A REVIEW ON PHASE CHANGING MATERIAL

A DISSERTATION

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Submitted by:

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CANDIDATE'S DECLARATION

I, (Anjali Tanwar, 2k21/MSCCHE/52) students of M.Sc. (Applied Chemistry), hereby declare that the project Dissertation titled "A Review on Phase Changing Materials" which is submitted by me to the Department of Applied Chemistry, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "A Review on Phase Changing Materials" which is submitted by [Anjali Tanwar, 2k21/MSCCHE/52] student of M.Sc. (Applied Chemistry) Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Phase Changing Material based thermal energy storage (TES) systems in buildings has become a topic of conversation among the researchers in recent years. PCM base thermal energy storage system provides high thermal storage density and that too within moderate temperature variations. PCMs can be used in active and passive heating or cooling systems. PCMs have the ability to store energy and other heat gains like latent heat within a particular temperature range, reduces energy consumption and increase in thermal comfort is observed by reducing temperature fluctuations. PCM has attracted growing attention due to its various thermal-physical, kinetic, economic and environmental properties.

The construction industries are responsible for consuming huge amount of energy therefore there is need for development of new materials which can reduce energy consumption and enhance thermal efficiency of the buildings. Using PCMs in construction materials have shown significant results in terms of thermal energy storage. This article summarizes previous works on thermal energy storage in buildings, types of PCM, its classification, methods of incorporation of PCM into building materials like macro encapsulation, micro encapsulation, direct incorporation and immersion, and their current applications in buildings such as PCM wallboards, PCM cement mortar and concrete etc.

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CHAPTER 1

INTRODUCTION

The rapid surge in human population and development has led to overuse of natural resources. The economic development has led to huge demand in energy consumption and hence exploitation of natural resources occurs. Most percentage of the present-day energy demands are fulfilled by Fossils fuels. According to a data published by BP Statistical review of energy 2020, one way or the other, approximately 84% of the energy consumption today is met by using fossil fuels. Since Fossil fuels are Non-Renewable in nature, so arrangements for its sustainable use must be done. However, the over use of the Fossil fuels is not only the problem, rather most of the harmful gases released from the use of these fossil fuel is also a considerable problem.

This increase in energy consumption can be attributed to majorly two parameters; the development rate in urban areas and the increase in the demand of comfort levels of the people. This causes excessive use of the fossil fuels and other forms of non-renewable forms of energy. This is not only deteriorating the fossil fuel levels but also producing huge impacts on the environment.

A huge amount of greenhouse emission happens from the households and buildings. According to a data published by European Union around 40% of the total fossil fuel energy is consumed by the households and buildings which in turn alone contributes 32% of the total greenhouse gas emission. Additionally, it was found that around half of this energy is used in heating, ventilating and air-conditioning (HVAC) systems of the buildings.[1] Similarly, in another data it was found as high as 60%. [2] Thus finding some alternative method to reduce the energy consumption as well as lesser the greenhouse emission is of utmost importance.

Energy equivalent to around 5 x 10^{24} J is given by the sun that reaches the land surface. Noticeably, this value is around 10,000 times higher than the energy required in a year.[3] So arrangements must be done to use this renewable form of energy. Since a huge part of energy is getting consumed by buildings, therefore more sustainable and energy efficient building can be a potential solution to the energy usage problem. Now, development of some novel technology in the buildings which promotes energy efficiency and reduces the greenhouse emission without altering the comfort levels in different weather conditions is the new aim of the researchers and policy makers.[4]

A very novel technique with respect to cooling and heating of buildings is using Phase changing material or "PCM" in construction. PCM has attracted attention of engineers and architects since last 4 decade. PCM work on Latent heat thermal energy storage principle (LHTES). It absorbs the excess energy and uses it efficiently to regulate the temperature thus, maintaining the supply and demand of energy by controlling the internal temperature. In this way it not only increases the comfort but also uses the natural energy sufficiently and sustainably. [5]**,**[6] With the use of PCM and its ability of efficient energy consumption has made it most suitable for use in construction materials so as to conserve the energy, do good for environment and contribute to sustainable development. The incorporation of Thermal energy storage (TES) technologies in building contributes by reducing the high demand of energy, allows usage of natural renewable energy provides efficient management of thermal energy thus improving the energy efficiency of building. [7]

As, a considerably large amount of land surface is now been covered by buildings therefore, using solar energy to power them and maintaining their temperature and comfort using PCM can be a very promising future. Therefore, combining phase changing material in construction can be a move towards sustainable future. Henceforth it is now necessary that construction factories should stop using the traditional methods of construction and start incorporating innovative ideas like PCM to solve the ever-existing problem of energy consumption.

1.1: - CONCEPT OF THERMAL HEAT STORAGE

Thermal energy storage system, as the name suggests is used for storing/stocking energy. Under such system, energy is stored and it is used for later for heating and cooling purpose. **[22]** TES systems are used for various purposes but their major role is seen in phase changing materials (PCMs) for energy storage and temperature regulation in buildings, industries and construction. Various advantages of TES are: it is one of the highly reliable and efficient methods for energy storage. It is economic in nature i.e., it reduces the cost of energy consumption for e.g., using PCMs, causes lesser pollution to the environment i.e., it does fewer greenhouse gas emission. **[23]** Hence, TES not only decreases the difference between the demand and supply of energy/electricity thanks to its energy storage property but also improves the quality and performance of the system wherever inducted. The various types of thermal energy storage are shown below in Figure shown below

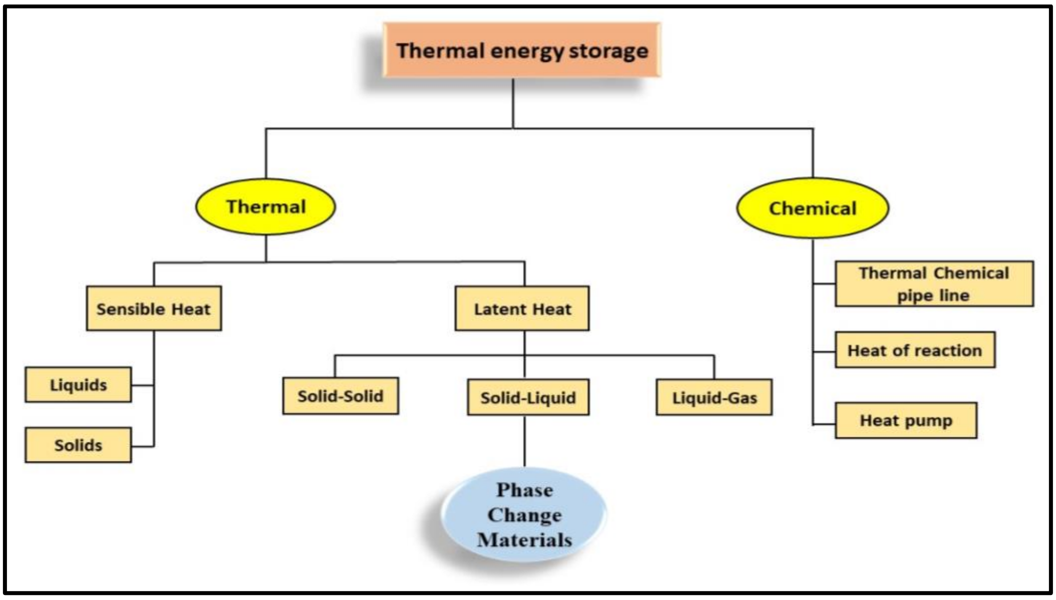

Figure 1. Classification of Thermal Energy storage

As shown in the figure above, broadly TES can be classified into two types: First, where energy storage happens by thermal mechanism and second where energy storage happens by chemical mechanism. Thermochemical heat storage (TCM-TES) due to its costly nature and lesser lifespan are not considered widely.[8] Thermal is further sub divided into Sensible and Latent Heat.

Sensible heat storage (SHS) is the easiest method of storing heat. It is done by heating or cooling any liquid or solid storage medium e.g., water, rock, salt etc. It is the cheapest method of heat storage. Latent Heat Storage (LHS) are also known as Phase change material due to their change in state while absorbing and releasing heat. The heat is stored and released accompanying phase transition. The use of LHTES using PCM is an effective method of storing and re-distributing energy. The main advantage of Latent heat over Sensible heat is that LHS is capable of storing heat at a similar temperature range. In the initial phase LHS acts as SHS and its temperature increases linearly with time as shown in Figure 2 below later on heat is absorbed or released at a constant temperature. This temperature range is known as effective working range. LHTES are further sub-divided on the basis of their heat transfer mechanism in the later sections of the review.

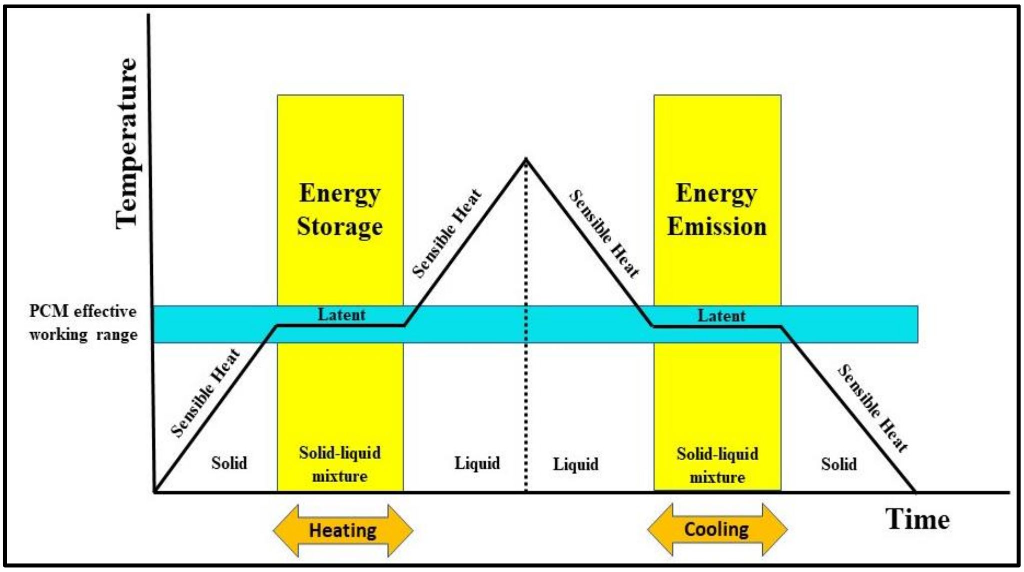

Figure 2. PCM phase transition

1.2: - PCM: OPERATING PRINCIPLE

We know that all the materials interact with the environment but major portion of the materials do not interact with the environment hence are not able to change their property according to the environment. But unlike these materials, PCM change their properties according to the environment temperature. Historically, Phase changing material and Thermal energy storage in building application to conserve energy was first used by Barkmann and Wessling [9] in 1975. Further it was studied by Telkes [10] and lane [11]. The credit for first work in nano-PCM was done by Elgafy and Lafdi in 2005 [12] Now the use of PCM and LHTES has become one of the most widely accepted techniques for thermal energy storage. Thanks to its various advantages like sustainability and lowering the energy consumption demand.

Phase change materials are that class of materials that have very high heat of fusion. Their melting and solidification happen at a particular temperature. They are even capable of storing and releasing energy. When the material changes its phase, heat energy is released or absorbed.[13] [14][15] A schematic showing the basic working principle of PCM is shown below in Fig 1.

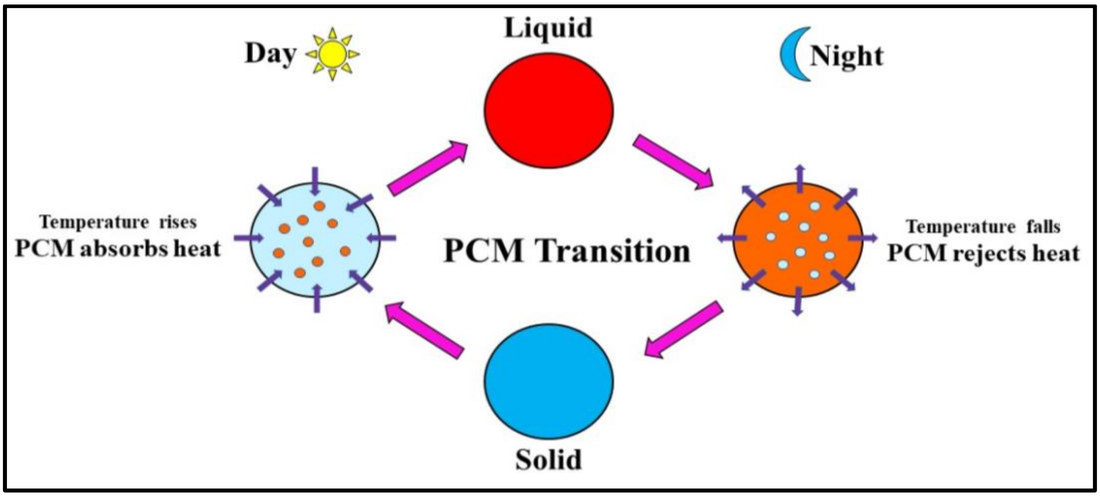

Figure 3. Working of PCM

When the temperature increases (generally during daytime) the PCM absorb and store the energy due to which there is a change in the state from solid to liquid. Whereas, when the temperature decreases (generally during night) they release the previously absorbed energy causing change in sate from liquid to solid state. During the change in phase of the material i.e., during phase transition of solid to liquid, PCMs store the energy in the form of latent heat that dissolves the chemical bonds. This process is endothermic in nature and therefore the phase change happens. Whereas, when cooling takes place, exothermic reaction happens and solid state is recovered.

There are various processes of phase change i.e., there can be various phase transitions like solid phase to liquid phase, solid phase to solid phase and solid phase to gaseous phase.[16] The phase change from solid phase to gaseous phase is high enthalpy reaction but during but the problem being, during phase transition high variation of volume and pressure is observed. The phase transition of solid-to-solid state is characteristically the same as solid-liquid transition but it has relatively low energy storage capacity. Solid-liquid phase transition is preferred for thermal energy storage because they don't show high volume change and they have good energy storage capacity too. [16][17][18]

1.3: - CLASSIFICATION OF PHASE CHANGING MATERIALS

On the basis of chemical composition, phase change materials are classified into three main categories: (1) Organic PCMs, (2) Inorganic PCMs and (3) Eutectics. The group of organics is further divided in paraffins and non-paraffins. Each group has its typical range of melting enthalpy and its range of melting temperature. Inorganic PCMs are also divided into salt hydrates, salts and metallics. For building applications and specifically their integration into walls and wallboards, only solid-liquid PCMs are used and are available with a wide range of phase change temperatures on the market [19].

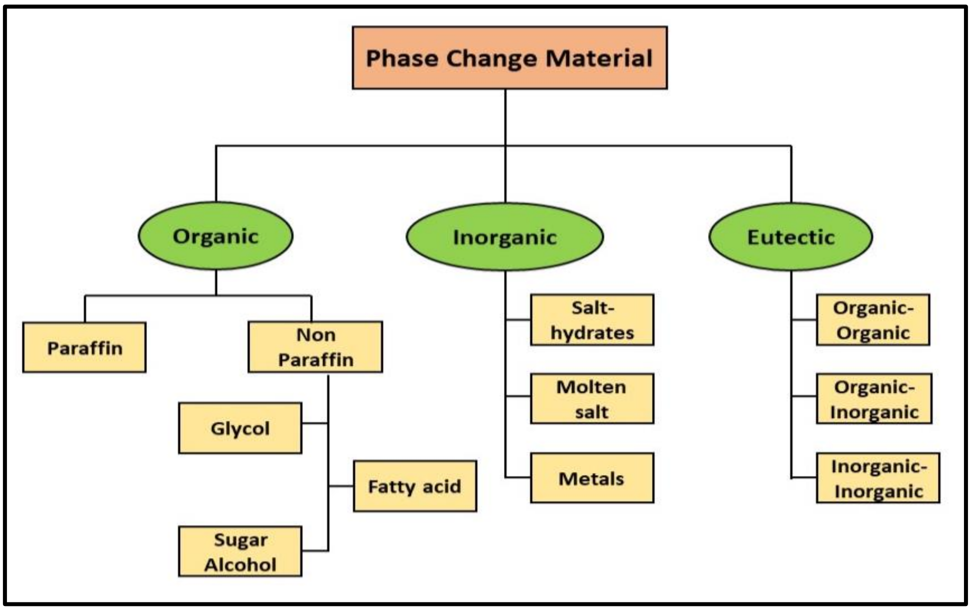

Figure 4. Classification of phase changing material

1.3.1 Organic Phase Change Materials

Most of the Organic PCMs in general are non-corrosive in nature, chemically stable, nontoxic, recyclable and having typically appropriate thermal properties like no or less subcooling and absence of phase segregation. Moreover, they are flammable and have low thermal conductivity. Also, their phase change enthalpy is lower than the other type of PCMs and undergo large changes during the phase transitions. Organic PCMs are subdivided into paraffins and non-paraffins.

1.3.1.1 Paraffin

Paraffin is the by-product of petroleum refinery consisting of carbon and hydrogen atoms which are joined together via single bond having a general formula: C_nH_{2n+2}, where n is the number of carbons present (C). If the value of n is between 1 to 4 carbon atoms, then the material is gaseous; between 5 to 17 carbon atoms is liquid, and solid for more than 17 carbon atoms. Paraffins are widely used for thermal energy storage because of the high latent heat storage, less expensive, easily available, non-corrosiveness and presence of straight chains of n-alkanes. On increasing the chain length, the melting point and phase change enthalpy of paraffin increases. Commercial paraffin waxes have a reasonable thermal storage density of 120kJ/kg up to 210kJ/kg . They are inert chemically, having a low vapour pressure in the melt, no phase segregation and available in a wide range of melting temperatures from approximately 20˚C up to about 70˚C.[20]

Some disadvantages of paraffins are its flammability and reduced thermal conductivity approximately 0.2W/(mK) which limits its applications.[20] Paraffins undergo huge changes in their volume during the phase transitions.[21] In order to increase thermal conductivity of paraffins metallic fillers and matrix structures are used, other than that plastic containers or containers with different geometries are used to decrease volume change during freezing or cooling. Apart from this paraffin as phase change emulsion has allowed for a potential application in cold storage and in high energy density applications.

1.3.1.2 Non-Paraffin

Non-Paraffin includes some organic compounds like fatty acids and their derivatives, esters, glycols and alcohols. Non-paraffins are stable both chemically and thermally, less corrosive, non-toxic and shows excellent cooling and melting properties.[21] They are much expensive than paraffins. Fatty acids based PCMs can be both saturated and unsaturated having one or more double bonds. Fatty acids are long chain of hydrocarbons having carboxyl group (COOH) at the end whose general formula can be given as $CH_3(CH_2)_{2n}COOH$. Different fatty acids can be incorporated with PCMs with different melting temperatures. Most commonly use fatty acids are divided into six categories: caprylic, capric, lauric, myristic, palmitic and stearic having 8 to 18 carbons per molecule respectively. 16 to 65°C is the range for their melting points, 17 to 64°C for freezing points and the heat of fusion lies between 155 to 180KJ/Kg.[20]

1.3.2 Inorganic Phase Change Materials

Inorganic PCMs are further categorised into salt hydrates, salts and metals. They are inexpensive, non-burnable, have higher phase changing enthalpy, good heat of fusion and good thermal conductivity. But it was found that most of them were corrosive in nature, undergo subcooling, phase segregation, phase decomposition and lack of thermal conductivity. These are some important cons that restricts their use and makes the organic PCMs much better. Hydrated salts are the most common type of inorganic PCMs.

1.3.2.1 Hydrated salts

When water molecules combine with inorganic salts in a definite ratio as part of the crystal, salt hydrates are the formed. The are represented by the formula $A_nB_m .zH_2O$ where A and B is cation and anion respectively and z denotes number of water molecules. Hydrated salts are widely used for thermal energy storage because of some unique properties: 1) High storage density of 240kJ/kg, 2) High thermal conductivity which is around 0.5W/mK and 3) less expensive as compared to paraffin waxes. [20] They are solid at room temperature and the hydrated salt starts to dissolve in their own water crystals when melting point is reached. Glauber's salt ($Na_2SO_4 \cdot H_2O$) with melting temperature between 32 and 35°C and high latent heat of 254 kJ/kg is one of the inexpensive materials that is used for thermal energy storage, but because of supercooling and phase segregation, it is restricted in its applications. [20] During the process of cycling, as the formation of lower salts takes place, hydrated salts will starts melting which reduces the energy storing capacity and makes the process irreversible. The ceramic-based composite thermal storage media provides the prospective of using phase change materials in direct contact heat exchange and it was observed that it exhibits a potential of cost development. Solid–solid PCMs can have large latent heats if one of the states is much more disarranged than the above and can be used as potential candidates for space heating and heat process implementations. [16], [21] Examples of solid-solid PCMs are pentaerythritol $C(CH_2OH)_4$, pentaglycerine $CH_3C(CH_2OH_3)_2$, polyethylene glycol and neopentyl glycol $(CH_3)_2C(CH_2OH)_2$ and their eutectic mixtures. Moreover, many of them are used as means of storage and a smaller number of solid–solid transitions are investigated and that occur at higher adverse temperatures, i.e., at 30°C up to 600°C.

1.3.2.2 Salts

The inorganic salts which are represented as A_xB_y, where A and B is cation and anion respectively are used at high temperatures. However, they have reduced enthalpy as compared to hydrated salts. For instance, a Concentrated Solar Power (CSP) plant that makes the use of salt to stock energy so that it can be used later on.

1.3.2.3 Metallics

The low melting metals and their eutectic mixtures are included in the subgroup of inorganic phase change materials. From the literature study it was observed that they are considered superior candidates for rising the temperature during the phase change as far as the volume in the system is concerned in the view of the fact that their high heat of fusion per unit volume. However, this subgroup of inorganic PCM has elevated thermal conductivity but specific heat and vapour pressure is low.

1.3.3 Eutectics

This subcategory of inorganic PCMs is a mixture of many solids in a specific proportion that their melting point is minimal, have in common high melting points and density of volumetric storage must be a little higher as compared to organic compounds. It is a combination of chemical elements or compounds having only one chemical composition and hardens at reduced temperature than any other composition achieved from the same components. These mixtures are further divided into three categories: organic–organic, inorganic–inorganic or inorganic–organic. [2], [22], [23] These combinations are worthy to be used as phase change material specifically in various cooling applications but they are widely used in building applications only disadvantage is that finite test data is accessible on their thermo-physical properties. [24], [25] The isolation of these constituents is highly unexpected as it is observed that the phase is changed without separation. The process of freezing leads to the formation of blend crystal. All the constituents throughout the time of melting undergoes a change in their physical state i.e., liquid.

CHAPTER 2

IMPREGNATION OF PCMs INTO CONSTRUCTION MATERIALS

As shown in figure 5 the heat transfer mechanism in the building is a complex process. The mechanism proceeds by various internal and external processes like conduction, convection and radiation. The external processes are generally by radiation coming from the sun and internal processes due to internal flux of the radiation and other human processes. An efficient building is one that has proper regulation of temperature to have a comfortable environment. Therefore, incorporation of PCM in a building can act as an envelope to the building and maintain the comfort. [26]

As discussed in the earlier section of the paper, PCM uses its property of LHTES to store and release the temperature. Noticeably, incorporating PCM into the various components of building like wall, floor roof can also increase the mass of those components. This would not only reduce the energy transfer but also regulate the fluctuations of the temperature.

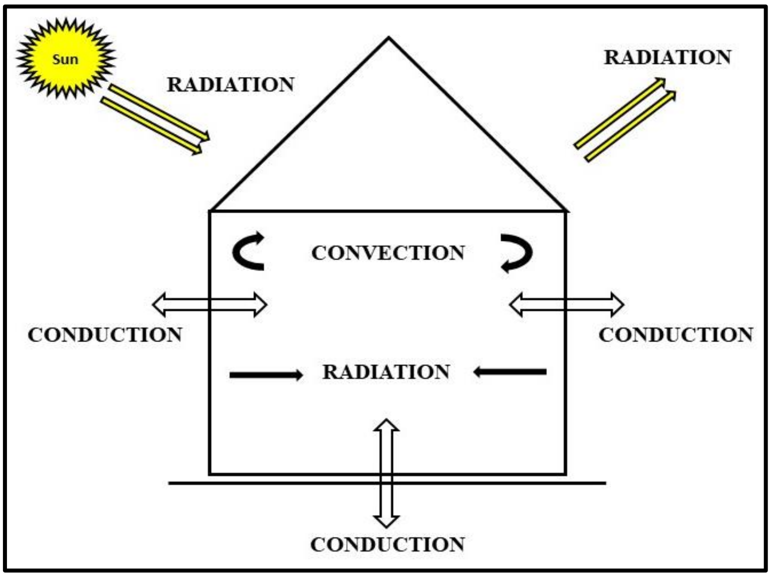

Figure 5. Heat transfer mechanism in buildings

Widely, there are 5 methods of incorporating of phase changing material in to buildings. They are: - 01: Direct impregnation or direct mixing. 02: Immersion. 03: Shape-stabilization. 04: Micro-encapsulation. 05: Macro-encapsulation. [25]

2.1: - TRADITIONAL METHODS

A report by Hawes et al.[9] indicated that the three most favourable methods to incorporate PCMs into the traditional construction materials were direct incorporation, immersion and encapsulation. On incorporating PCMs into the building materials it was observed that there was a small variation in their melting and freezing temperatures.

2.1.1 Direct Incorporation

Direct incorporation is the most uncomplicated, simple, workable and low-cost method in which PCMs are directly blended with construction materials. [27]–[29] In this method, PCMs, liquid or powdered, are directly mixed in the construction materials like gypsum, concrete and plaster during their production. The main advantage of using this technique is that no additional equipment is required. However, some problems can occur due to leakage of these materials in the melting state, which can reduce the fire resistance and can lower the compatibility of the mixture. [30], [31] Kuznik et al. [32] and Memon SA [25] reported that in this incorporation technique especially for cement should not affect these four things: 1) durability of the product, 2) mechanical properties of the mixture, 3) the hydration process and their product [20] and lastly 4) bonding between aggregate and paste. [33]

2.1.2 Immersion

It is a technique in which building structural components (like bricks, concrete, gypsum and wallboards etc) are immersed into liquid PCMs, and then this melted PCM is absorbed into their internal pores through capillary action. [33] But it was observed that PCM may leak especially after subjected to large number of thermal cycles. [30]–[32] Also, it may exert an influence on mechanical and durability properties of the building components and because of this development is restricted. Especially, the leaked PCM in contact with the cementitious binder may interfere with the hydration reactions; [25], [34], [35] it may also cause the corrosion of reinforcing steel that, in return, influence the service life of the concrete structure. [36] Hence, we can say that both the techniques direct incorporation and immersion can be successfully used to incorporate PCMs directly into the traditional building materials.

2.1.3 Encapsulation

2.1.3.1 Micro- encapsulation

Micro-encapsulation is defined as the process of containing droplets of liquid, solid or gas in any inorganic shell. This is done to prevent any leakage when the phase change takes place.[37] It gives a protective effect to the PCM. The products of this process are known as microparticle, microsphere and microcapsule. These particles are different on the basis of their morphology and internal structure. [38] This technique also improves the conductivity of the PCM and hence increases its efficiency. Broadly, there are 3 methods of PCM microencapsulation viz., Physical, physical chemical and chemical methods.[39] Presently**,** several microcapsules for PCM are made for use in building construction industry. Most of such capsules are cementitious composites.[38]

Generally, it is observed that PCM microcapsules, in constructions are used directly by mixing it with concrete in place of sand. Incorporating using micro encapsulation not only increases the thermal conductivity of the material but also increases the mechanical properties by changing the specific heat capacity of the material. Table 1 gives the summary of the popular PCM Microcapsules that are used. It is clearly visible from the table that mostly cementitious made PCM microcapsules are used.

S.No.	Material	PCM	Reference
01:	Mortar	Micronal DS 5008	[40]
02:	Concrete	Micronal DS 5001	[41]
03:	Mortar	Micronal DS 5001	[42]
04:	Gypsum	Micronal	[43]
05:	Concrete	Micronal DS 5001	[44]
06:	Geopolymer	Microtek MPCM 28	[45]
07:	Plaster	Micronal DS 5001	[46]
08:	Wood and Plastic	Micronal, Microtek	[47]

Table 1 List of commercial PCM microcapsules

There are about 50 different polymers known that can be used for wall in microencapsulation techniques. They are various natural as well as synthetic polymer used according to the different conditions. The material that is coated on the shell must have some particular requirements. They are: The polymer must have the capability to form thin film i.e., it must have the property of cohesion with respect to the core material. It must be stable as well as pliable. It should not react with the core of the shell i.e., it must be non-reactive. It must be soluble in some aqueous solvent. Ultimately it must give the desired properties viz., strength, impermeability, stability and low cost etc. [48] The thickness of the film thus obtained can be changed according to the surface area of the coating material and other properties of the system.

Methods of microencapsulation: -

The core and shell are two very important facets of microcapsule fabrication because function of the shell is to protect the core and avoid leakage and the function of the core is to keep the active material or the PCM. Different microencapsulated phase change materials (MPCMs) have different morphology and internal structure. Figure 6 below shows the different morphologies.

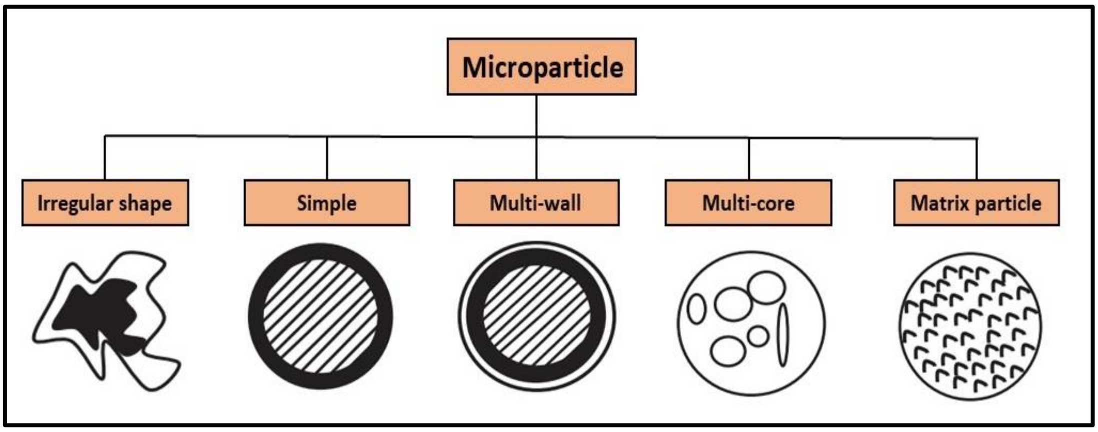

Figure 6. Morphology of different MPCMs

Broadly, on the basis of microparticle formation there are three different methods to microencapsulate PCM. They are physical, physical and chemical and chemical method.

2.1.3.2 Macro-encapsulation

Micro-encapsulation is a technique in which PCMs are encapsulated into capsules. Likewise, in macro-encapsulation PCMs are enclosed in a container. Size of these containers (tubes, spheres and panels etc) is generally larger than 1cm and this was reported by Cabeza et al. [13] A major drawback of this technique is that some PCMs have reduced thermal conductivity so it leads to solidification at the corners. Due to this slower energy release and uptake can occur. This helps in preventing the system from discharging completely during the night time. The macro-capsule obtained from this technique needs to be protected against destruction otherwise their integration into the building materials will become very difficult. This is the only reason which makes this technique expensive. [49]

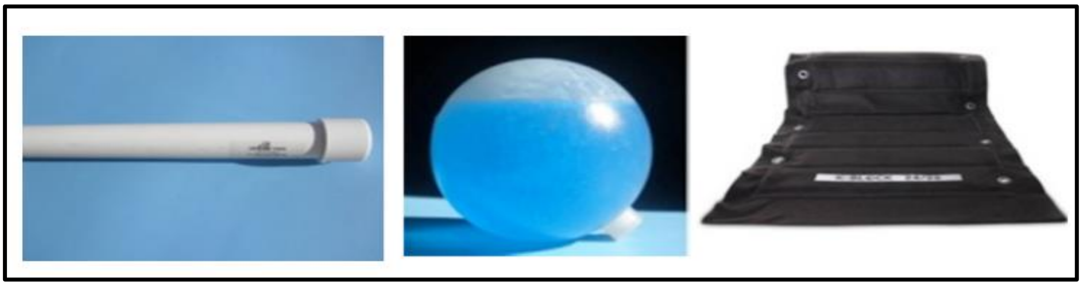

Figure 8 Examples macro-encapsulation of PCMs [50]

CSM modules, a type of PCM panel, produced by RUBITHERM, are made up of aluminium which is coated to make these panels corrosion-resistant. [51]

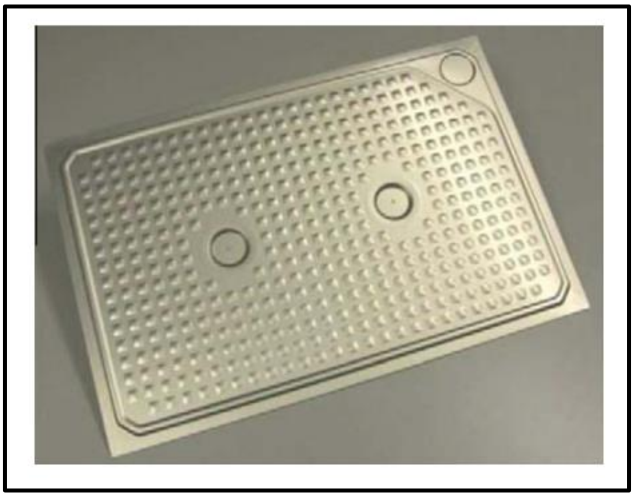

Figure 9 PCM containing CSM Panel [51]

Many commercially used PCMs can be encapsulated using this technique. This also helps in preventing the problem of leakage and the structure of construction remains unaffected.

2.1.4 Shape Stabilization

This is a technique in which shape-stabilized PCMs are obtained using PCM and a supporting material. The most widely used supporting materials found in literature are high density polyethylene (HDPE) and styrene-butadiene-styrene (SBS). This reaction occurs at high temperature. Usually, a PCM and supporting material both are melted and blended together which is followed by cooling of the supporting material. It is observed that this supports in leakage prevention which is one of the major problems with other incorporation techniques. However, the applications of shape-stabilized PCMs are restricted as the PCMs obtained through this method have reduced thermal conductivity and that why they are not used widely in latent heat storage systems. Some well-known characteristics of shape-stabilized PCMs are mentioned below[30], [52]–[54]

1) Huge apparent specific heat.
2) Suitable thermal conductivity.
3) The shape remains stabilized throughout the phase change transitions.
4) It is thermally dependable specifically melt or freeze cycle over a prolonged period.
5) The mass percentage of PCM is likely up to 80%.

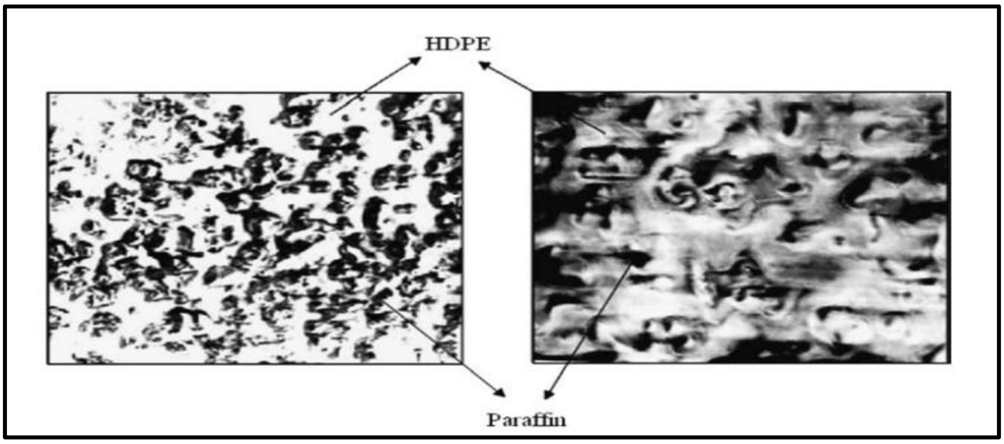

Figure10 SEM image of High-density polyethylene

PCM	Supporting materials	Ratio of PCM and Support material
Paraffin	High density polyethylene	75:25
Paraffin	High density polyethylene	75:25
Paraffin	High density polyethylene	80:20
Paraffin	High density polyethylene	70:30
Paraffin	High density polyethylene	77:33
Paraffin	High density polyethylene	74:26
Paraffin	Styrene-butadiene-styrene (SBS)	70:30
Fatty acids	graphite	92:8

Table 2 Various studies on Shape-Stabilized PCMs [53], [55]–[61]

2.2: - CONTAINERS

Containers are the materials which are used to enclose PCMs. Gypsum board, concrete, plaster and bricks that are usual building stuff, can hold PCMs. For encapsulating PCMs, panels (like PVC and CSM panels), plastic and aluminium foil can also be used. Various containers that can be used for impregnating PCMs are given in the table 3.

Containers	PCM	PCM %	Reference
Gypsum board	Butyl stearate	~25	[62]
Gypsum board	Mixture of butyl stearate-palmitate	~20	[63]–[65]
Gypsum board	(Capric acid+lauric acid) Eutectic mixtures	~26	[66], [67]
Copolymer	Paraffin wax	60	[68], [69]
Concrete	Butyl stearate (Autoclaved block)	5.6	[70]

Table 3 Containers for impregnating PCMs and relative % of PCMs

CHAPTER 3:

APPLICATIONS OF PCM AND THEIR THERMAL PERFORMANCE

3.1: - CHOICE OF PCM FOR BUILDING APPLICATIONS

For building applications, PCM possessing certain desirable properties such as thermal-physical, kinetic, chemical, economic and environmental properties can be used. But it is hard to find such a material possessing all the properties. Therefore, the criteria for best choice of PCM are listed below [20], [23], [30], [31], [71]–[73]:

- Appropriate phase transition temperature for building applications.
- Thermally reliable and stable phase transition.
- The material must be having heat capacity and latent heat as high as possible.
- The change in volume during phase transition must be small.
- No subcooling of PCM in liquid phase.
- Non-flammable, non-explosive and chemical compatibility with encapsulated/construction materials must be high.
- Non-corrosive
- Non-toxic and non-polluting so that it is safe for environment and humans.
- Recyclable
- Low cost
- Commercially available
- Do not degrade after large number of thermal cycles.

3.2: - CURRENT APPLICATIONS OF PCM

Applications of PCMs are many but in this section, we will be focusing on the applications listed below:

1. PCM enhanced wallboards
2. PCM enhanced cement mortar and concrete
3. PCM shutters and windows

3.2.1 PCM enhanced wallboards

Incorporating PCMs in building structure is through wallboards. These are the following reason behind incorporation of PCM in wallboards and why wallboards are suitable for doing so[20].

a) Frequent use in lightweight construction.
b) PCM is held by them due to the presence of surface tension forces.
c) Ease of testing
d) Having smaller surface exchange depth
e) Having larger heat exchange area
f) Can be used on both external and internal surfaces

PCM wallboards are considered as an effective and less expensive alternate to standard thermal mass. They are generally used for storing solar heat. Wallboards enhanced with PCM are successful in providing thermal storage which is distributed in the entire building.

The efficiency of these PCM enhanced wallboards depends on several factors and some are listed below:

a) The melt temperature of PCM means the temperature range at which melting occurs
b) Latent heat capacity per unit area of the wall
c) Manufacturing method means how PCM is incorporated in wallboards and the orientation of wallboards
d) Climatic conditions and direct solar gain
e) Ventilation rate and colour of the surface

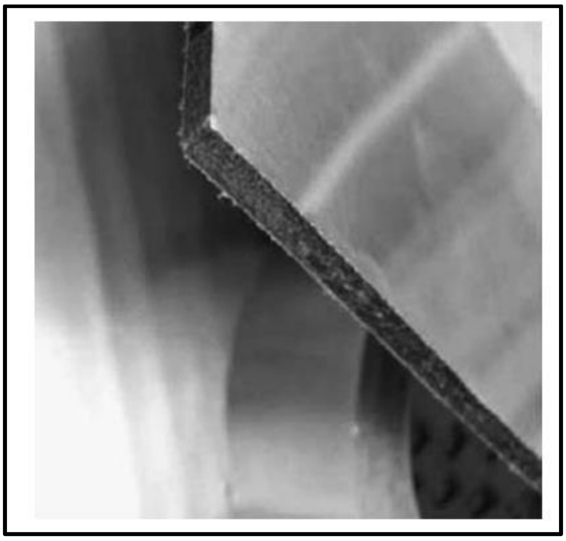

Figure 11. 60 weight % microencapsulated in 5cm thick copolymer composite wallboard [249]

Some manufacturing methods of PCM:

I. Addition of PCM filled pellets at the time of manufacturing for enhancing wallboards with PCM but this method was not that good and efficient because of low surface to volume ratio.

II. Impregnation of PCM in wallboards. This method is frequently used for enhancing wallboards with PCM because of the application of developed PCM in labs can be easily done. This method of impregnation was given by Feldmen et al.[74] Using this technique there are chances of achieving higher storage capacity than adding PCM filled pellets during manufacturing.[21], [62], [75]–[77]

III. Fabrication method: This method is based on manufacturing of gypsum boards on industrial level. This is done by mixing calcinated gypsum ($CaSO_4 \cdot \frac{1}{2}H_2O$) with water and other additives. The paste obtained is poured between the two layers of wallboards and cut. To remove extra water, the paste is dried. At this point PCM is added to the paste matrix by mixing it into a homogenous mixture.

For good dispersion and to ensure stability some dispersing agents like poly(vinyl alcohol) and salts of Na is used. As a result, it was found that the wallboards obtained from this method possess hygric and mechanical properties as compared to traditional wallboards made up of gypsum.[78]

Some investigations done by different researchers on the thermal performance of PCM wallboards.

a. Scalat et al. [65] investigated that by making use of PCM enhanced wallboards can successfully maintain room temperature within the human comfort zone for longer durations when the heating or cooling system is shut off.

b. The thermal performance of PCM gypsum board in a direct-gain outdoor test room was investigated by Athienitis et al.[62] It was observed that the room temperature was reduced by maximum of 4℃ during the daylight.

c. Another study by Neeper [79] on the thermal dynamics of room. He used fatty acid and paraffin waxes gypsum wallboard. He concluded that maximum diurnal energy storage occurs when the melting temperature of phase changing material is kept close to the average room temperature. Diurnal energy storage is decreased when there is phase change transition over a long range of temperature.

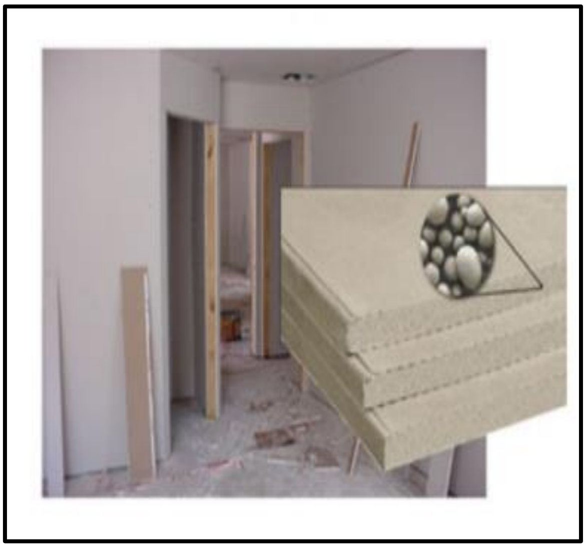

Figure 12 PCM enhanced gypsum boards [80]

PCM wallboards proved better than the conventional wallboards as PCM wallboards have comparable flexural strength, mor durable, more energy storing capacity, thermal conductivity value in the range ± 15%, increased weighted which was accepted by the industries, more compatible with paints and wallpapers and brilliant resistance to fire.

3.2.2 PCM enhanced cement mortar and concrete

3.2.2.1 PCMs in concrete

In order to increase the heat storage capacity of large and heavy construction materials that are used in buildings, PCM is incorporated in concrete materials. Most frequently used construction material in buildings is concrete. The PCM enhanced concrete is also called as thermocrete. Thermocrete is a medium for heat storage. These are obtained by combination of suitable PCM and concrete matrix or open cell cements. Low-cost storage materials with thermostatic and structural properties can be produced using thermocretes.

Concrete is a composite building material and the most commonly used construction material. Concrete is considered suitable material as far as incorporation of PCM is concerned. Here are the following reasons:

a) Extensively used in construction of buildings
b) Simple testing
c) Just like PCM wallboards, they also have high heat exchange areas and smaller heat exchange depth.
d) Exchange of heat takes place at faces or core surfaces or combination of both.
e) Capillary and surface tension forces are responsible for holding PCM.
f) Production and quality is under control.

Addition of PCM directly into concrete has resulted in lowering of thermal conductivity and inclination in the thermal mass at particular temperature. Lesser strength, long term stability and lower resistance to fire are some undesirable properties of PCM enhanced concrete. Thes properties were studied by Ling and Poon.[81]

Manufacturing methods

I. Internal curing of concrete: In this method, the pre-wetted lightweight aggregates which are present in concrete acts as reservoir (internal) which supplies water if needed by cement and other components at the time of hydration. Because of the porous nature of concrete, these aggregates get absorbed easily. Also, these aggregates can also be filled with PCM and this is how incorporation of PCM takes place in the concrete. Reduction in temperature experienced in the early curing stage of large concrete structures. However, concrete strength decreases because of high curing temperature which leads to more hydration.[82]–[84]

II. Second method deals with the mechanism of absorption so as to diffuse desired amount of PCM in concrete. [85] Large surface area of porous concrete act as good matrix where melting of PCM can occur also it was observed that 57 vol.% of phase change material can be absorbed into the pores of concrete composites.

3.2.2.2 PCMs in mortars

In order to reduce large energy consumption related to building conditioning incorporation of PCM in mortars is the most useful and attractive method. Incorporation pf PCMs in mortars is an efficient method because of the following reasons:

a) Provides large surface areas for heat exchange

b) Available in different sizes and shapes

c) Quality of the produce materials can be monitored and checked

Addition of PCM in mortars not only increased thermal conductivity but also the heat storing capacity of the material. Phase change material is also responsible for reduction in temperature fluctuations. Indoor temperature comfort can be improved effectively by using composite materials.[86]–[92]

Larger is the quantity of PCM in mortars, more will the heat storing capacity of that material.[93], [94]

PCM enhanced mortars have both economic and environmental advantage. When PCM is incorporated in mortars, it is observed that the final product has the potential of enhancing thermal comfort. The need for cooling and heating conditioning is also decreased. This leads to economic savings. Most importantly, making use of PCMs in the building structures also reduces the energy consumption. Different types of PCMs can be incorporated: inorganic, organic and shape stabilized PCMs etc. As inorganic-

PCMs are not that expensive as compared to organic ones which makes the process much cheaper. Shape stabilized PCMs are prove to be better option as they give promising results but the only problem is that they are expensive.[95], [96]

Conventional building elements have higher environmental impact as compared to PCMs. Minimization of environmental impact is possible by making us of PCMs which are recyclable, biodegradable, safe for environment and having long lasting effects.[97] Most of the phase changing materials are recyclable. Inorganic PCMs are harmless and organic ones are biodegradable. Using phase changing materials in various system like cooling and heating with conventional systems are helpful in minimizing environmental impact.

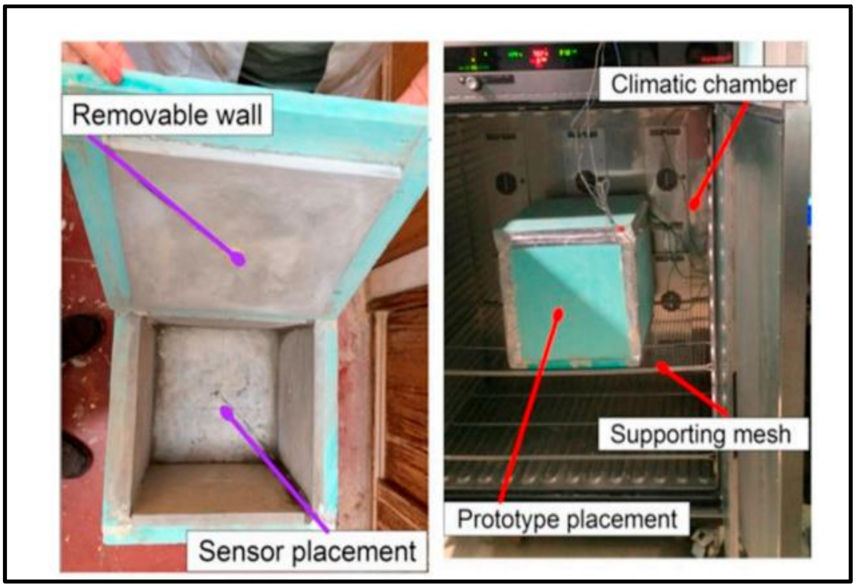

Figure 13. Prototype test cell including PCM mortar [98]

3.2.3 PCM Shutters and Windows

In the areas where climatic conditions are cold, huge amount of energy is lost due to the glass facades therefore mechanical heating is needed in such areas whereas in the areas where temperature is high mechanical cooling is needed and is dominated by cooling load. This was investigated by Ismail et al.[99]

Figure 14 PV-PCM Roof

With the help of latest technologies, many solutions have been found for this problem some of them are electrochromic windows (they allow only selective radiations to enter inside the room depending upon the temperature of the room.), self-cleaning glazing, e-glazings, BIPV- building integrated photovoltaics etc.

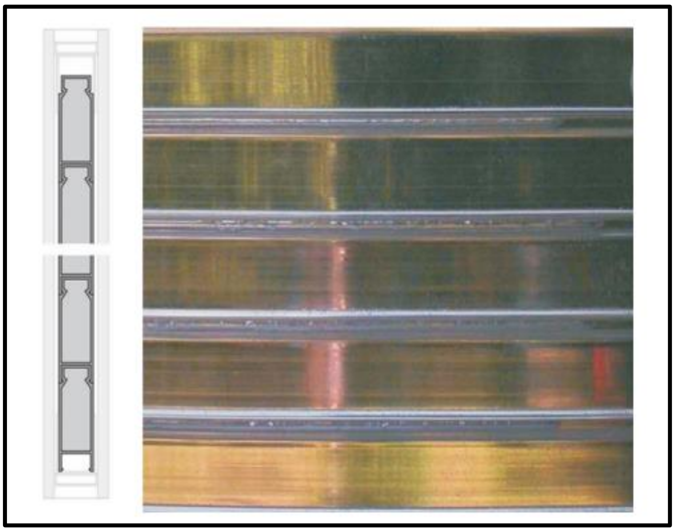

Figure 15: PCM filled window (left) and commercialized PCM window in liquid state (right)

To study the effect on thermal comfort during different seasons- hot season, cold season and mid-season. From the investigations made by Goia et al in which he compared the traditional insulating unit (double glazed) with the PCM prototype system ang following observations [100] were made: in case of PCM prototype results were better on hot days whereas on partly cloudy days, similar effect was observed on both the systems.

Figure 16 PCM Shutters

CONCLUSION

This paper is all about PCM and their recent applications. PCMs are now used more frequently because of their advantages in various fields but here we are only concerned about their usage in building applications. PCMs are considered to be the most influential substitute to conventional materials when it comes to heating and cooling techniques. The idea behind the working of PCMs is latent heat storage and they are of three types: organic, inorganic and eutectic mixtures. Depending upon the requirements selection of PCM for a particular application is done. In buildings, PCMs are incorporated into construction materials and this enables the active of energy. PCMs have brilliant storing capacity therefore the excess energy in the areas with hot climatic conditions can be used for cooling the building similarly the same energy can be released for making the building warm in the colder areas. PCM enhanced wallboards, roofs, tiles, shutters etc are used in construction and their usage is so easy that it hardly requires any alterations in the present way of construction. Energy consumption is an important factor and it is necessary to find an alternate to it therefore PCMs are efficient material which not only provide thermal comfort in building but also reduce the energy consumption. There is a large variety of PCMs available commercially to choose from. Paraffins are most commonly used because of its different properties such as low cost, resistant to corrosion, stability etc. the only disadvantage with paraffin is that the thermal conductivity is low. It is observed that shape stabilized PCMs are very much in demand now a days and the results are very promising. Active and passive are two techniques which are operational in buildings. In passive form, the charging and discharging is dependent on the temperature differences between day and night whereas in active form, discharging takes place during the daytime and charging is done using conventional cooling systems and helps in cooling the environment of the building.

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