

Chapter 2

Short History of PCM Applications in Building Envelopes

2.1 PCM for Building Applications—Background

Ongoing improvements in building envelope technologies suggest that residences will soon be routinely constructed with low heating and cooling loads. The use of novel building materials containing active thermal components (e.g., PCM, sub-venting, radiant barriers, and integrated hydronic systems) would be an ultimate step in achieving significant heating and cooling energy savings from technological building envelope improvements. The key benefit of using PCM is that it affords structures improved thermal storage capabilities with minimal change to the existing building design (Sharma 2013). The main methods for incorporating PCM into building materials include the use of gypsum plaster boards and other structural boards, blending PCM with thermal insulations, and by macro-packaging. The thermal energy storage property of PCM is based on its latent heat storage capacity, given that large amounts of energy can be stored in a small volume. Therefore, the material containing PCM can absorb and release heat more effectively than conventional building materials. However, the selection of the PCM locations, PCM transition temperature range, and the amount of used PCM are essential for effective and durable use of the PCM-enhanced technologies, considering a relatively long life span of building envelopes.

Present-day residential and commercial buildings are becoming more structurally lightweight, and concerns are been raised over indoor thermal comfort due to reduced thermal storage potential. A strong tension exists between the drive to build better efficient structures with less impact on the environment and the tendency to add more mass to the structure for thermal storage. These issues are further heightened by global climate change and the continual rise in energy cost. Without counting traditional arctic ice igloo constructions, 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 (Telkes 1978; Frysinger and Sliwowski 1987; Ghoneim and Klein 1991). During the 1980s, bulk

encapsulated paraffinic PCM had been manufactured for building applications. 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 (Abhat 1983; Lane 1983; Shapiro et al. 1987; Peippo et al. 1991; Schossig et al. 2005; Sharma and Sagara 2005; Mehling and Cabeza 2008). In active cooling scenario when air-conditioning is used, at least part of the PCM's energy is discharged by the space conditioning systems—so, this is not happening without associated energy cost. In some buildings, this cyclic process may result in a reduction of heat flow from the outdoor to the indoor enclosures, which in turn shifts peak cooling loads to off-peak periods, thereby evenly distributing the demand for electricity and avoiding energy shortages often encountered during the peak periods. PCM-enhanced building envelopes offer higher per unit heat storage capacity than conventional building materials and provide lightweight structures the benefit of increased thermal mass (see Kośny and Kossecka 2013). The capabilities of incorporating PCM in structures to thermally stabilize interior space and shift peak-hour cooling loads are highlighted in publications of Castellón et al. (2007), Zhuang et al. (2010), Kośny et al. (Kośny et al. 2010a, 2014), Tardieu et al. (2011), and Childs and Stovall (2012). Since available surface area for heat transfer is significantly greater in building envelopes, in comparison with encapsulated local heat storage applications, large amounts of energy can be stored with minimal fluctuations in the transition temperature. As a result of the improved thermal performance gained from PCM incorporation, lighter and thinner building envelopes can be designed and constructed to take full advantage of the performance.

2.2 First PCM Application for Passive Solar Heating

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.

The first documented use of a PCM for passive solar heating of the residential building took place in 1948 by Dr. Maria Telkes (December 12, 1900–December 2, 1995), a Hungarian born researcher at the Massachusetts Institute of Technology (MIT—Cambridge, MA, USA). By her friends and co-workers, she was called the Sun Queen because of her long fascination by the possibilities of solar heating,

since the 1920s. Unable to get a research grant from MIT, Telkes collaborated with sculptor Amelia Peabody, the client, who personally funded the project, and architect Eleanor Raymond.¹

The first PCM residential house was constructed in Dover, Massachusetts, USA (Telkes 1947). It contained approximately 4 m³ of Glauber's salts, which were packed in steel drums located in the southern glazed sun spaces that were ventilated with fans to move the warm air into the living space during the winter. In summer months, PCM thermal storage was able to cool surrounding rooms as well (see Telkes 1978, 1980). The Dover house worked very well for two and half seasons. Unfortunately, Glauber's salt disintegrates during a short-time period and loses its phase transition capability, if not sealed and chemically enhanced. During the third winter season in the Dover house, containers with Glauber's salts permanently stopped working. As a result, the experiment was terminated. However, Dr. Telkes stayed for long time optimistic for PCM application in solar heating applications. In 1951 she wrote—"Sunlight will be used as a source of energy sooner or later anyway. Why wait?"²

Since 1948, more resources have been invested in the development of PCM-based heat storage technologies. These systems have been extensively studied over decades, notably in the late 1980s and 1990s (see Mancini 1980; Feldman and Shapiro 1989; Peippo et al. 1991; Hawes and Feldman 1993; Bromley and McKay 1994; Salyer and Sircar 1989; Stetiu and Feustel 1996). The next, portion of rapid development PCM technologies experienced during the first decade of twenty-first century—to be discussed on the following sections. Yet, despite numerous experimentally proven performance pluses and the fact that a large portion of difficulties associated with designing of PCM-enhanced systems and their long-term durability have been already resolved, the technology is still moving through the bumpy road of development and market acceptance. In 2014, the assumption could be drawn that for many PCM applications the cost-to-benefit ratio is simply still too high for many PCM applications, to become a common design option of choice.

2.3 PCM Solar Thermal Storage Walls

Applying a PCM in building construction can utilize both the heat from external solar energy gains and thermal loads produced by mechanical heating and cooling systems. Effective storage of this energy is then required in order to match the energy demand of the building sufficiently and at the appropriate time. PCM solar walls are typically used in mixed and cold climates. Generations of passive solar walls containing PCM have been studied for decades as a way of heating buildings from a renewable energy source. A key ingredient of these walls is their heat

¹<http://www.technologyreview.com/article/419445/the-house-of-the-day-after-tomorrow/>.

²<http://www.uh.edu/engines/epi2608.htm>.

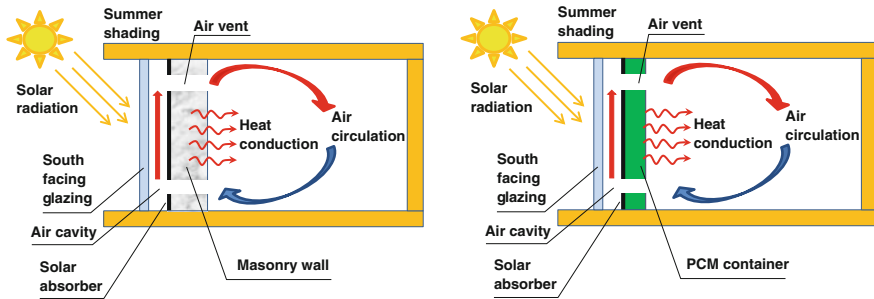


Fig. 2.1 Schematics of conventional Trombe Wall and PCM-enhanced Trombe Wall

storage capacity. 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.

PCM solar walls are designed to trap and transmit solar energy efficiently into a building. They are sometimes called solar thermal storage walls with PCM. A single- or double-pane glazing is used as an outer thermal barrier of the wall and to provide a greenhouse effect. Research has been carried out on various building applications to determine the effectiveness of PCM latent heat storage. Generations of building thermal designers and solar architects pursued very often an early idea of passive solar walls, which were developed by French engineer Félix Trombe and architect Jacques Michel.³ The Trombe wall is an example of an indirect gains approach to passive heating which has been tested both experimentally and theoretically with the integration of PCM. The working principal of a Trombe wall is based on sensible heat storage and can be seen in Fig. 2.1. Single or double glazing is usually placed on the exterior surface of the massive heat storage module, with a thin air gap separating these two materials. The exterior surface of the heat storage part is usually painted black so as to absorb the solar energy, which is then stored and conducted through the wall over the period of the day. In winter solar heating scenarios, when the evening and night heating energy demands approach and the internal space temperature drops, heat from the wall storage radiates into the building from the Trombe wall over several hours.

During the last decades, several modifications have been developed from the basic design of a classical Trombe wall and composite Trombe–Michell wall (Zalewski et al. 1997, 2002; Sharma et al. 1989; Jie et al. 2007). Originally, Trombe walls have been built using either masonry or water to provide the appropriate sensible heat storage capacity. This requires large areas of space in order to construct the walls. For this reason, the greater heat storage per unit mass provided by

³<http://solarhousehistory.com/book/>.

PCM is seen as the ideal property which can be incorporated into the existing systems and optimize the space for other practical uses. Thinner PCM walls are also much lighter in weight in comparison with the traditional concrete and masonry materials. These factors offer convenience and attractive reductions in the construction costs associated both with construction of new buildings and their retrofit applications (see Tyagi and Buddhi 2007).

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. Initially, hydrated slats have been sampled for this purpose. Telkes (1978, 1980) 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. In experiments performed by Swet (1980), Ghoneim et al. (1991), and Chandra et al. (1985), 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. Bourdeau and Jaffrin (1979) and Bourdeau et al. (1980) 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 3.5-cm wall using PCM could replace a 15-cm-thick conventional wall made of concrete. In a following project, Bourdeau (1982) studied the behavior of Trombe wall made of polyethylene containers placed on a wood shelf behind a double glazing. A series of field tests was carried out at Los Alamos National Laboratory, USA (Balcomb and McFarland 1978; Balcomb et al. 1983). 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 the following work, varieties of natural- and petroleum-based hydrocarbons have been used as thermal storage. Knowles (1983) used paraffin mixed with metal shavings for increasing the overall conductivity and efficiency in the Trombe wall. Using numerical analysis, Knowles developed a guidelines for the design of low-mass, high-efficiency walls. One conclusion from this experiment was that thermal resistance of the solar thermal wall should be as low as possible. Compared with concrete, paraffin-metal mixtures were found to offer a 90 % reduction in storage mass and a 20 % increase in thermal efficiency. Stritih and Novak (1996) investigated a passive solar wall, which absorbed solar energy into a black paraffin wax (with a melting point between 25 and 30 °C). The stored heat was used for the space heating with efficiency close to 79 %. The results of numerical analysis showed that the optimum thickness of paraffinic heat storage should be close to 5 cm and the melting point of PCM should be few degrees higher from the room set point temperature. In early 1980s, Kośny and Starakiewicz (1987) tested PCM Trombe wall using as a thermal storage a 5-cm-thick metal container with beeswax. Benard et al. (1985) performed a 3-year field experiment in test cells on composite Trombe walls containing 40-cm-thick layer of concrete, 8-cm hard paraffin, and 8-cm soft

paraffin. These test cells allowed the analysis of various degrees of thermal coupling between the wall and the conditioned space behind.

The subsequent development included an application of fatty acids and esters for thermal storage. For example, Buddhi and Sharma (1999) measured the transmittance of solar radiation through a solar storage wall containing stearic acid. This parametric analysis was performed at different melting temperatures and wall thicknesses. In addition, Benson et al. (1985) 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 °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. Similar to the Los Alamos test findings discussed earlier, Benson et al. (1985) concluded that a Trombe wall containing PCM could be four times thinner and a factor nine lighter than its equivalence made of concrete.

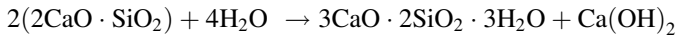
2.4 Impregnated Concrete Blocks and Ceramic Masonry

The passive use of PCM-enhanced construction and finish materials is relatively not a new concept. As discussed earlier, there were several moderately successful attempts in the 1970s and 1980s to utilize different types of organic and inorganic PCMs to reduce peak loads and heating and cooling energy consumptions (Balcomb 1979; Balcomb et al. 1983; Salyer and Sircar 1990; Hawes and Feldman 1993). These investigations focused on impregnating concrete, gypsum, or ceramic masonry with salt hydrates or paraffinic hydrocarbons.

For decades, masonry blocks or other building materials impregnated with a PCM have been tried in building construction, resulting in successful applications in structures with enhanced thermal inertia and without the heavy-weight mass associated with it. However, an incorporation of PCM in concrete masonry materials is a complex technological process. Some of the concerns include volume changes during melting and freezing, slow heat transfer rates of inorganic PCM products, problems of PCM leakage, and adverse effects on the physical properties of the PCM carrier materials. One of the simplest PCM-enhancement methods consists of impregnation of the concrete block with PCM in a constant volume liquid PCM (see Lee et al. 2000). This is a flexible method which can be applied to different PCM transition temperatures. Concrete blocks can be impregnated as a part of continuous process during their manufacturing.

Concrete is a common construction material made of four components: cement, water, aggregates, and additives. PCM can be either introduced to concrete as an additive or during the impregnation process. Cement is the bounding concrete element that is activated by water. Frequently used Portland cement usually consists

of the following four major mineral ingredients: tricalciumsilicaat ($3\text{CaO} \cdot \text{SiO}_2$), dicalciumsilicaat ($2\text{CaO} \cdot \text{SiO}_2$), tricalciumaluminaat ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$), and tetra-calciumaluminaatferriet ($\text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$). Occasionally, blast furnace cements or fly ash cement can be used in concrete mixtures instead of, or in addition to the portland cement. Sometimes lime and clay are added to the concrete mixture as well. A typical concrete hydration process can be described as the following development of C–S–H (Calcium–Silicate–Hydrates):



In 1980s and 1990s, impregnation was used as the major method of introduction of melted PCM to the carrier material. Incorporation of PCM into concrete masonry products was carried out through an immersion process into a liquid PCM bath. Hawes et al. (1990, 1992) have studied latent heat storage of concrete with different types of PCM in different types of concrete blocks. Innovative methods of PCM containment in hollow-core building blocks were studied by Salyer et al. (1995). One significant technical innovation from this work was development of a new PCM composite that could be made by blending of PCM with high-density polyethylene (HDPE)/ethylene-vinyl acetate (EVA) and silica in defined proportions. PCM-hydrophobic silica dry powder was incorporated into the concrete wet mix to provide an effective thermal storage material. Based on this discovery, Salyer and his team have developed different methods of PCM incorporation to building masonry products: by imbibing the PCM into porous materials, PCM absorption into silica or incorporation of PCM into polymeric carriers. Silica fume and fly ash were used often to reduce the alkalinity of concrete and to improve the compatibility with alkaline sensitive PCM. Romanowska et al. (1991) have analyzed the thermal performance of organic PCM's added by impregnation to different types of ceramic masonry. Lee et al. (2000) have studied and presented the results of macro-scale tests that compare the thermal storage performance of ordinary concrete blocks with those that have been impregnated with two types of PCM, butyl stearate, and commercial paraffin. Hawes et al. (1990, 1992) presented the thermal performance of PCM's (butyl stearate, dodecanol, paraffin, and tetradecanol) in different types of concrete blocks. This analysis has covered the effects of concrete alkalinity, temperature, immersion time, and PCM dilution on PCM absorption during the impregnation process. Hadjieva et al. (2000) have applied the same impregnation technique for concrete but with sodium thiosulphate penta-hydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$) as a PCM. They concluded that the large absorption area of cellular concrete may serve as a good carrier material of an incongruently melting inorganic PCM and improving its structure stability during thermal cycling.

Another PCM application method incorporating concrete products has been highlighted in more recent work performed by Zhang et al. (2004), Bentz and Turpin (2007), and van Haaren (2012). In these experiments, lightweight aggregates with high porosity were used as the PCM carriers to achieve adequate heat storage

capacity. In some types of PCM-enhanced masonry products, porous aggregates are surrounded by tight cement-based paste, which reduces a potential for PCM leakage. In early 2000, Bentz and Turpin (2007) investigated the effectiveness of thermal storage mortar with lightweight expanded shale aggregates impregnated with paraffin and polyethylene glycols.

In addition to early applications of salt hydrates, Hawes et al. (1990) and Hawes and Feldman (1993) studied the thermal performance of several organic PCMs, such as butyl stearate, dodecanol, tetradecanol, and paraffin, in different types of concrete masonry products. However, it was found that most of the above methods of PCM introduction to the masonry products may have drawbacks of interacting with building structure and change the material matrix, causing possible leakage over its lifetime, among other issues (see Schossig et al. 2005). Despite many benefits, the problem of PCM leakage has been observed in many building applications after repeated thermal cycling. To reduce potential durability problems, in research work performed by van Haaren (2012), the introduction of PCMs into the concrete was achieved in two different ways: (1) The sand from a standard mixture was replaced by PCM particles and (2) porous lightweight aggregates were impregnated with PCM and later a concrete mix was made with use of impregnated and not impregnated lightweight aggregates (see Fig. 2.2).

Encapsulation of a solid–liquid PCM during its phase transition is crucial in most cases to hold the liquid phase of the PCM and to reduce PCM leakage and the reactivity of PCM with the outer environment (see Hawlader et al. 2003). In Microencapsulation, micronized materials (both liquids and solids) are packaged in the form of microcapsules, which range in size from less than 1 μm to more than 300 μm . The outer skin of the capsule can be made by using natural and synthetic polymers which provides a hard shell. Depending on the size of the final products, encapsulation can be classified as follows: macro-encapsulation or microencapsulation. Keep in mind that in early PCM building research, Collier and Grimmer (1979) already showed that a macro-encapsulated PCM material cemented within



Fig. 2.2 Microscopic view of the concrete—*inorganic PCM mixture (left) and test samples of PCM—enhanced concrete (right)* (van Haaren 2012)

masonry building blocks results in significant increase in the system performance over an equivalent volume of concrete. In Spain, the results from a field study of concrete blocks using microencapsulated PCM were presented by Cabeza et al. (2007). Improved thermal inertia was observed for PCM-enhanced products, which indicated a potential for energy savings in buildings. Other types of masonry products can be used as well as PCM carriers. For example, the application of PCM-treated ceramic bricks was investigated by Romanowska et al. (1991) and Lai and Chiang (2006). In addition, Mehling et al. (2002) found that PCM can be combined with lightweight wood concrete (holz-beton) and that the mechanical properties of the structure do not change significantly.

2.5 PCM-Enhanced Gypsum Board and Interior Plaster Products

As mentioned in the previous section, PCM can be easily blended with many construction materials, including gypsum building products. This makes it possible to increase the latent heat capacity of lightweight constructions by applying it in the form of interior plaster or finish gypsum boards. In natural form, gypsum is a common soft sulfate mineral composed of calcium sulfate dihydrate, with the chemical formula $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Manufacturers of commercial gypsum remove purposely much of natural gypsum's inherent water by crushing the rock into powder and heating the powder to remove its water molecules. Dehydration of gypsum allows the gypsum to become rehydrated later. After addition of water, the rehydrated gypsum dries and sets, it becomes a rock-hard substance, which is commonly used in variety of building materials.

For decades, paraffinic PCM has been the most widely used latent heat storage material for thermal enhancement of gypsum boards and plasters. The reason for this is very simple; in interior environments, PCM with a melting temperature between 19 and 24 °C can be used with best results, since this is a temperature range, which is close to human comfort level. Keep in mind that paraffin waxes (such as *n*-hexadecane, *n*-heptadecane, and *n*-octadecane) match the necessary temperature range well. That is why a large number of building applications used today by construction industry largely use paraffin for heat storage. However, due to relatively high cost of paraffin-based PCM, its flammability, and origin in non-sustainable petrochemicals, other organic PCMs are being explored now, including fatty acids, coming from agricultural and food industry waste.

Interior building surfaces of walls, ceilings, or floors have been traditionally considered as the best locations for the PCM. In gypsum board and plaster applications, PCM is used to stabilize the temperature of the building interior. As shown in Fig. 2.3, PCM concentrated in gypsum boards interacts mostly with the interior of the building. The energy storage capacity of the PCM-enhanced gypsum is used to reduce interior space temperature swings and absorb solar gains coming through

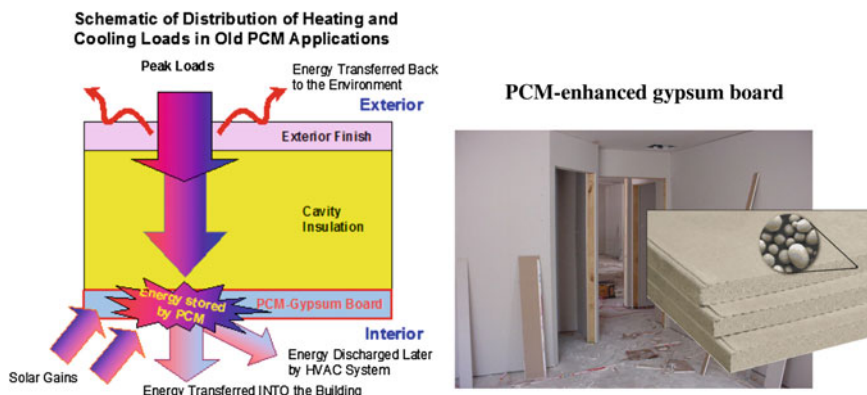


Fig. 2.3 PCM as part of the interior surface of the building envelope

the glazing. In this working scenario, heat stored in PCM needs to be discharged through, most-often, ventilation during the night or by the building's space conditioning systems. In the second case, when mechanical system is used, there may not be direct energy savings. The only energy benefits associated with this PCM setup can be peak-hour load savings and peak load shifting. In addition, in buildings using air-conditioning, due to the relatively small interior temperature fluctuations, PCM applications facing the interior of the building may require a long time to discharge the stored energy.

During the last two decades of twentieth century, interest has increased toward the energy saving potential achieved when combining PCM into wall or ceiling interior finish materials. PCM-enhanced wallboards are capable of stabilizing interior space temperature by capturing dynamic internal thermal loads and a large proportion of incident solar radiation falling on building surfaces. They are also relatively easy to install and are used in a wide variety of applications. Most of the earliest studies focused on wallboard that had been immersed into the molten paraffin. Gypsum, in wallboard, can absorb up to 30 weight percentage of PCM (Stovall and Tomlinson 1995; Neeper 2000). Initially, porous building materials such as gypsum were dipped into a molten PCM bath, absorbing the material into pores by capillary action. Next, the building material was removed from the paraffin immersion and was cooled, allowing the PCM to set. The great advantage of this method was that it enabled ordinary wallboard to be converted to PCM wallboard simply, inexpensively, and when it was required, i.e., imbuing the material either prior to installation or at the building site. The major disadvantage was potential leaking of PCM from the product causing aesthetical surface discolorations.

Non-encapsulated paraffins were the initial material of choice in early investigations of the PCM-impregnated gypsum boards. Today, they are still the most common PCM substances considered for thermal enhancement of gypsum boards, however, after microencapsulation. Research by Feldman and Shapiro (1989), Feldman et al. (1991), and Peippo et al. (1991) showed that gypsum-paraffin

composites can be used to reduce room cooling loads. Paraffinic hydrocarbons generally perform well while impregnating gypsum boards with liquid material, but they increase the flammability of the building envelope (see Slayer and Sircar 1989; Tomlinson et al. 1992; Kissock et al. 1998). Salyer and Sircar reported that during the testing of wallboard with PCM, after 3 months of continuous exposure to cycled 40 °C air, there was no significant loss of PCM. In addition, Kissock and co-workers investigated the wallboard which contained a paraffin-based PCM mixture made up mostly of *n*-octadecane. This PCM had a mean melting temperature of 24 °C and a latent heat of fusion of 143 kJ/kg. They reported: "...it was easy to handle and did not possess a waxy or slick surface. It scored and fractured in a manner similar to regular wallboard. Its unpainted color changed from white to gray. The drywall with PCM required no special surface preparation for painting" (see Kissock et al. 1998).

In first PCM gypsum applications analyzed by Oak Ridge National Laboratory, USA, gypsum boards impregnated with paraffin were installed directly on the interior building surfaces (see Drake 1978; Tomlinson and Heberle 1990; Tomlinson et al. 1992). A following study focused on gypsum board impregnated with non-encapsulated PCM demonstrated a potential for significant cooling energy savings. However, this work indicated a need for greater convective heat exchange between PCM-enhanced gypsum boards and interior space air (see Stovall and Tomlinson 1995). In addition, Neeper (2000) examined gypsum wallboard infused with fatty acids and paraffin waxes, subjected to the diurnal variation of room temperature, but not directly illuminated by the sun. Kondo et al. (2000), with a research team from Kanagawa University and Tokyo University, Japan, researched the thermal storage of PCM-enhanced gypsum boards using the dual-PCM mixture containing 95 % octadecane and 5 % hexadecane.

Since, PCM must be able to cycle continuously day after day, it is critical to optimize its amount, phase transition temperature, and location within building envelopes. Numerical analysis is very helpful for this purpose. It has been used in many research projects worldwide in conjunction with laboratory or field experiments. For example, Athienitis et al. (1997) conducted extensive field experiments combined with one-dimensional nonlinear numerical simulation study in a full-scale outdoor test room with PCM gypsum board as inside wall lining. Their numerical results were compared with good agreement against the experimental data. Finite-difference heat transfer simulations were used by Lawrence Berkeley National Laboratory, USA, (Feustel 1995; Feustel and Stetiu 1997) and Oak Ridge National Laboratory, USA, (Stovall and Tomlinson 1995) to numerically evaluate the latent storage performance of PCM-enhanced wallboard. Simulation results for a living room with high internal loads and weather data in Sunnyvale, California, USA, showed significant reduction of room air temperature when heat was stored in PCM-treated wallboards. In the case of the prototype International Energy Agency (IEA) building located in California climate zone 4, it was estimated that PCM wallboard would reduce the peak cooling load by 28 % (see Feustel and Stetiu 1997).

According to many authors, the PCM used on wall surfaces may decrease overheating in the interior spaces and reduce energy consumption for space conditioning (see Kuznik and Virgone 2009; Schossig et al. 2005). In 2006, Kisko and Limas of University of Dayton, USA, investigated paraffinic PCM that can be added to the walls, to reduce the peak diurnal cooling and heating loads transmitted through the envelope (Kisko and Limas 2006). This work was a combined numerical–experimental study to quantify the effectiveness of PCM in reducing thermal loads through the building envelope components and to develop a design strategy for the placement of PCM within the massive walls. The PCM studied was paraffin octadecane, with an average melting temperature of 25.6 °C. For the climate of Dayton, OH, thermal loads through the PCM-enhanced wood-frame wall were simulated using an explicit finite-difference procedure with the indoor air temperature held constant. While comparing to the conventional wall, cooling load savings were close to 16 %. The simulation technique has been validated against the experimental work.

In addition to simple paraffinic PCM, a great variety of organic compounds, including fatty acids and esters, were also used for gypsum board impregnation. Shapiro (1989) investigated a potential of several methyl-esters PCM for introduction into gypsum wallboard with possible thermal storage applications for the Florida, USA, climate. These materials were blends of 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 were not fully sufficient for the internal wall location—PCM had problems with full cycling everyday. Similarly, (Feldman and Shapiro (1989), Feldman et al. (1991) performed extensive research on different organic compounds as candidates for PCM heat storage. This work included fatty acids (capric, lauric, palmitic, and stearic), butyl stearate, dodecanol, and polyethylene glycol 600. Various materials were considered as PCM carriers, including different types of concrete and gypsum products. The PCM gypsum board was made by soaking conventional gypsum board in liquid butyl stearate, a PCM with phase-change temperature range of 16–20.8 °C. The PCM gypsum board contained about 25 % of PCM by weight. Its thermal properties were measured with a differential scanning calorimeter (DSC). Wallboards with incorporated organic PCM were also analyzed by Shilei et al. (2006). Capric acid and lauric acid, as PCM, were applied in building wallboards for low-temperature latent heat storage due to their low carbon chains. It was found that they can automatically absorb indoor redundant heat, which can greatly reduce the building thermal loads and save electric energy for space conditioning. In full-scale experiments, a wallboard containing about 26 % PCM by weight was installed on top of the existing conventional wall. Compared with an ordinary room, it was found that the PCM wallboard room could greatly reduce the energy cost of HVAC systems and notable shift electric power peak load.

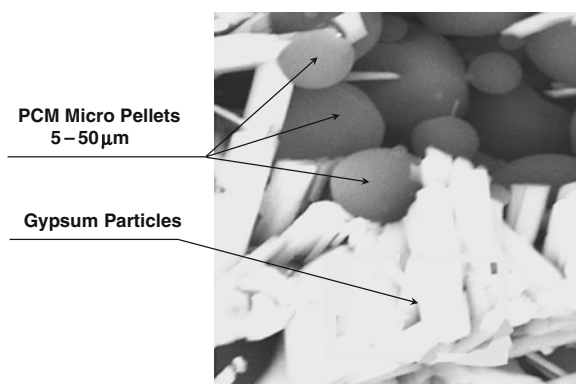
It is good to remember that PCM must be able to cycle continuously for years without loss of its reacting volume. In order to prevent PCM's loss in mass through leaking, while in melted stage or through evaporation, PCM must be enclosed,

either by means of micro- or macro-encapsulation. Later studies of wallboards and plasters containing microencapsulated PCM have shown promising results in terms of thermal performance but also in the effectiveness of the manufacturing processes used to produce these types of components. The microencapsulation of PCM has allowed a PCM weight ratio to reach about 30 % in gypsum-based composites (see Fig. 2.4). In recent years, we have seen the advent of composite materials that can contain up to 60 % by weight of PCM (Athienitis et al. 1997). The opportunities presented by the microencapsulation of PCM in gypsum plaster were also investigated by Schossig et al. (2005). It has been found that, since the PCM micro-pellets are very small, the mechanical destruction of capsules during the production process is highly unlikely. The fine distribution of the PCM particles in the matrix provides larger surface area for heat transfer, so the heat transfer rate during melting and freezing cycle is enhanced significantly. It has been shown that microencapsulation of PCM results in easy application, improved heat transfer, and good compatibility with conventional construction materials. The PCM walls facilitate low fluctuations in the indoor air temperature.

An innovative method of incorporation of microencapsulated PCM into the plaster mix for indoor use was developed by Zamalloa et al. (2006). Thermal and mechanical properties of the developed new material and long-term PCM durability have been tested. Thermal simulations were performed to study the optimal distribution of this material inside the building. These simulations were validated in the field by the construction of two real-size concrete cubicles, using in one of them the PCM-enhanced plaster. The results of the study showed that the new plaster is effective to diminish the thermal oscillations inside the buildings and reduce the energy needs up to a 10–15 % in heating and about 30 % in cooling seasons.

In recent years, heat conduction boosting agents are added to PCM-enhanced building products to improve their overall thermal performances. Earlier ORNL research on PCM-impregnated gypsum boards showed that PCM boards required a significant increase of the surface convection coefficient (up to three times), to provide proper conditions for charging and discharging of PCM. It was related to

Fig. 2.4 Electron microscope image of gypsum-PCM composite



limited temperature fluctuations available inside the building space (see Stovall and Tomlinson 1995). It was also found that heat conduction enhancement of the interior wall surface layers may improve overall effectiveness of many PCM gypsum products. Adding high conductive materials such as metal (aluminum powder and sometimes silver), metal oxide, and expanded graphite into PCM produced effective thermal storage materials and enhanced heat transfer rates with the interior space (see Zhou et al. 2007, 2014; Sari et al. 2004; Sari and Karaipekli 2007; Kim and Drzal 2009). It was found that with the addition of 3 % by weight of expanded and exfoliated graphite, the thermal conductivity of PCM composites increased between 14 and 24 %. A series of thermal storage and release tests of pure hexadecane and aluminum/hexadecane composite demonstrated significant improvement of heat conduction. Darkwa and Zhou concluded that thermal response rate especially heat-flux rate was accelerated by introducing aluminum powder. Heat conductivity of composite was more than 8 times higher comparing to pure hexadecane (Darkwa and Zhou 2011).

2.6 Use of PCM-Enhanced Wall Cavity Insulation

Similarly to, earlier described, PCM applications in wall masonry units, air gaps in massive walls and framed wall cavities can be very convenient locations for PCM. As shown in Fig. 2.5, the application placing PCM inside the wall cavity takes advantage of the large temperature fluctuations that take place on the exterior building envelope surfaces. These energy fluctuations, which can be a significant part of the building cooling and heating loads, are largely absorbed by the PCM-enhanced insulation and later transferred to the environment without affecting the interior building energy balance. In this application, phase transition temperature

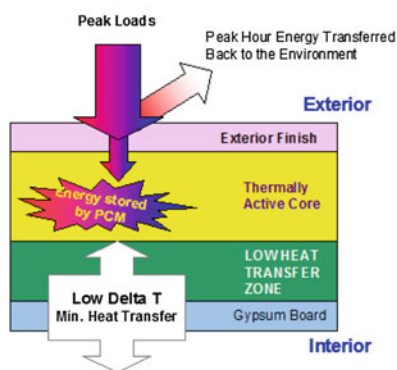


Fig. 2.5 PCM-enhanced materials used as an integral part of the building thermal envelope. *Right picture* shows construction of an experimental double wall with exterior layer of cavities containing PCM-cellulose insulation

range of PCM should be as close as possible to the interior space set point temperature. As a result, heat transfers between the core of the building envelope and the interior space is reduced. This simple change in material configuration means real space conditioning energy savings. It is also expected that this new placement method for PCM should significantly reduce flammability issues that were common in earlier technology developments. In addition, detailed optimizations performed for PCM applications showed significant potential for reduction of initial costs and a corresponding reduction in cost payback time (Kośny 2008; Kośny et al. 2009; Kośny et al. 2012a). A challenge for this application can be a need for significant latent heat storage capacity in place where PCM is located.

Ismail and Castro (1997) presented the results of a theoretical and experimental study of PCM-filled brick walls and attic floor insulation under real operational conditions to achieve passive thermal comfort. In theoretical analysis, Ismail and Castro used a one-dimensional finite-difference model for simulations of the phase transition problem in a wall constructed of two layers of brick with the PCM core. The results obtained were compared with field measurements. The experimental setup consists of a small room with movable roof and side wall. The test wall contains the PCM heat sink which was composed of two commercial grades of glycol in order to obtain the required fusion temperature range. Another wall, identical but without the PCM, was also used during comparative tests. Field tests demonstrated that in Brazil climate the PCM used was capable to maintain the indoor room temperature close to the thermal comfort levels. Economical analysis indicated that the PCM application concept may effectively help in reducing the electric energy consumption and improving the energy demand pattern in Brazilian buildings.

Another PCM application concept was proposed by Kośny and Yarbrough in 2002/2003 to the US Department of Energy (US DOE). The concept is based on incorporating PCM thermal insulation into the internal cavity of lightweight framed walls (see Kośny et al. 2006, 2007). This application is counter intuitive, because it deliberately restrains energy transport between the PCM and the conditioned space and the exterior environment (Khudhair and Farid 2004). However, this PCM location controls the temperature profile within the building envelope component, and thus influences the overall heat exchange. In some configurations, this can reduce the net energy transported through the interior envelope surfaces; in others it only changes the time when the peak energy crosses that boundary. In most air-conditioning operations, a night-time precooling is a well-established energy saving method. In the case of PCM application, the time delay can prove especially valuable, in economic terms, when utilities lower off-peak-time electricity rates. In energy consumption terms, the air-conditioning system can operate more efficiently (less costly) during the time of the shifted space conditioning loads.

Zhang and Medina of University of Kansas, USA, developed a thermally enhanced wood-frame wall that integrated a paraffinic PCM via macro-encapsulating (Zhang et al. 2005). Results from the field testing show that the PCM wall reduced wall peak heat fluxes by as much as 38 %. For a period of several days (in experiment that included walls facing different directions), the average wall peak

heat-flux reduction was approximately 15 % for a 10 % concentration of PCM and approximately 9 % when a 20 % PCM concentration was used. The average space-cooling load was reduced by approximately 8.6 % when 10 % PCM was applied and 10.8 % when 20 % PCM was used.

In research work initiated by the US DOE on fiber insulations blended with PCM, in addition to microencapsulated paraffins, new PCM produced from organic fatty-acid esters was used (Kośny 2009). Compared to the paraffinic PCM, fatty-acid esters are less expensive and significantly less flammable. They are made from underused feedstocks such as soybean oils, coconut oils, palm oils, and beef tallow. Because these esters are fully hydrogenated, the fatty-acid ester PCM is expected to remain stable during thousands of phase-change cycles with no risk of oxidation.

PCM-enhanced cellulose was one of the first successful developments of PCM-enhanced thermal insulations in the building area (Kośny et al. 2006, see Fig. 2.6). Subsequently, PCM blended with blown fiberglass (Kośny et al. 2010a) and building plastic foam insulations were introduced (Kośny et al. 2007, 2010b; Mehling and Cabeza 2008). From 2006 to 2007, ORNL performed a series of dynamic hot-box tests of wall assemblies containing PCM-enhanced insulations. For the wood-framed wall containing PCM-enhanced foam insulation, Kośny reported that it can reduce wall-generated peak-hour cooling loads by about 40 % (Kośny et al. 2007, 2010a). The major advantage of PCM-enhanced insulations is their capability of significant lessening and shifting the peak-hour thermal loads generated by building envelopes. A detailed explanation of dynamic hot-box testing procedures is presented in the following chapters. Below, a short description is available for the dynamic hot-box test performed on the wood-frame wall insulated with PCM-enhanced cellulose.

In dynamic hot-box testing, nominal 2.4×2.4 m lightweight-frame wall specimens were used (see Fig. 2.7). One of the first test walls was constructed with 6×15.2 cm wood framing installed 40 cm on center. Three wall cavities were insulated with plain cellulose of a density of about 42 kg/m^3 . Three remaining wall cavities were insulated with a cellulose-PCM blend of a density of about 42 kg/m^3 and containing about 22 % by weight of PCM. It is estimated that about 17 kg of

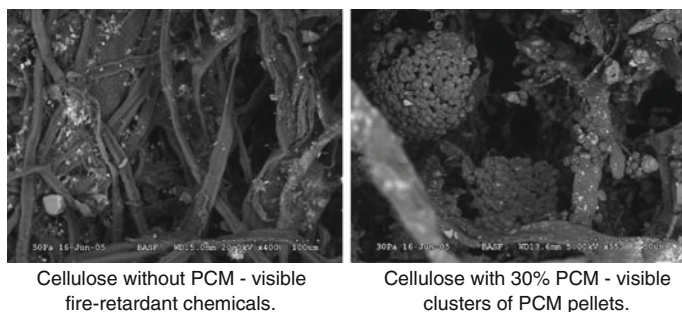


Fig. 2.6 Scanning electron microscope images of the PCM-cellulose blend. Clusters of PCM microcapsules are shown on the *right photograph*. BASF's Micronal PCM was used



Fig. 2.7 Installation of PCM-enhanced cellulose in the test walls

PCM-enhanced cellulose insulation was used for this dynamic experiment (Kośny 2008). Comparisons of measured heat flow rates on the wall surface, which was opposite the thermal excitation, enabled an estimate of the potential thermal load reduction generated by the PCM (3 test wall cavities contained about 3.6 kg of the microencapsulated PCM manufactured by BASF). In reality, most daily thermal excitations generated by solar irradiance are no longer than 5 h (peak-hour time). In this dynamic experiment, during the first 5 h after the thermal excitation, measured heat flux was reduced by about 40 % thanks to the PCM application.

In 2009, the dynamic hot-box experiment was performed on the wood-framed wall containing blown PCM-enhanced fiberglass insulation (see Fig. 2.8). This insulation was jointly developed by ORNL, Johns Manville (insulation manufacture), and Microtek Labs (bio-based PCM manufacture) (see Kośny et al. 2010a). Comparisons of measured heat flow rates on the wall surface opposite to the thermal excitation enabled estimation of the potential thermal load reduction generated by the PCM. On average, the PCM part of the wall demonstrated over 27 % total reduction of the heat flow during 8-1/2 h, and over 50 % during the first two



Fig. 2.8 Installation of the test wall containing PCM-enhanced fiberglass insulation. *Left side* presents wall cavity instrumentation with array of thermocouples installed across the wall cavity. *Right side* Cavity finish task, after blowing in fiberglass insulation

hours after the rapid heating process. It took about 15 h to fully charge the PCM-fiberglass wall. Recorded load reduction for the entire 15 h time period was close to 20 %. Thermal lag time for that heating process was between 7 and 8 h for the PCM part of the wall (Kośny et al. 2010a).

In addition to dynamic hot-box experiments, a series of full-scale field tests was performed on lightweight walls containing the PCM-enhanced cellulose insulation (Kośny 2008). A novel production method was developed and tested on a small-scale pilot line in the Advance Fiber Technologies production facility in Bucyrus, OH, USA. Then, cellulose/PCM material was produced in full-scale commercial plant conditions. Two field experiments were performed in test facilities located in Oak Ridge, TN and Charleston, SC, USA. Reduction of cooling loads averaged 42 % for PCM-insulated cavities at the southern oriented Oak Ridge test site. Heating loads during mixed season and winter were reduced by 16 % at the same location. A 5 % cooling load reduction was observed for the wall cavities insulated with PCM at the northwestern-oriented Charleston test facility. Peak-hour load reductions of 30 % were observed for PCM-insulated walls at the Charleston site during the summer months.

The incorporation of PCM-enhanced cellulose insulation for use as latent heat storage and for potential reduction of energy requirements in buildings was also analyzed by Evers et al. (2010). Two types of PCM, paraffin-based products and hydrated salt, were mixed into loose-fill cellulose insulation with 10 and 20 % by weight. A square 1.22 m \times 1.22 m lightweight wood-frame wall was used in this experiment. The test walls containing PCM-enhanced cellulose insulation were heated and allowed to cool down in a dynamic wall simulator that replicated the sun's exposure to a wall of a building on a typical summer day. Peak heat fluxes, total "daily" heat flows, and surface and air temperatures were measured and recorded. Results show that the paraffin-based PCM-enhanced insulation reduced the average peak heat flux by up to 9.2 % and reduced the average total "daily" heat flow up to 1.2 %. At the same time, cellulose insulation blended with inorganic PCM did not work. Because of the hygroscopic behavior of non-encapsulated hydrated salt, the hydrated salt-based PCM-enhanced insulation did not provide any thermal storage benefit.

2.7 PCM-Enhanced Floors and Ceiling Systems

Traditional passive solar systems have relied for decades on sensible heat storage of internal walls and floors for energy savings. However, recent research has also investigated advantages of latent heat storage for additional energy savings in passive solar applications. This can be accomplished by the incorporation of PCM into flooring materials used in passive solar houses. For this purpose, floor boards, tiles, or panels can be enhanced with PCM. Storing available solar energy during daytime and releasing it in the evening can help in reducing the building energy need for thermal comfort even during relatively cold nights. Depending on the

specific phase transition temperature, which needs to be around a comfortable room temperature between 21 and 23 °C, the PCM is expected to be effective during early and late winter as well as during spring and fall seasons. In these seasons, solar gains and peak ambient temperatures can be sufficient enough to melt PCM during daytime. During the evening or night, the ambient temperature can be low enough to discharge energy stored in PCM. An example of passive solar sunspace designed with PCM-enhanced floor components was the PCM floor system investigated by Stamatiadou et al. (2009) for the climate of Athens, Greece. It has been shown that the addition of paraffinic PCM (of specific heat capacity at 110 kJ/kg) to conventional floor tiles used for floor applications has a positive impact on the heating load, in cases of direct exposure to solar radiation. The PCM floor tiles in the sunspace, used for the numerical analysis, were compared to a typical marble floor tile. Two considered types of PCM-enhanced tiles contained 10 and 20 % of microencapsulated PCM by weight. The passive solar heating system yielded maximum solar savings of around 4 %, which can be directly translated to reduced building heating load requirements and can be expected when applying floor tiles containing 20 % of PCM by weight.

Research performed at the Colorado State University, USA, introduced a new flooring material that contained PCM (see Hittle 2002). An agglomerate floor tile containing 20 % by mass of encapsulated octadecane was manufactured. Peak melting transition temperature was determined to be 27.2 °C with a latent heat of 33.9 J/g of tile. It was determined that the maximum phase-change material content was 20 % by mass. Supplementary analysis of energy savings using this floor tile containing 20 % by mass of PCM was performed by A.S. Lee as a part of her PhD research at Colorado State University (Lee 2005). A series of dynamic whole building energy simulations was performed to enhance understanding of performance of PCM-enhanced floor tiles in residential applications (Barbour and Hittle 2006). The prototype tiles incorporating microencapsulated PCM have undergone preliminary testing indicating that the annual heating cost can be reduced by an average of 24 %. The prototype tiles were optimized to have similar physical properties as tiles without PCM.

In a similar research project performed by the University of Twente, the Netherlands, a series of field experiments was focused on PCM applications in concrete floors (Entrop et al. 2009, 2011). As shown in Fig. 2.9, the test containers used in this study had a similar configuration to what was originally used ten years earlier by the University of Dayton, OH, in the USA (see Kisscock et al. 1998). The University of Twente study demonstrated that PCM-enhanced floors can significantly improve indoor thermal comfort in southern oriented rooms. It was recorded during the summer that in concrete floors containing PCM, maximum floor temperature was reduced by up to 16 °C \pm 2 % comparing to similar assemblies without PCM. For the winter months, an increase of minimum floor temperatures up to 7 °C \pm 3 % was reported.

In parallel work, Li et al. (2009) analyzed the usage of microencapsulated PCM in floor elements made out of a composite of high-density polyethylene and wood composites. Moreover, a research team from the Southeast University, Nanjing,



Fig. 2.9 Test containers used by University of Twente, the Netherlands, to test PCM floor tiles. Entrop et al. (2011)

China, investigated a new double-layer PCM floor system (Jin and Zhang 2011). The two layers of PCM had different phase transition temperatures. It was found that compared to the floor without PCM, the energy released by the floor with PCM in peak heating demand time period can be increased by around 40 %, depends on PCM temperature range. PCM of a total enthalpy about 150 kJ/kg was analyzed in this work.

From the design perspective, PCM cooling applications in ceilings are either passive (similar to PCM-enhanced wall gypsum boards or internal plasters) (see Fig. 2.10), or active, which are usually a part of more complex, dynamic air-conditioning systems using over-night precooling with often incorporated space conditioning components (i.e., hydronic systems, micro-tubing heat exchangers, and air channels) (see Fig. 2.11). Earlier research focused on conventional ceiling cooling systems demonstrated that they can offer significant advantages over traditional space air-conditioning technologies (see Kochendörfer 1996; Antonopoulos et al. 1997; Conroy and Mumma 2001). Briefly, considerable energy savings may be observed, primarily because thermal comfort is obtained with higher indoor temperatures, typically 28 °C. Additional energy savings are obtained because of the available large cooling surfaces, which enable higher cooling water temperatures. Comfort is improved due to minimization of air motion and surface temperature differences, elimination of noise associated with fan coils, and uniformity of indoor air temperature. Also, peak cooling loads may be reduced because of cool

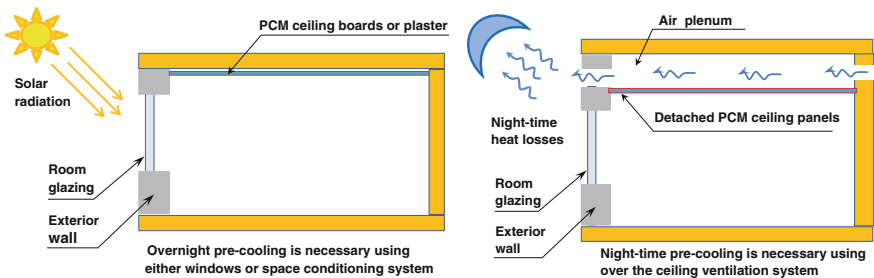


Fig. 2.10 Passive applications of PCM-enhanced ceiling systems

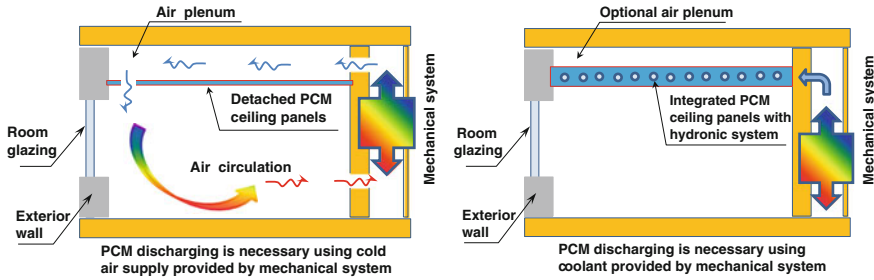


Fig. 2.11 Active applications of PCM-enhanced ceiling systems

storage within the ceiling and adjoining structural elements. Decades of testing and demonstrations worldwide have proven that adding PCM to the ceiling cooling systems can notably improve their energy performance and reduce a risk of moisture condensation. Due to a large variety of ceiling systems containing PCM described in engineering literature (see Fig. 2.12), this section is only limited to a small number of most typical, representative research projects, and applications.

One of the first passive solar heating systems that incorporate a PCM located in the ceiling was developed by Guthertz and Schiler (1991). Sun reflectors were used to direct the solar energy entering via the windows on to the PCM. The main advantage of the system was that it allowed a large area to be dedicated to heat storage without the need for large volumes of storage medium that would be required with sensible heat storage. It was shown that the use of such a system has the potential to recover 17–36 % of heat lost over the initial gains.

In an office building study performed by Kondo and Ibamoto (2006) from Kanagawa University, Japan, the PCM-enhanced ceiling rock wool boards were used, in order to reduce the cooling peak load of the air-conditioning system.



Fig. 2.12 Passively working delta cool ceiling panels containing inorganic PCM. Dörken GmbH & Co. KG, Germany

The melting point and latent heat of fusion of used PCM were 24.51 °C and 174.4 kJ/kg, respectively. Please notice that the thermal capacity of the PCM-enhanced ceiling board was approximately 663 kJ/m², which is about 5 times more comparing to ordinary rock wool ceiling boards. The tested ceiling was basically the same as the conventional plenum ceiling system used in other office buildings in Japan. The chilled air from the air-handling unit was passed through the ceiling plenum area to allow the PCM in the PCM-enhanced ceiling board to refreeze. This system required approximately 2 h of plenum cooling to fully recover PCM's heat storage capacity. It was found that due to the PCM application, the peak-hour cooling load was reduced by 14.8 %, compared to the conventional ceiling without PCM. There was a small increase in the night operation time for the space conditioning system. However, in Japan, off-peak electricity cost is significantly lower than in the middle of the day. As a result, the overall electricity cost was 8.4 % lower than that of using the rock wool ceiling boards. From these results, it can be concluded that the PCM ceiling system acts effectively to enable peak shaving and load shifting, bringing cost savings in electricity cost for space cooling.

The research team from the National Technical University of Athens, Greece, utilized the combined numerical–experimental methodology for the solution of the transient three-dimensional heat transfer problem for night cooling with use of the PCM-enhanced ceilings containing embedded piping (see Antonopoulos 1992; Antonopoulos and Democritou 1993; Antonopoulos et al. 1997; Antonopoulos and Tzivanidis 1997). This research demonstrated that thermal comfort requirements for the indoor space can be better satisfied during the day and night with an application of active PCM-enhanced ceiling systems, while compare to similar non-PCM concrete ceiling technologies. It was found that PCM applications yield significantly lower temperature fluctuations. For example, in case of the PCM-enhanced ceiling system, approximately 2.8 °C indoor temperature variations were observed, compared to about 4.4 °C in the case of the traditional concrete slab application. In addition, cycling of the space conditioning equipment was notable reduced during daily operation.

In the past, several research centers have considered an application of PCM-enhanced heat exchangers containing hydronic tubing or plastic micro-tubing systems. Very often, hydronic piping is not directly embedded in the concrete slab of the ceiling, as in many European ceiling applications. Instead, it is placed in a layer of the latent heat storage material located between the lower surface of the ceiling structure and the bottom, indoor-facing finish layer. Turnpenny et al. (2000) introduced a latent heat storage unit incorporating heat pipes embedded in phase-change material. The latent heat storage capacity in this dynamic system was restored during the night, to be available for cooling purposes in daytime. To allow sizing of an experimental mechanical system, Turnpenny also developed a one-dimensional mathematical heat transfer model of energy transfer from air to PCM.

At the same time, a large number of demonstration and commercial projects focused on novel chilled ceilings with integrated PCM have been studied by the Fraunhofer ISE, Germany (Schossig et al. 2003, 2005; Kalz et al. 2007; Haussmann et al. 2009). Different combinations of ceilings and mechanical systems were analyzed to demonstrate the main advantages of using PCM for space conditioning.



Fig. 2.13 Installation of the active-chilled ceiling system containing PCM-enhanced plaster and plastic micro-tubing. Fraunhofer ISE, Germany (<http://www.ise.fraunhofer.de/en/areas-of-business-and-market-areas/energy-efficient-buildings/hot-and-cold-storage>)

The aim of this research work was to develop new space conditioning technologies enabling reduction of the primary energy consumption associated with space conditioning. It was found that the best approach for these targets is adding PCM thermal mass to construction material which shifts building thermal loads and allows decoupling the cooling demand from the cold production. This allows moving cold production from day to night, where most space conditioning systems can work more efficient and cost-effective due to lower night air temperatures and lower energy prices. As shown in Fig. 2.13, a chilled ceiling with integrated PCM gypsum plaster and plastic micro-tubing was installed in five office rooms with an overall surface area of 100 m^2 . The layer of the PCM plaster was about 3 cm thick with a density close to 950 kg/m^3 . The overall system heat storage capacity in a 6 degree temperature range was nearly 162 Wh/m^2 . For comparison, for the same ceiling without PCM, heat storage capacity would be just around 62 Wh/m^2 . The experimental and analytical results show that the energy demand for cooling could be reduced by optimizing the control strategies. Shifting the energy demand from day to night by adding thermal mass to the building is a good solution to enhance the efficiency of most cold sources. Increasing the heat exchange area and the utilization capacity of a cold source is another important advantage achievable by using PCM in a chilled ceiling as dispersed storage. Measurements with chilled PCM ceilings also show that power output and response time are not negatively affected by the PCM, especially since the increased thermal mass only has an effect within the PCM operation temperature range. Outside the phase transition range, the PCM-enhanced ceilings react in a similar way as conventional non-PCM chilled ceilings.

According to Hasnain (1998), Khudhair and Farid (2004), and Farid et al. (2004), the ceiling structures containing PCM may store considerably greater amounts of heat than those stored in conventional concrete slabs. A properly designed application of PCM, under favorable conditions and the right temperature levels, may increase the storage capacity by more than five times or decrease storage space accordingly (Zalba et al. 2004). In hydronic ceiling applications, PCM solidification and further cooling by the cooling water take place during the

night off-peak time at the reduced electricity price. During the day, melting and further heating of the PCM take place, following the daily thermal excitations generated within the conditioned indoor space.

2.8 PCM Used in Roofs and Attics

Currently, conventional roofs and attics are thermally designed based on a steady-state criteria with thermal resistance (R -value) being used by the majority of the building standards as a metric of thermal performance. At the same time, most of these building envelope components are subject to dynamic environmental conditions. Building loads are very often complex and dynamic combinations of convective, radiative, and conductive heat transfer mechanisms with frequently added air leakage, ventilation, or hygrothermal-related mass transport process. The steady-state principles used in design and code requirements for the roofs and attics and their dynamic operation are seriously conflicting. As a result, the dynamic operation combined with shortened thermal designs yields relatively low overall thermal efficiencies. The author believes that with proper thermal design incorporating heat storage, thermal breaks, and radiation control technologies, a significant part of these dynamic loads can be reduced, or even totally eliminated, thus improving overall building energy efficiency. Well-designed roof or attic thermal systems will not only improve overall thermal resistance, but also minimize transmission of dynamic thermal excitations (by shaving and shifting dynamic loads). Some advance thermal systems can also exhaust or absorb part of the dynamic environmental loads (depending on the climatic season).

Dynamic roofs containing PCM have been investigated in the USA for several decades. In 1994, blends of lightweight aggregates and salt hydrates were analyzed and tested by Oak Ridge National Laboratory, USA, as dynamic attic floor insulation (Petrie et al. 1997). This novel attic configuration contained inorganic PCM which was sandwiched between two layers of conventional insulation. The PCM heat storage that was used consisted of hydrated calcium chloride dispersed in perlite and contained in test cells. One cell had a PCM/perlite ratio of 2:1 by weight; while the other had a 6:1 mixture. Extruded polystyrene foam (XPS) was the insulation below and above the PCM. Heat-flux transducers on the top and bottom of each cell as well as arrays of thermocouples from the top to the bottom of each cell allowed to follow the progression of freezing and melting in the PCM as the project team subjected the cells to both steady and diurnally varying simulated outside temperatures. The above testing of the perlite granulates impregnated with PCM, demonstrated excellent capability for reduction of temperature fluctuations in comparison with traditional fiberglass insulation. For example, in the 2:1 PCM system, 22 % lower thermal loads were observed comparing to the conventional fiberglass system. Its peak heat flux was reduced by 42 % as well. In addition, a four-hour delay time was observed. The 6:1 PCM insulation system showed 32 %

lower total cooling loads. The thermal load profile was essentially flat at a level that was 21 % of the peak fiberglass heat flux (79 % cooling load reduction).

Very often, dynamic roofing and attic systems utilizing PCM were designed based on earlier experiences gained during similar projects focused on wall assemblies. Following findings from earlier wall performance investigations, in 1997, Ismail and Castro (1997) presented the results of a theoretical and experimental study of the PCM-enhanced roofing insulation system under real operational conditions to achieve passive thermal comfort in a test building. The experimental setup consists of a small room with movable roof and side walls. The roof was constructed in the traditional way using attic floor insulation with added PCM. Thermocouples were distributed across the cross section of the roof. Another roof, identical but without the PCM, was also used as a baseline. It was found that for Brazilian climate conditions PCM-enhanced envelopes can help in keeping the interior of the building within desired thermal comfort zone.

In 2006, Kissock and Limas investigated paraffinic PCM that can be added to the steel commercial roofs, to reduce the peak diurnal cooling and heating loads (see Kissock and Limas 2006). This work was a combined numerical–experimental study where the numerical algorithm was validated against the experimental data. The PCM studied was the paraffin octadecane, with an average melting temperature of 25.6 °C. The metal roof that was analyzed had two 1-inch-thick layers of polyisocyanurate foam. The bottom layer of the foam was enhanced with the paraffinic PCM. For the climate of Dayton, OH, USA, thermal loads through the PCM-enhanced polyisocyanurate board were simulated using an explicit finite-difference procedure while the indoor air temperature was held constant. When compared to a conventional roof (no PCM), cooling load savings were close to 14 %.

A prototype residential roof using a cool-roof surface, natural subventing, and PCM heat sink was designed and field tested by the author (Kośny et al. 2007; Miller and Kośny 2008). A multilayer configuration of PCM-enhanced polyurethane foams, PCM-impregnated fabrics, and highly reflective aluminum foil was used. As shown in Fig. 2.14, the PCM roof also used 10-cm air channels to exhaust excess heat during peak irradiance (subventing). Two reflective membranes were placed above the roof sheathing boards with the aluminized surfaces facing each other across the 10-cm air gap. Loading of PCM was about 0.39 kg/m² of the surface area. Two types of PCM were used with two melting temperatures, which were around 26 and 32 °C. The total storage capacity of the PCM heat sink was about 54 kJ/m². The field test results show that when comparing the heat flow penetrating the conventional shingle roof to the similar metal roof assembly using cool-roof pigments, reflective insulation, and subventing air channels, the summertime peak heat flow crossing the roof deck was reduced by about 70 %. Installation of the PCM heat sink on the metal roof generated an additional 20 % reduction in the peak-hour heat flow, bringing the total load reduction to over 90 % (see Fig. 2.15).

A similar configuration of a roof containing metal roof panels with photovoltaic (PV) laminates and PCM heat sink was field tested during 2009–2010 in East Tennessee, USA, climatic conditions (Kośny et al. 2012b). It was a new solar roof



Fig. 2.14 Construction details of a roof assembly containing, reflective insulation, and subventing air channels, followed with two PCM insulation systems produced by Outlast, USA (PCM-enhanced foam and PCM-impregnated fabric, see *left photograph*)

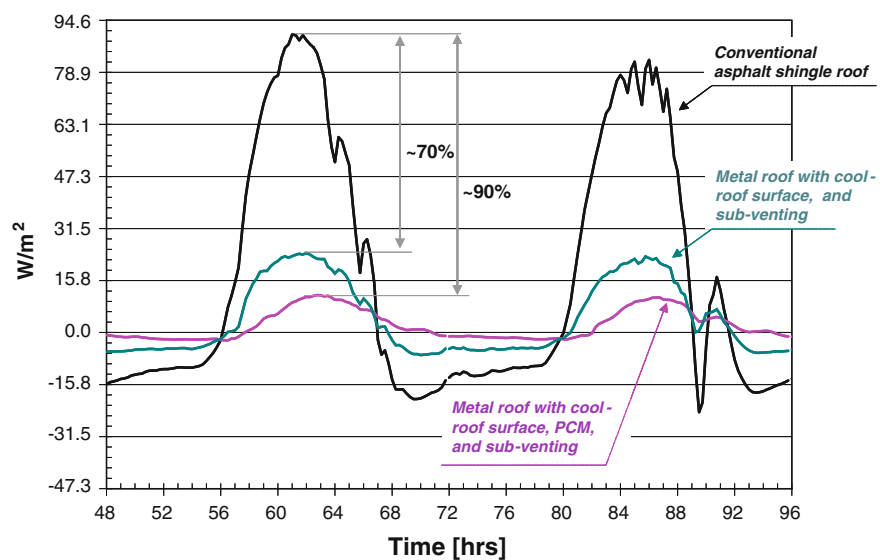


Fig. 2.15 Heat transfer penetrating the roofs of a direct nailed asphalt shingle, standing seam metal roof (containing, cool-roof pigments, reflective insulation, and subventing air channels), and a similar metal roof containing PCM

technology utilizing metal roof panels with integrated amorphous silicon PV laminates, a ventilated air cavity, dense fiberglass over-the-deck insulation with reflective surface, and arrays of bio-based PCM cells (see Fig. 2.16). The thermal performance of the experimental roof was compared to a control attic with a conventional asphalt shingle roof. The test data demonstrated that, during winter, without the phase-change contribution, the PV-PCM attic had a 30 % reduction in roof-generated heating loads compared to a conventional shingle attic. Conversely,



Fig. 2.16 Construction of the experimental PCM-PV roof—Oak Ridge, TN, USA

during the cooling season, the attic-generated cooling loads from the PV-PCM attic were about 55 % lower than the shingle attic. In addition, about 90 % reductions in peak daytime roof heat fluxes were observed with the PV-PCM roof.

Heat transmission across the concrete roof structure containing PCM was also analyzed for Indian climatic conditions (Sathyamangalam, Tamilnadu State) by Ravikumar and Srinivasan (2012, 2014). A transient numerical procedure was developed to analyze thermal performance of the PCM roof. A numerical model was validated against the available experimental data. The analysis shows that the melting and solidification of PCM, over the day–night cycle and over summer–winter cycle during the year, compensate for all the external climatic excitations and keep the roof bottom surface temperature almost constant and close to room air temperature. On a yearly basis, there was about a 56 % reduction in heat transmission observed into the room with a PCM roof in comparison with the conventional Indian concrete roof design.

A development of microencapsulated PCM which can be installed as a part of the attic insulation system was a critical step in development of modern building envelopes. Subsequent introduction of the insulation blends with microencapsulated PCM was another noteworthy technology improvement during the first decade of twenty-first century. PCM-enhanced cellulose was one of the first dynamic insulation products successfully developed for building applications (Kośny et al. 2007). In about the same time, PCM blended with blown fiberglass (Kośny et al. 2010a) and plastic foams (Mehling and Cabeza 2008; Kośny 2008) were introduced. The major advantage of PCM-enhanced insulations is their capability of significantly lessening and shifting peak-hour thermal loads generated by building envelopes.

Dynamic hot-box experiments were performed on a residential attic module containing PCM-enhanced attic floor insulation (see Fig. 2.17). The attic module was tested under periodic temperature changes in the Large Scale Climate Simulator (LSCS) at the Oak Ridge National Laboratory, USA (see Kośny 2008). Two concentrations of microencapsulated PCM were tested (5 and 20 % by weight). The main focus of the attic tests included discharging time of the PCM-enhanced



Fig. 2.17 Experimental attic module containing microencapsulated PCM blended with cellulose insulation, ORNL, USA, testing facility

insulation (time necessary to refreeze PCM). PCM charging is not a problem in attics because of the intensive fluctuations of the attic air temperature during sunny days (a rapid increase in temperature caused by the sun). However, the attic cooling process is significantly slower. In a well-designed PCM application, 100 % of the PCM material should be able to fully discharge its energy before daytime operation the next day. During the dynamic LSCS tests, the attic test module was subjected to periodic changes of temperature. The following temperature schedule was used: 18 °C for about 16 h, rapid temperature ramp to 50 °C and kept for about 4 h, followed by natural cooling back to 18 °C. One of the noteworthy findings was that only layers of insulation located higher than 10 cm from the attic floor were involved in the phase-change process. It took about 6–8 h to fully discharge the energy stored in these layers. It is interesting that even in attic insulation containing only 5 % PCM by weight, notable evidences of phase change were observed (Kośny 2008).

During the summer of 2008, a full-scale experimental attic was constructed and instrumented in order to field test blown fiber glass insulation combined with microencapsulated PCM in the ORNL test facility. Bio-based microencapsulated PCM, manufactured by Microtek Labs., USA, was utilized in this experiment. The main goal of this experiment was to investigate at what level and how often PCM was going through the phase-change process. As shown on Fig. 2.18, a full-scale residential attic was filled with about 26-cm blown fiber glass insulation with the approximate density of 29 kg/m³. Next, on top of this insulation, four 1.3-cm-thick layers of the PCM-adhesive blend were installed with 1.3-cm-thick layers of blown fiber glass installed in-between. The total thickness of added PCM-fiberglass multilayer sandwich was approximately 10 cm (Kośny et al. 2010a). Results of DSC testing and numerical analysis indicated that in order to make PCM fully melt, attic air temperature should be—during the peak of the day—higher than 32 °C. It was also found that during the night, attic air temperature should be below 20 °C to allow PCM to refreeze. Melting temperature of microencapsulated PCM used was at about at 29 °C. A temperature difference between melting and freezing peaks

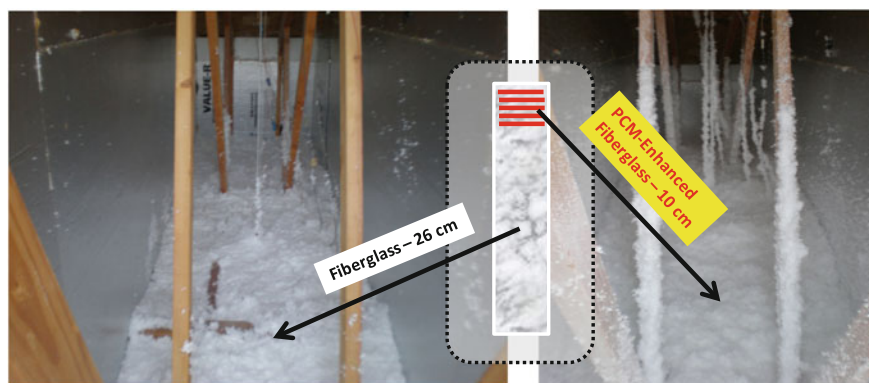


Fig. 2.18 Field test attic module containing PCM-enhanced fiberglass insulation

(PCM subcooling effect) was about 6 °C with freezing temperature close to 23 °C. The phase-change enthalpy was about 170 kJ/kg. Detailed temperature profiles across the roof, attic space, and within the attic insulation were collected for two summer seasons of 2008 and 2009. It was found that for East Tennessee, USA, climate, the second week of May was a beginning week for PCM to have at least two full phase changes a week. This process ended during the first week of October. In May and September, calculated number of active days for PCM was close to 50 % of total number of days. During the months of June and August, during about 75 % of days, full phase transition processes took place. In July, due to increased night temperature, a number of days when PCM was fully active went down to below 50 %. Theoretical analysis showed that, in order to improve PCM effectiveness during July, it is possible to use PCM of higher melting point (Kośny 2008; Kośny and Kossecka 2013). However in that case, a number of active days can be reduced for May and September. This work demonstrated that numerical analysis is usually necessary to optimize the PCM roof design for a specific climate.

A series of thermal simulations of the 25-cm-thick attic floor insulation showed significant reductions to the total thermal loads, generated by the PCM attic. In general, PCM-enhanced attic insulation assemblies may reduce peak-hour loads by 25–44 % when compared to non-PCM systems of equivalent *R*-value—subject to the PCM load and PCM location (see Kośny et al. 2014).

2.9 PCM-Enhanced Windows and Window Attachment Products

As presented in earlier sections, an application of PCM is an interesting solution for improving opaque building envelopes. However, PCM can be also an attractive alternative for fenestration products as they generate a significant part of building

thermal loads. In conventional applications, thermal performance of fenestration is most-often improved by the use of absorbing gases filling the gap between glass sheets, or by an application of thermally insulated glass windows. When only translucency is required, the other thermal improvement possibilities may incorporate novel filling materials into glass panes, such as silica aerogel or a semi-transparent PCM. Both of these options require serious consideration of optical properties and window functionality. The objective of using PCM in the window glazing or the shutters is to utilize their high latent heat of fusion to reduce window-generated thermal loads by absorbing the heat gain before it reaches the indoor space. The phase-change cycle may stabilize the indoor building temperature and reduce the heating and cooling loads. 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. 2.19a. In dynamic windows, PCM changes its phase from solid state to liquid when heated, thus absorbing available solar energy in the endothermic process. At the same time, PCM's translucency is usually changing as well. When the ambient temperature drops during the night, the melted PCM of required optical properties solidifies into a solid-state material while giving off the earlier absorbed heat in the exothermic process. A suitable phase-change temperature range, depending on climatic conditions and desired comfort temperatures, as well as the ability to absorb and release large amounts of heat energy are needed for proper work of PCM windows. It is essential that both phase-change transition ability, as well as PCM optical characteristics do not deteriorate in time, which is a crucial condition when selecting PCM for fenestration application.

Translucent Trombe walls are constructed in a way that they can transmit light and illuminate the building interior. In conventional solar fenestration systems, the

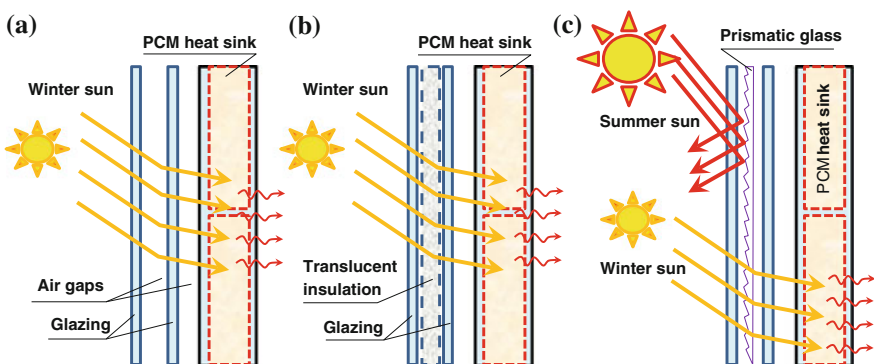


Fig. 2.19 Different configuration options of semi-transparent PCM solar fenestration: **a** Semi-transparent Trombe Wall containing PCM heat sink. **b** Translucent Trombe Wall with PCM heat sink and translucent insulation. **c** Solar fenestration system using PCM heat sink and selective prismatic glass

temperature gradient within the assembly results in winter time significant heat losses from the heated interior to the cold exterior. As shown in Fig. 2.19b, heat losses through the glazing can be reduced using a transparent insulation (vacuum) or translucent insulating fillers (i.e., aerogels) placed between window panes. The transparent or translucent thermal insulation transmits solar radiation, which is then absorbed by a layer of PCM, which is usually partly transparent when melted. In order to further improve thermal performance, translucent/transparent storage walls may use selective glass. During the summer, the outer prismatic glass may be used to reflect the high-angle rays of the sun—Fig. 2.19c.

Various paraffins are typical examples of PCM in building products, but a low thermal conductivity (Farid et al. 2004), significant volume change during phase transition (Hasnain 1998) and poor optical properties limit their fenestration applications. Askew (1978) used a collector panel made of a thin slab of paraffin placed behind the double glazing of a building and found that thermal efficiency was comparable to a conventional flat plate solar thermal collector. In a following research performed by Nayak (1987), a Transwall solar system was used as a transparent modular wall that provides both heating and illumination of the dwelling space.

Further design possibilities emerge from the variable translucency of some PCM-based products. 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 (Mehling and Cabeza 2008). Manz et al. (1997) 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. Experimental data were gathered over a period of 5 months. The authors concluded that overall system performance could be improved by changing of the PCM melting temperature from 26.5 to about 21 °C. Another semi-transparent solar window system containing PCM has been introduced by the INGLAS company from Friedrichshafen, Germany.⁴ 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 (Mehling and Cabeza 2008). In this technology, a variable transparency is utilized

⁴<http://www.inglas.eu/glass/company.html>.

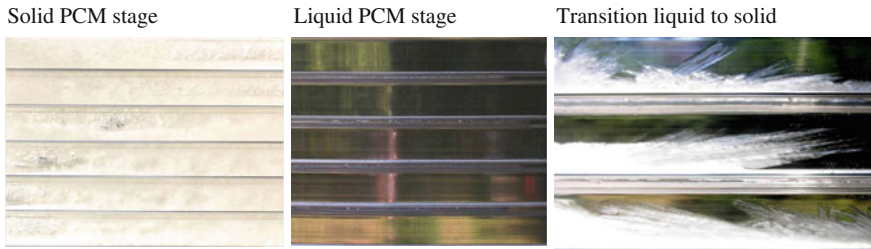


Fig. 2.20 PCM-enhanced window component with variable optical properties, Dorken, Germany (<http://www.cosella-dorken.com/bvf-ca-en/projects/pcm/kempen.php>)

for an effective diffuse illumination of the interior space. PCM optical properties are changing to some degree between the solid and liquid states (see Fig. 2.20).

Parametric analysis and performance comparisons with other advanced fenestration products are important factors, in designing of low energy buildings, which needs to be undertaken with advanced thermal modeling on a system scale, with use of whole building energy simulations. As an example, Ismail et al. (2008) numerically analyzed performance of the PCM-filled window and the window filled with the infrared absorbing gas. The use of absorbing gases and filling the gaps between glazing sheets appears to be an alternative solution for thermally insulated glass windows. In this work, a thermal efficiency comparison between glass window, filled with an absorbing gas and the other one containing a PCM heat sink was analyzed for a hot cooling-dominated climate.

A concept of solar windows using PCM-enhanced window attachment products is an attractive alternative for described above fenestration systems with PCM heat sinks. However, this technology is still awaiting successful implementation. Additionally, many semi-transparent and translucent solar walls have several disadvantages. One is reduced optical transparency. The other one is limited thermal storage capacity. These systems need to have sufficient thermal mass resulting in significant thickness coming from added PCM components. This is where PCM-enhanced window attachments (blinds, shutters, or curtains) offer a unique solution: a thin, movable layer of PCM which can be easily used “as needed” without compromising window optical properties (see Alawadhi 2012). A fenestration system using movable PCM heat sink needs to be installed on the south-side windows. When PCM window attachments are in use (during the sunny day), the window heat sink is heated by incoming solar radiation, melting the PCM. At night that heat is utilized to warm the interior space.

The window shutters and blinds are often made of extruded plastic or foam-filled aluminum profiles. The same extruded profiles can be used as PCM containers. PCM can fill existing cavities or replace foam as a filling material there. PCM-enhanced window attachments can be installed on the interior side of south-facing windows. In cooling scenario, the PCM blinds are used in the same way as conventional blinds, yet absorb excess solar radiation. The PCM is regenerated at night through radiation to the exterior or/and by cool air (from outside ventilation flaps or

tilted-open windows). According to Alawadhi, the numerical result indicates that heat gain through the windows can be reduced as high as 20–30 % depends of climatic conditions, window type, and PCM configuration (Alawadhi 2012). A similar window attachment systems using PCM have been installed in four offices⁵ (two in Kassel City Hall and two in the EnBW building in Karlsruhe, Germany). The solar protection system consists of vertical blinds; there is an approximately 1-cm-thick layer of PCM in each of the slats.

In another concept, window shutters containing PCM are placed outside of window areas. During daytime, they remain opened to the outside. However, the shutter surface is still exposed to solar radiation and heat is absorbed causing PCM to melt. At night, the shutters are closed, insulating the windows and heat from the PCM radiates into the rooms. Buddhi et al. (2003) studied the thermal performance of a test cell (1 m × 1 m × 1 m) with and without PCM. Lauric acid with melting point of 49 °C was used as a PCM latent heat storage material. It was 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 nighttime. In another research project focused on PCM-enhanced window attachments, Ismail and Henriquez (2001) numerically and experimentally studied thermally effective windows with moving PCM curtains.

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⁵<http://pcm-demo.info/objective.htm>.

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