PHASE CHANGE MATERIALS (PCMs) APPLICATION IN BUILDING ENVELOP

(A REVIEW)

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Abstract

Global contribution of energy consumption of building sector, both residential and commercial, is very high and steadily increased. In buildings, chief energy consumer is heating ventilation &air conditioning (HVAC) system used for thermal comfort and maintaining indoor air quality. Building envelope plays vital role in regulating indoor thermal comfort conditions as it is interface between indoor and outdoor environment. The key component of building envelop are walls, roof, floor and fenestrations. Energy consumption of HVAC system can be reduced up to desired limit by using different methods in construction of building envelop. One of these innovative methods is use of phase change materials (PCM). PCM are considered as a possible solution for controlling energy demand of buildings. PCM's are substances that can absorb and release thermal energy by changing their phase from solid to liquid at room temperature and stabilize thermal comfort inside the building with reduced carbon dioxide emissions. In this paper recent developments in the field of PCMs, their application in building envelop, incorporation and their influence on energy reduction are reviewed.

Key Words: *Energy consumption, Building Envelope, Phase Change Material (PCM).*

1. Introduction:

The rapid increase in energy demand due to industrial development and population growth raised concerns over supply difficulties, depletion of energy reservoirs and hazardous impacts on environments like ozone depletion, climate change and global warming etc. (Lombard et al., 2008). Developing countries like Pakistan has critical energy demand situation. Pakistan is facing worst energy crises of the history, which affects the normal lives of the people as well as creates obstacles in the development of country. To cope up with these energy crises, cutting of energy demand is the best solution leads to reduction in CO_2 emissions (Shaheen et al., 2016). International energy agency (IEA) reported that by increasing energy demands up to 49%, CO_2 emissions has increased up to 43% over last 20 years (IEA, 2006). According to report of private power and infrastructure board (PPIB) department, sector wise energy consumption for year 2014-2015in Pakistan is, domestic 46.5 %, commercial 7.5%, industrial 27.4%, agriculture 11.8% and others 5% (Power system statistics, 2015). Energy consumption in building sector is 46.5%, which is high, and it is expected to increase further due increased living standards. This much energy consumption is responsible for 30% greenhouse gas emissions.

A total of 55% in building energy consumption is used for HVAC systems (Souayfane et al., 2016). HVAC systems are used to maintain indoor temperature comfort. As building envelop is barrier between in-door and out-door climate, so its design involves many considerations, material is one of the most important considerations. So, materials of construction for building envelop must be durable, easy to maintain and resistant to weather. As a well-designed building envelope provides acoustical comfort and key aspect for achieving energy reduction (Cheung et al., 2005).

By using different techniques in building envelop one can limits energy consumption for buildings, one of them is integration of phase change materials (PCMs) in building envelop. As name indicates PCMs change their phase from solid to liquid by absorbing heat and control inside temperatures (Pomianowski et al., 2013). Their working principle is to absorb latent heat first and then release it later. Phase change materials are considered highly efficient solution for reducing energy consumption (Soares et al., 2013). Every phase change material has its own temperature, PCM absorbs heat without rise in inside temperature, at its specific temperature it turns to liquid, when outside temperature drops, its releases heat and turns to solid again (Hussein et al., 2016). The selection of appropriate PCM is important for building envelop in context to surrounding environmental temperatures ranges as shown in Figure 1(Baetens et al., 2010). Many studies have been carried out on use of PCM in building industry and ended up with improved indoor temperatures and reduced energy consumptions. Many studies show difficulties of use and their draw backsof PCM. PCMs are used in wide range of applications in building, but this paper aims to investigate the use of PCMs in building envelop components that are walls, windows, floor and roof and find out their impacts on energy savings.

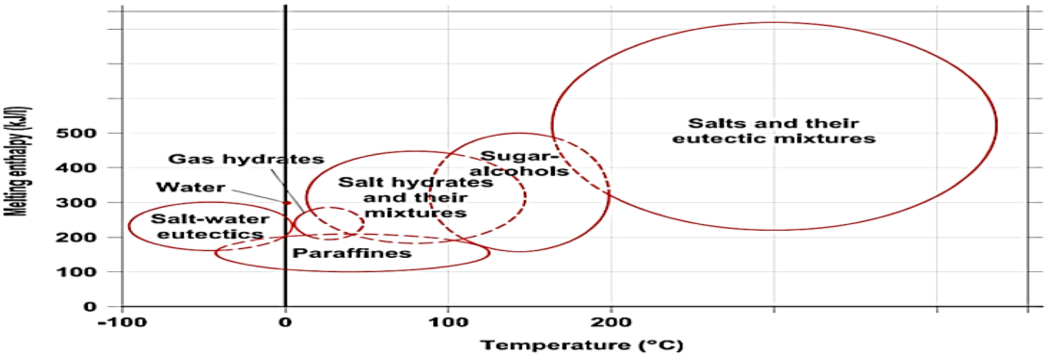


Figure 1: PCM melting enthalpy and temperature relationship for the different groups of PCM (Souayfane et al. 2016)

2. Phase Change Materials (PCMs):

PCMs are used to control temperature swings and store energy. There is a variety of temperature changes available in PCMs. Chemically PCMs are categorized as eutectic mixtures, organic compounds and inorganic compounds, having unique range of melting temperatures see Figure 2.

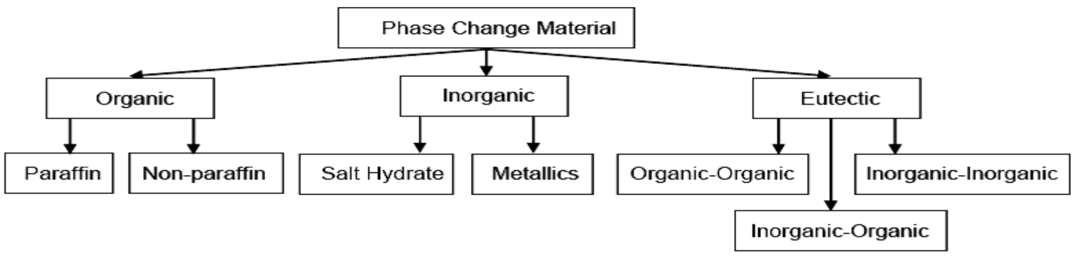


Figure 2: PCM classification (Memon et al., 2015)

Melting temperatures and enthalpy are considered for their use in building envelops (Tyagi and Buddhi, 2007). PCM can be incorporated as finishing materials, inside walls, roofs and floors and as thermal insulation etc. Every PCM has its own performance properties and poor characteristics, which can be controlled by different methods (Zalba et al., 2004).

Organic phase change materials are fatty acids, paraffin and non-paraffin, alcohols and glycols etc. Mostly Organic PCM are non-reactive, resist corrosion and non-toxicant and best for latent heat storage. They work better for low temperatures. Inorganic PCM are mostly hydrates and metals (Seong and lim, 2013). They are relatively cheaper than organic PCMs and extinguishers. They are not compatible with metals and can be corroded. But slat hydrates can store more energy than organic PCMs (Gracia and Cabeza, 2015). Eutectics are mixture of PCMs to get desired higher latent heat and melting points. Combinations of eutectics are organic-organic, inorganic-organic and inorganic-inorganic (Parameshwaran et al., 2012). Mostly Organic PCMs are used in buildings with temperature ranges 29°C to 60°C.

3. PCM for Building Envelop

Building envelop is separator between indoor and outdoor climate. It protects form heat and cold, wind, rain, visibility, glare, fire and noise. Key components of building envelop are exterior walls, foundations, roofs, windows and doors. The performance of HVAC systems depends upon building envelop. If building envelop is air tight and well insulated HVAC loading will decrease (Cheung et al., 2005). There are several methods to attain thermal comfort and above stated protection from building envelop. There are different standards and guidelines for building envelop design. Research shows, by playing with building envelop, up to 85% energy reduction can be achieved. The research conducted in Lahore indicated 34.1%-36.8% reduction in cooling loads by improving building envelop (khan et al., 2013). Another research conducted in Architectural Engineering department resulted 29% decreases in cooling loads (Arif et al., 2013). PCMs used for HVAC equipment are mostly mechanically operated. But when PCMs used in building envelop they operated passively (Abhat, 1983). PCMs can integrated in building envelop as a part of structure or a building component. PCMs are encapsulated for proficient use; else the liquid phase can stream from applied location (Baetens et al. 2010). Encapsulation of PCM can be done by two ways. The first way is micro-encapsulation, in which small particles of spherical-shaped or rod-shaped are enfolded in a thin, high molecular weight polymeric film. The second method is macro-encapsulation, consisting of the inclusion of PCM in some sort of package such as pouches, tubes, spheres, panels or other receptacles (Regin et al., 2008). Macro-encapsulation is commonly used, whereas Micro-encapsulation is a modernized technique. Several researchers gave different encapsulation methods of the PCM. These can be incorporated directly in building applications. They can be used as plaster, gypsum plaster boards or Concrete made up of microencapsulated paraffin. PCM are incorporated either in gypsum or in concrete (Seong and lim, 2013).

PCMs can be used to enhance thermal resistance which in turns helps to conserve energy. PCMs selected for building components must have melting point ranges 10 °C to 30°C depending upon climatic conditions for occupant's comfort (Sharma et al., 2009).

a. Walls

Frequently Organic and inorganic PCMs are used in building walls. PCMs integrated in walls, as wall construction material or as an additional component of wall. PCMs, as wall boards are most commonly used in building walls shown in Figure 3 (Kuznik et al., 2012). In recent years, a large number of researches have been conductedon replacing plaster board as PCM. In Germany, microencapsulated PCM made up of microscopic polymer spheres and filled with paraffin wax were used in addition to drywall panels (with 26°C operational temperature) to cut temperature peaks and reduce HVAC loading (Ubinas et al. 2012).

Figure 3: PCM enhanced gypsum board(Kośny et al. 2012)

For maintaining thermal comfort after shutting down HVAC systems, PCMs are observed as a best solution.By employing gypsum boards in outdoor testing room 4°C temperature reductionwas observed inside room (Athienitis et al. 1997). PCM wall boards supported by graphite nano-sheets are used to enhance energy distribution shown in Figure 4 (Biswas et al., 2014).PCM plaster sheets are used on concrete wall for heat exchange (Mehling and Cabeza, 2008). Hybrid PCM plaster board are best for controlling indoor temperature (Lachheb et al., 2017).

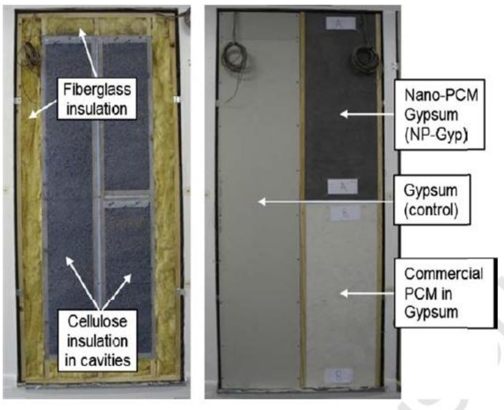


Figure 4: Test wall with PCM enhanced wall boards (Biswas et al., 2014)

Applying location of PCM boards is important for improved efficiency; different location of PCM can be seen in Figure 5. Three different locations were used for optimize performance (Jin et al., 2011). Another study regarding PCM Thermal shield was conducted by same author. Five different locations were studied, while optimal location for PCMs was at 1/5L from internal surface and delay in heat transfer was almost 2 hours and 41% reduction was evaluated using peak heat flux reduction(Jin et al., 2013).

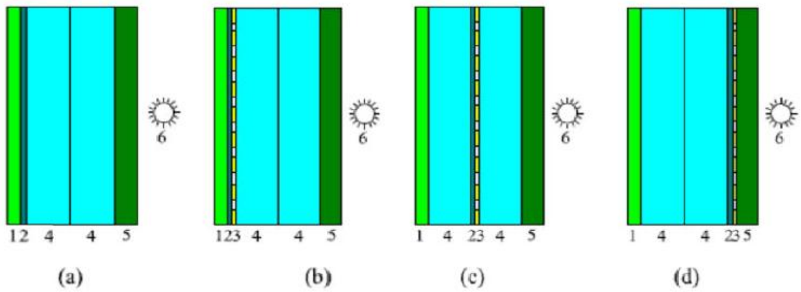
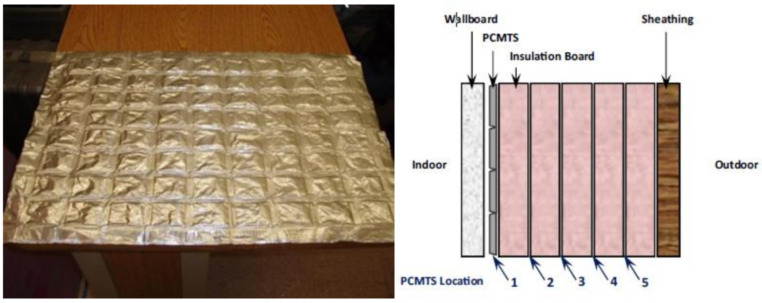


Figure 5: Wall Including PCM in different locations (Jin et al., 2014)

Another study with 5 different locations showed reduction of 51.3% in peak heat flux for south wall and 29.7% for east wall and delay in heat transfer for three different locations was different as 6.3 hour for south wall, 2.3 hour for west wall and 2 hours for in west wall Figure6 (Lee et al., 2015).In California, a research was conducted, microencapsulated phase change materials were used in exterior concrete wall. Annual Energy savings was more for west and south facing walls. They observed 53-85% reduction in energy costs (Thiele et al., 2015).



(a) (b)

Figure 6:(a) A sheet of PCM thermal shield (PCMTS) (b) Schematic of a wall section showing the locations of the PCMTS(Lee et al., 2015)

PCM made up of dodecanal and octadecane were used in light weight building walls assembly as shown in Figure 7 by employing technique as night ventilation and highest 11.33 % decrease was observed in indoor temperature (Seong and Lim, 2013).

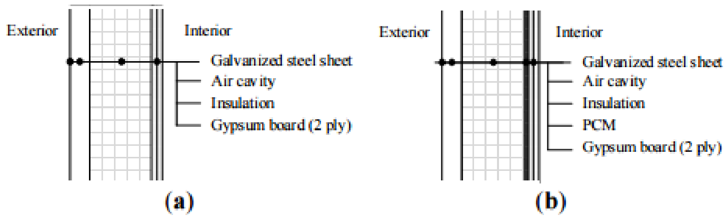


Figure 7: Wall section (a) without PCM (b) with PCM(Seong and Lim, 2013)

The payback period of PCM layer in external wall was evaluated using TRNSYS. They used three configurations as shown in Figure 8.The optimized configuration was where PCM applied nearer to external wall and gave 28.6% reduction in cooling loads with payback period of 14 ½ years, while PCM combined with insulation resulted 66.2% reduction with 7 ½ year which was more economical in terms of payback period (Panayiotou et al., 2016). PCM used in building mortar can be hybrid blend of two different types of PCM. Researchers used several mortars with and without PCMs. The snapshots from microscopy (SEM) and thermal characterization (DSC) of hybrid PCM resulted a better inside comfort without damaging hydration products and strength of mortar (Kheradmanda et al., 2014).

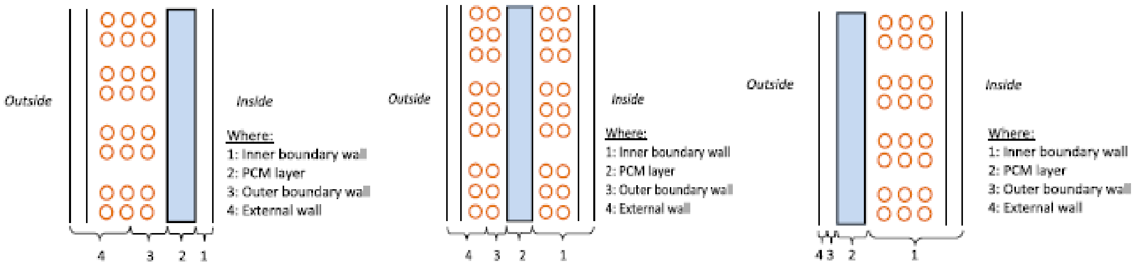


Figure 8: Different Configuration of PCMs(Seong and Lim, 2013)

Experimental assessment of macro encapsulated PCM in concrete wall was evaluated. For this purpose, they used externally bonded laminated and internally bonded macro encapsulated PCM. Finding of study showed that by using PCM relative humidity control can be achieved in addition to temperature reduction. Study was conducted in Honk Kong near coast shown in Figure 9. Maximum temperature reduction was 4°C with 11 year payback period (Shi et al., 2014).

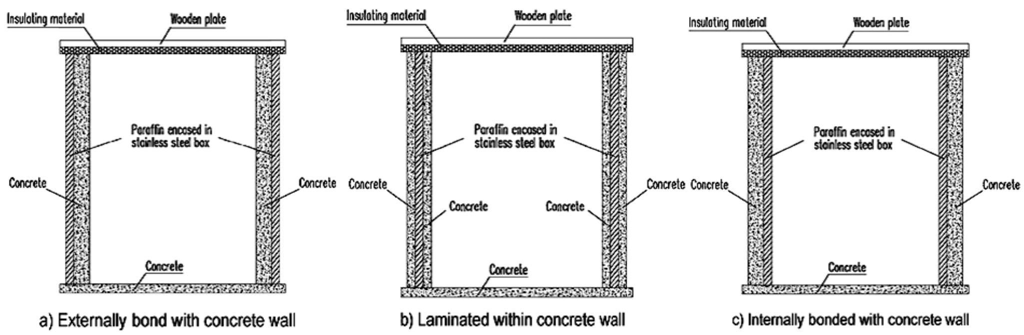


Figure 9: (a) Externally bond (b) Laminated within concrete wall (c) Internally bonded (Panayiotou et al., 2016)

Macro capsulated PCM can be used in light weight aggregate concrete structures. Porous lightweight aggregate (LWA) can serve as the carrier for PCM in China. In the research, Solid particles were first mixed in dry state then water was added with super plasticizer, after that LWA-paraffin particles were added to mixture (see Figure10). Control room was developed to investigate behavior. This mixture gave 41.8% reduction in shrinkage and 15MPA additional strength, 70% absorption capacity due to that inside temperature was reduced approximately 4 ° C and 465 kg CO_2-eq/ year reduction in was achieved (Memon et al., 2015).

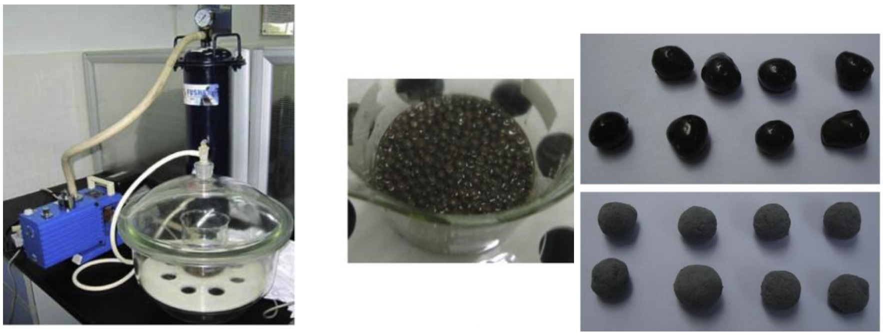


Figure 10: Illustration of macro encapsulated thermal energy storage LWA (Memon et al., 2015)

The research on a brick wall made up of SSPCM (shape-stabilized phase change materials) having 70% paraffin as shown in Figure11 was done. The mix proportion for making brick mass was of Portland cement, yellow sand and SSPCMs was 37.5%, 22.5% and 40%. SSPCM wall performed well for entire year including summer, winter and mid-season. Energy savings for three seasons were 24.32%, 10-30 and 9-725 respectively (Wang et al., 2016).

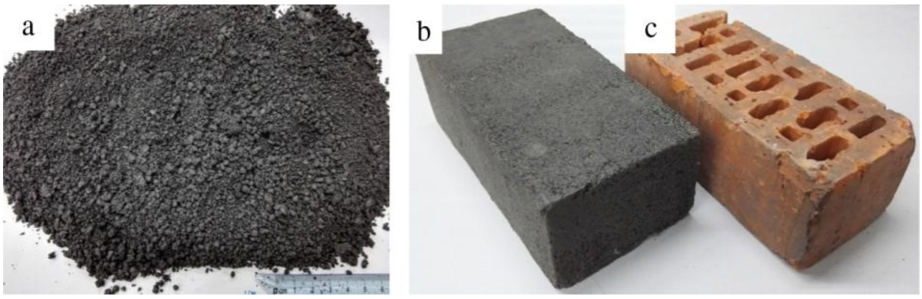


Figure 11:(a) SSPCMs (b) SSPCMs-brick (c) perforated vitrified brick (Wang et al., 2016)

b. Roof

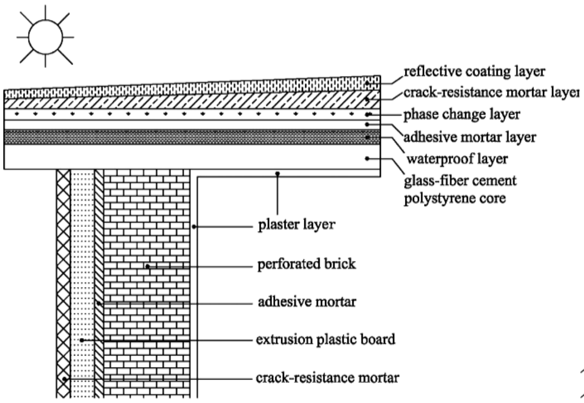
Some examples of PCM integrated in building roof are present in literature. A study conducted on use of paraffinic PCMs in steel roofs for reducing the cooling and heating loads. Paraffin octadecane as PCM was used with average melting temperature of (25.6°C). Roof metal was consisted of two polyisocya nurate foam layers having thickness of 1-inch. Paraffinic PCM was applied along bottom layer. Cooling load savings were almost 14%,when compared to the conventional roof (Kissock and Limas, 2006).

PCM-enhanced polyurethane foams with impregnated fabrics are reflective aluminum foil were used in prototype residential roof in Figure12. Two types of PCMs were used in this configuration. Their melting temperatures were 26°C and 32°C. Their field experiment proved 70% reduction for peak heat flow for this roof assembly (Kośny et al. 2012).

Figure 12: Roof assembly comprising ofinsulation and subverting air channels with two PCM insulation systems(Kośny et al. 2012)

Experiment evidence of novel roof technique made up of PCM and cooling material proved average peak difference about 5.76°C and the maximum up to 8.13°C. They investigated the behavior of three compositions. Basic composition was mortar layer, adhesive mortar layer, water proof layer and roof base layer. One has reflective coating layer, PCM layer was added in second configuration. Third configuration had both PCM and reflective layer as shown in Figure 13 and depicted best results due to reflective layer outside temperature above roof surface will be reduced 4.46-5.76◦C (Lu et al., 2016).

Double glazed roof filled with PCMs was investigated thermally. They emphasized on significance of semi-transparent property, time lag, zenith angle and transmitted energy. PCM reduced transmitted energy and time lag. They came up with result that increasing PCMs thickness time lag difference will be less effective but thermal performance will increase rapidly, configuration is shown in Figure 14 (Liu et al., 2016).



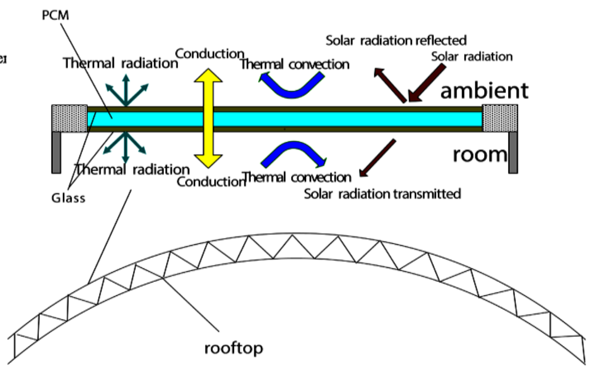


Figure 13: Different configuration used in experiment (Liu et al., 2016)**Figure 14:** Double glazed roof filled with PCM(Lu et al., 2016)

The idea of using PCM doped roof tiles for reducing inside temperatures was investigated. Their results showed that the PCM doped tiles reduced the temperature. The working principle of doped tiles is, they lower surface temperature by maintaining lower temperature in the chamber in summer and during winter PCM doped tiles keep chamber temperature high while lowering surface temperature. They are equally effective in both seasons (Chung and Park et al. 2016). Thermal performance of roofs of residential house with different PCMs in Northeast, China, was done numerically. They studied impact of several factors like PCMs layer thickness, absorption coefficient, roof slope and solar radiation etc. Their result gave 3hour time lag more than common roof (Dong et al. 2016). Urban Heat Island is a critical concern for populated cities because of increased threat of climate change. To lower consumption of heat PCM was used in roof to make cool roof. They investigated results for seven different climatic zones. The maximum heat gain through roof was 54%lesser for the PCM roof as compared to the cool roof. Likewise, the maximum sensible heat flux of the PCM roof type was 40% lesser than the cool roof technology (Roman et al., 2016).

c. Floors

PCM application in floors is considered best for heating periods. Floors having PCMs showed lower connectivity of heat transfer coefficients (Nagano et al., 2006). PCM tiles can be used in floors. A research found in literature resulted as innovative solution of heating of houses in winters by using PCMs tiles. They used tiles in floor and set a direct angle with sun by using glazing. PCM tiles absorbs heat from sun and in evening it releases to make inside temperature comfortable shown in Figure 15 (Ceron et al., 2011).

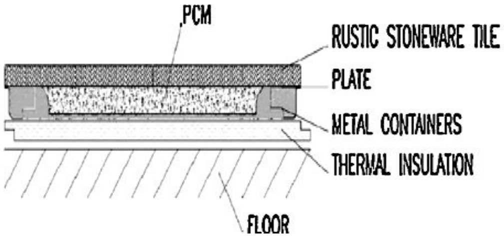


Figure 15: Details of the prototype tile (Ceron et al., 2011)

Another study conducted regarding benefits of PCM tiles in summer. PCM base floor system was used. A prototype type model with light weight piped radiant, integrated with PCM layer was used, as shown in Figure 16. They found it effective for controlling temperature without any energy source (Ansuini et al. 2011).

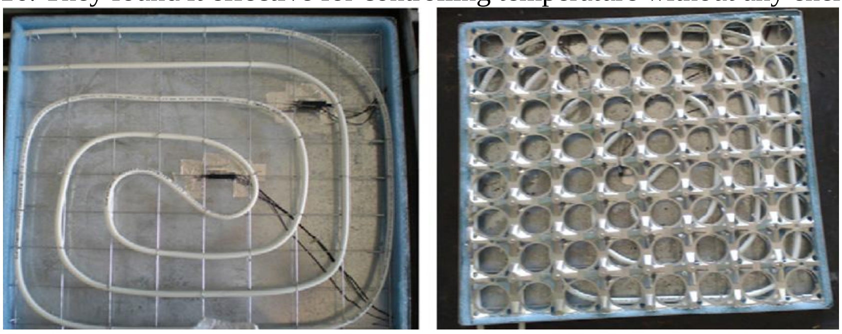


Figure 16: PCM based radiant floor experimental set-up (Ansuini et al. 2011)

The double layer PCM floor was analyzed. They used PCM layers between surface layer and concrete layer shown in Figure 17. Melting temperature for cooling was 18˚C and for heating was 38˚C. Their results showed 41.1% and 37.9% savings for heating and cooling at peak loads (Jin and Zhang, 2011).

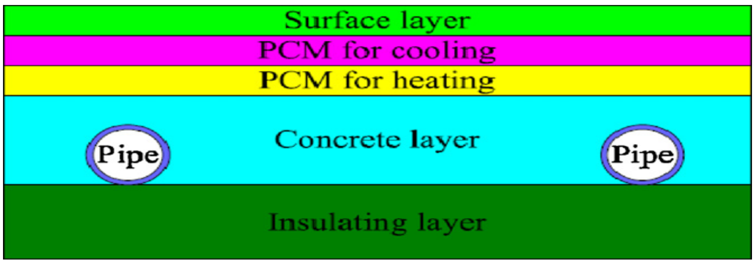
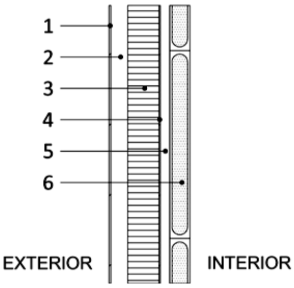


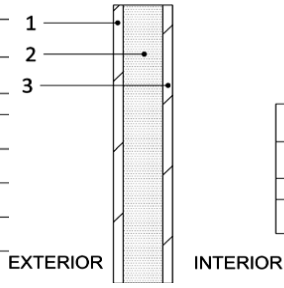
Figure 17: The scheme of the double layer PCM floor (Jin and Zhang , 2011)

d. Windows

In 1997, evident of translucent PCM was found in the literature (Manz et al., 1997). Their model is shown in Figure 18. Later a researched found on the composite glass filled windows with PCM shown in Figure 19. They were first, who worked on translucent PCMs. They evaluated Infrared and ultraviolet radiations by changing glass sheets, their thickness and gap between them, then results were compared with experimental data (Ismail and Henriquez, 2002).



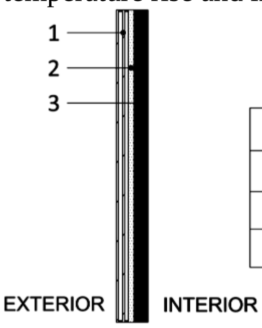
Layer Id	Description	Thickness [mm]
1	Glass pane	-
2	Air gap	-
3	Transparent insulation material	-
4	Glass pane	-
5	Air gap	-
6	PCM in a glass container	-



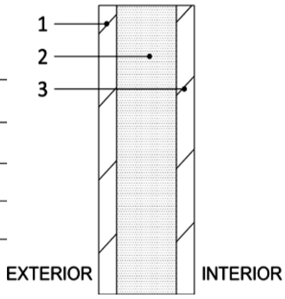
Layer Id	Description	Thickness [mm]
1	Glass	-
2	PCM Layer	-
3	Glass	-

Figure 18: TIM–PCM external wall system (Manz et al, 1997)**Figure 19:**Double glass window with PCM(Ismail and Henriquez , 2002)

Later researchers proposed two layers passive wall system using salt hydrate PCM and transparent honey comb type insulation. These were commercially termed as glass block, they gave simple mode by suggesting layout consist of double glass windows filled by PCM (Fokaides et al., 2015). Numerical analysis of a double glaze window containing PCM with 10mm air gap is shown in Figure 20. PCM was encapsulated between transparent plastic layers (Weinlaeder et al. 2005). Another researcher compared prototype of PCM glazing system with conventional double glaze unit and concluded that PCM gives better indoor thermal conditions. Their proposed configuration is shown in Figure 21(Goia et al., 2013). Blind equipped with PCM can also be used to delay temperature rise and inside heat release and can be fix inside and outside of windows.



Layer Id	Description	Thickness [mm]
1	Double Glazing	-
2	Plastic container with PCM	16
3	Wall heating/cooling	-



Layer Id	Description	Thickness [mm]
1	External glass pane	3/16
2	PCM Layer	10/16
3	Internal glass pane	3/16

Figure 20: Layout of PCM-facade panel (Weinlaeder et al., 2005)**Figure 21:** Layout of PCM glazing(Goia et al., 2013)

4. Discussion

A review of PCM was carried out focusing on applications of PCM in building envelops. Studies were based upon numerical simulations and experimental data focusing on reduction in cooling loads as well as change of indoor temperature. In literature most of the studies were based on experimental conclusions, lesser used full-scale models and few used small-scale models. In some situations, it is not possible to experiment full scale models due to barriers of time, cost, instruments, lack of professional skills etc. A great emphasis was on reduction in electricity generation to mitigate the effect of global warming. To achieve goals a thorough understanding of characterization and working of PCM was required. Mostly Paraffin (organic PCM) was used in building passive application. In literature, we have found almost 60% of Paraffin applications. Reason is its melting temperature and compatibility with building envelops components and chemical stability. Fatty acids are also used in building applications but nearly 12% due to temperature range 22°C-33°C and salt hydrates was used in transparent building applications. Researchers reported that by using PCMs in building envelop, thermal and energy performance can increase since indoor temperature can be control and does not reach much so. If HVAC system are employed in building, they supplies cold air and PCM served as cold energy storage so that air with in building remains cool for longer period, we can take advantage of the off peak energy savings. The effectiveness of PCMs is highly dependent on local climatic conditions, PCMs melting temperatures, temperature should be in mid-range of diurnal temperature of that region.

Comprehensive literature has shown in Table no.1 various characteristics of PCMs. It is evident most of PCM usage is in building walls, after that we have roof and PCM in truculent building envelop has been less used. There are few examples in literature about use of PCM in windows shutter and blinds, if we implement it might be interesting additions to building envelop.

5. Conclusion:

Although PCM seems innovative but there are many aspects that need to be explored and improved. Partial solidification of PCMs is one of the major problems faced by researchers. PCM does not solidify with in required time, so, temperature range will hinder proper operation. Second is required rate of heat transfer between air and PCM is not attainable yet and need to be accomplished. Another issue is requirement of optimal material for PCM storage for efficient operation in micro and macro size ranging. Different implementations techniques of PCMs application in building envelop are available in literature, but, the need of hour is optimization of those techniques. Further studies are required to eliminate the current deficiencies and hindrances in using PCMs in large scale buildings.

Table 1: A summary of previous studies

Author(s)	PCM name	PCM type	Melting point (°C)	location/climate	Method of study	Software	Capsulation type	PCM location	Factors of study
Manz et al. 1997	$CaCl_2$-6H2O	Inorganic	24–29		Experiment			External wall system composed of transparent insulation material (TIM) and translucent phase change material (PCM)	Reflectance and Spectral transmittance Refraction index of the PCM
Athienitis et al., 1997	butyl stearate	Organic	16.8–20.9		Outdoor test facility			Gypsum board	Latent heat Transition temperature sand Differential scanning calorimeter (DSC)
Ismail and Henriquez, 2002	Mixture of glycol	Organic			Experiment Spectrophotometer			PCM glass systems of thicknesses 3, 4, 5, 6 and 8 mm	Transmittance Reflectance
Weinlaeder et al, 2005	Paraffin wax RT25	organic	22–26		Outdoor test facility			Double glazing combined with PCM	Temperature Heat flux Incoming solar radiation
Cerón et al 2011	ACUAL 20		20	Madrid		IES		floor tiles	PCM tiles placed in the floor are beneficial for summer season during night. -The system works more proficiently as a heat sinks. - Higher effectiveness can be accomplished in the sunny tiles.
Kuznik et al, 2012	product from DuPont	Organic	22	CETHIL-INSA de Lyon, France	Full-scale test room		Micro	internal partition wall	Overheating effect was considered and temperatures of wall faces improved the thermal comfort conditions by radioactive effects
Kosny et al 2012	Bio-based PCM	Organic	18	Poland , France and Egypt in summer hot period	Test rooms		micro	Fiber wood-framed wall.	Indoor temperature gains Energy reductions

Goia et al, 2013	Paraffin wax	organic	Peak of 25/30/35		Experimental	Halogen lamp (CATRAM) Three array spectrometers		In transparent system	Reflectance absorptance
Biswas et al., 2014	Paraffin	Organic	21.1	Charleston, South Carolina,	Full-scale experiment	COMSOL Metaphysic	Macro	Wallboard	TemperatureRelativeHumidity, heat flux
Jin et al., 2014	Salt hydrate	Inorganic	25-34	25-34 variations of the temperature	Experiment		Macro	Wall	Different PCM locations
Shi et al., 2014	Paraffin	Organic	20.8	Shenzhen, Hong Kong	Small-scale experiment		Macro	Wall	Indoor temperature, Relative humidity
Memon et al., 2015	Paraffin	Organic	25-28	Shenzhen, Hong Kong	Small-scale		Macro	Roof, wall, window	Temperature, environmental evaluation and economic
Gracia et al., 2015	SP-22 from Rubitherm	Eutectic	21.5	11 cities all over the world	Full-scale experiment & numerical		Macro	Wall	Net energy supply, Potential of PCM solidification, Cooling supply during discharge
Wang & Zhao, 2015	Calcium chloride hexahydrate	Inorganic	30	Sinusoidal variations of temperature		Experimental	Macro	window	PCM melting temperatures,Different air gap thicknesses
Fokaides et al., 2015	Paraffin MG29	Organic	27-29	Nanjing, China hot summer and cold winter	Experiment & numerical	FLUENT	Macro	Window	Window latent heat of fusion, melting temperature and the difference between liquids temperature and solidus temperature
lee et al., 2015	Hydrated salt	Inorganic	30-34	Daqing, China	Numerical study	FLUENT	Macro	slope roof	slope roof Solar radiation intensity, transition temperature and latent heat of PCM, roof slope, PCM layer thickness
Lu et al, 2016	Capric acid	Organic	26-30	Tianjin, CH	Experimental			Roof and Wall	Inside surface temperatures of walls and roofs
Panayotou et al , 2016	Bio PCM	Organic	29	Cyprus	Test rooms	TRNSYS	Macro	Test room envelop	Energy Savings

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