in building can have two different goals. Firstly, using natural heat, that is solar energy, for heating or night cold for cooling. Secondly, using artificial heat or cold sources. In any case, storage of heat or cold is necessary to match availability and demand with respect to time and also with respect to power. Basically, there are three different ways to heating or cooling a building. They are:

- PCMs in building walls;
- PCMs in other building components other than walls;
- PCMs in heat and cold storage units.

The first two options are passive systems, where the heat or cold stored is automatically realised when indoor or outdoor temperature rises or falls beyond the melting point. The last one is an active system, where the stored heat or cold is in containment thermally separated from the building by insulation, so the heat or cold is only used on demand not automatically. Some authors classified passive systems applications in the building envelope into two main categories, PCM “integrated” and PCM as “component”. PCM applications with active and passive systems are summarized in the synthetic diagram shown in Fig. 3.15.



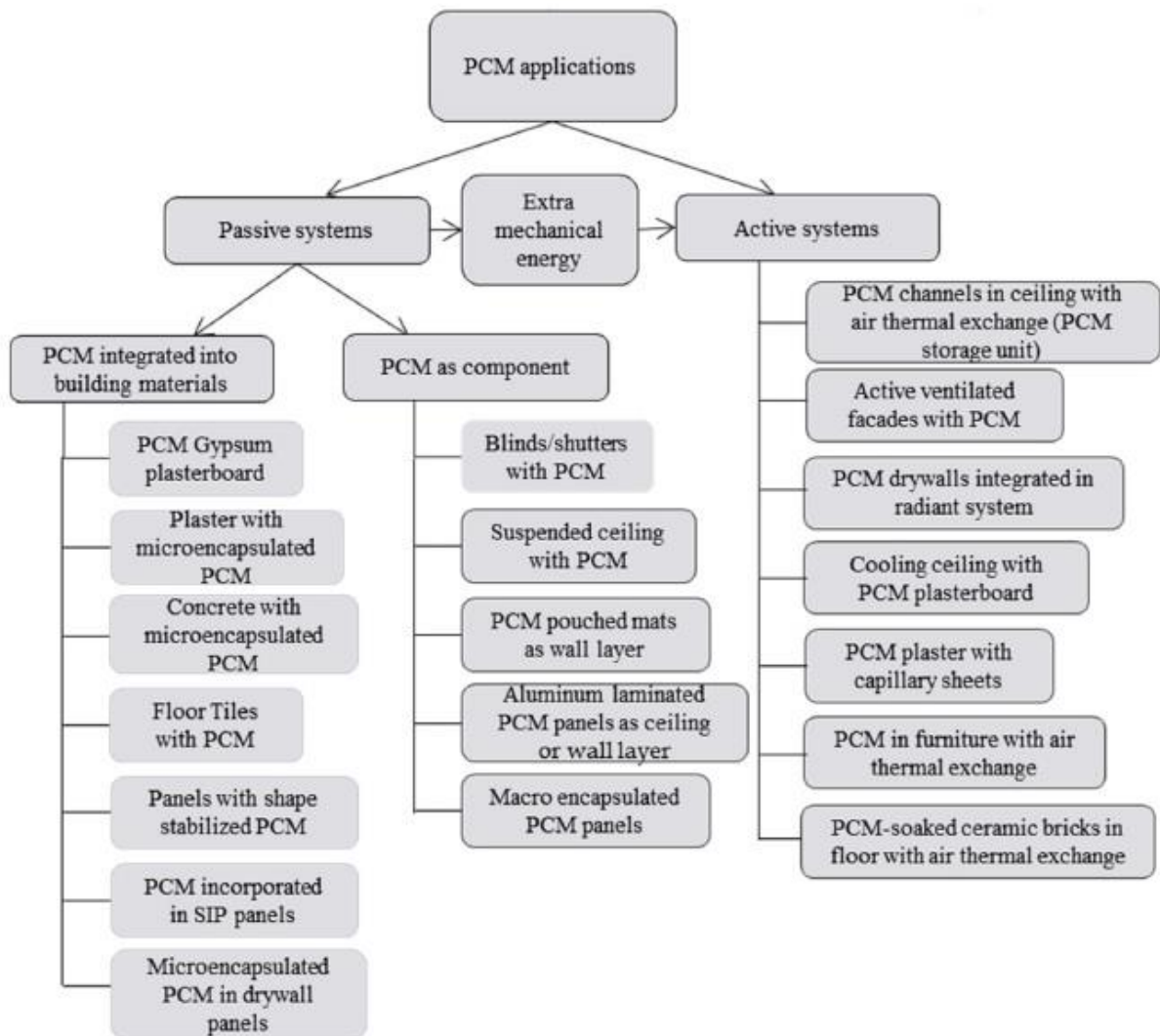


Fig. 3.15. - A synthetic diagram of PCM cooling applications, adap.[14]

The main difference between them is that component can be manufactured before the building being constructed and have a particular design. For example, blinds with integrated PCM are considered as component [7].

Moreover, Kalnæs and Jelle [60] presented many examples of integration of phase change materials for passive systems, exploring possible areas and materials where PCM can be usefully incorporated. Pomianowski et al. [31] presented various construction materials of the building (gypsum and wallboards, concrete, bricks) which were blended or combined with PCM in passive systems. Zhue et al. [8] presented an extensive list of PCM passive systems investigated experimentally with important results. Different possibilities of the use of PCM and their application in the American Solar Decathlon, including the descriptions of the systems and the factors that affect their performance, as well as results of simulations and experimentation were presented by Rodriguez-Ubinas et al. [10]. Soares et al. [9] also explored PCM application in passive systems, and investigated the effect of these systems on the energy performance of buildings. Examples of passive system applications are presented and developed in the chapter 4.

As mentioned above, PCMs incorporated in building envelopes (PCM walls, PCM roof or ceiling and PCM floor) used for passive solar heating in winter can increase thermal capacity of light building envelopes, thus reducing and delaying the peak heat load and reducing room temperature fluctuation. Several PCM applications in buildings such as passive solar heating, active heating and night cooling are shown in Fig. 3.16. [6].

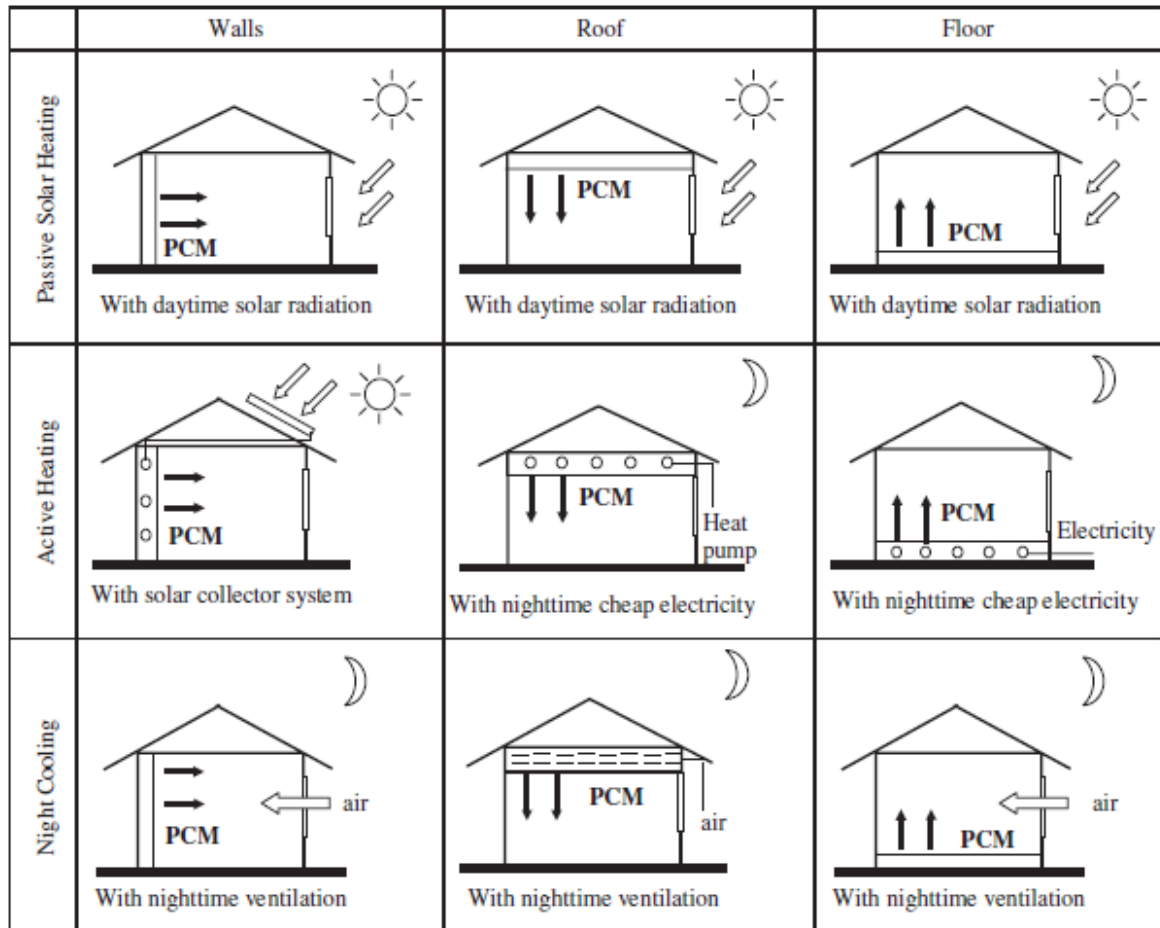


Fig. 3.16. - The forms and effects of PCM building envelope [6]

So, PCMs can provide high latent heat thermal energy storage (LHTES) density over the narrow range of temperatures typically encountered in buildings. Therefore, they are taken into account for application.

Thermal comfort can be defined by the operating temperature that varies by the time of the year. The ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) have listed suggested temperatures and air flow rates in different types of buildings and environmental circumstances. Normally, the suggested room temperature is 23.5°C–25.5°C in the summer and 21.0°C– 23.0 °C in the winter. In the building applications, the PCMs with a phase change temperature (18°C–30°C) are preferred to meet the need of thermal comfort [30].

As it is well known, inorganic PCMs, typically hydrated salts have some attractive properties such as a higher energy storage density, a higher thermal conductivity, being non-flammable, being inexpensive and readily available. However, they also have some obvious disadvantages such as being corrosive, being incompatible with some building materials and needing supporting containers. Some organic PCMs are getting more and more attention due to the avoidance of the problems inherent with

inorganic PCMs. They have little supercooling and segregation, and are compatible with and suitable for absorption in various building materials, though, they are flammable and have volume changes and low heat conductivity, which are concerns in many recent studies [20]. Eutectic or non-eutectic mixtures of organic or inorganic PCMs could be used to deliver the desired melting point required. Shape-stabilized are being applied in building envelopes due to their good thermal performance over a long period, and form stability during heat melting and solidification, which remarkably distinguishes them from common organic PCMs. Also, shape-stabilized PCMs can be easily compounded with common building materials for their shape stability and then can be manufactured into various composite building materials. Fig. 3.17 demonstrates comparative values storage capacity of building materials in the same conditions.

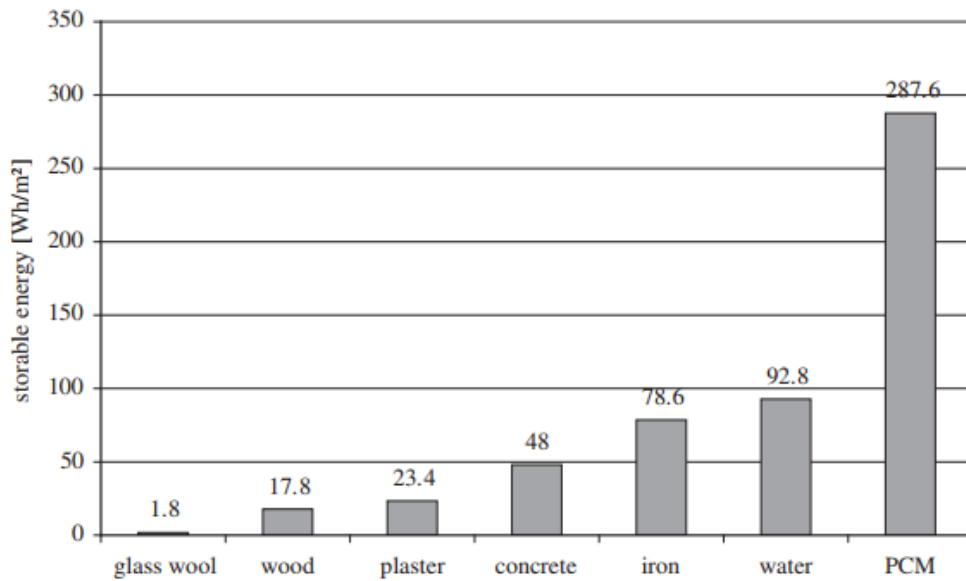


Fig. 3.17. - Comparative values storage capacity of building materials in the same conditions [75]

For a comprehensive understanding of the potential PCMs that can be applied in buildings, the suitable PCMs investigated in the literature are listed in Table 3.1. and Table 3.2.

Table 3.1. - Thermal properties of commercial PCMs

PCMs	Melting temperature (°C)	Heat of fusion (kJ/kg)	Specific heat (kJ/kg K)	Thermal conductivity (W/m K)
RT 20	22	172		
RT 25	25	147	2,90 (s)	1,02 (s)
			2,10 (l)	0,56 (l)
RT 27	26 - 28	179	1,80 (s)	0,20
			2,40 (l)	
STL 27	27	213		
Climsel C23	23	148		

Climsel C24	24	216		
S 27	27	190	1,50 (s)	0,79 (s)
			2,22 (l)	0,48 (l)
TH 29	29	188		
SP 22 A 17	22	150		0,60
SP 25 A 8	25	180	2,50	0,60
SP 29	29	157		0,60

Table 3.2. - Commercial PCMs available in the International market

PCM Name	Type of Product	Melting Point (°C)	Heat of Fusion (kJ/kg)
RT 20	Paraffin	22	172
Climsel C23	Salt hydrate	23	148
Climsel C24	Salt hydrate	24	216
RT 26	Paraffin	25	131
RT 25	Paraffin	26	232
STL 27	Salt hydrate	27	213
S27	Salt hydrate	27	207
RT 30	Paraffin	28	206
RT 27	Paraffin	28	179
TH 29	Salt hydrate	29	188
Climsel C32	Salt hydrate	32	212
RT 32	Paraffin	31	130

### 3.7. CHAPTER SYNTHESIS

With the above methods, extensive advances have been made on the thermal performance of PCM applications in buildings such as PCM walls, PCM ceiling, PCM floor with electric heating, and night ventilation etc.

When selecting PCMs, their phase change temperature should be close to the average room temperature and appropriate values should be required for latent heat and thermal conductivity. Other properties such as fire characteristics and long-term stability should also be considered for organic and inorganic PCMs, respectively. PCMs can be integrated by direct incorporation, immersion, and encapsulation or as a single laminated panel. SSPCM is a promising encapsulation method due to the

effectiveness in reducing the danger of leakage as well as its relatively low cost. Thermal analyses showed that PCM walls, floor and ceiling etc. can be effective in shifting heating and cooling load from peak electricity periods to off-peak periods, or storing solar radiation for use during sunless hours.



# 4

## PCM SOLUTIONS FOR BUILDINGS

### 4.1. INTRODUCTION

The use of phase change materials (PCM) in the buildings is a possibility to achieve the reduction of energy dependency as it allows the use of latent heat storage to increase the thermal inertia without significantly increasing the building weight.

It's was explained in the previous chapters that PCM-enhanced materials function as lightweight thermal-mass components of buildings, and contribute to reducing energy use in buildings and to the development of "net-zero-energy" buildings through their ability to reduce energy consumption for space conditioning and peak loads [4].

The use of PCM, to ensure the thermal inertia, in addition to the use of thermal insulation and shading systems, allows the reduction of the winter heat losses and summer heat gains. The use of solar gains, night cooling and off-peak electricity will reduce the evening temperature fluctuations and peak temperatures, increasing comfort conditions inside buildings. These measures will lower both annual energy consumption and the maximum power consumption, saving energy and running costs, for both heating and cooling seasons, both in residential or office buildings and have potential for application in retrofit projects [2, 4].

The phase change in the PCM takes place over a small temperature span thus large amounts of energy can be stored by small temperature change in the PCM [2]. This means that PCM will not absorb any heat from the air until it has reached the desired temperature range, thus only excess heat will be stored. PCM can be used to store or extract heat without substantial change in temperature. Hence it can be used for temperature stabilization in a building. The main advantage of PCM is that, depending on the PCM type, it can store about 3 to 4 times more heat per volume than sensible heat in solids and liquids at an approximate temperature of 20°C [5].

Between all phase change materials possible applications in buildings, the most interesting is its incorporation in construction materials altering their materials thermal properties. The PCM may be used for thermal storage of passive solar heating being integrated in the floor, walls or ceilings, as well as being an integrating part of the most complex energetic system, such as heat pumps and solar panels [78].

When selecting a PCM, the average room temperature should be close to the melting/freezing range of the material. Moreover, the day temperature and solar radiations fluctuations should allow the material phase change. Then many factors influence the choice of the PCM: weather, building structure and thermophysical properties [12].

That's why experiments must be carried out to effectively assess the use of PCM. This is one of many examples given in this chapter. Scalat et al. [13] conducted a full-scale thermal storage tests in a room lined with PCM (Emerest 2326) wallboard and the results show its efficient function as a thermal storage medium, the human comfort can be maintained for longer periods using PCM wallboard, after the heating or cooling system was stopped.

In this chapter we will summarize current building applications and their performance analyses always with references to different authors. These are the PCM building applications:

- Gypsum board and interior plaster products;
- Ceramic floor tiles;
- Concrete elements (walls and pavements);
- Trombe walls;
- Windows;
- Concrete or brick;
- Underfloor heating;
- Ceilings;
- Thermal insulation materials;
- Furniture and indoor appliances.

#### **4.2. GYPSUM BOARD AND INTERIOR PLASTER PRODUCTS**

Through the last years, various researchers have studied and developed a vast variety of this type of materials. The main purpose of integrating PCM into lightweight construction materials is to increase their thermal mass. As a result, such products could be used to decrease temperature fluctuations in existing and renovated buildings as well new lightweight buildings.

PCM has been successfully incorporated into wall materials such as gypsum wallboard and concrete to enhance the thermal energy storage capacity of buildings with particular interest in passive solar applications, peak load shifting [78]. It's also the most studied, general and suitable solution for implementing PCM into buildings. Fig. 4.1. shows PCM gypsum board.



Fig. 4.1. PCM enhanced gypsum board [14]



The wallboards are cheap and widely used in a variety of applications, making them very suitable for PCM encapsulation. However, the principles of latent heat storage can be applied to any appropriate building materials. Kedl and Stovall [17] and Salyer and Sircar [36] used paraffin wax impregnated wallboard for passive solar application. The immersion process for filling the wallboards with wax was successfully scaled up from small samples to full size sheets. Processes where by this PCM could be incorporated into plasterboard either by post-manufacturing imbibing of liquid PCM into the pore space of the plasterboard or by addition in the wet stage of plasterboard manufacture were successfully demonstrated [7].

Peippo et al. [202] were one of the first to discuss the use of PCM walls for short-term heat storage in direct-gain passive solar applications. The PCM considered was fatty acid. Approximate formulae were presented for optimum phase change temperature and thickness of the PCM wall. And direct energy savings of 5%–20% were expected.

In Feldman et al.'s [21] experiment, a tenfold increase of energy storing capability was obtained by the direct incorporation of 21%–22% commercial grade butyl stearate (BS) at the mixing stage of conventional gypsum board production. Feldman et al. [21, 66, 67] carried out extensive research on the use and stability of organic compounds for latent heat storage, including fatty acids (capric, lauric, palmitic and stearic), butyl stearate, dodecanol and polyethylene glycol 600. In addition to the studies of their properties, research was also carried out on materials, which act as PCM absorbers.

Shapiro et al. [90] investigated methods for impregnating gypsum wallboard and other architectural materials with PCM. Different types of PCMs and their characteristics were described. The manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which were impregnated with PCMs. Shapiro [91], showed several PCMs to be suitable for introduction into gypsum wallboard with possible thermal storage applications for the Florida climate. These materials were mixtures of methyl-esters namely: methyl palmitate, methyl stearate and mixtures of short chain fatty acids (capric and lauric acids). Although these materials had relatively high latent heat capacity, the temperature ranges required in achieving the thermal storage did not fall sufficiently within the range of comfort for buildings in hot climates.

Various materials were considered, including different types of concrete and gypsum. The utilization of latent heat storage over a comfortable indoor temperature range in buildings can result in an increase in the thermal storage capacity in the range of 10%–130%. The PCM gypsum board was made by soaking conventional gypsum board in liquid butyl stearate, a PCM with phase change range of 16°C–20.8°C. The PCM gypsum board contained about 25% by weight proportion of butyl stearate. Its thermal properties were measured with a differential scanning calorimeter (DSC). In another study, investigation of the thermal performance and estimation of the benefits from the application of PCM gypsum board in passive solar buildings in terms of the reduction of room overheating and energy savings was done by Hawes et al. [20].

During the 1980s, several forms of bulk encapsulated PCM were marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial PCM products was inadequate to deliver heat to the building passively after the PCM was melted by direct solar radiation. In contrast, the walls and ceilings of building offer large areas for passive heat transfer [7]. Neeper [41] in his study concluded that gypsum wallboard impregnated with PCM could be installed in place of ordinary wallboard during new construction or rehabilitation of a building, thereby adding the regarding thermal storage for passive solar heating as well as creating opportunity for ventilate cooling and time-shifting of mechanical cooling loads. Little or no additional cost would be suffered for installation of PCM wallboard in place of ordinary wallboard.

Neeper [42] found that the thermal storage provided by PCM wallboard would be sufficient to enable a large solar heating fraction with direct gain. Neeper [43] examined the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes as PCMs subjected to the diurnal variation of room temperature but not directly illuminated by the sun. He found that the diurnal storage achieved in practice may be limited to the range  $300 \text{ kJ/m}^2$ – $400 \text{ kJ/m}^2$ , even if the wallboard has a greater latent capacity. A wide phase transition range would provide less than optimal storage, but would be consistent with application of the same PCM to either interior partitions or to the envelope of the building. The melting temperatures of these PCMs were adjusted by using mixture of ingredients. He examined three parameters of PCMs wall boards that may influence the energy that can be passively absorbed and released during a daily cycle: (a) the melt temperature of the PCM; (b) the temperature range over which melt occurs; and (c) the latent capacity per unit area of wall board.

Heim and Clarke [59] conducted numerical simulations for a multi-zone, highly glazed and naturally ventilated passive solar building. PCM-impregnated gypsum plasterboard was used as an internal room lining. The results show that solar energy stored in the PCM–gypsum panels can reduce the heating energy demand by up to 90% at times during the heating season.

Several authors investigated methods for impregnating gypsum and other PCMs [45, 53, 57, 58, 82–86]. Limited analytical studies of PCM wallboard have been conducted, but few general rules pertaining to the thermal dynamics of PCM wallboard are available [7]. It was documented that in gypsum materials can be combined up to 45% by weight of PCM when reinforcing the structure with some additives and up to 60% by weight in wall board composites.

Voelker et al. [69] have developed the gypsum board with integrated microencapsulated PCM, mineral aggregates and have added some admixtures to improve working properties of the board. The incorporated PCM had a melting range between  $25^\circ\text{C}$  and  $28^\circ\text{C}$ . The sensible and latent heat of the material was measured with differential scanning calorimetry (DSC) with a constant heat and cooling rate of  $2\text{K/min}$ . The thermal conductivity of PCM-modified gypsum was determined with use of a laser flash instrument.

The developed PCM boards were tested in the special light weight chambers. The two identical test chambers were built next to each other (Fig. 4.2.), and in the first one, walls were covered with PCM plaster boards and in the second one with ordinary plaster boards. The thickness of the gypsum board was varied between 1cm and 3cm. The test series were carried out under controlled variable conditions. It was discovered that during warm days a reduction of the peak temperature of about 3K in comparison to the room without PCM could be achieved. On the other hand, temperature in the test chamber was allowed to fluctuate from very low to very high temperatures (approximately  $14^\circ\text{C}$ – $35^\circ\text{C}$ ). In real building conditions, such high temperature amplitude would not be acceptable and therefore also utilization of the latent heat of PCM in the gypsum boards would be decreased. Additionally, authors do not elaborate on obtained PCM to gypsum ratio in the developed gypsum boards.

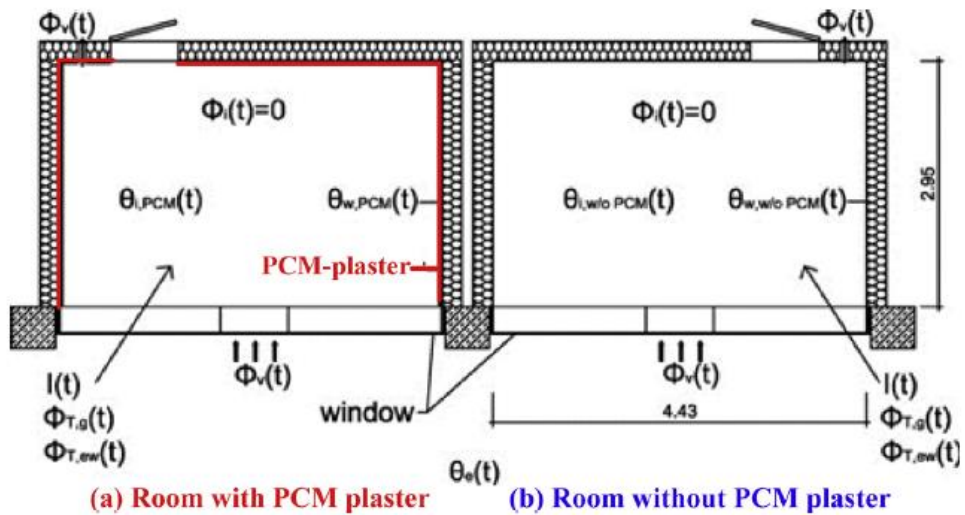


Fig. 4.2. Test rooms without PCM plasterboard [69]

Kuznik et al. [74] investigated a renovation project in the south of Lyon-France using PCM wallboards. By testing a room in the same building that was renovated without PCM and then comparing it to the room with PCM, they concluded that the PCM increased the indoor thermal comfort, but it appeared unable to use its latent heat storage capacity for a number of durations due to the incomplete discharge overnight.

The week-end of March 28th/29th is a very interesting example from a storage analysis point of view. The Fig. 4.3. shows the weekend of March 28th/29th for which the temperature of the rooms rises to about 40°C. In such conditions, the PCM is completely in the liquid phase and there is no latent storage effect in the wallboard: the two rooms have very close air temperature evolutions.

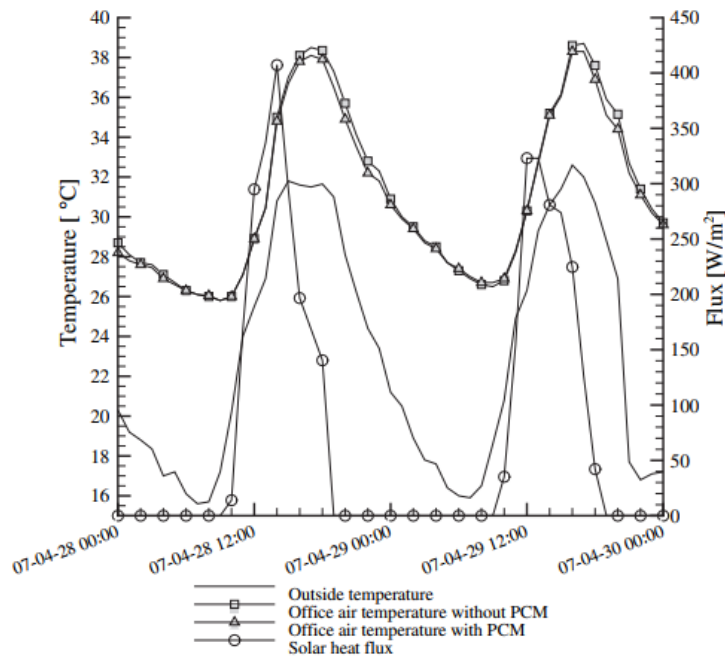


Fig. 4.3. Week-end of March 28th/29th 2007. Outside and offices air temperatures [74]

Kuznik et al. [75], experimental tests on composite PCM product ENERGAIN® from Dupont de Nemours Society that contained 60% of microencapsulated paraffin (Fig. 4.4.) and the rest was copolymer can be found. The thermal conductivity has been measured using a guarded hotplate apparatus and in the liquid state it was at 0.22W/(m.K) and in the solid at 0.18W/(m.K). The enthalpy of the composite PCM has been measured using DSC method at heating cooling rate of 0.05K/min. Melting peak temperature was obtained at 22.2°C and freezing peak at 17.8°C. Composite boards were tested in the specially designed full scale test room MINIBAT. The test room was equipped with thermal guard surrounding room where the temperature was stabilized at certain temperature of 20.5°C. The test cell was also equipped with a solar simulator located in the climatic chamber that was attached to the test chamber to simulate external thermal condition. The climatic chamber was separated from the test room with a glass. The temperature inside the climatic chamber could vary between -10°C and 40°C and could be dynamically controlled so that any temperature evolution can be generated. In the investigation, three types of test were conducted:

- A summer day: temperature in the climatic chamber varied between 15°C and 30°C, there was night cooling to improve PCM storage/release effect;
- A mid-season day: temperature in the climatic chamber varied between 10°C and 18°C;
- A winter day: temperature in the climatic chamber varied between 5°C and 15°C, heating system in the test room was turned on when temperature in the room dropped below 20°C.

For all tested cases, the solar flux is preserved as the same. The experiment was conducted in a comparative manner for the test room with PCM and without PCM boards on the walls. Based on the results obtained, authors concluded that PCM composite is an interesting solution for the building application to enhance the human thermal comfort due to three reasons:

- The PCM included in the walls reduced the overheating effect and energy stored was released to the room when temperature was minimum;
- The wall surface temperature peaks were flattened;
- The stratification of air temperature in the room with PCM was not observed as it was for room without PCM.

Still the allowed temperature fluctuations for the tests were very high. For example, for a summer day the air temperature was allowed to fluctuate between approximately 19°C and 32°C for the room without PCM and from 19°C to 29°C for the room with PCM. Based on that, it can be concluded that if the test rooms were equipped with some additional measures to reduce temperature fluctuations, for example solar shadings, the utilization of PCM in the room would be smaller and also the improvement with regards to the room without PCM would drop.

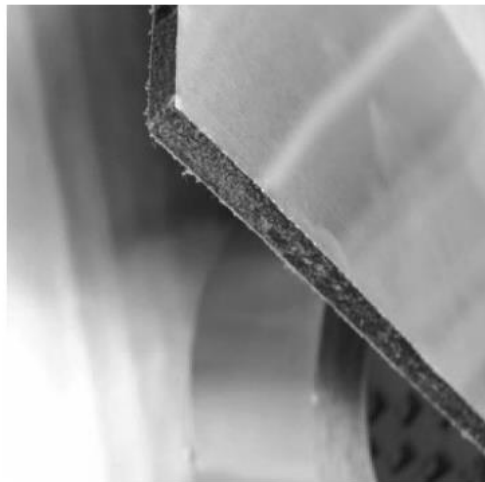


Fig. 4.4. Dupont de Nemours PCM composite wallboard [75]

Athienitis et al. [76] performed an experimental and numerical simulation study in a full-scale outdoor test room with PCM gypsum board as inside wall lining. The PCM gypsum board used contained about 25% by weight proportion of butyl stearate (BS). An explicit finite difference model was developed to simulate the transient heat transfer process in the walls. It was shown that utilization of the PCM gypsum board may reduce the maximum room temperature by about 4°C during the day and can reduce the heating load at night significantly.

In P. Schossig et al. [40], measurements of a full-size room equipped with microencapsulated-PCM plaster boards are presented. Prior to the full scale measurements, some small scale experiments with specially designed plate apparatus to test wall samples have been conducted. A small sample of 50cm×50cm area was pressed between two copper plates, which can be heated and cooled independently. The thermal performance of the wall samples with PCM was tested for the constant heat flux on both sides of the sample and temperature in the middle of the sample was registered. It was discovered that for the samples with PCM temperature instead of rising linearly begins to deflect within PCM melting temperature range. Consecutively, the full scale measurements have been conducted in the specially built light weight test rooms. One room was equipped with the ordinary reference plaster and the other with the PCM plaster. Both rooms were facing south. In the article, it was not written how much of internal area was covered with gypsum and where the plaster boards were located. Within the project, two different PCM products were tested: dispersion based plaster with 40% weight PCM and 6mm thickness and gypsum plaster with 20% weight PCM and 15mm thickness. The experimental study indicated that PCM gypsum helped to decrease high and low temperature peaks. Over period of 3 weeks, the reference room was warmer than 28°C for about 50h while the PCM room was only 5h above 28°C. Authors pointed out that microencapsulated PCM has the advantage of easy application and there is no danger of leakage like with macroencapsulated PCM.

Gypsum products as construction materials can be improved by improving their physical, mechanical, thermal, and sound insulation properties. Su-Gwang Jeong et al. [61] conducted a study manufactured heat storage gypsum board which contains two types of shape-stabilized phase change materials (SSPCMs). Each type of SSPCM has different phase change temperatures for targeting the heating and cooling seasons. Paraffinic organic PCM based shape-stabilized phase change materials (SSPCM) and fatty acid based SSPCM were prepared by using exfoliated graphite nanoplatelets (xGnP) to solve the leakage problem, retaining their efficient thermal storage quantity, and improving the thermal conductivity.

The two types of shape-stabilized phase change materials (SSPCM) composites (Hybrid SSPCM) were incorporated to make heat storage gypsum board. The hybrid SSPCM was manufactured for reducing heating and cooling load in severe season such as winter and summer by two types of PCMs with different phase change temperature.

In this experiment, the maximum mix ratio of SSPCM was considered as 30wt% in the light of workability and banding strength of heat-storage gypsum board. All samples were made with a composition of gypsum and 10wt%, 20wt%, and 30wt% of hybrid SSPCM, in comparison with the gypsum powder weight. For the preparation of hybrid SSPCM gypsum board, the water ratio at 45% was selected, in comparison with gypsum powder. The prepared hybrid SSPCM has a board shape of 100mm x 100mm x 20mm (length x width x height). The morphology and heat storage concept of prepared hybrid SSPCM gypsum boards are shown in Fig. 4.5.

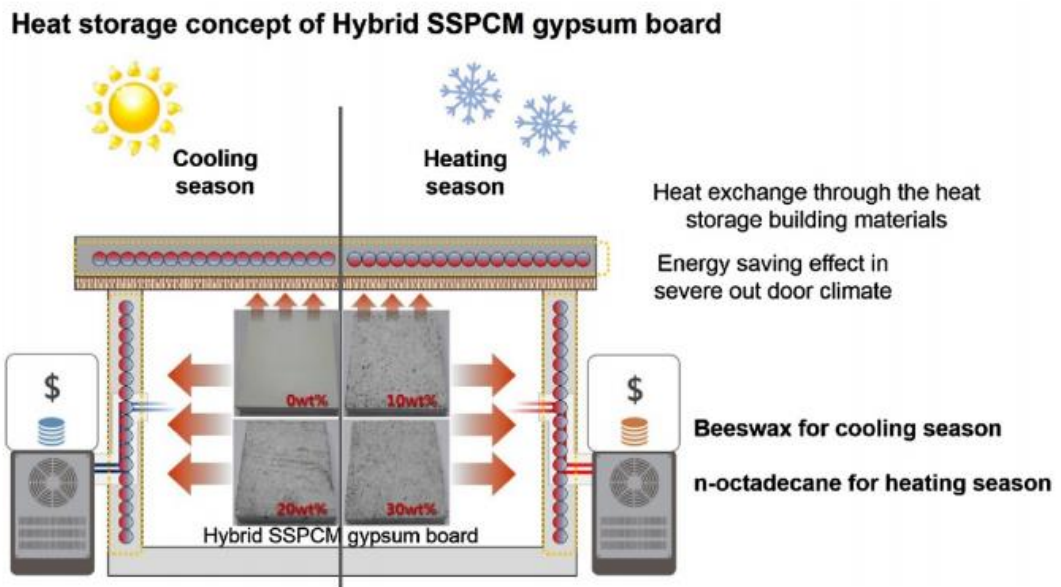


Fig. 4.5. Heat storage concept of hybrid SSPCM gypsum board [61]

Bharat Chhugani et al. [80], investigated the effectiveness of PCM wallboards in lightweight buildings. The investigations have been carried out on two different types of PCM wallboards, the Knauf Comfortboard-23 and DuPont Energain board (Fig. 4.6.).

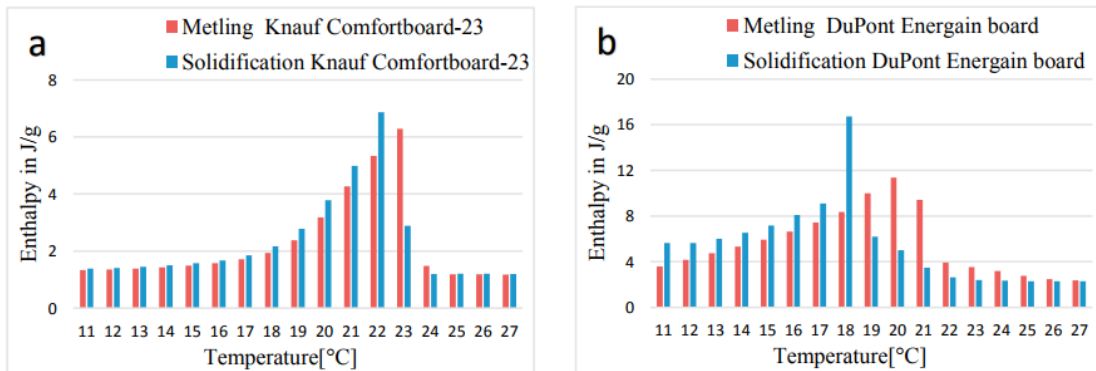


Fig. 4.6. Enthalpy-temperature graph (a) Knauf Comfortboard-23; (b) DuPont Energain board

The experimental results showed that PCM wallboards can provide passive cooling powers of around  $8\text{W/m}^2$  under typical office room conditions. The experiments proved that PCM wallboards can almost store twice as much heat compared to conventional gypsum boards and can provide a passive cooling power which is comparable to a concrete wall with a thickness of 15cm. However, the regeneration behavior of PCM wallboards plays a major role in its efficiency. The results reveal that Knauf Comfortboard-23 shows a better regeneration behavior than the DuPont Energain board. Still, the average regeneration rate of the Comfortboards-23 during the summer months in the offices of the Energy Efficiency Center was found to be below 20%. The regeneration of the DuPont Energain board was nearly impossible being 1% in average.

### 4.3. CERAMIC FLOOR TILES

Ceramic tiles are an extensively used material for paving, yet the incorporation of PCMs into ceramic tiles has been rather neglected, as observed by Pomianowski et al. [31], in their review.

Cerón et al. [87] reported the production, development and experimental method, to test its performance, of a prototype tile. Nonetheless, the design of the tile was rather complex requiring numerous layers (top stoneware tile, metal sheet, a metal container with PCM and a bottom thermal insulation layer). The developed tiles were tested over a period of 60 days in one side of the solar house placed in Madrid that had door-window toward south. It was observed, that high effectiveness was achieved for tiles close to the door-window where the direct solar radiation hit the tiles. The contribution of the tiles in the deeper location, further from the window, was very small. Therefore, the key conclusion was that the scheme should be limited to the portion of the floor that can receive the direct solar radiation. It has been considered essential to make a new prototype of tile that could be placed directly on the framework (Fig. 4.7.) and not on a technical floor, since this is a more usual and cheaper solution for housing. It was also considered necessary to develop the system in such a way that it met the acoustic requirements demanded by the Technical Building Code in Spain (CTE) [87].

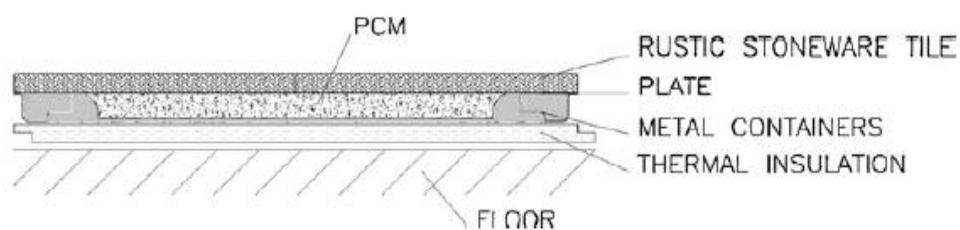


Fig. 4.7. Cross-section of the prototype [87]

Temperature were measured continuously on the surfaces of the tiles with PCM and without PCM, subjected to the same physical conditions (Fig. 4.8.).

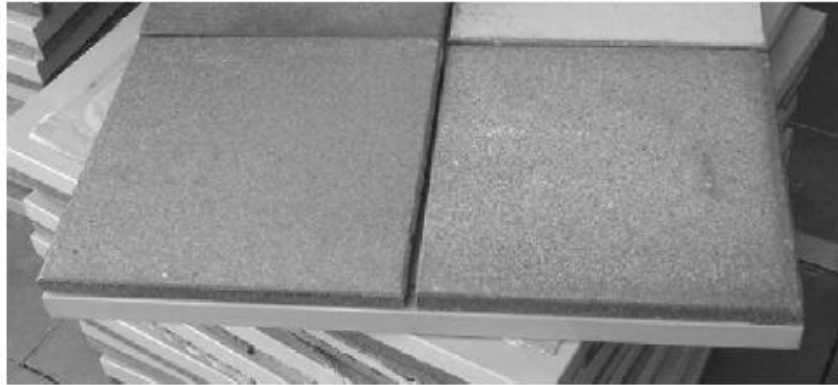


Fig. 4.8. Image of the prototype [87]

The frame of the window casts a shadow on the tiles during the day (Fig. 4.9.). The effect of this shadow can be seen in Fig. 4.10., as discontinuities of the curves at two positions during the thermal storage period. The shadows on the tile with PCM significantly alter the thermal behaviour of the pavement, by reducing their efficiency in solar energy storage. In order to get a high efficiency in the process of thermal storage it is important to avoid obstacles that cause significant shadows on the pavement that contains PCM. The shadows caused by the aluminium frame of the window, results in a decrease of the surface temperature of the tile down to 6°C over a period of one hour, with solar radiation 1000W/m<sup>2</sup>, and this reduces the amount of energy accumulated in that period [87].



Fig. 4.9. Monitoring of the prototypes [87]



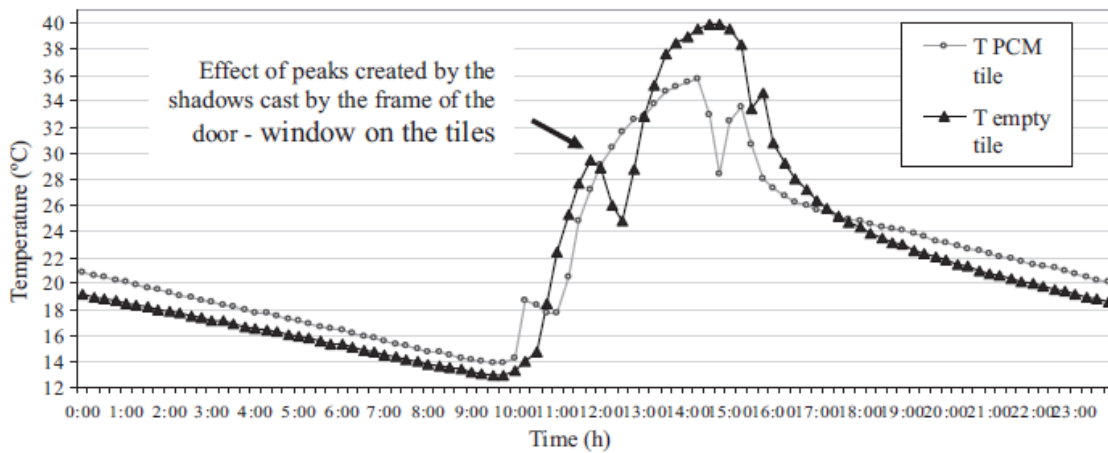


Fig. 4.10. Surface temperature of the tiles with PCM and without PCM. Direct solar radiation. Magic Box 2009 [87]

Hittle et al. [93] wrote an assignment which proposal consists in substituting microencapsulated phase change material for much, if not all of the quartz powder to make it. He also was able to replace some of the chips without degrading the tile appearance. The tile with PCM it was named here in after. Putting phase change material in the floor tile dramatically increases its ability to store thermal energy. Also, the energy is stored at a nearly constant temperature. One application is the use of the tile in sunroom floors where it can absorb solar energy during the day and release it at night to reduce mechanical heating. Because agglomerate floor tiles have exceptional wear resistance properties, they are often marketed to institutional clients that have high traffic areas. He came to the conclusion that these tiles have structural properties that are not quite as good as agglomerate tiles without PCMs, but are significantly better than fired clay tiles often used in residential applications. Each prototype tile contains quartz chips and powder, polyester resin and encapsulated paraffin wax. Tiles were made with varying amounts of quartz powder, encapsulated wax and resin. The amount of quartz chips will be held constant to ensure structural integrity of the tile. Resin will be varied from 5% to 10% of the total mixture. Proportions of encapsulated wax and quartz powder will be directly dependent on each other. The ideal case would be a tile containing all phase change material and no quartz powder.

One of the standard agglomerate floor tiles manufactured today consists of quart chips, quartz powder (filler), dyes, and a polyester binder. Components are mixed in a giant cement mixer. The mix, appearing and feeling much like damp sand, is placed in a vibrating vacuum assembly to remove all air and to compress the material. Next, the portions of material are heated to cause catalysis. Later, pieces are cut and polished to produce the desired tiles (Fig. 4.11.).

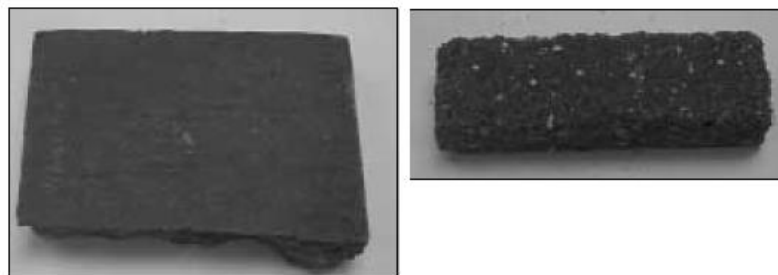


Fig. 4.11. Sample tile with phase change material incorporated without and with visible clumps [93]

In a very intricate paper the production of novel PCM-ceramic tiles for indoor temperature control was described and developed by Rui M. Novais et al. [92]. The PCM was directly incorporated into lightweight porcelain stoneware ceramic tiles, without the need for other materials or containers. The incorporation of PCM in ceramic tiles increases buildings' thermal inertia, and reduces the indoor space temperature variation by up to 22%. The tiles combine a dense top-layer with a porous bottom-layer. The novelty of this investigation is the development of ceramic tiles with a PCM that was directly included on the porous layer of the lightweight porcelain stoneware tiles. Wood wastes (sawdust) were used as a pore forming agent, which is an environmental friendly approach. The density of these novel ceramic tiles (below  $2\text{g/cm}^3$ ) allows their use not only in the floor, but also as wall coverings, which increases the surface area inside the buildings and, therefore, the energy savings.

Fig. 4.12. illustrates the procedure for impregnating the bi-layered ceramic tiles with PCM. Initially, a beaker containing PCM was placed inside an electric oven, which was connected with a vacuum pump.

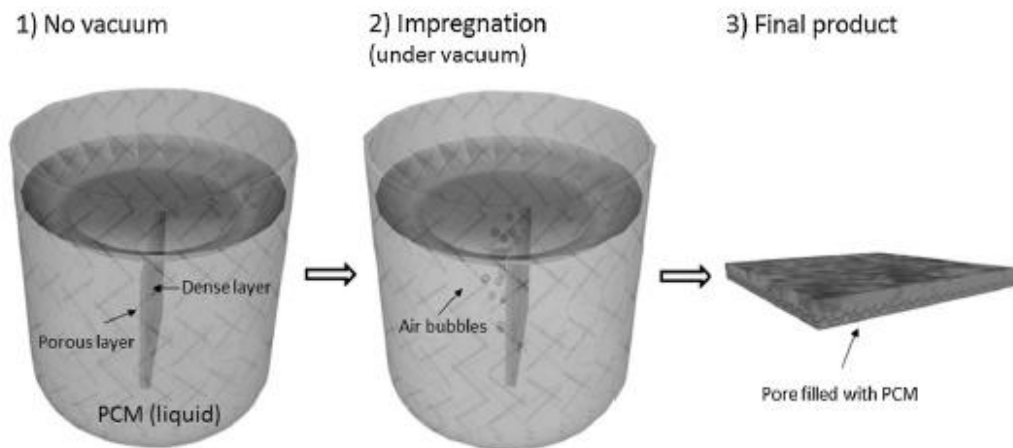


Fig. 4.12. Schematic drawing of the PCM impregnation process [92]

An IR camera was used to record the temperature evolution on the upper side of the tile. Fig. 4.13. shows the surface thermal map for the two samples measured upon heating. Differences are in agreement with the temperature evolution recorded by the four thermocouples.

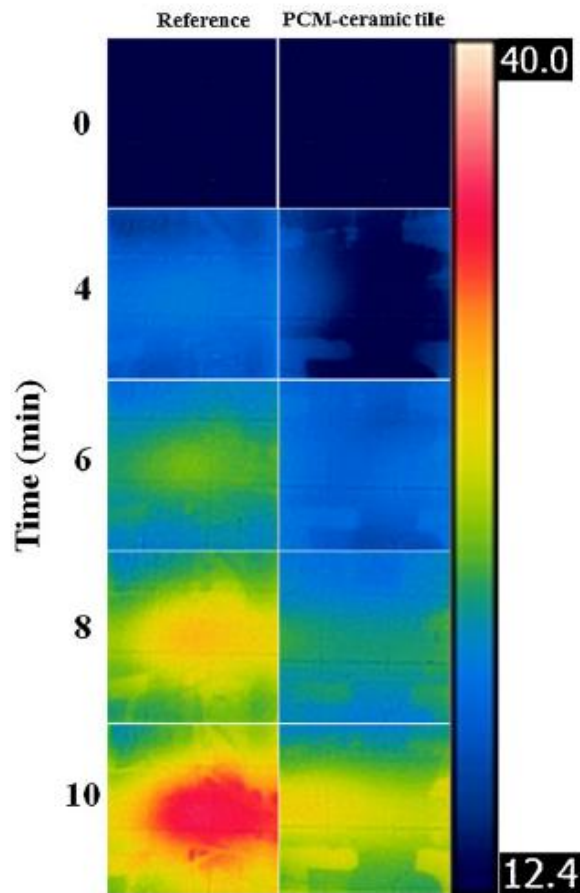


Fig. 4.13. Thermal map for the upper surface of tiles without PCM (left column) and with 8.1wt% PCM, when the bottom surface is heated in a hot plate during the same period of time [92]

Two major factors control the PCM-ceramic tiles thermal performance: (i) PCM load and (ii) PCM-ceramic tile thermal conductivity. Higher PCM content induces narrower temperature fluctuations, yet reduces the PCM-ceramic tile thermal conductivity. The incorporation of 5.4wt% PCM was found to be the optimal content, which is a rather small amount in comparison with other PCM-building materials.

Fig. 4.14. illustrate the temperature evolution inside the test cells and the temperature differential between the 0% PCM and 5.4wt% PCM-ceramic tiles test cells, respectively. Fig. 4.14a) confirms the enhancement of thermal insulation with the PCM-ceramic tiles when using a 10min dwell: 0.9°C reduction on the minimum temperature and differences exceeding 1°C on the maximum temperature. The overall indoor space temperature amplitude decreased about 2°C. However, the minimum temperature reached inside the test cell (~20.5°C) is insufficient to promote the complete solidification of the PCM, which affects its functionality as pointed out by Voelker et al. [69]. In fact, when the PCM has sufficient time for the occurrence of complete melting and solidification, its performance is improved as confirmed in Fig. 4.14. b) and c). For example, with 90 min dwell time, the temperature amplitude in the test cell coated with PCM-ceramic tiles decreased by 2.7°C. The enhancement of the PCM performance when its complete melting and solidification is ensured [92].

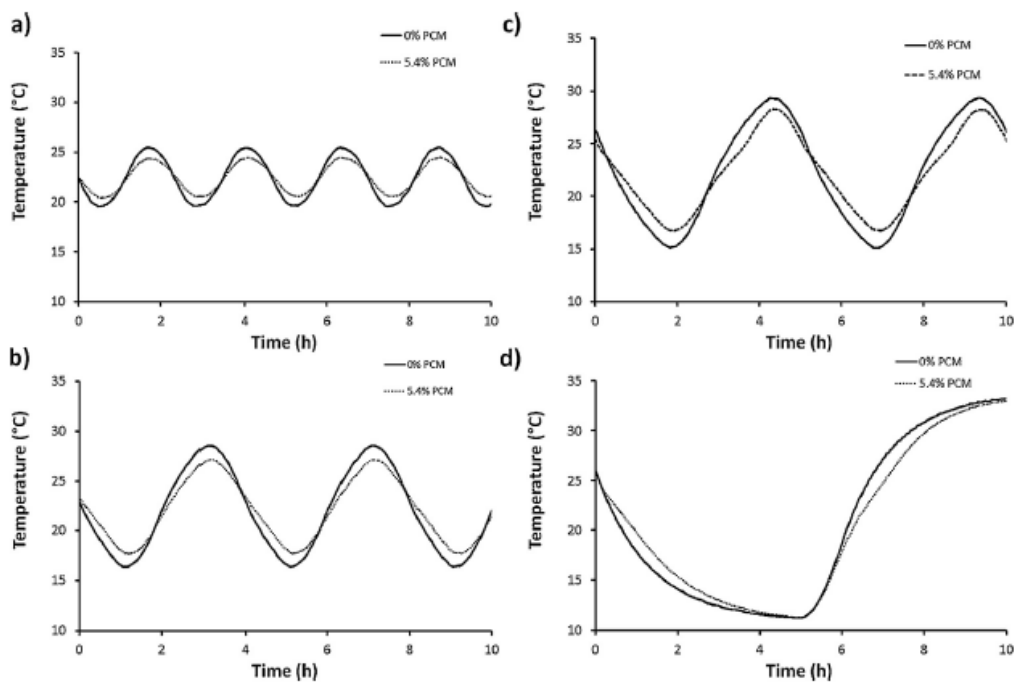


Fig. 4.14. Temperature evolution inside the test cells with ceramic tiles without PCM and with 5.4 wt% PCM with different dwell at the peak temperatures: (a) 10 min, (b) 60 min, (c) 90 min and (d) 300 min [92]

In conclusion, PCM-ceramic tiles present remarkable potential for improving the thermal comfort inside buildings due to their ability to reduce indoor space temperature fluctuations. Additionally, if associated with under-floor electric systems the energy consumption can be transferred for off-peak period providing substantial energy savings.

#### 4.4. CONCRETE ELEMENTS (WALLS AND PAVEMENTS)

The thermal response of concrete walls containing PCMs has been reviewed extensively, Tung-Chai Ling et al. [176] shows that among the PCM types, organic PCM and particularly paraffin wax PCM, seems to be one of the most suitable latent heat storage materials that can be used in concrete. The main reasons are the chemical stability, inactivity in the alkaline environment of concrete, an appropriate transition temperature of about 26°C (human thermal comfort) and low degree of super cooling; they are also relatively inexpensive and have desirable thermal stability. The test results of different means of PCM incorporation in concrete showed that: Immersion: suitable for concrete with a relatively high porosity. The time required for immersion is mainly controlled by (i) the absorption capacity of the porous concrete, and (ii) the temperature of the container in which the melted (liquid) PCM is filled. Basically the immersion process takes several hours. Impregnation: vacuum impregnation seems to be more effective compared to the simple immersion technique. By comparing the results of absorption behavior of PCM in different types of porous aggregates, expanded clay or shale aggregates are the more suitable porous materials for PCM impregnation. Direct mixing: encapsulation of the PCM with a chemically and physically stable shell is required before it can be directly mixed into concrete. The surface (shell) hardness of the PCM microcapsules can be reinforced by the use of Zeolite or Zeocarbon [176].

In brief, most experimental studies of walls or rooms exposed to outdoor conditions have reported that adding PCM to building walls reduced the amplitude of the temperature oscillations at the wall surface and time-shifted the temperature peak. Castellón et al. [46] constructed outdoor cubicles in Lleida, Spain made with plain brick, plain brick with polyurethane insulation and 1.9 mass% macroencapsulated PCM with a melting temperature of 27°C, alveolar brick, and alveolar brick containing 3.3 mass% macroencapsulated PCM with a melting temperature of 25 °C. The cubicles were equipped with a heat pump to maintain an indoor temperature of 24 °C. Their electricity consumption over the course of a summer week was reduced by up to 15% and 17% by adding PCM to the plain and alveolar brick cubicles, respectively. However, as acknowledged by the authors, the performance could be further improved by optimizing the PCM melting temperature. Such optimization would be costly and time consuming to perform experimentally. Moreover, it remains unclear whether these conclusions would be valid in other parts of the world with different climates. Rigorous numerical simulations can address these issues by assessing the effects of the climate conditions and of design parameters of PCM-composite walls such as the melting temperature and the PCM volume fraction on the thermal load of buildings in a rapid, systematic, and rational way.

#### 4.5. TROMBE WALLS

The concept of Trombe wall was patented by E.S. Morse in the 19<sup>th</sup> century and developed and popularized in 1957 by Félix Trombe and Jacques Michel. In 1967, in Odeillo, France, they built the first house using a Trombe wall [128]. Fig. 4.15. illustrates the general classification. Each configuration of Trombe wall is discussed in detail next.

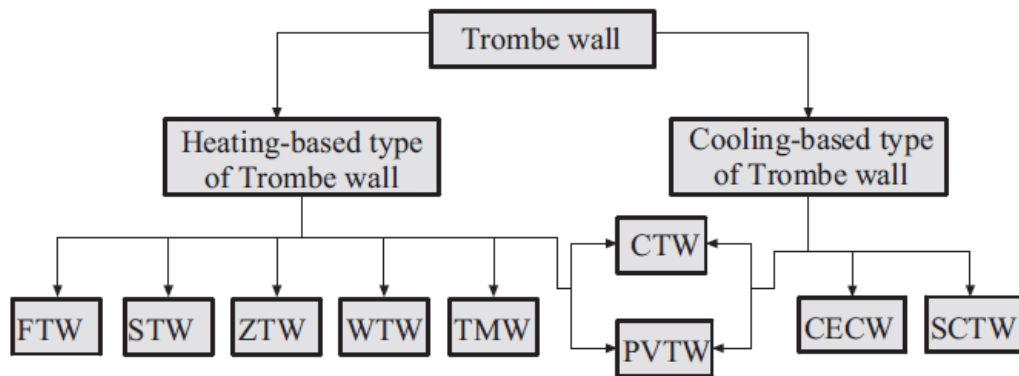


Fig. 4.15. Trombe wall classification [128]

Fig. 4.16. shows examples of heating-based type of Trombe wall. The first one Fig. 4.16(a) is known as photovoltaic (PV) Trombe wall is invented by incorporating solar cells with classic Trombe wall. The PV-Trombe wall not only provides space heating, but also generates electricity; meanwhile it brings more aesthetic value. Fig. 4.16(b) represents the first cooling-based type of Trombe wall, the ceramic evaporative cooling wall. The wall employs an external reflective thermal insulation blinds to avoid direct solar gain.

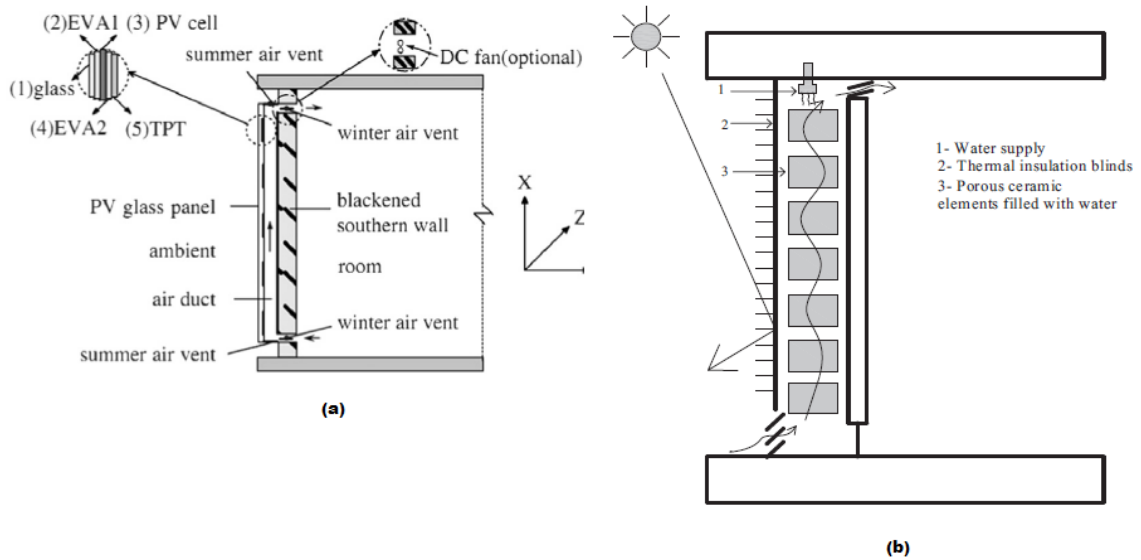


Fig. 4.16. (a) PV-Trombe wall with DC fan for winter heating; (b) Ceramic evaporative cooling wall [128]

A trombe wall is a primary example of an indirect gain approach. A single or double layer of glass or plastic glazing is mounted about four inches in front of the wall's surface. Solar heat is collected in the space between the wall and the glazing. The outside surface of the wall is of black colour that absorbs heat, which is then stored in the wall's mass. Heat is distributed from the trombe wall to the house over a period of several hours. When the indoor temperature falls under that of the wall's surface, heat begins to radiate into the room. Heat loss from the trombe wall can be controlled by an insulating curtain that is closed at night in the space between the glazing and the wall. Traditionally trombe walls rely on sensible heat storage, but because of the potential for greater heat storage per unit mass, the PCM trombe wall is an attractive concept still awaiting successful implementation [7]. Schematic diagram of PCM trombe wall is shown in Fig. 4.17.

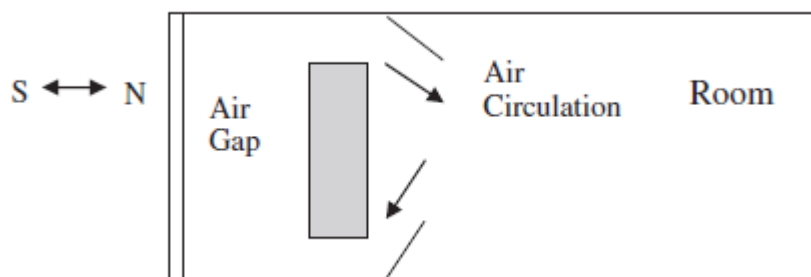


Fig. 4.17. Schematic diagram of PCM trombe wall [7]

Over time, modifications have been made to Trombe walls in order to improve their efficiency. Based on the main utilizing functions of Trombe walls, they are classified into two types: a heating-based type of Trombe wall and a cooling-based type of Trombe wall. To increase the thermal resistance of the classic Trombe wall (Fig. 4.18.) and control supplies, another heating-based type of Trombe wall, which is known as composite Trombe wall or Trombe-Michel wall (Fig. 4.19.) was developed.

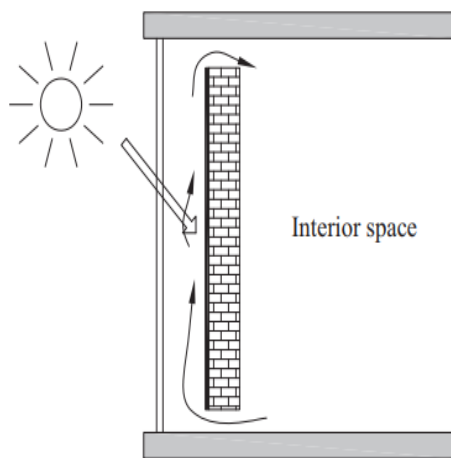


Fig. 4.18. A classic Trombe wall for winter heating

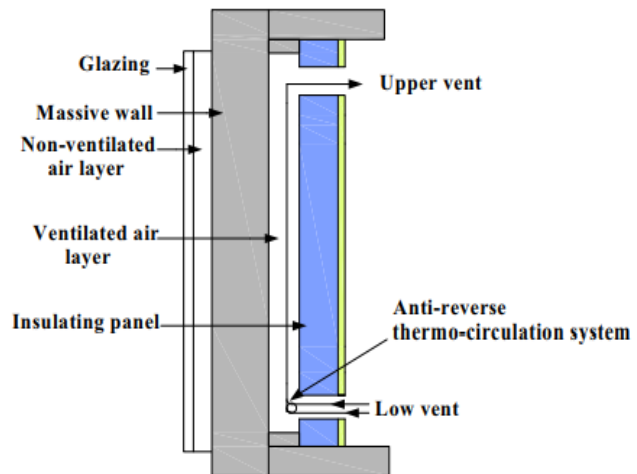


Fig. 4.19. A composite Trombe wall

During the last decades, several modifications have been developed from the basic design of a classical Trombe wall and composite Trombe–Michel wall [95, 103-105]. Zalewski et al. [126] performed an experimental study of a small-scale composite solar wall where PCM was inserted into the wall in the form of brick-shaped package. The PCM used is a mixture of hydrated salts (water +  $\text{CaCl}_2$  +  $\text{KCl}$  + additives) with melting point of  $27^\circ\text{C}$ . They concluded that the solar gains are released with a time lag which indicates the advantage of this composite solar wall. They also pointed out that the efficiency of the solar wall could be improved by limiting losses to the outside and increasing exchanges in the cavity.

The Trombe-Michel solar wall or composite solar wall is a variant of the classic trombe wall with the aim to contribute to the thermal comfort in buildings using solar energy. The main idea of the Trombe-Michel wall is to use the component as a part of building envelope that stores energy from solar radiation during the day and releases it as heat, indoor at night or in a cloudy period [94]. The thermal energy recovered by this type of wall passes through the storage element by conduction transfer and then by natural convection in a ventilated air gap.

In conventional non-PCM applications, the storage capacity increases weight and volume of passive solar systems, which makes difficult their merge with, common today, lightweight construction methods and limits integration into the existing buildings. To alleviate this problem, conventional heavy weight thermal mass is replaced by PCM. For a given amount of heat storage, the phase change units require less space than water walls or mass trombe walls and are much lighter in weight. These are, therefore, much convenient to make use of in retrofit applications of buildings. Salt hydrates and hydrocarbons were used as PCMs in the trombe wall [7].

A large number of experimental and theoretical assessments have been conducted to investigate the energy performance and long-term reliability of the PCM based Trombe wall heat storage components. It was found that the thermal performances of the Trombe wall depend on various parameters such as the size of air gap and vents, wall area and orientation, wall thickness, glazing, insulation and operation strategy [128]. In terms of the selection of Trombe wall materials, a study was carried out by Stazi et al. [110] during both the pre-use phase and use phase of Trombe wall on three wall materials: concrete, brick and aerated concrete. Considering both pre-use and use phases, the best

overall performance was obtained using the wall with aerated concrete blocks that combines a production cycle with low environmental impacts and high energy performances in the use phase.

Onishi et al. [106] numerically investigated the effects of PCM as a heat storing material on the performance of a hybrid heating system with a CFD (computational fluid dynamics) code. Simulated results indicated the effectiveness of PCM and suggested the possibility of developing low-energy houses with the hybrid system introduced in this study. The TIM (transparent insulation materials) – PCM (phase change material) wall system also showed the higher efficiency of solar radiation utilization and decreased heat losses by using corresponding PCMs [107, 108]. Fig. 4.20. shows the proposed two-layered passive wall system, it is a combination of a salt hydrate phase change material.

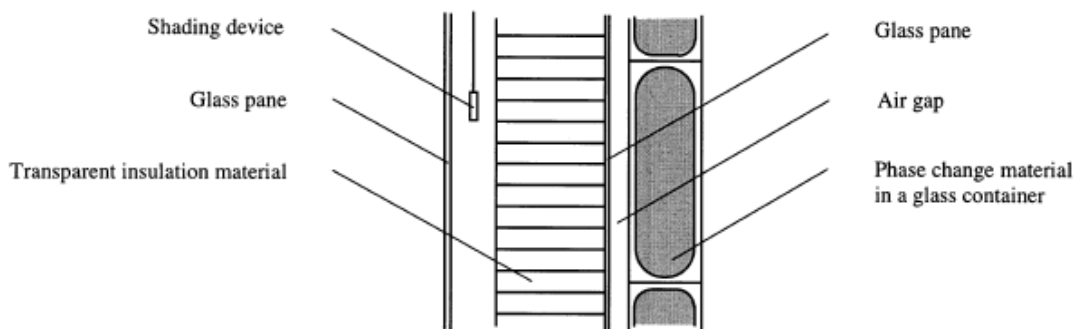


Fig. 4.20. Prototype of a TIM–PCM external wall system for solar space heating and daylighting [107]

So, initially, hydrated slats have been sampled for this purpose. Telkes [111-113], proposed the inclusion of PCMs in walls, partitions, ceilings and floors to serve as temperature regulators. The PCMs have been used to replace masonry in a trombe wall and worked on a construction similar to the Trombe wall, using Glauber’s salt behind a polyhedral glazing. Her work was only a first-order theoretical analysis demonstrating the potential for energy and space savings.

Askew [114] used a collector panel made of a thin slab of paraffin wax and mounted behind the double-glazing of the building and found that the thermal efficiencies are comparable with the conventional flat plate collectors. Farouk and Guceri [115] studied the usefulness of the PCM wall installed in a building for night time home heating using Glauber’s salt mixture and SUNOCO P-116 wax. It was observed that if the PCM wall is designed properly, it eliminates some of the undesirable features of the masonry walls with comparable results.

In experiments performed by Swet [116], Ghoneim et al. [117], and Chandra et al. [118], a Glauber’s salt was utilized as well (sodium sulfate decahydrate with melting point 32.1°C) as a phase change material in a south facing Trombe wall. Experimental and theoretical tests were conducted to investigate the reliability of PCMs as a trombe wall. They reported that trombe wall with PCM of smaller thickness was more desirable in comparison to an ordinary masonry wall for providing efficient thermal energy storage (TES).

Knowles [127] presented numerical results as well as approximate simple stationary state formula with the purpose of establishing guidelines for the design of low-mass, high-efficiency walls. One conclusion was that thermal resistance of the wall should be as low as possible. Exploration of binary and ternary composite of metals, masonry and phase change materials was studied. Compared with concrete, paraffin–metal mixtures were found to offer a 90% reduction in storage mass and a 20% increase in efficiency.



Bourdeau and Jaffrin [120] and Bourdeau et al. [121] simulated and tested a Trombe wall using chliarolithe ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ) as a PCM heat storage. A numerical model demonstrated that a 3.5cm wall using PCM could replace a 15cm thick conventional wall made of concrete. In a following project, Bourdeau [119] studied the behaviour of Trombe wall made of polyethylene containers placed on a wood shelf behind a double glazing. These experimental results were used to validate the numerical model, which demonstrated that a Trombe wall with latent heat storage was more efficient than conventional concrete walls. This research indicated that the optimum thickness of a PCM wall was of a factor 4 thinner than an equivalent concrete wall.

In addition, Benson et al. [122] carried an analysis on polyalcohols used as PCM. They also performed numerical analysis on PCM-enhanced Trombe walls compared to conventional concrete structures. They found an optimum melting temperature for PCM which was close to  $27^\circ\text{C}$ . Numerical analysis demonstrated that an increase in thermal diffusivity can be beneficial to the thermal performances of PCM solar walls. Accordingly, laboratory tests demonstrated that diffusivity can be increased by a factor of five through the addition of 2% of graphite, which should lead to about 30% improvement in performance. They concluded that a Trombe wall containing PCM could be four times thinner and a factor nine lighter than its equivalence made of concrete.

Buddhi and Sharma [123] measured the transmittance of solar radiation through phase change material at different temperatures and thickness. Stearic acid was used as a phase change material. They found that transmittance of the phase change material was more than the glass for the same thickness and suggested a new application of phase change material in windows/walls as a transparent insulating material.

Strith and Novak [124] presented a solar wall for building ventilation, which absorb solar energy into black paraffin wax (melting point,  $25^\circ\text{C}$ – $30^\circ\text{C}$ ). The stored heat was used for heating the air for the ventilation of the house. The efficiency of the absorption was found to be 79%. The result of the simulation showed that the panel dictates the amount of stored heat as sensible or latent and that the melting point of the PCM has an influence on the output air temperature. The analysis for the heating season gave the optimum thickness of 50mm and the melting point a few degrees above the room temperature.

D. Sun and L. Wang [125] studied the energy saving characteristics in winter, using an experimental room. They explored a new system: passive solar collector-storage wall contained PCMs on both sides surface. The heat transfer performance and energy saving characteristics were investigated theoretically and experimentally. Paraffin/expanded perlite/graphite PCMs was added into collector mortar layer and interior mortar layer to storage energy. Phase change temperature and latent heat are  $19.45^\circ\text{C}$  and  $128.46 \text{ J/g}$ , respectively. The illustration of passive solar collector-storage wall system with PCMs is shown in Fig. 4.21. A part of solar energy transmits into the room through air channel and vents to improve indoor temperature, a part of solar energy store in the collector mortar layer through PCMs and the rest solar energy is conducted slowly through massive wall to the room by radiation and convection. The advantage of passive solar collector-storage wall system with PCMs is storing more heat from sun during the day and releasing it into the building during the night. The results indicate that the new passive solar collector-storage wall system with PCMs can promote indoor air thermal circulation and decrease indoor air temperature fluctuations. Its good heat storage capacity can apparently improve indoor thermal environment.

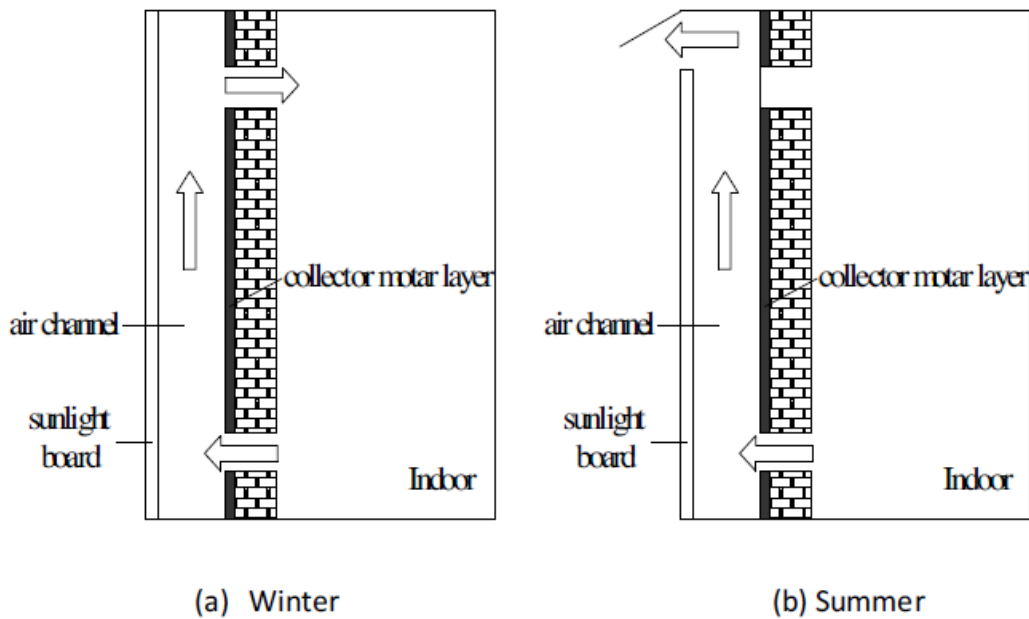


Fig. 4.21. Illustration of passive solar collector-storage wall system with PCMs [125]

Fiorito [129] selected five cities of different climate zones in Australia and modeled the effect of PCMs (n-paraffin and wax) integrated in collector-storage walls. The simulation results showed that PCM improved the thermal inertia of lightweight constructions and its position and melting temperature need to be optimized according to the corresponding climate conditions.

Kara and Kurnuc [130] applied novel triple glazing for PCM wall (33wt% paraffin granules in the plasterboard) to prevent overheating in summer and their experimental results indicated that the wall including PCM (GR35) with relatively lower melting temperature  $t_m = 34^\circ\text{C}$  presents better performance than that including PCM (GR41) with  $t_m = 45^\circ\text{C}$  while both could provide 14% of annual heat load of the test room.

Li and Liu [131] experimentally investigated the thermal performance of a PCM (paraffin,  $t_m = 41^\circ\text{C}$ ) based solar chimney under three different heat fluxes on the absorber surface and found that  $700\text{Wm}^{-2}$  of heat flux drives the highest air flow rate ( $0.04\text{kg/s}$ ) while  $500\text{Wm}^{-2}$  generates the highest average outlet temperature ( $20.5^\circ\text{C}$ ). They also reported that phase change periods are nearly 13h50 min for all cases investigated.

In [128] a test was carried out for a whole day with charging period of 6.5h and discharging period of 17.5h, respectively. Wall and air temperatures as well as air velocity in the gap were measured for analysis. The results showed that the PCM surface temperature increases first rapidly, then slowly and rapidly again during the charging process, which in turn corresponds with the three storage stages: sensible heat (solid), latent heat (melting) and sensible heat (liquid), respectively; The indoor temperature was found to be above  $22^\circ\text{C}$  during the whole discharging period (17.5h) under present conditions, which indicates that the indoor thermal comfort could be kept for a long time by using PCM in collector-storage wall system. As shown in Fig. 4.22., the experimental setup comprises radiation source, collector-storage wall and measurement system. A test room was reconstructed into the collector-storage wall system for experiment, which was shown in Fig. 4.23.

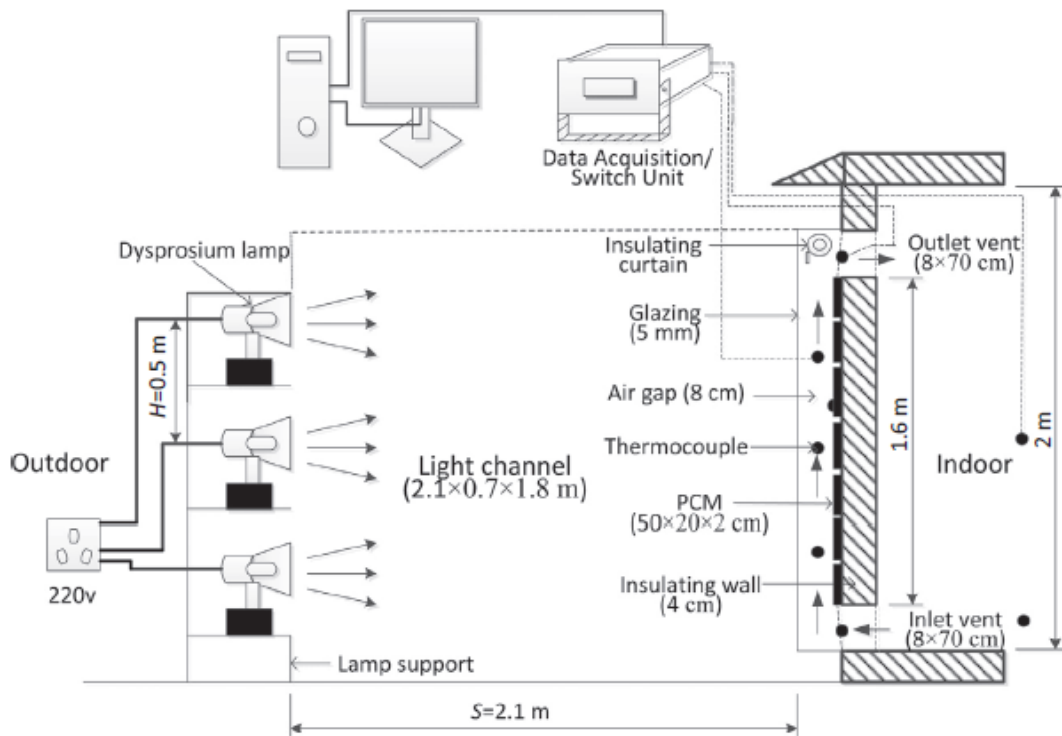


Fig. 4.22. Schematic sketch of the experimental setup [128]

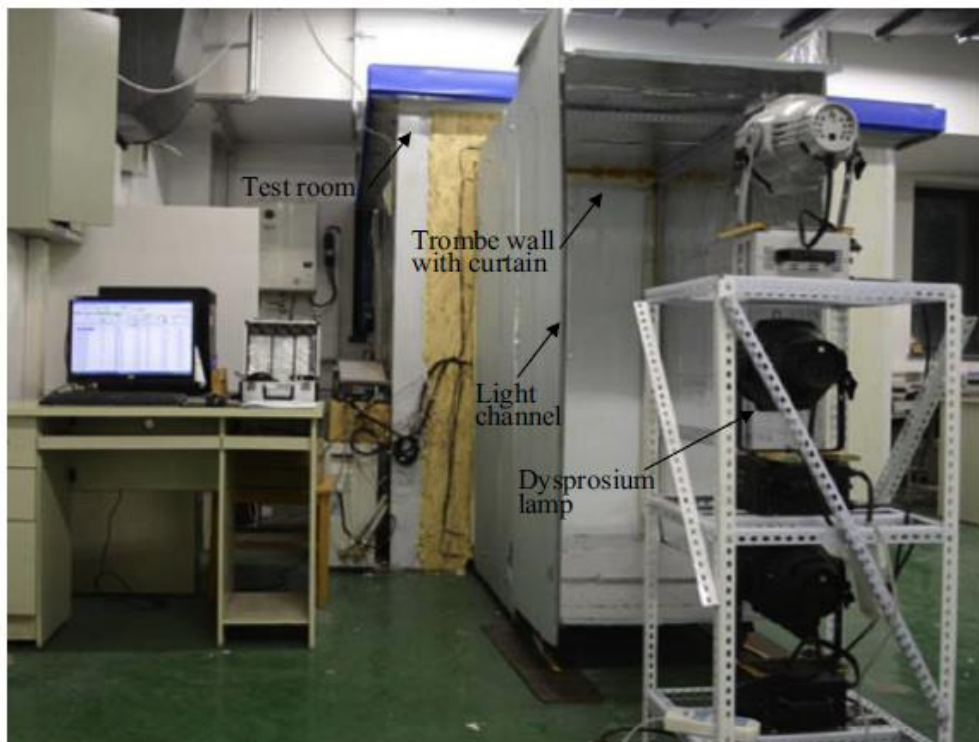


Fig. 4.23. The photo of the experimental system [128]

Z. Hu et al. [132] achieves the main conclusion, the larger Trombe wall area means the more high efficiency. However, it is limited the total south wall area, that is, it is related to ( $\alpha$ ), the ratio of the Trombe wall's area to the total wall area. Massive wall materials and thickness contribute importantly to the efficiency of the wall's heat storage and release capacity. Any material characterized by high storage capacity can be used to construct Trombe walls. However, the use of lightweight materials with high storage capacity in a relatively small volume is more preferable, such as PCM. With regard to the wall thickness, 30cm–40cm concrete Trombe walls have performed well in many geographical locations. In addition, thermal insulation on massive wall is considered a remedy for the deficiency of a classic Trombe wall. Glazing properties, such as the materials and the number of glazing layers significantly affect the performance of Trombe walls.

However, the selection of glazing depends on many variables including the longitude and latitude of the project. Normally, low double glazing is recommended. Channel depth mainly contributes to the flow resistance. It is not only related to height of Trombe wall but also depend on the dimension of inlet and outlet. In addition, the structural safety should be considered when design the channel depth because an excessive depth of channel will results in an insufficient thickness of massive wall. Shading devices, such as: overhang, roller shutter and venetian blinds can control the performance of Trombe wall and address some of the shortcomings: overheating in hot summer and heat loss in winter night. Similar to thermal insulation on massive wall, proper insulation of building envelope have perform well.

Due to solar radiation can strike the indoor floor or its adjacent walls directly through a window, therefore the design of windows should be considered including the size and position (relative to the Trombe wall). Solar radiation level has an important influence in generating air movement in a Trombe wall channel.

Generally, Trombe wall efficiency increases with increasing of solar radiation. Moreover, for a building with Trombe walls located in the north hemisphere, the south facing facade (with 45° variations) seems to be the most effective orientation in capturing the solar gain. The wind speed and direction are related to the heat loss coefficient and wind pressure. The Trombe wall tends to perform better if the wind speed is small, and in this direction, further investigation should be carried out in the future.

#### **4.6. WINDOWS**

The glazed areas and the shading devices have a significant role over the energy building consumption, so many research studies and prototypes have been developed in the last years to increase the thermal and the energy efficiency of this boundary. The improvement of the thermal performance through the glazing area of the building can be accomplished resourcing to new materials, geometries and new techniques to produce solutions with higher energy efficiency [135]. New approaches, as the building orientation and the use of natural resources, as wind and solar radiation could decrease the energy needs and improve the energy transfer of these boundaries.

From the thermal perspective, PCM windows work like the optically transparent or translucent Trombe walls. They usually consist of a single or multilayer glazing panel made of conventional glass, integrated with a layer of a transparent or translucent PCM product. Fig. 4.24. shows the different configuration options of semi-transparent PCM solar fenestration.

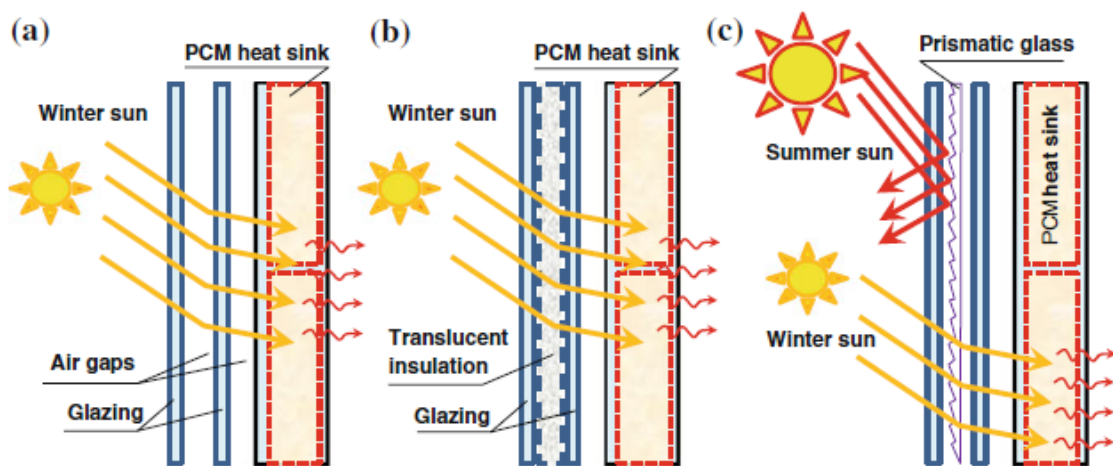


Fig. 4.24. Different configuration options of semi-transparent PCM solar fenestration: (a) Semitransparent Trombe Wall containing PCM heat sink; (b) Translucent Trombe Wall with PCM heatsink and translucent insulation; (c) Solar fenestration system using PCM heat sink and selective prismatic glass

Nowadays, the building design frequently includes large translucent areas, mainly in offices and commercial buildings. However, the use of large facade glazing areas could lead to thermal and visual discomfort of indoor space and their occupants [134]. Windows represent a part of the building that is considered to lead to higher energy consumption. In warm climates dominated by cooling loads, excessive solar heat gain lead to an increased need for mechanical cooling. In cold climates, large parts of the energy escape through glazed facades, leading to a need for mechanical heating [133].

However, glazed facades still suffer from low thermal inertia, and have no way of storing excess heat. Transparent PCMs for use in windows represent an opportunity that has been explored for this purpose. They provide dynamic thermal characteristics and a source of natural lighting to the building. The energy state of these assemblies is visualized as transparent or translucent when PCM is melted and milky when PCM is frozen [5].

Manz et al. [108] studied a solar facade composed of transparent insulation material and translucent PCM used both for solar heat storage and daylighting. The PCM was hexahydrated calcium chloride ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ) with 5% of additives. The numerical model was developed for analysis of the radiative heat transfer inside the PCM-enhanced solar window. The authors concluded that overall system performance could be improved by changing of the PCM melting temperature from 26.5°C to about 21°C.

Another semi-transparent solar window system containing PCM has been introduced by the INGLAS company from Friedrichshafen, Germany [142]. This technology combines design principles of passive solar walls with fenestration function and a semi-transparent heat reservoir. As a result, this solar window efficiently transfers solar light and absorbs the heat developed in the process. The absorbed heat is stored by the heat sink utilizing organic PCM. According to manufacture, large amounts of solar energy can be stored during daytime and released into the building at night, when PCM cools down and solidifies.

In similar research performed in Germany, an application of semi-transparent PCM components from Dorken has been jointly investigated by the glass company Glaswerke Arnold and research institute ZAE Bayern. A complete system is made of two glass sheets on the outside and a macro-encapsulated PCM on the inside [5]. Fig. 4.25. shows a commercialized glazing filled with a PCM, also portraying the visibility in its liquid state.

As of today, only translucent PCMs have been used for PCM windows, though they enable relatively high amounts of visible light to pass through, they do not offer the same visibility as regular windows. PCM optical properties are changing to some degree between the solid and liquid states.

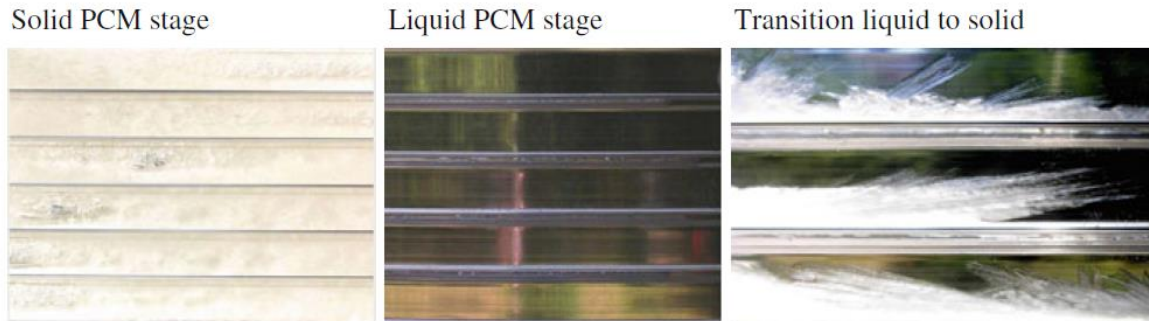


Fig. 4.25. Illustration of a PCM filled window (left) and commercialized PCM window in its liquid state (right) (GlassX [141])

The solar transmittance of a commercial grade PCM was tested by Jain and Sharma [143]. For a pure PCM with a thickness of 4mm-30 mm the solar transmittance was found to be 90.7%–80.3%, respectively. Due to the fact that PCMs have low thermal conductivity, they concluded that PCMs may be interesting as a transparent thermal insulating medium.

Goia et al. [144] compared a prototype PCM glazing system (DGU\_PCM) with a conventional double glazed (DGU\_CG), insulating unit with regard to the effect on thermal comfort in the winter, summer and mid-season. (Fig. 4.26.). The two glazing systems were measured over a six-month experimental campaign, and the data was used to numerically evaluate an indoor office room. The thermal conditions were considerably improved for most parts of the year with the PCM prototype compared to the regular double glazing. However, on cloudy days, the two systems showed similar properties on thermal comfort. The study also highlighted the importance of selecting the correct melting temperature for the PCM as this could affect the system negatively if not optimized. Two layers (8mm and 6mm) of glass compose the double glazed unit with PCM (DGU\_PCM) and the air cavity (15mm) between the two layers was filled with commercial paraffin (RT35). The DGU\_PCM element area is about 1 m<sup>2</sup> (1.4x0.72 m<sup>2</sup>), inserted in an experimental test cell with 3.6m wide, 5.4 long and 3.0 high. The PCM was introduced into the air cavity and the volume of the PCM was 13dm<sup>3</sup> (E13 kg of RT35). They performed a Differential Scanning Calorimetry (DSC) analysis to characterize the thermal properties of the PCM. According the DSC analysing the latent heat of fusion ( $\Delta h$ ) is about 145 kJkg<sup>-1</sup> and the melting temperature about 34°C with a temperature range of 10°C. They concluded that the indoor conditions reached by the application of the DGU\_PCM solution increased considerably the thermal comfort comparatively to the conventional solution (DGU\_CG) for the most time of the different seasons. They suggest (i) the application of PCM with lower melting temperature for cold climates and winter season and (ii) the application of PCM with high melting temperature for hot climates and summer [144].



Fig. 4.26. Experimental test cell with the two glazing systems (DGU\_PCM and DGU\_CG) [144]

A similar study was performed by Weinläder et al. [146], comparing a double glazing unit combined with PCM compared to a regular double glazing unit. The test specimens were studied experimentally in an outdoor test facility and the data gained from the experiment was used for further simulations. The light transmittance from this solution was found to be 0.4, giving them the ability to be used as daylighting elements. Compared to regular double glazing they gave a more equalized energy balance, achieving moderate heat gains with very low heat losses. During the winter season, PCM windows improved the thermal comfort considerably and in the summer they shifted heat gains to later in the evening. However, the PCM windows cannot be used where visual contact to the environment is desired.

Goia et al. [145] performed a full-scale test on a PCM glazing prototype. The test was performed on a south facing wall during summer, mid-season and winter days in a sub-continental climate and compared to a conventional double glazing for reference. The experiment showed that PCM glazing can reduce the energy gain in the summer by more than 50%. In the winter, heat loss reduction during the day was observed, however this technology might not be effective if the purpose is to achieve solar heat gains. The experiment also pointed out the importance of removing the stored heat during the night via e.g. night cooling, and selecting the correct phase change temperature, if the system is to function optimally.

Grynning et al. [147] performed measurements on a state-of-the art commercial glazing including a PCM in a large scale climate simulator. The tested glazing was a 4-layer glazing with a prismatic glass in the outer pane and a PCM fill in the cavity between the inner panes. A cross-section of the window is shown in Fig. 4.27.

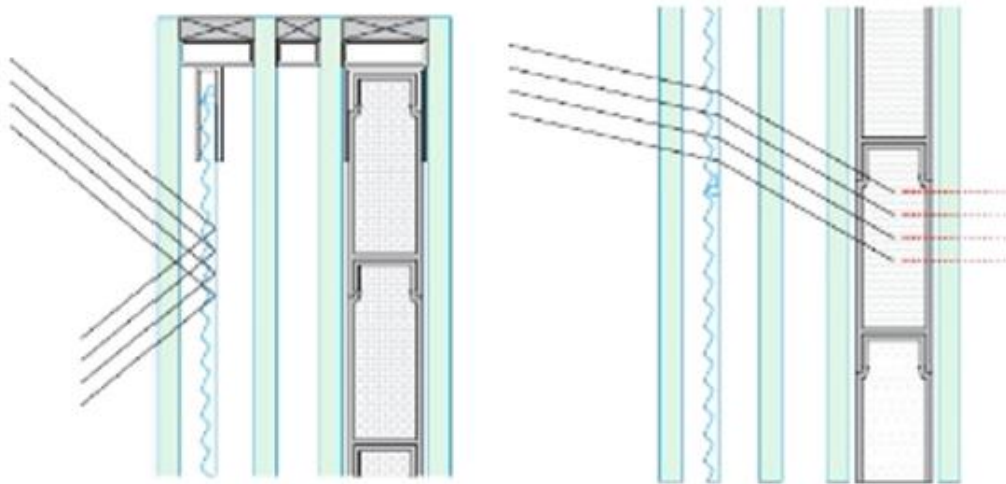


Fig. 4.27. Vertical cross sections of the PCM window. (GlassX, 2012). The figures illustrate the angular properties of the solar reflector in the outer cavity, of the solar reflector in the outer cavity, where radiation with high incidence angles (typical summer days) are reflected and low-angle incident radiation (typical winter days) is let through [147]

The study showed that characterization of static components (e.g. U-value, solar heat gain coefficient, thermal transmittance) is insufficient for describing the performance of PCMs due to their dynamic nature.

A zero energy office building using translucent PCMs in the window construction has been built in Kempen, Switzerland (Fig. 4.28.). In this project, each second window panel has been equipped with PCM windows. The aim for the windows is to effectively store solar energy during the warmer parts of the day, and release thermal energy throughout the colder periods of the day to reduce the total energy required for space heating [60].



Fig. 4.28. Zero energy office building from Kempen, Switzerland [60]



Alawadhi [148] investigated the possibility to implement PCMs in window shutters, where the goal was to see if the solar heat could be absorbed before it reached the indoor space. The results indicated that the magnitude of PCM melting temperature and its quantity in the shutter have a significant effect on the thermal performance of the PCM shutter. The melting point of the PCM in the shutter should be close to the upper temperature limit of the windows during the daytime. The PCM should be prevented from completely melting during the working hours and its amount should be sufficient to absorb large amount of heat during the daytime. When compared to foam shutters, the shutters containing a PCM could lead to a reduction in heat gain through the windows by as much as 23.29%.

In this concept, shutter-containing PCM is placed outside of window areas. During daytime they are opened to the outside the exterior side is exposed to solar radiation, heat is absorbed and PCM melts. At night we close the shutter, slide the windows and heat from the PCM radiates into the rooms. Buddhi et al. [149] studied the thermal performance of a test cell (1m x 1m x 1m) with and without phase change material. CG lauric acid (melting point, 49°C) was used as a latent heat storage material. He found that the heat storing capacity of the cell due to the presence of PCM increases up to 4°C for 4–5 h, which was used during night time [7].

Mehling [150] recommended that the maximum shading temperature should be delayed by 3h and room temperature should be reduced by 2°C with the application of the PCM shutter. The photograph of PCM shutter is shown in Fig.4.29.



Fig. 4.29. PCM shutter [150]

Soares, Costa [151] evaluated the potential of a PCM-shutter containing phase change materials. In their study, numerical studies were carried out to analyse the influence of the imposed external and internal conditions and the heat transfer coefficients of the system performance. The PCM-shutter system is composed by five main layers, as shown in Fig. 4.30.

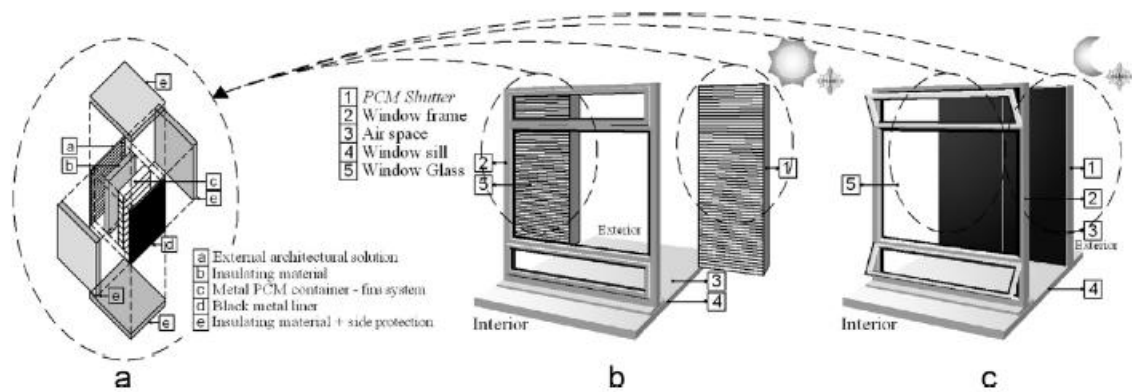


Fig. 4.30. Schematic of the PCM-shutter [151]

Shuhong Li et al. [152] conducted an experiment to investigate the dynamic thermal and energy saving performance of the experimental systems of two reference windows (DW + PCM and triple-pane window (TW + PCM)). The experiment was conducted in summer sunny days and summer rainy days in hot summer and cold winter in an area of China. Fig. 4.31. shows Structure comparison of the three kinds of windows.

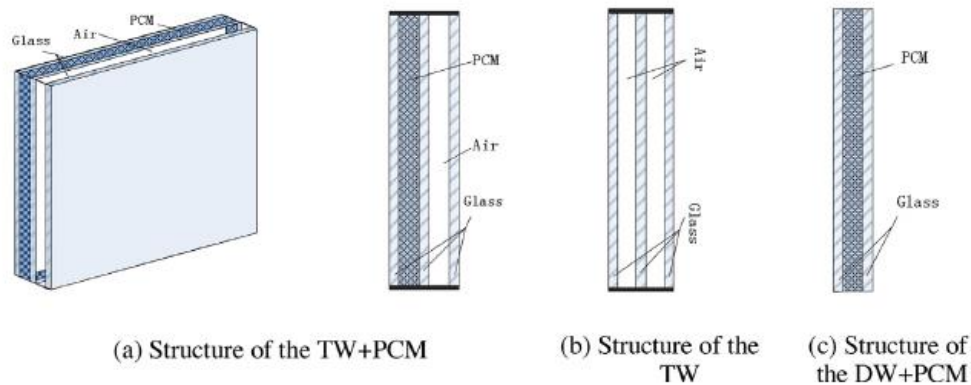


Fig. 4.31. Structure comparison of the three kinds of Windows [152]

The result of the dynamic thermal performance of the TW + PCM (triple-pane window) in the sunny and rainy summer days shows that the TW + PCM have a good performance on reducing the temperature fluctuation indoors and saving the energy consumption.

In the sunny summer day with high outdoor air temperature and strong solar radiation, the temperature on the interior surface of the TW + PCM is 2.7°C and 5.5°C lower than that of the DW + PCM and TW respectively, which means the overheating risk, is avoided effectively, and the heat transferred into room through the TW + PCM is reduced by 16.6% and 28% compared with the DW + PCM and TW respectively. During the discharge period of PCM in the night, the heat released from the PCM into the testing chamber reduces. It shows the same function with the DW + PCM on the delay of peak-temperature time. It can adjust the peak load of the air conditioning system and save the air-conditioning energy consumption.

In the rainy summer day with low outdoor air temperature and weak solar radiation, the temperature on the interior surface of the TW + PCM is  $0.74^{\circ}\text{C}$  and  $1.65^{\circ}\text{C}$  lower than that of the DW + PCM and TW respectively, and the heat transferred into room through the TW + PCM is reduced by 14.7% and increased by 4.5% comparing with the DW + PCM and TW respectively. The TW + PCM play a good performance on reducing the temperature fluctuation of the interior surface and the heat entered the room, but it is unsatisfactory in reducing the peak heat flux of the interior surface and delaying the peak temperature. Fig. 4.32. shows the melting process of the paraffin MG29 in the PCM-filled windows in the sunny summer day and Fig. 4.33. keeps the minute of the most melted PCM, which is shot in 14:00 [152].

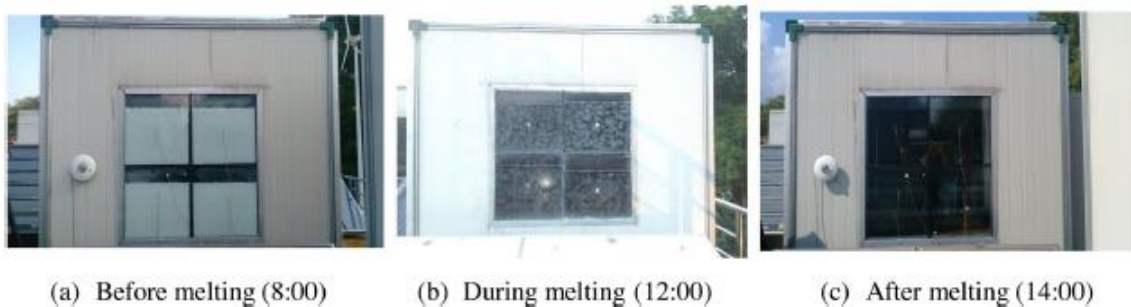


Fig. 4.32. The melting process of the PCM of the TW + PCM in the sunny summer day [152]



Fig. 4.33. The melting state of the PCM in the rainy summer day (14:00) [152]

Changyu Liu et al. [153] developed a mathematical model for the heat transfer that evaluated with good agreement the effect of (i) the glass properties; (ii) the convection heat transfer coefficient; (iii) the surfaces temperatures; and (iv) the air temperature. The main results show that. The influence of the solar radiation through the glass is significant for the heat flux increment. If the difference of temperatures, between the surface and the air (from the inside to the outside of the room) do not exceed  $2^{\circ}\text{C}$ , therefore the total heat flux effect can be neglect.

The convection heat transfer coefficient does not affect significantly the overall heat flux. Heat transfer is improved by the solar radiation in winter but has an adverse effect in summer.

Gomes et al. [154] determined both solar and visible properties of a glazing system with venetian blinds using a net radiation method. They compared the numerical results with the experimental data measured from an outdoor test cell. They concluded that the developed model can be used to simulate different system configurations, such as glazing and/or shading devices (including venetian blinds) and the model can be introduced into building energy simulations and building design tools. The numerical results were compared with the experimental data and for overcast sky conditions. For these conditions they got excellent fitting results, but for the clear sky conditions the comparison of the results presented some discrepancies. A venetian blind control strategy was used and they conclude that is more important for southern European regions. To help designers and users to improve the thermal and daylighting indoor conditions they presented some design plots with information about how to adjust the slat orientation of the venetian blinds.

Tiago Silva et al. developed an experimental procedure that follows a test on a cell that was located in Aveiro, Portugal a region with a Mediterranean climate. Considering the weather database available (from the weather station at the University of Aveiro) the adequate melting temperature of the PCM was chosen. According to the selected PCM the shape of the window blade (used as a macrocapsule) was defined and also the material. With the components of the window shutter prepared the system was assembled and applied in the outdoor test cell. Two compartments compose the test cell and each has two window shutters installed (two filled with PCM for one compartment and the others two without PCM). The performance of a window shutter with phase change materials was experimentally tested at fully scale. The PCM recorded to provide an extra thermal inertia for this compartment that is recorded and pursued by the indoor air temperatures and heat flux results were attained.

The maximum indoor temperature of the compartment with the PCM shutter is 37.2°C which is 16.6°C lower than the indoor air temperatures of the reference compartment. Comparing the indoor temperatures over time, the reduction of temperature can reach 90% (when the indoor air temperatures increases) and up to 35% (when the indoor air temperatures drop). For the maximum indoor air temperature peak the difference between both compartments is 30% to 40%. However, the minimum indoor air temperature peaks are similar, so for this situation the potential improvement of the PCM incorporation is null, proving that other features come into play such as thermal bridges losses, large glazing areas. Therefore an exercise of the compatibility and the optimization of these different features are necessary.

The maximum and minimum heat flux measured on the internal partition wall of the reference compartment was  $16\text{Wm}^{-2}$  and  $-8\text{Wm}^{-2}$ , respectively. The compartment with the PCM shutter presents more steady results of the heat flux and the maximum heat flux recorded was  $6.5\text{Wm}^{-2}$  and the minimum  $-3\text{Wm}^{-2}$ .

#### **4.7. CONCRETE OR BRICK**

Adding PCMs directly into concrete has shown some promising results through lower thermal conductivity and an increase in thermal mass at specific temperatures. However, PCM concrete has shown some undesirable properties such as lower strength, uncertain long-term stability and lower fire resistance [177].

Several studies have been conducted on PCM-concrete and have shown positive effect through reduced indoor temperatures in warm climates [60].

Then, two typical construction materials, conventional and alveolar brick, were experimentally tested by Castell et al. [180]. Several cubicles were constructed and their thermal performance throughout the time was measured, as shown in Fig. 4.34.

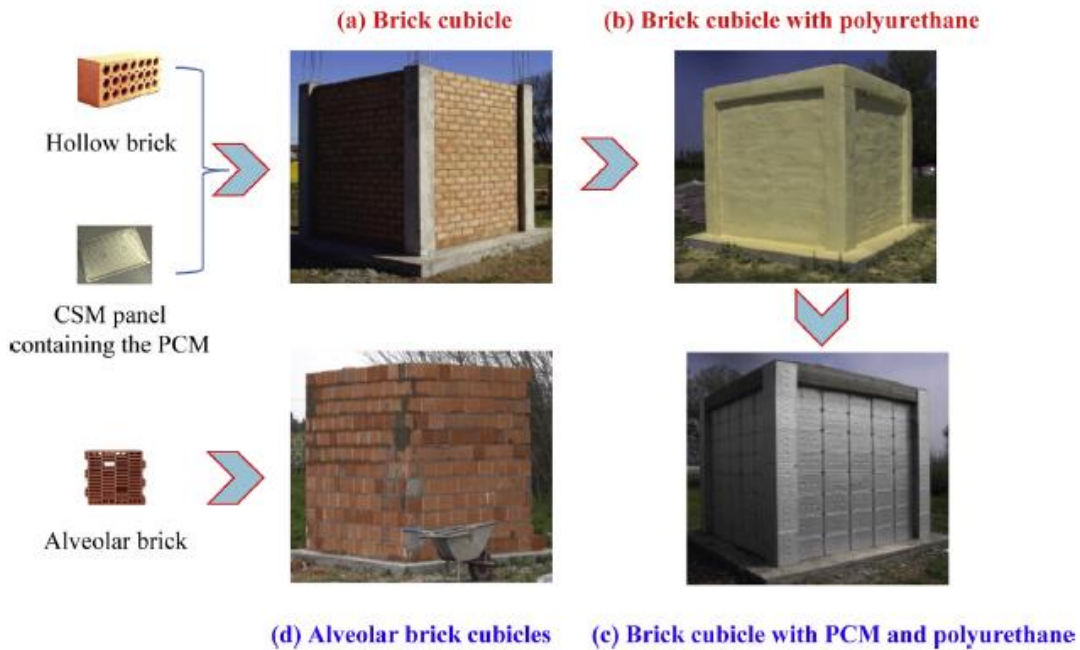


Fig. 4.34. PCM bricks and the test cubicles [180]

The free-floating experiments showed that the PCM has reduced the peak temperatures up to  $1^{\circ}\text{C}$  and smoothed out the daily fluctuations. Moreover, the electrical energy consumption was reduced about 15% in the PCM cubicles in summer. These energy savings resulted in a reduction of the  $\text{CO}_2$  emissions about  $1\text{kg/year/m}^2$ – $1.5\text{kg/year/m}^2$  [180].

Later, to control and shape the PCMs, a new composite construction material that embedded micro-encapsulated PCM in plastering mortar was developed and tested by Sá et al. [181], indicating the peak temperature of the indoor air was reduced by  $2.6^{\circ}\text{C}$  after the PCM mortar used. That means, when the PCMs are used in plastering mortar, concrete, brick and cubicle, the thermal environment control performance could be improved, as well as the structure stability of buildings unaffected. The physical arrangement of this setup can be observed at the photos of the test cell/monitoring shown in Fig. 4.35. Regarding the monitored values registered for both test cells under Spring day conditions, shown in Fig. 4.36., it can be observed that the maximum internal temperature inside test cell REF was of  $26.3^{\circ}\text{C}$ , whereas the corresponding temperature in test cell PCMM was  $23.7^{\circ}\text{C}$  [181].

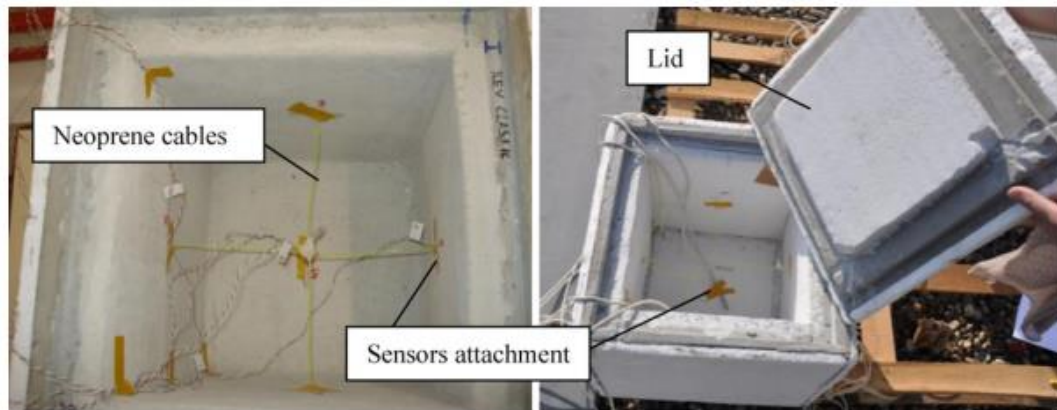


Fig. 4.35. Photo of sensor arrangement inside pilot test cells [181]

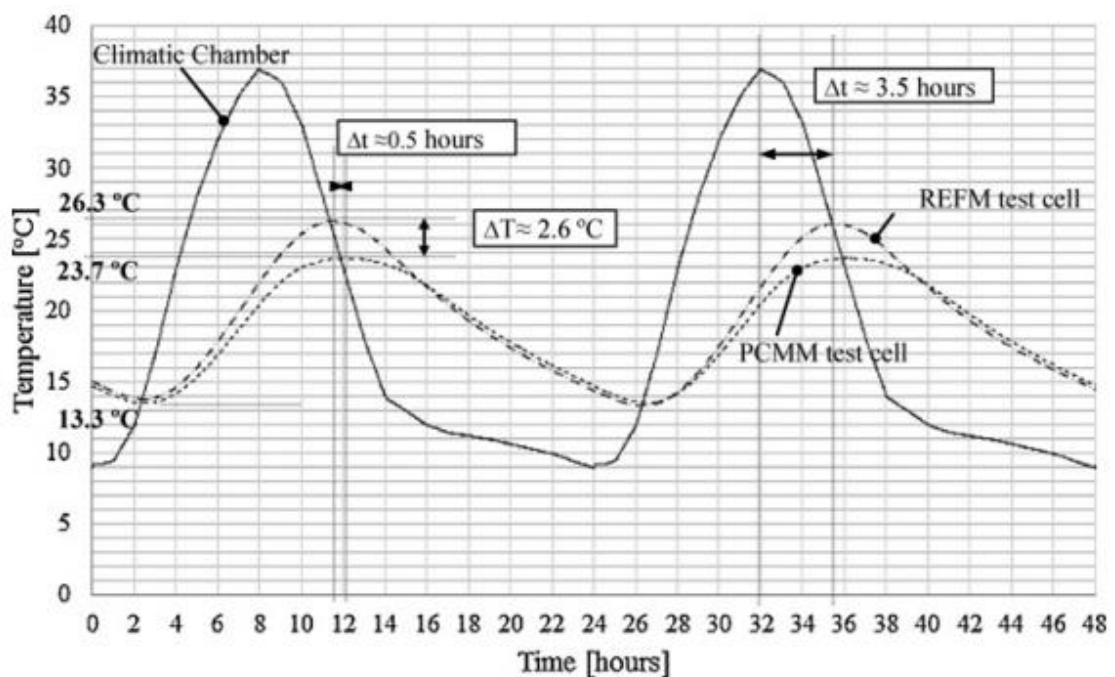


Fig. 4.36. Monitored temperatures of the pilot test cells with inner coatings made of PCMM and REFM (Spring day) [181]

Combining concrete structures with PCMs have been tried in several different ways. One studied solution is to drill holes in the concrete which may then be filled with a PCM [178].

Royon et al. [179] tested the possibility of filling the already hollow areas in a hollow concrete floor with PCMs. The concrete was filled with paraffin PCM with a melting temperature of 27.5°C. This test showed that the temperature on the other side of the hollow concrete was lower during summer conditions. Hence, such floors can be used as a passive thermal conditioner during the summer. However, more tests are needed with real life climate conditions to validate the effects (Fig. 4.37.).

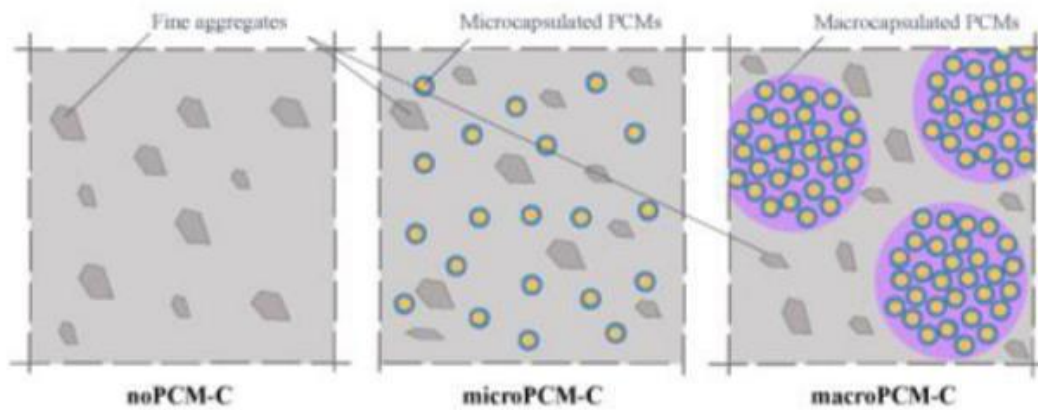


Fig. 4.37. Schematic representation of the tested concretes (not to scale) [177]

A most surprising research was aimed at developing and testing the multifunctional performance of new PCM-filled structural concretes for building applications by Anna Laura Pisello et al. [177]. Such concretes were prepared by adding 5% in weight of encapsulated phase change material for thermal-energy storage applications. Moreover, the included PCMs were selected in order to identify the best capsule geometry for structural and thermal purpose. In particular, the same paraffin PCM with melting temperature at 18°C was selected and industrially capsulated in two ways. The microcapsules included about 85%-90% of PCM in small capsules with diameter of about 17microns -20 microns. The second configuration concerned the macrocapsuled PCM, consisting in a sort of matrix with PCM microcapsules inside, having a whole diameter of 3mm-5mm and a whole PCM concentration of 80%.

To concluded, the realistic potential to increase dynamic heat storage capacity of concretes by incorporation of PCM is doubtful. Firstly, the thermal mass increase is not as high as expected and secondly, thermal conductivity decreases significantly due to addition of PCM to concrete. As a result, the energy from the air has difficulty in being transported to the inside of PCM concrete construction within daily realistic indoor temperature variations. Moreover, maximum amount of PCM in the concrete is not higher than 5%–6% by weight (material is still workable), which means not much latent heat capacity can be introduced to sensible heat storage capacity. Consequently, 5%–6% by weight of PCM corresponds to approximately 12%–15% by volume of concrete, which means that the share of PCM in concrete is rather high and as a result, the price of the composite would be high due to rather high price of PCM.

#### 4.8. UNDERFLOOR HEATING

Areas which are in direct contact with solar radiation hold large potential for storage of thermal heat energy. Floor solutions incorporating PCMs in areas of a building where the sun shines for large parts of the day may benefit from incorporating PCMs. Fig. 4.38. shows flat profiles filled with PCMs that were used in the floor in North House, a competitor in the US Department of Energy's solar decathlon



Fig. 4.38. Flat profiles which can be installed under floor to store and release latent thermal heat energy [60]

Xu et al. [182] performed a simulation of the thermal performance of PCMs used in a passive floor system during the winter season. The performance on the systems was influenced by the choice of covering material, the air gap between the PCM and covering material and the thickness of the PCM. For the simulations performed, the thickness should not exceed 20mm as this would not increase the influence of the thermal storage significantly.

Fig. 4.39(a) shows the structure of the box and view on the four test boxes. As reported, the application of PCMs in concrete floors resulted in a reduction of maximum floor temperatures up to  $16\pm 2\%$  and an increase of minimum temperatures up to  $7\pm 3\%$  [183].

A hollow concrete floor panel was incorporated with PCMs by Royon et al. [190, 191], as shown in Fig. 4.39(b). Thermal response to a temperature variation was also investigated, showing a decrease of the surface wall temperature amplitude and an increase of thermal energy stored for this novel floor. Clearly, it is very convenient for this method to storage energy in the PCMs.



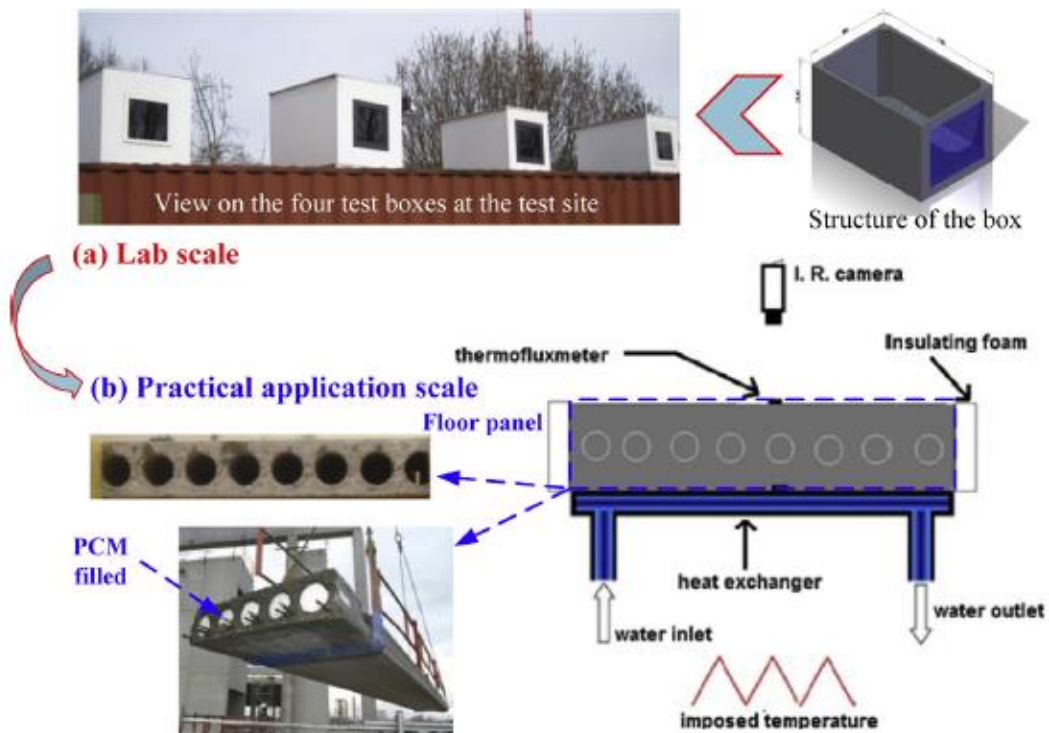


Fig. 4.39. Structure of the PCM-concrete floor [190,191]

Ansuini et al. [184] using a lightweight piped radiant floor prototype with an integrated PCM layer, with their experimental floor specimen shown in Fig. 4.40(b). A new PCM floor was also investigated by Huang et al. [185], as shown in Fig. 4.40(c), revealing the new PCM floor was able to release 37,677.6 kJ heat for 16h in the pump-off period in a room of 11.02m<sup>2</sup> and that accounted for 47.7% of energy supplied by solar water.

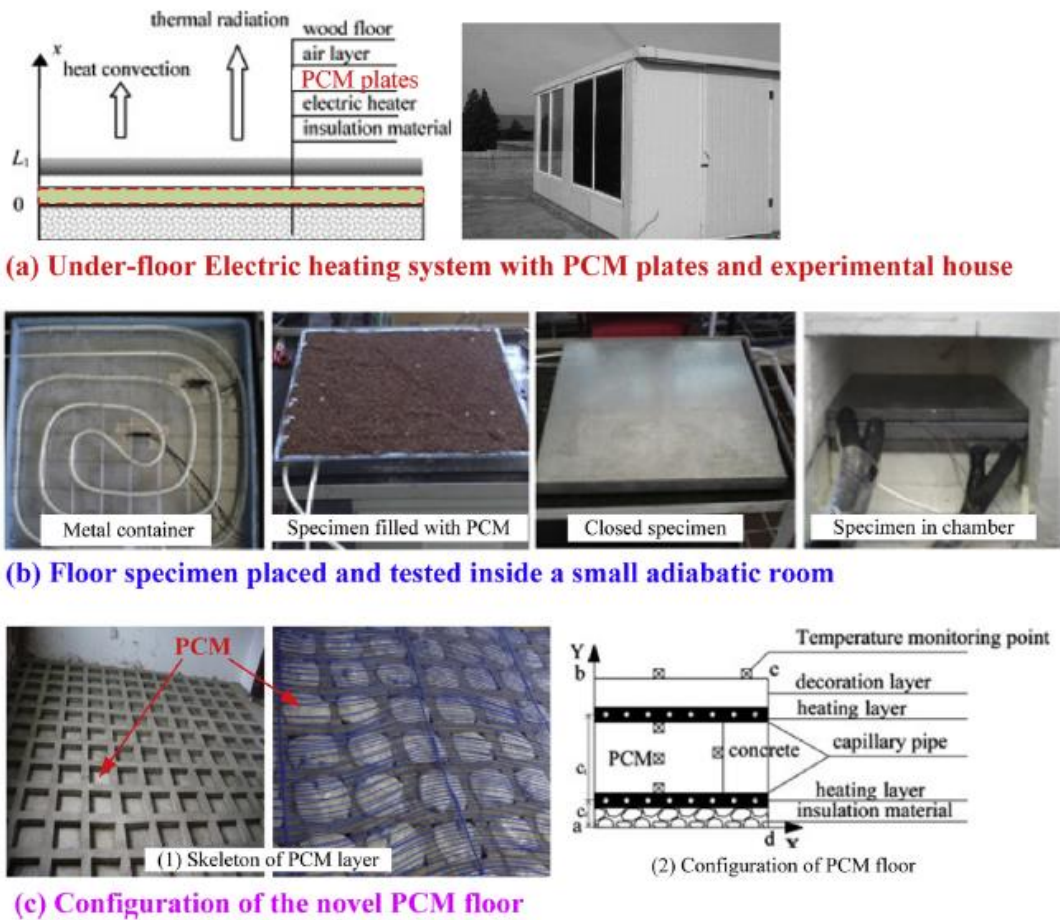


Fig. 4.40. Schematic of PCM-electric heating systems [41]

Later, the performance of a PCM floor radiation heating system was experimentally investigated by Zhou et al. [186], indicating the advantages of using PCM-capillary mat combination for low-temperature floor panel typical of solar-hot-water heating system. A two-dimensional coupled heat transfer model based on variable thermophysical parameters of PCM was established by Zhao et al. [187], concluding that the air temperature fluctuation in the cavity with PCM structure was in a smaller magnitude.

A new double-layer radiant floor system with organic PCMs was proposed and tested by Xia et al. [188], showing that the double-layer radiant floor system with PCM could meet the thermal need of users under heating mode. The above research studies showed that the designed PCM floor was capable of achieving large-span intermittent heating and lower thermal conductivity for the decoration material, and helpful for adjusting the floor surface temperature in the present design.

PCM embedded floor and a chilled ceiling also attracted researchers' attention. Belmonte et al. [189] reported a numerical study on PCM incorporated into the floor, and a hydronic radiant ceiling system was used as the energy discharge system. Fig. 4.41 shows the structure of system and the heat balance on the floor inside face. The simulation results revealed that when accompanied by an air-to-air heat recovery system, this configuration could reduce the cooling energy demand and the energy consumption more than 50%. However, the degrees of occupant comfort will inevitably vary, for example, the predicted percentage dissatisfied (PPD) increases by 2%~5%. In the view of thermal comfort study, this system is valuable to be further investigated.

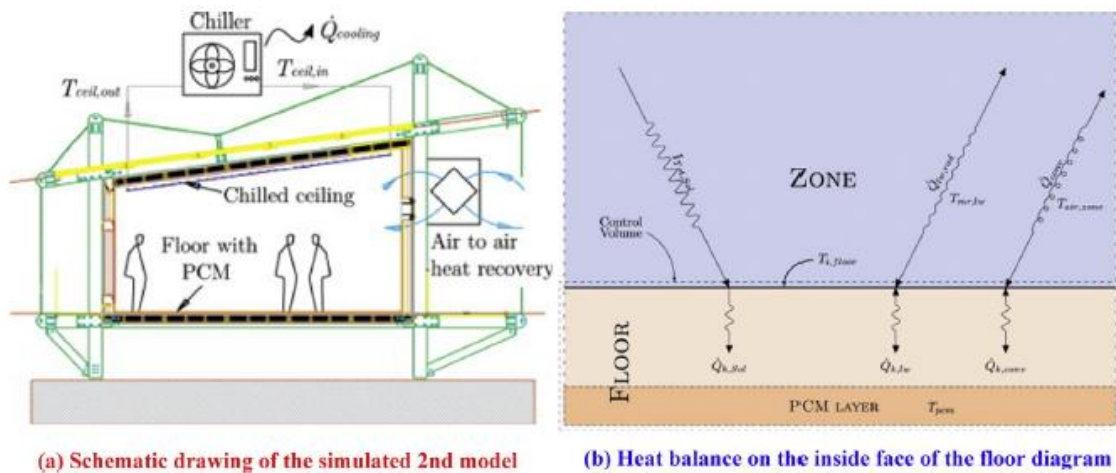


Fig. 4.41. Structure of system and the heat balance on the floor inside face [189]

In summary, studies on PCM-floor are concentrated on two aspects: (1) integrating PCMs into floor materials or PCM slabs as a layer in the floor construction, and (2) coupling a PCM-TES with floor heating system. All researchers paid their attention on energy saving for building, while few of them take the indoor thermal comfort into consideration in their experimental and simulation studies. Although most of experimental cases on PCMs were carried out, most of them were tested in the lab. To exactly calculate the indoor thermal comfort, a true building environment should be prepared, and thus field test in real building should be conducted.

#### 4.9. CEILINGS

Implementing PCMs into roof systems does not seem to have received much attention, a few studies on the possible effects of PCMs in passive roof systems have been found. The thought is that PCMs placed on the roof will be able to absorb the incoming solar energy and the thermal energy from the surroundings to reduce temperature fluctuations on the inside [60].

Pasupathy and Velraj [192] studied the effects of a double layer of PCM for a year round thermal management in Chennai, India. An experiment was performed with a PCM roof panel compared to a reference room without the PCM panel. The PCM used was an inorganic eutectic of hydrated salts. The experiment showed that the PCM panel on the roof narrowed the indoor air temperature swings, and that such a system could perform during all seasons when the top panel had a melting temperature  $6^{\circ}\text{C}$ – $7^{\circ}\text{C}$  higher than the ambient temperature in the early morning during the peak summer month, and the bottom panel had a melting temperature near the suggested indoor temperature.

Kosny et al. [193] set up a naturally ventilated roof with a photovoltaic (PV) module and PCMs to work as a heat sink (Fig. 4.42.). The goal was that the PCM would absorb heat during the day in winter and release it in the night to reduce heating loads. In the summer the PCM would absorb heat to reduce the cooling loads in the attic beneath. A full scale experiment was performed over a whole year from November 2009 until October 2010 in Oak Ridge, Tennessee.



Fig. 4.42. PV-PCM roof [193]

The data from the tests were compared with a conventional asphalt shingle roof. The PV-PCM attic showed a 30% reduction in heating loads during the winter and a 55% reduction in cooling loads. Furthermore, a 90% reduction in peak daytime roof heat fluxes was observed.

Affording to Simen Edsjø Kalnæs and Bjørn Petter Jelle [60] the thought is that PCMs placed on the roof will be able to absorb the incoming solar energy and the thermal energy from the surroundings to reduce temperature fluctuations on the inside.

Markus Koschenz [195] developed a study that describes the development of a thermally activated ceiling panel for incorporation in lightweight and retrofitted buildings. As alteration and refurbishment schemes look set to account for an increasing proportion of construction work, the focus was on minimizing overall panel thickness while providing ample storage capacity. It was demonstrated, by means of simulation calculations and laboratory tests that a 5cm layer of microencapsulated PCM (25% by weight) and gypsum suffice to maintain a comfortable room temperature in standard office buildings. The system's features also make it ideal for use in lightweight structures, the incorporation of additional thermal mass offering an efficient means of moderating temperature amplitudes in this type of building. (Fig.4.43.)

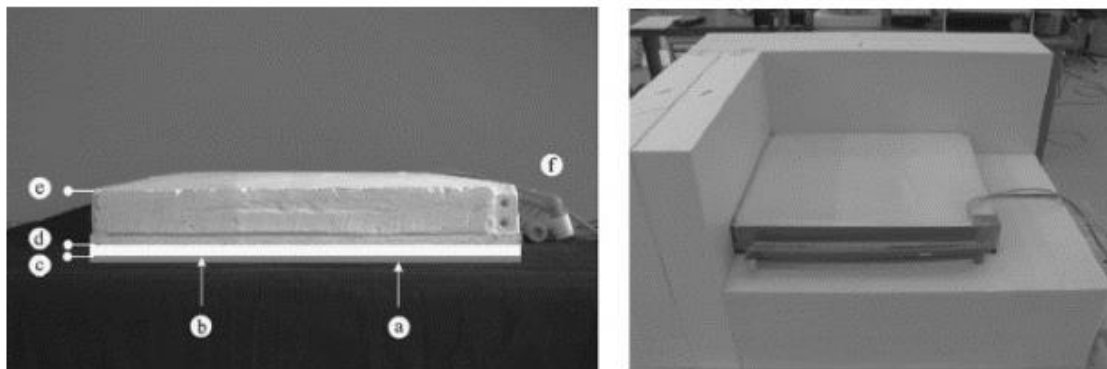


Fig. 4.43. Laboratory test set-up with prototype ceiling panel [195]

Also in his study, we can find that there are some simulation calculations for specification of required ceiling panel properties. Simulation calculations were performed to determine the required ceiling panel characteristics, based on the properties of the basic materials. Key parameters included the thickness of the PCM/gypsum composite layer, the proportion of paraffin and the minimum requirements placed on the PCM in terms of melting range and latent heat of fusion. An overall panel thickness of 5cm is required to store the total heat gain of  $320\text{Wh/m}^2$  day. The quantity of PCM in the gypsum must be at least 25% by weight. In order to meet the required temperature boundary conditions, it is important for the melting range of the paraffin to be carefully adjusted to the specific situation. The region with maximum values of specific heat must therefore correspond to  $21^\circ\text{C}$ – $22^\circ\text{C}$ .

To avoid large temperature gradients inside the material, the ceiling panels must exhibit good thermal conductivity over the entire cross-section. Here, the simulation calculations showed a mean target value of  $\lambda=1.2\text{W/mK}$  to be practicable.

Helmut Weinläder et al. [196] carried out a research that was part of the project “Development and Practical Performance Testing of Building Components with PCM in Demonstration Buildings”. In this paper a ventilated cooling ceiling with PCM was evaluated in a long-term monitoring programme in two offices and a conference room. The system showed a significant cooling potential in summer and some considerable synergetic effects if combined with a sun protection system with PCM. While the ventilated cooling ceiling with PCM and the sun protection system with PCM alone reduced the maximum operative room temperature by 2K, the temperature reduction with both systems together was up to 4K. The ventilation system of the cooling ceiling would also be advantageous for the regeneration of the PCM blinds.

Fig. 4.44. shows the operation modes of the ventilated cooling ceiling: During daytime, the ventilation is in purely circulating operation guiding the warm room air onto the PCM; during night time, cool outside air is used to regenerate the PCM.

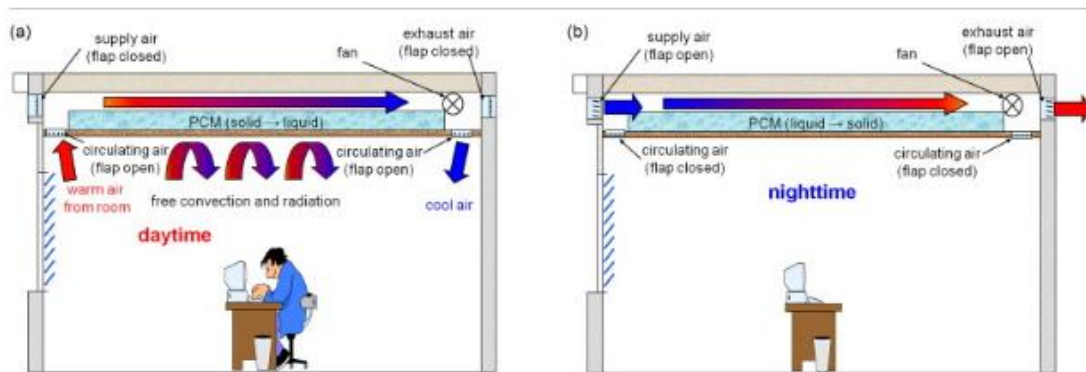


Fig. 4.44. Cooling (a) and regeneration mode (b) of the ventilated cooling ceiling with PCM

#### 4.10. THERMAL INSULATION MATERIALS

Recently, incorporation of PCMs into fibrous thermal insulation materials has received considerable attention. Kosny et al. [155] performed an experimental and numerical analysis of a wood-frame wall containing PCM enhanced fiber insulation. The wall assembly had an R-value of  $4.14(\text{m}^2\text{K})/\text{W}$  (U-value of  $0.241\text{W}/(\text{m}^2\text{K})$ ). For fiber insulation filled with 30wt% PCM in summer conditions, results showed a reduced peak hour heat gain of 23%–37% in Marseille and 21%–25% in Cairo and Warsaw.

Lei et al. [156] developed a numerical simulation in order to calculate building energy performance by integrating a PCM for cooling load reduction in a tropical climate using Energy Plus. The results demonstrated that a small amount of heat gain reduction of 4.5% was achieved with a 10mm “solid PCM” layer. In addition, a meaningful heat-gain reduction of around 40.7% was obtained by adding another PCM layer.

Jin et al. [157] experimentally studied the influence of PCM position on the thermal performance of building walls. The effects of the state of a variety of salt-hydrate PCM on its phase change performance were investigated with differential scanning calorimeter (DSC) examinations and cooling experiments.

The results demonstrated that the PCM was in the fully melted state before cooling when the PCM locations were  $2/5L$  (near internal layer),  $3/5L$ ,  $4/5L$ , and  $L$ , while in the PCM location of  $1/5L$ , the PCM was in the partially melted state prior to cooling. During the experiments, there were six locations for installing the PCM layer in the wall, as shown in Fig. 4.45.

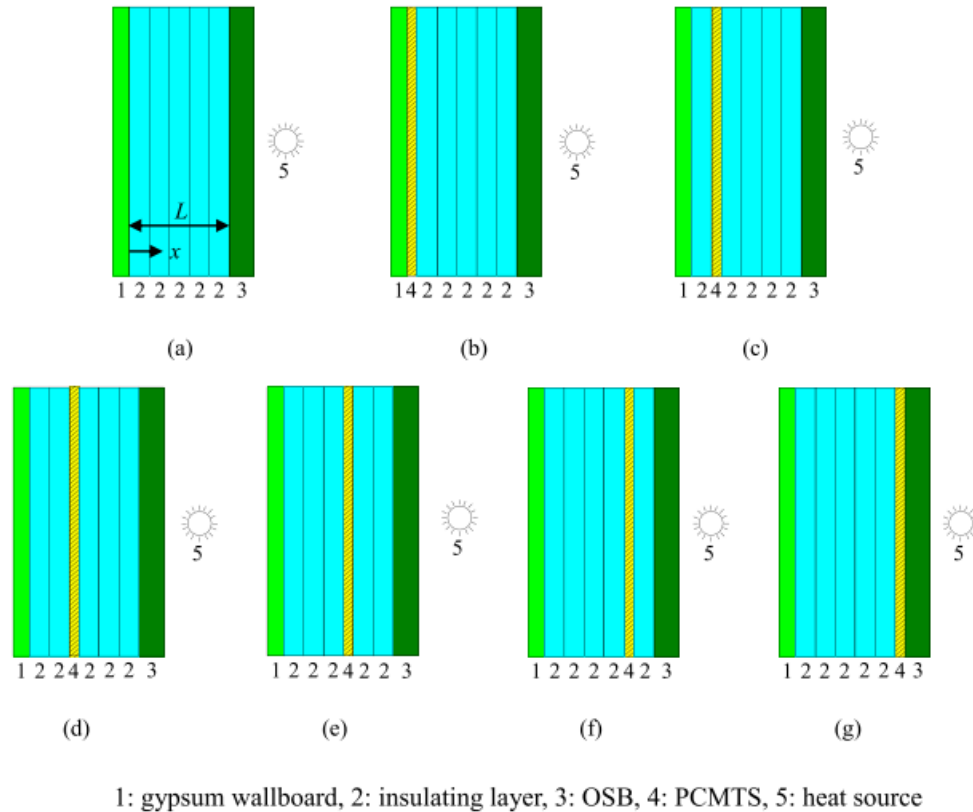


Fig. 4.45. - Schematic of wall construction (a) control wall (No PCMTS) (b) location  $0/5L$  (c) location  $1/5L$  (d) location  $2/5L$  (e) location  $3/5L$  (f) location  $4/5L$  (g) location  $5/5L$  [157]

Izquierdo-Barrientos et al. [158] developed a one-dimensional transient heat transfer model using a finite difference method to investigate the impact of PCMs in external building walls. Furthermore, several external-building-wall arrangements were analysed for a typical building wall by varying the position of the PCM layer, the orientation of the wall, the ambient conditions and the phase transition temperature of the PCM. They found that there was no important reduction in the total heat lost during winter regardless of the wall orientation or PCM transition temperature.

Kuznik et al. [159] investigated an experimental method for the thermal performance of a PCM-copolymer-composite wallboard in three different climates. The results showed that for all the cases tested, the ratio between the amplitude of the indoor air temperature in the cell with PCM and the amplitude of the reference test cell was between 0.73 and 0.78. In addition, the PCM tested kept the room air temperature within the comfort zone while the maximum air temperature of the room could be decreased by as much as  $4.2^{\circ}\text{C}$ .

Vicente and Silva [138] investigated an experimental testing of wall elements integrated by PCM macro-encapsulation. The results showed that the maximum amplitude reductions were about 50% and 80% for two different specimens. In addition, the delay time within the source specimen and the imposed temperature was nearly one hour but this value extended to three hours for other specimens with the incorporation of PCM.

Evola et al. [161] reported a complete evaluation methodology for optimising PCMs to enhance summer thermal comfort in lightweight buildings. In addition, they investigated the intensity and duration of the thermal comfort for the occupants. Finally, they analysed a new case study, including organic PCMs, on a lightweight office building. This study was useful to assist with detection of the most appropriate PCM and its installation pattern as a function of the climatic operating conditions and of the comfort requirements.

Xing Jin et al. [162] investigated the dependence of wall thermal performance on PCM location leading to the most appropriate PCM locations. They evaluated a dynamic model of walls with and without a PCM thermal shield. The experimental results showed that the optimum location of the PCM thermal shield was  $1/5L$  from the interior. In this location, the peak reduction of heat flux was approximately 41% and time lag was around 2h. They also evaluated the optimal location of a “thin” PCM layer while varying PCM thickness, melting temperature, heat of fusion and interior surface temperatures, to increase thermal capacity and shave peaks of heat flux within the wall. Based on a mathematical model, the optimal locations of the PCM layer were determined to be closer to the exterior surface of the wall. While the thickness, heat of fusion, and the melting temperature of PCM were increased, the optimal position of PCM was closer to the interior surface.

#### **4.11. FURNITURE AND INDOOR APPLIANCES**

A point that has not been investigated with the same affluence, but should be mentioned, is the possibility of using PCMs in furniture and other indoor appliances. The benefit of PCMs is as mentioned their ability to store heat in periods where there is a surplus, and release the heat when there is a deficit. It would be interesting to study how incorporation of PCMs into other components in a building besides the structural components, could benefit energy savings and thermal comfort [60].

PCMs have already been widely studied for textile applications [163], showing that there is a possibility of adding PCMs to various forms of materials. The large surface area of the furniture exposed to the indoor environment can be ingeniously used for latent heat thermal energy storage (LHTES) with the integration of phase change materials (PCMs). Their appreciable energy storage density is an interesting asset for increasing the thermal inertia of light structure buildings and for extending the applicability of the TES strategy.

PCM furniture could allow integration of LHTES in low thermal inertia dwellings without the need for building renovation.

Horikiri et al. [165] used computational fluid dynamics (CFD) to assess the effect of room occupancy and furniture arrangement with and without heat generation in terms of local thermal comfort. Three different configurations of furniture and occupants were compared with the empty room case.

The study pointed out that addition of non-heat generating furnishing in the ventilated room can induce complicated flow re-circulations and high local air velocities around edges of the furniture. However, it has little influence on room temperature and airflow buoyancy strength, compared with that of unfurnished room case.

Finally, the heat generation from the TV did not have important impact on the thermal comfort and heat transfer. As seen in Fig. 4.46(a). This configuration includes a double panel radiator as a heat source, a glazed window, and a ventilation system (i.e. an inlet above the window for extracting cold fresh air, and an outlet on the opposite wall for exhausting warm air), respectively (denoted as model S0 thereafter).

The origin of the coordinate system is located at the mid-point of the intersection line between the floor and the inner wall surface with inlet slot and window along the span wise direction, as shown in Fig. 4.46a. Analysis of the impact of occupied room on indoor thermal comfort is carried out by three different layouts/scenarios with furniture and/or occupants (S1–S3) (see Fig. 4.46b–d), compared with the original empty model room layout/scenario S0.

The furniture considers a cabinet (or a TV stand) with a TV at a fixed position, located at the middle of one side-wall opposite to the sofa, and two different types of sofa. A small sofa that has no armrest is located at the back wall, facing to the window wall (denoted as the layout S1) while a large sofa with armrest is located at the middle of one side-wall (denoted as the layout S2). In the layout S3, two sofas are both included. All sofas and cabinet/TV-stand are attached to the walls, assuming that the gap between the walls and the non-heat generating furniture is so small that the local heat transfer and fluid pattern inside the gap space do not have significant influences on the domain of interest, i.e. the central space of the model room [165].

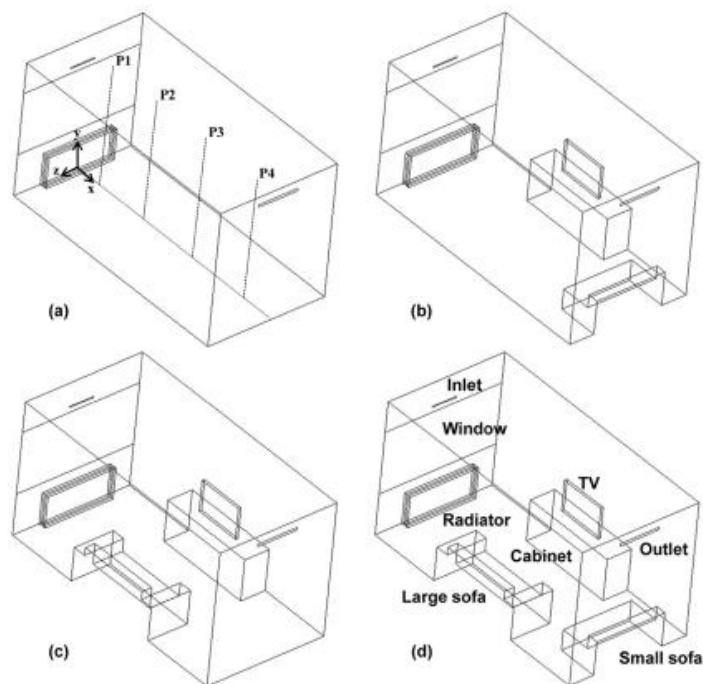


Fig. 4.46. Schematic views of four 3-D configurations of furniture with monitoring four lines (P1–P4): (a) layout S0, (b) layout S1, (c) layout S2, (d) layout S3 [165]

The humidity buffering effect of materials located in the thermal zone can reduce humidity variation. It improves thermal comfort and decreases energy consumption of the mechanical systems for humidification or dehumidification.

Yang et al. [166] conducted full-scale experiments on moisture buffering capacity of interior surface materials and impact of the presence of furniture in the interior space. The results showed that the indoor humidity variation decreased by up to 12% and the total moisture buffering potential of the room increased by up to 54.6% for a fully furnished case. The authors explained that furnishing elements present much more surface area for moisture exchange and buffering than envelope inner



surfaces. Furniture materials can also hold more water vapor than interior surface ones. In addition, the variation of moisture contents of walls screened by furnishing is not always the same as in an empty room. The results also indicated that a bookshelf with books and a bed with mattress present higher moisture buffering capacity than tables, chairs and curtains. A full-scale test hut composed of two identical test rooms, one on top of the other, was assembled inside a large-scale environmental chamber, as shown in Fig. 4.47. The envelope of the test rooms was of typical Canadian residential wood-framed construction. Each room had an interior dimension of 3.62m by 2.44m by 2.43m high. Two hygroscopic materials, uncoated gypsum board or wood panelling, were installed as the interior finishing materials on two of the vertical walls. The rest of the indoor surfaces were covered with aluminium metal sheets (0.8mm thick) to avoid any moisture interaction. Tests were carried out independently in each room [166].

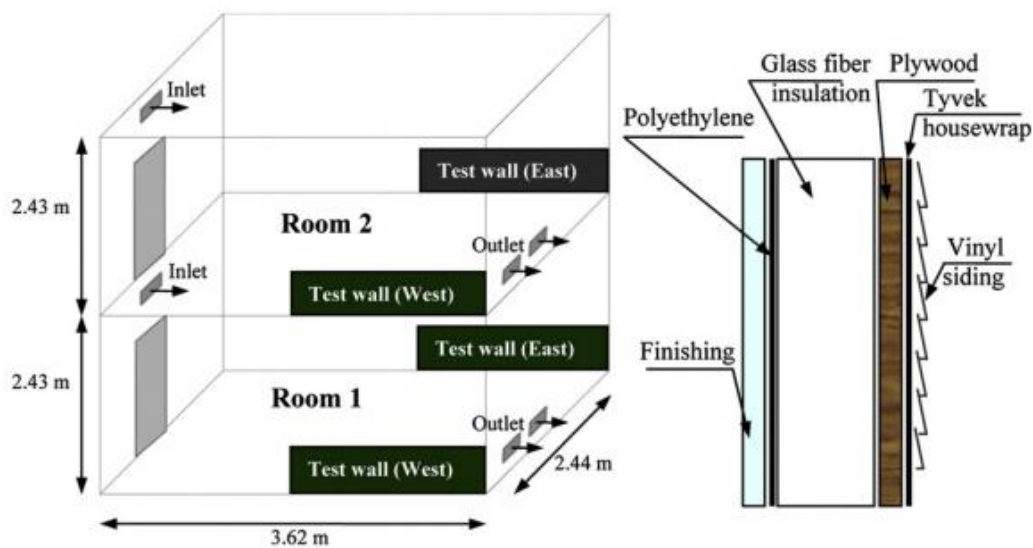


Fig. 4.47. Configuration of two identical test rooms and the test wall assemblies [166]

Mortensen et al. [167] explored the local micro-climate created by furnishing elements close to cold walls. A piece of furniture placed near a poorly insulated external wall can lead to condensation on the inner side of the building envelope. The authors used particle image velocimetry to perform a two-dimensional experimental analysis of the airflow pattern in a small air gap between a chilled wall and a closet placed next to it. Two air gap widths were tested: 25mm and 50mm. Length of legs of the furniture varied from 0mm to 200mm. The study indicated that vertical flow dominates with similar behavior as in between vertical plates heated asymmetrically. The flow in the air gap was not fully developed and maximum velocities were found near the cold wall. Finally, the flow rate increased when the gap was expanded or if the furniture was elevated from the floor.

Corcione et al. [169] published numerical studies showing a non-negligible decrease in the heat transfer from radiant surface systems to the furnished indoor space in comparison to an empty room case. The air and mean radiant temperature were also impacted. Fontana extended this work with experimental investigations using a small-scale test setup to look at the impact of furniture pieces with different surface areas, locations and distance from the floor. The author concluded that 40% of floor covering with different kinds of furniture can reduce the heat flux from the radiant floor to the room by 25%–30%.

Pomianowski et al. [168] conducted a full-scale experiment concerning the influence of an internal obstacle on the overall heat transfer in a room when using displacement night time ventilation. The presence of a table changed the average convective heat transfer coefficient in the test chamber and the mean heat flux at the ceiling by 3.96% and 9.84% respectively, when applying an air change rate of  $6.6 \text{ h}^{-1}$ . The only noticeable drops in the temperature efficiency caused by the presence of the table were observed at low air change rates. The studies presented above pointed out that the influence of furniture cannot be neglected when designing a radiant floor system. Surprisingly, it has been found that Fontana [170] was the only one to publish the results of an experiment investigating the impact of furniture on radiant systems. As mentioned by Le Dréau [171], further experimental researches are required to quantify the effect of furniture on the effectiveness of radiant systems [73].

Antonopoulos and Koronaki [172] characterized the thermal capacitance, time constant and thermal delay of typical Greek detached houses with a one-dimensional finite-difference model. The authors took into account the presence of furniture thermal mass and modelled it as an equivalent one-side wooden slab of  $6 \text{ m}^2$  per  $\text{m}^2$  of floor area and a thickness of 5cm, which gives an internal mass density of about  $180 \text{ kg per m}^2$  of floor area. No justification was given for the choice of this value. Solar load and internal heat gains were applied to the air node only. The results showed that the envelope, partition walls and furniture represented 78.1%, 14.5% and 7.4% respectively, of the total effective building thermal capacitance. The authors concluded that furniture/indoor mass can increase the building time constant and thermal delay by up to 40% (25% for interior wall partitions and 15% for the furnishings) [172]. As seen in Fig. 4.48., the total internal mass is often over-estimated.

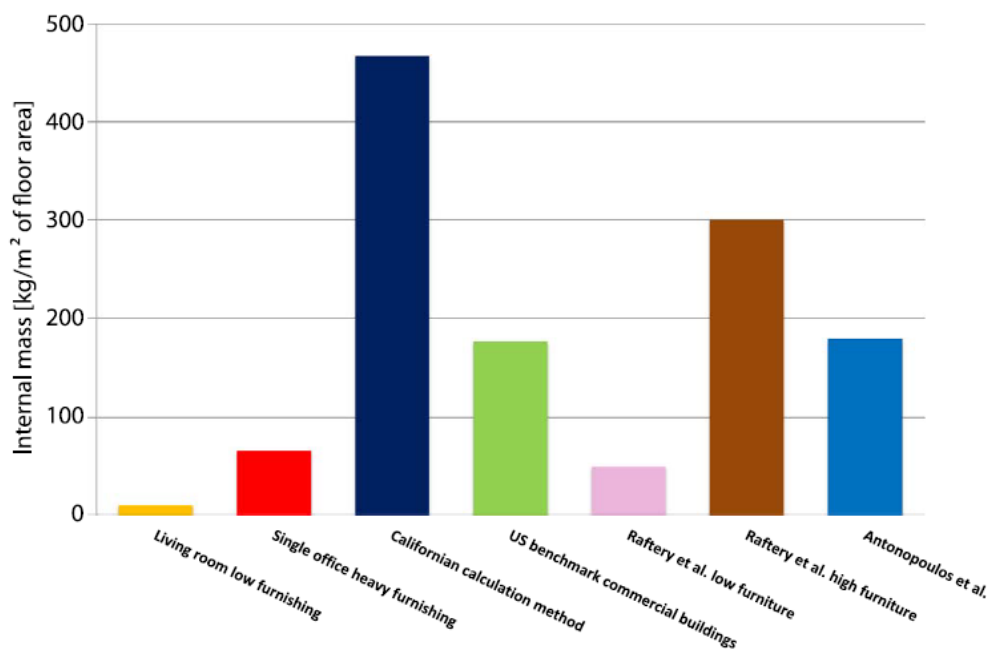


Fig. 4.48. Comparison between results of the survey and other published values [73]

Yam et al. [173] developed a simplified building model with adiabatic envelope and no internal sun load to examine the nonlinear connection between internal thermal mass and natural ventilation. They found that a maximum indoor temperature phase shift of 6h can be reached if the fresh air is directly supplied from the outdoor environment, presenting periodic temperature variations. The authors

proposed that an appropriate amount of thermal mass should be used in building passive design because further increase above an optimum point does not change the phase shift of the system.

Wolisz et al. [174] carried out a numerical analysis on the impact of modelling furniture and floor covering in thermal building simulations with temperature set point modulation control. The study cases were a massive building and a light frame building, both with very good insulation levels and under-floor heating systems. The furniture element was represented by an equivalent horizontal board of wood or metal. Long-wave radiation heat exchanges were modelled by coupling inner surfaces to a fictive massless black body node in a star network scheme. One internal wall had 50% of its surface area covered by furniture. It was found that after 4h of increased set point, an empty massive room was 1.2°C warmer than the one with flooring and furniture. A fully equipped massive room can have a time delay of more than 7h to raise its temperature by 5°C, compared to an empty room. Furnishing and floor covers can change cool-down times by up to 2h in the case of periodic set point control. The floor covering presented more significant effect on the heating time than the furniture element because the under-floor radiant system was used as a heating source. However, the effect of furniture became more important for the lightweight room with periodic set point scenario. The authors concluded that both the furniture and the floor covering of a room have a distinct and significant impact on the indoor temperature for dynamic set point control [174].

Raftery et al. [175] executed a sensitivity analysis on the influence of furniture on the peak cooling load of a large open space multi-story office building located in San Francisco. The authors used the Energy Plus software and varied multiple parameters such as type of HVAC system, building orientation, window to wall ratio, envelope thermal inertia and amount and surface area of the internal mass element. Two different furniture models were tested: a simplified non-geometric furniture element, which is not taken into account for solar radiation and long-wave heat exchange and a new model with a geometric representation of an equivalent furniture slab located in the center of the room, 0.5m above the floor. With the latter, direct and diffuse solar radiation repartition can be executed accordingly with shading effect of the planar element on the floor. Long-wave radiation heat exchange can also be calculated with correct view factors. Results were presented using the median value following by the lower and upper quartiles in parentheses. The study found that internal mass can change peak cooling load by -2.28% (-5.45%, -0.67%). The geometric modelling changed peak cooling load by -0.25% (-1.02%, +0.23%) when compared to the non-geometric model. This geometric modelling had a larger effect in cases with high direct solar radiation and almost no effect for low solar loads. The impact was also found more important for HVAC radiant systems, which yield a surface temperature asymmetry. The thickness of the internal mass element had a relatively large impact on results. Very thin elements with a small time constant convert the solar load into a convective load quickly and can thus increase the peak cooling load. The authors concluded that the choice of modelling method is not significant compared to the uncertainty on the internal mass characteristics such as surface area, material properties, weight and thickness [73].

#### **4.12. SAFETY REQUIREMENTS**

The safety requirements for materials used in buildings are crucial points for the PCMs to fulfil. As mentioned earlier, PCMs should not be toxic or flammable. However, for many organic PCMs flammability and possible release of toxic fumes during combustion have been an issue. Solutions have been made to counter this issue, such as ignition resistant microcapsules for PCMs and the adding of fire retardants [60].

Hence, it is of significance that manufacturers of PCMs for building applications are required to give reliable information about the fire performance of their products. Nguyen et al. [197] reviewed the work that has been carried out to improve fire safety of PCMs. This work investigated the use of fire retardants to increase fire resistance of composite PCMs.

#### **4.13. CHAPTER SYNTHESIS**

Incorporating phase change materials (PCM) into a building enables a more dynamic use of energy. Due to the storage capabilities of PCMs, excess heat can be stored during warm periods and released during cold periods. It may also work the other way around, storing cold energy and using it for free cooling systems in warm periods. The benefits of using PCMs in buildings mainly revolve around a decrease in energy usage along with a peak load shifting of energy required for heating or cooling and an increase in thermal comfort by decreasing temperature fluctuations [60].

Commercial products have been developed and released on the market with some success. What makes PCMs particularly interesting is the fact that many PCM solutions, e.g. wallboards, floor tiles, window, bricks and concrete can be added to the construction with fairly little alterations to the current way of building.

However, there are a wide range of materials which can be used as PCMs and identifying the correct PCM for the specific application and for the specific climate conditions is an area which needs further research. Calculations of payback periods for PCM installations are also needed to further validate the use of the PCM technology.

Though solutions have been tested to increase thermal conductivity for more effective absorbance and discharge cycles, this has come at the cost of lower latent heat storage per unit weight and unit volume, hence giving the PCMs less storage potential.

Fire safety is still an issue for organic PCMs, though here as well, solutions which show promise have been introduced.

The PCM technology seems promising. However, there are still some hurdles which need to be overcome for a large-scale application of this technology. Standards which state test methods and can help identify the correct PCMs for various climates, to enable proper cycling and optimization of PCM systems, are needed. Research into new PCM technologies is also of major importance.

# 5

## CONCLUSION

### 5.1. SUMMARY OF THE MAIN FINDS AND CONCLUSIONS

It was carried out a review of thermal energy storage using phase change materials with focus on the building application. The information gathered is divided into the different application of PCM. From the research, it can be concluded that PCM application for passive solutions in construction materials has been studied for a couple of decades and by many academics.

There are several materials that can be used as phase change materials. A common way to distinguish them is by dividing into organic, inorganic and eutectic PCMs. These categories are divided based on the various components of the PCMs. Paraffin and binary organic acids are the mainly phase change materials used in envelopes.

Flammability risk is still an issue so all products with PCM shall be tested with respect to fire retardation and accomplish necessary fire codes and standards. Suitable thermal properties of PCMs and their composites, such as, thermal conductivity, thermal diffusivity, specific volumetric heat and specific heat capacity have to be determined as a function of temperature to properly determine dynamic performance and potential for the entire energy storage system. Regarding measurements of thermal properties of PCMs and their composites, some experimental methods are presented. For specific heat capacity measurements, DSC isothermal step mode, DTA and T-history methods can be recommended. On the contrary, results from DSC dynamic mode might be dependent on sample size and temperature ramp.

Heat stored in the PCM during high temperature periods (days) should be discharged during low temperature periods (nights) to be able to perform on the consecutive day, so phase change materials can decrease energy consumption, shift the peak loads of cooling energy demand, decrease temperature fluctuations providing a thermally comfortable environment, and reduce the electricity consumption. The thermal inertia, which can be defined as ‘time lag’ and ‘decrement factor’, is one of the important parameters to estimate the thermal performance of the buildings.

When studying the potential of PCM products, boundary condition (temperature fluctuation, heat transfer on the surface) and heating loads in experimental set ups and in simulations have to represent realistic condition, otherwise their performance will be either over or underestimated. When used in buildings, PCMs can be incorporated into other building materials. This topic has attracted a lot of interest as it will allow buildings to be built in a similar way that they are built today, but with materials that have an increased thermal energy storage capacity. In the reviewed literature it was recognizable that wall systems integrating PCMs have received the most attention.

As most PCMs designed for building applications go through a liquid phase, encapsulation is needed to avoid complications such as leaking of PCM to the surface and spreading of low viscous liquids throughout the material. Therefore, methods such as direct incorporation and immersion of PCMs in building materials are not well suited for long-term applications.

Nevertheless few detailed studies on the overall effect of PCMs in real life constructions, commercial PCM products have already been used in several projects.

Gypsum materials can be combined by up to 45% by weight of PCM when strengthening the structure with some additives and up to 60% by weight in the wall board composites. On the other hand, in the concrete materials only up to approximately 6% (by weight) of PCM has been implemented.

When looking for PCM in the glazed envelopes, only few researches can be found and much less work has been documented comparing to the opaque constructions with PCM. Based on the reviewed studies, it can be concluded that PCM in glazing, shading and shutters might be an interesting addition to the building envelope in order to minimize solar heating loads. Application of PCM in the glazed surfaces shall be carefully designed, since on one hand, it can help reduce solar thermal loads during the hot season, but on the other hand, it can decrease thermal resistance of windows and by that increase heat losses during the cold season. Therefore, potential of PCM in the glazed envelopes should be carefully studied with respect to the climate condition.

PCM-ceramic tiles present remarkable potential for improving the thermal comfort inside buildings due to their ability to reduce indoor space temperature fluctuations.

The accurate potential to increase dynamic heat storage capacity of concretes by incorporation of PCM is doubtful. Firstly, the thermal mass increase is not as high as expected and secondly, thermal conductivity decreases significantly due to addition of PCM to concrete. Only, 5%–6% by weight of PCM corresponds to approximately 12%–15% by volume of concrete, which means that the share of PCM in concrete is rather high and as a result, the price of the composite would be high due to rather high price of PCM.

Furnishing elements offer a large surface area exposed to the indoor environment, which makes them a good candidate for PCM integration. It can be an interesting solution for the implementation of passive latent heat thermal energy storage (LHTES) systems without construction work and thereby improving thermal inertia and energy flexibility of light buildings. Though, the integration of PCM in furniture raises new issues concerning their defiance with fire regulation, recycling process and total life cycle analysis.

It can be concluded, that potential of latent heat application should always be compared to realistic and relevant reference systems/constructions, heat storage potential of PCM technologies should always be analyzed taking into account thermal properties of PCMs/PCM composites but also heat transfer condition on the surface.

## **5.2. SUGGESTIONS FOR FUTURE WORK**

Further investigations still need to be carried out on the incorporation methods for PCMs to be embedded in existing building structures, long-term stability and any other problems which may affect the safety, reliability and practicability of the thermal energy storage used in buildings.

In published studies, most of the information concerning high-temperature PCMs lacks completeness. Consequently, it is necessary for researchers to attach importance to completing and providing various aspects of information when actively conducting experiments to develop new materials. The most

important items of information are thermal conductivity in the operating temperature range, specific heat in different phase states, environmental impacts, costs and other factors, so as to be able to measure each material's application value more comprehensively and objectively.

There is no standard method (such as British Standards or EU standards) developed to test for PCMs, making it difficult for comparison to be made to assess the suitability of PCMs to particular applications. A unified platform such as British Standards, EU standards needs to be developed to ensure same or similar procedure and analysis (performance curves) to allow comparison and knowledge gained from one test to be applied to another.

In PCM research community there is a lack of one thermal analyses (TA) method convenient to measure larger PCM samples. T-history is the suitable candidate. It is important to get in consensus among all researchers to suggest a common instrumental setup, data analysis and presentation of final results.





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