1. Materials

1.1. Phase change materials (PCM) for building application

Construction industry in general and buildings during their life cycle are the largest energy-consuming sector in the world. For example, in the EU the construction sector accounts for around 40% of the total final energy consumption ("Resource efficiency in the building sector," 2014) and produces nearly 40% of the total CO2 emissions (Asadi, da Silva, Antunes, & Dias, 2012) (Diakaki, Grigoroudis, & Kolokotsa, 2008). Therefore, in the framework of this Project new technological solutions of Nearly Zero-Energy buildings will be selected to promote sustainable development of construction industry as well as to contribute positively towards objectives set out in the National Energy-efficiency Action Plan for the construction sector[1]. The NZEB concept could be a part of the energy efficiency-related activities and policies at regional, national and international levels.

Ongoing improvements in building envelope technologies suggest that residences and commercial buildings will soon be routinely constructed with low heating and cooling loads. The use of novel building materials containing active thermal components (e.g., PCM, subverting, radiant barriers, and integrated hydronic systems) would be an ultimate step in achieving significant heating and cooling energy savings from technological building envelope and construction improvements. The key benefit of using PCM is improvement of thermal storage capabilities of structures with minimal change to the building design (Kumar & Assistant, 2013).

Present-day residential and commercial buildings are becoming more structurally lightweight, and concerns are being 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.

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 (Jeanjean, Olives, & Py, 2013) The location of the PCM within the building is of big importance for the optimum performance of the system. Fig.1.1 shows different locations in a typical lightweight building construction system (Jin, Medina, & Zhang, 2014).

[1] EMZinoPielik2_150514_Buildings renovation strategy LV.docx; Ēku renovācijas ilgtermiņa stratēģija 2014. – 2020.gadam, https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_lv_latvia.pdf

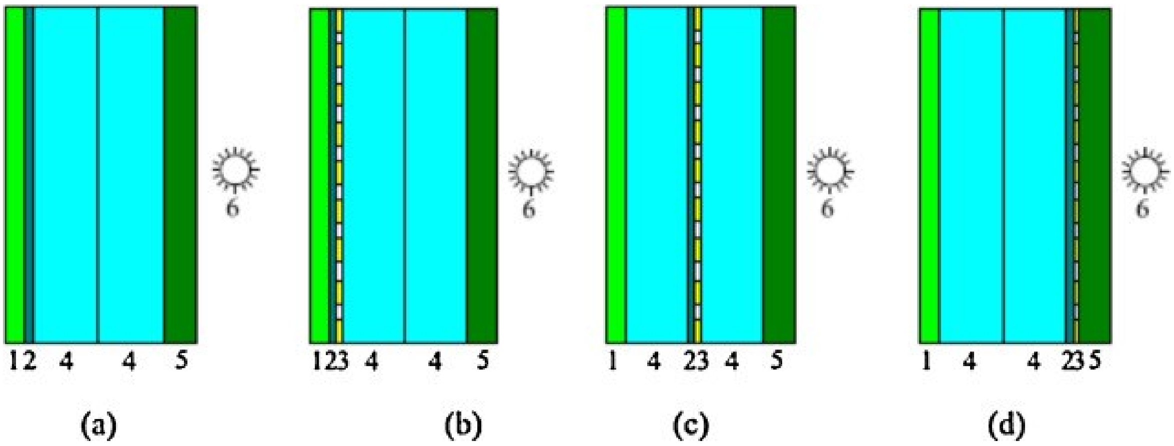

Figure 1.1. *Wall including PCM in different locations: (a) control wall; (b) PCM located next to the internal face of a gypsum wallboard; (c) PCM located between two insulation layers; and (d) PCM located next to the internal face of an oriented strand board (Jin et al., 2014)*

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.

Wall constructions with PCM typically are used in mixed and cold climates (Fig. 1.2.). A key ingredient of these wall constructions is their heat storage capacity, then conventional heavyweight thermal mass is replaced by PCM and thermal mass of lightweight constructions is noticeably increased.

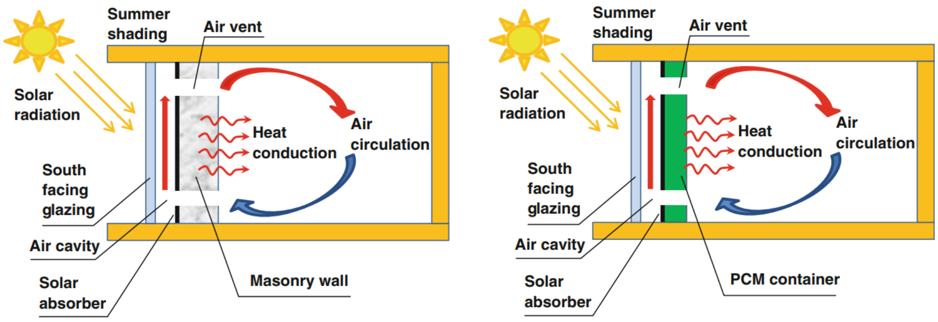

Figure 1.2. *Schematics of conventional Trombe Wall and PCM-enhanced Trombe Wall (Kośny, 2015)*

Combination concept of Trombe wall system with PCM-enhanced building envelopes shows great potential for integration into low energy consumption buildings (Fig. 1.3.). However there are still problems regarding their application and design, for example to improve heat accumulation of the massive wall in winter, some researches install an absorber plate in the air gap and use a black surface of the heat storage wall (Saadatian, Sopian, Lim, Asim, & Sulaiman, 2012), (Hu, Luo, & He, 2015).

The exterior surface of the heat storage part of Trombe wall 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.

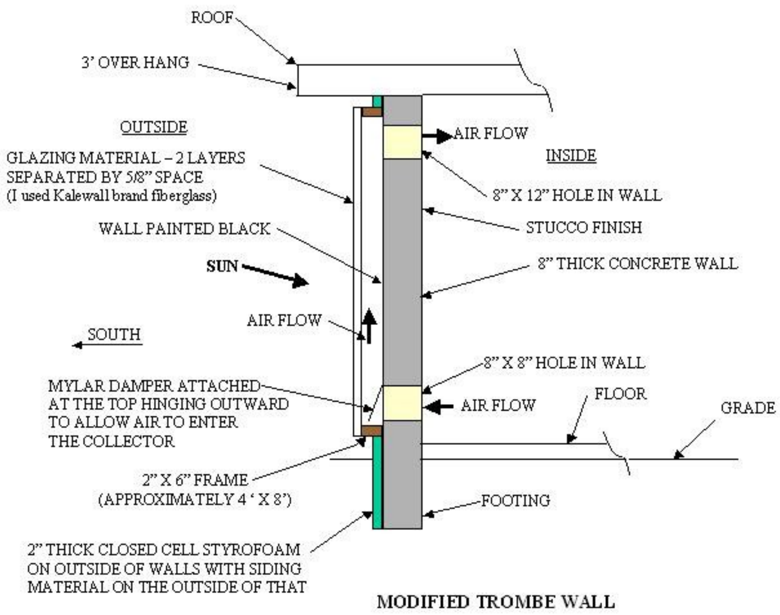

Figure 1.3. *Schematic draw of Trombe wall (Pless & Torcellini, 2004)*

A Trombe wall is a passive solar building design where a wall is built on the winter sun side of a building with a glass external layer and a high heat capacity internal layer separated by a layer of air. Light close to UV in the electromagnetic spectrum passes through the glass almost unhindered then is absorbed by the wall that then re-radiates in the far infrared spectrum which does not pass back through the glass easily, hence heating the inside of the building. Trombe walls are commonly used to absorb heat during sunlit hours of winter then slowly release the heat over night. Trombe walls work on the basic greenhouse principle that heat from the sun in the form of near-visible shorter-wavelength higher-energy ultraviolet radiation passes through glass largely unimpeded. When this radiation strikes objects the energy is absorbed and then re-emitted in the form of longer-wavelength infra-red radiation that does not pass through glass as readily.

Higher window to wall ratios (WWR) entail larger thermal exchanges, and consequently longer thermal discomfort periods and increased energy consumptions for space conditioning. Andric in this study investigates the potential of passive latent heat storage using Phase Change Materials (PCM) as a retrofit measure in high-rise apartments in Toronto (Andrić et al., 2017). The results showed significant reduction of overheating and daily temperature swings in units with 80% WWR in Toronto. A significant potential for the composite PCM system in reducing energy consumption and improving thermal comfort was observed in the simulation study.

The capabilities of incorporating PCM in structures to thermally stabilize interior space and shift peak-hour cooling loads are highlighted in publications of many researchers (Mavrigiannaki & Ampatzi, 2016), (Iten, Liu, & Shukla, 2016),(Osterman, Butala, & Stritih, 2015). 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.

Interior building surfaces of walls, ceilings, or floors have been traditionally considered as the best locations for the PCM and PCM is used to stabilize the temperature of the building interior. PCM can be easily blended with many construction materials. This makes it possible to increase the latent heat capacity of lightweight constructions by applying into wall or ceiling interior finishing materials. 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.

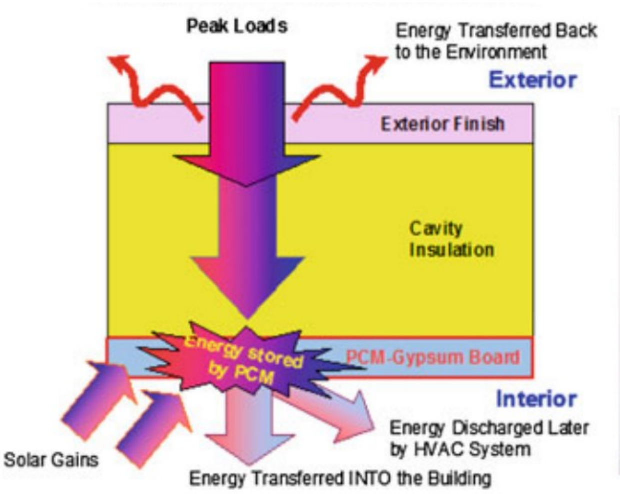

Figure 1.4. *PCM as part of the interior surface of the building envelope (Kośny, 2015)*

According to many authors, the PCM used on wall surfaces may decrease overheating in the interior spaces and reduce energy consumption for space conditioning (Delgado, Lázaro, Mazo, & Zalba, 2012),(L.Li, Q.Yan, L.Jin, 2012), (Memon, 2014), (Lee, Medina, & Sun, 2015). In 2006, Kissock 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 (Sutrisna Limas Kelly Kissock, 2006), (Fig. 1.4.). Similar investigation was done by Lleida University where energy-efficient solar residential house in Andorra was tested (Llovera, Potau, Medrano, & Cabeza, 2011).

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, floor boards (Desai, Miller, Lynch, & Li, 2014), wall boards or panels (Biswas, Lu, Soroushian, & Shrestha, 2014), (Lai & Hokoi, 2014) (Fig. 1.6.), tiles, bricks (Castell, Martorell, Medrano, Pérez, & Cabeza, 2010) (Fig. 1.5.) and etc. can be enhanced with PCM.

Figure 1.5. *Clay bricks including PCM macrocapsules (Silva, Vicente, Soares, & Ferreira, 2012)*

PCM can be incorporated in construction materials using different methods, such as direct incorporation, immersion, encapsulation (Fig. 1.9.), microencapsulation (Fig. 1.10.) and shape-stabilization (Memon, 2014). In direct incorporation and immersion potential leakage has to be assessed. When the PCM is encapsulated or added in a shape-stabilized new material, a new layer appears in the construction system of the wall.

Figure 1.6*. Gypsum* board enchansed with PCM microcapsules (Kośny, 2015)

Similarly, PCM can also be impregnated or mixed with concrete (Desai et al., 2014) or mortar (Joulin, Zalewski, Lassue, & Naji, 2014). One of the objectives pursued here is to maintain the concrete mechanical properties, while increasing its specific heat capacity. It is interesting to highlight that the addition of PCM in concrete decreases its density, which would have an interesting impact in the building structure weight.

PCM in these interior finishing materials could be expected to be effective during early and late winter as well as during spring and fall seasons. It was recorded during the summer that in concrete floors containing PCM, maximum floor temperature was reduced by up to 16 °C ± 2 % comparing to similar assemblies without PCM. For the winter months, an increase of minimum floor temperatures up to 7 °C ± 3 % was reported (Entrop, Brouwers, Reinders, & Müthing, 2009).

Li et al. (Li, Xue, Ding, Han, & Sun, 2009) analysed the usage of microencapsulated PCM in floor elements made out of a composite of high-density polyethylene and wood composites. 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.

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. 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 (Kosny, Kossecka, Brzezinski, Tleoubaev, & Yarbrough, 2012).

Another PCM application concept was proposed by Kośny and Yarbrough. The concept is based on incorporating PCM thermal insulation into the internal cavity of lightweight framed walls (Kośny J, Yarbrough DW, Miller WA, Childs P, 2007), (Fig. 1.7).

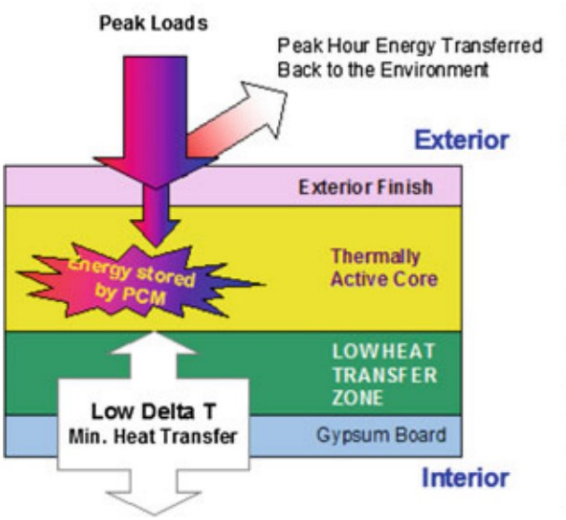

Figure 1.7. *PCM-enhanced materials used as an integral part of the building thermal envelope (Kośny, 2015)*

Figure 1.8. *Construction of an experimental double wall with exterior layer of cavities containing PCM-cellulose insulation (Kośny, 2015)*

PCM-enhanced cellulose was one of the first successful developments of PCM enhanced thermal insulations in the building area (Jan Kosny, David W. Yarbrough, Kenneth E.Wilkes, Doug Leuthold, 2006), (Fig.1.8). Subsequently, PCM blended with blown fiberglass (William Miller, Jan Kosny, David W. Yarbrough, 2010) and building plastic foam insulations were introduced (William Miller, Jan Kosny, 2010), (Fig.1.9.).

Figure 1.9. *Installation of the test wall containing PCM-enhanced fiberglass insulation (Kośny, 2015)*

Another approach to incorporate PCM into insulation materials has been reviewed by Yang et al.(Yang, Fischer, Maranda, & Worlitschek, 2015) who showed that the joint advantages of the storage capacity of PCM and the insulation performance of polyurethane foams has a great potential to promote energy efficiency in buildings, but still research is needed to improve this composite.

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). Additional energy savings are obtained because of the available large cooling surfaces, which enable higher cooling water temperatures. Decades of testing and demonstrations worldwide have proven that adding PCM to the ceiling cooling systems can notable improve their energy performance and reduce a risk of moisture condensation (Fig. 1.10).

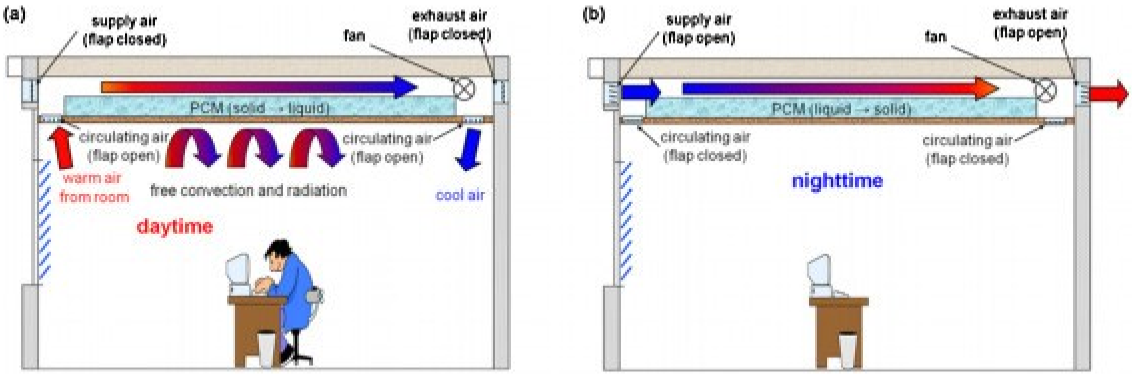

Figure 1.10. *Cooling (a) and regeneration mode (b) of the ventilated cooling ceiling with PCM (Weinläder, Körner, & Strieder, 2014)*

From the design perspective, PCM cooling applications in ceilings are either passive (similar to PCM-enhanced wall gypsum boards or internal plasters), (Fig. 1.11.) 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), (Fig.1.12).

Figure 1.11. *Passively working delta cool ceiling panels containing inorganic PCM (Kośny, 2015)*

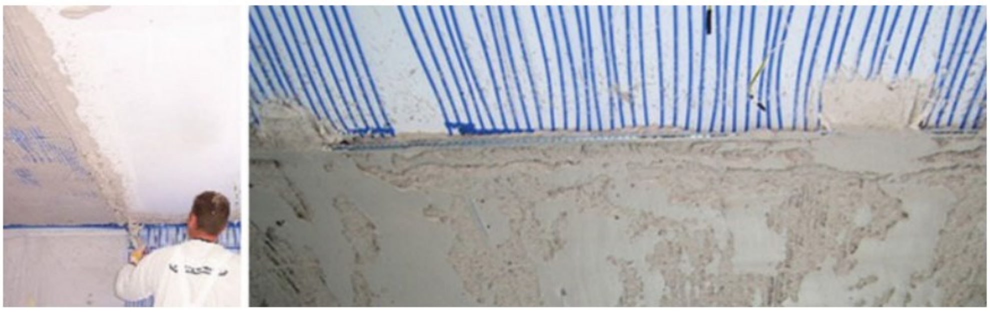

Figure 1.12. *Installation of the active-chilled ceiling system containing PCM-enhanced plaster and plastic micro-tubing (Kośny, 2015)*

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.1.13.).

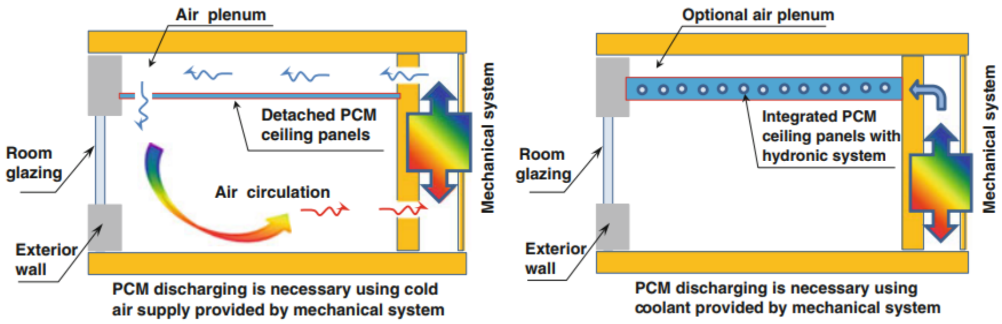

Figure 1.13. *Active applications of PCM-enhanced ceiling systems (Kośny, 2015)*

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.

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.

Furthermore, TES have been used in building solar systems in order to convert an intermittent energy source and meet the heating and domestic hot water demand (usually also intermittent but at different periods of time) (Cabeza, 2012)

The concept of new solutions for nearly zero-energy buildings involve smart, new generation load-bearing structures with reduced dead weight and increased thermal energy storage properties (passive energy storage materials or systems will be incorporated into these structures). As a result, significant increase of the heat storage properties of the structures will be obtained ensuring that the building will not become overheated and has cost-efficient use of energy during the heating season. The envelope of the building will be made of materials with high thermal mass and same time with increased thermal isolation properties. Smart civil engineering systems selected for NZEB concept will provide increased of energy efficiency and use of renewable energy resources in buildings as well as optimally designed heating, ventilation and air conditioning systems will create an indoor climate, which is favourable to the human health and work performance.

1.2. General overview

The objective of this project is to develop know-how concerning an energy efficient and sustainable construction under the temperate climatic conditions, with selection of the appropriate innovative technological solutions for the nearly zero energy buildings in climate with a great diurnal temperature variation and to develop solutions using passive elements with adaptive features to essentially increase the thermal inertia.

One of the widest used such passive elements are Phase change materials which uses a principle of latent heat thermal energy storage. Although these materials have been known for more than 70 years, only recently they have started gaining some significant attention due to lowering cost of their production and ever-increasing energy prices. PCM essentially provide large thermal energy storage capacity at reduced thickness. They can reduce peak loads on cooling and heating and provide more uniform indoor air temperature reducing fluctuations and increasing thermal comfort. And their reduced size allows for their active use for building retrofitting.

In scope of construction industry PCMs can be classified in two large groups – organic and inorganic PCMs (Fig.1.15.) Organic PCMs can be classified as paraffin's and non-paraffin's. They cover melting temperatures from -20 to 200 ºC (Fig.1.14.). Because of their weak covalent bond these materials are unstable at higher temperatures. Density of organic PCMs is below 100 kg/m^3, lower than inorganic PCM.

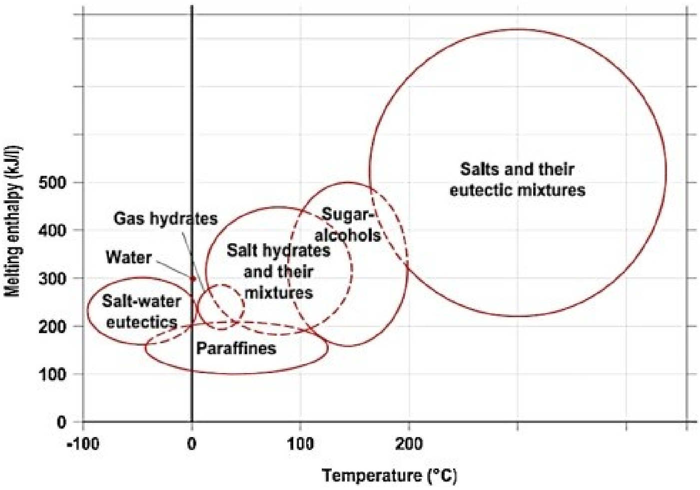

Figure 1.14. *Relationship between PCM melting enthalpy and temperature for the different groups of PCM (Baetens, Jelle, & Gustavsen, 2010)*

Because of this organic PCM usually have lower melting enthalpy. Main properties: during melting materials does not dissipate into ingredients, permanent nucleation process and non-corrosive.

Parafins are alkanes with formula C_nH_{2n+2}. Parafins in melted state between C_5 and C_{15} are liquids, others are waxes. Swelling because of melting is up to 10%, they are not soluble in water. Wax paraffin's show good melting-crystallization stability, low reaction to other materials, low difference between melting and solidification temperatures, which make them appropriate for construction industry. Downsides of organic PCMs are their high reaction to fire, low thermal conductivity and low volumetric latent heat storage capacity.

Fatty acid formula is $CH_3(CH_2)_{2n}COOH$. Their melting enthalpy and other properties are similar to paraffin, but their price is two to three times higher, which makes them commercially unappealing. Similarly are with aldehydes, whose properties is comparable with paraffin's but their price is higher (Mehling & Cabeza, 2008).

Inorganic PCMs are classified as salts and salt hydrates. They exhibit large melting enthalpy on one material mass unit. They are cheaper than organic PCMs and are non-combustible. Downsides are low forming of nucleating centres and with it super-cooling, which requires special additives to enhance. Also they can be corrosive with metals.

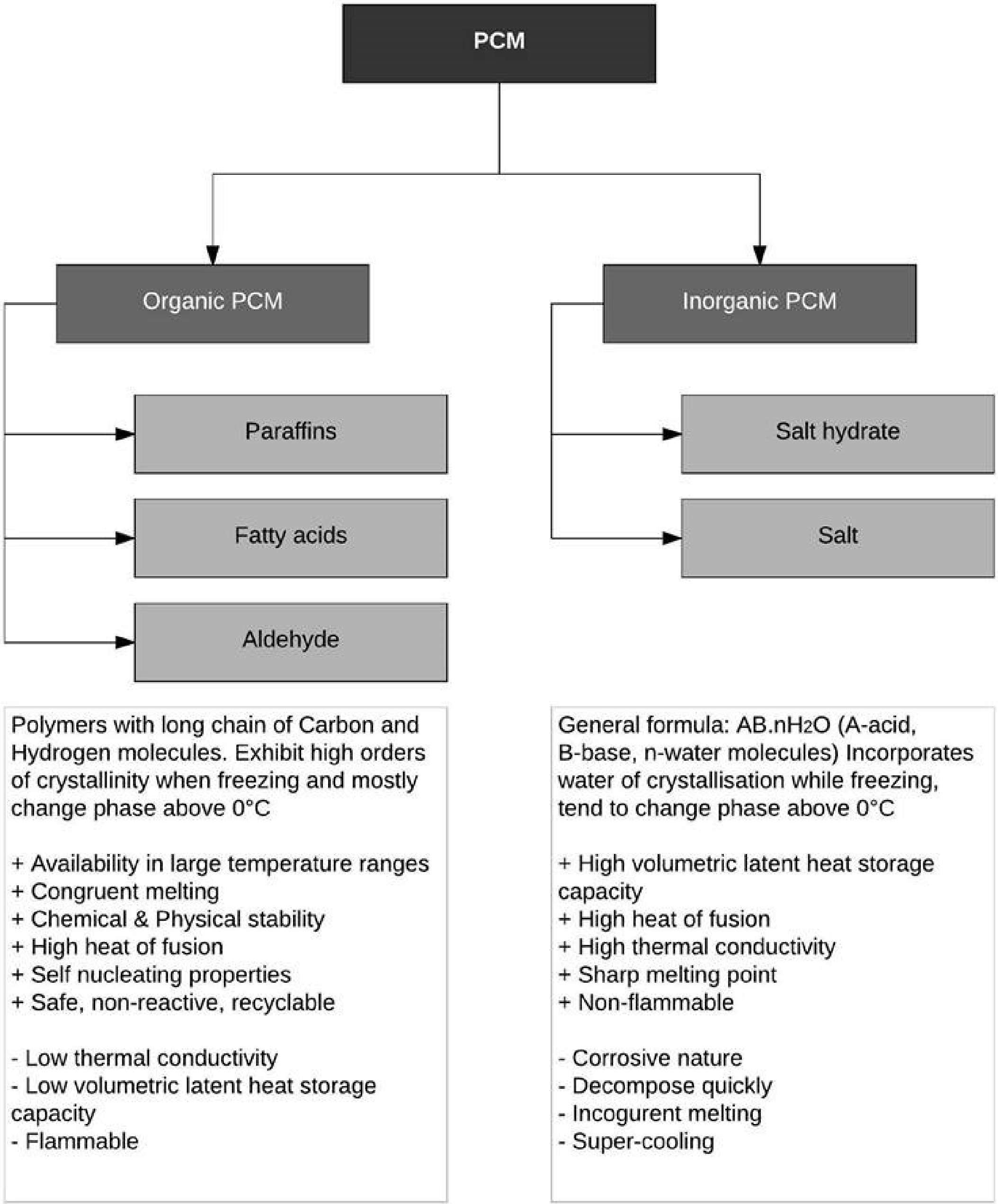

Figure 1.15. *PCM classification (Sharma, Tahir, Reddy, & Mallick, 2016)*

Salt hydrates are most common PCMs, they consist of salt and chemically bounded water, which in the solidification process creates unified matrix. Their upsides are low costs and availability, on their other hand their melting temperature range are narrower than for organic PCM.

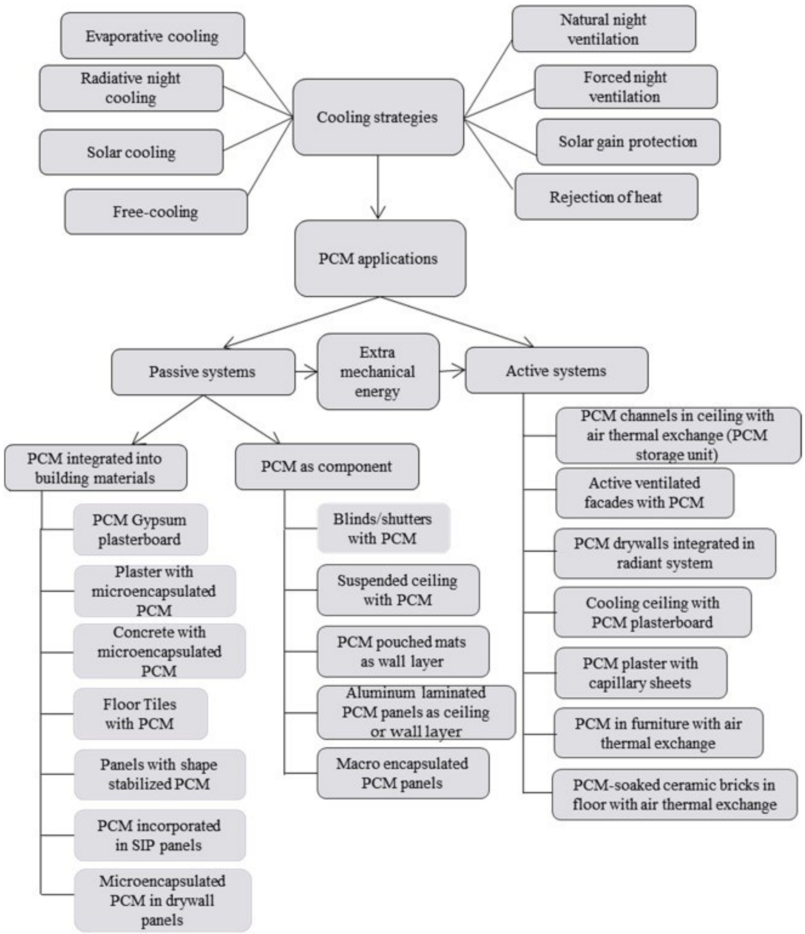

Figure 1.16. *A synthetic diagram of PCM cooling applications (Souayfane, Fardoun, & Biwole, 2016)*

Possible applications of PCM on cooling can be seen in Fig.1.16. and Table 1.1. In scope of this research more interesting are the passive systems which are reviewed further.

Table 1.1. *Summary of major results from various research studies*

Reference	PCM considered	PCM location	Objectives of study	Major result	Methodology
(Weinläder, Beck, & Fricke, 2005)	RT25 (12 mm) and S27 (8.6 mm)	PCMs located in transparent plastic containers placed behind a double glazing with an air gap of 10 mm	Investigated on a south facade panel in Würzburg, Germany	25% of energy gains can be reduced in summer; likewise 30% heat losses and 50% solar heat gains can be reduced in winter	Experiment and simulation
(Ismail & Castro, 1997)	Mixture of commercial Glycol wax	Incorporated in walls and roofs	An existing building in Campinas, SP, Brazil was	Save 19% and 31% energy for cases using window and	Simulation and experiment

			considered	central AC units	
(Zhang, Medina, & King, 2005)	Highly crystalline, paraffin-based PCM	PCM frame walls	A full instrumented test house of 1.83 m × 1.83 m × 1.22 m in Lawrence, KS, USA	The space cooling load and the average wall peak heat flux were found to be reduced about 8.6% and 15%, respectively	Experiment
(Nagano, Takeda, Mochida, Shimakura, & Nakamura, 2006)	PCM composed of foamed glass beads and paraffin waxes	PCM was embedded directly below OA floor boards in the form of granules	A small experimental system with a floor area of 0.5 m2 was investigated	89% daily cooling load can be stored in night using a 30 mm thick packed bed of the granular PCM	Experiment
(S. Limas Kelly Kissock, 2006)	K18 with an average melting temperature of 25.6 ◦C	Integrated in walls and roofs	Study includes concrete sandwich walls, low-mass steel walls under the typical meteorological weather data in Dayton, Ohio	The peak loads can be reduced by 19%, 30%, and 16% in concrete sandwich walls, steel roofs and gypsum wallboards, respectively	Simulation
(Halford & Boehm, 2007)	Salt type PCM that is held in stasis by a perlite matrix	Between two layers of insulation in a configuration known as resistive, capacitive, resistive	A geometry in which the wall/ceiling structure was assumed as a three-layer plane wall having the PCM in the center layer	The results suggest that 19–57% of maximum reduction in peak load as compared to a purely resistive R-19 wall can be achieved	Simulation
(Medina, King, & Zhang, 2008)	Paraffin-based PCM	PCM is in thin-walled copper pipes and inserted into horizontal slotscut into the polystyrene foam	Fully instrumented test house of 1.83 m × 1.83 m × 1.22 m was analyzed	The peak heat flux can be reduced by 37% and 62% using a PCMSIP with 10% and 20% PCM concentrations	Experiment
(Stetiu & Feustel, 1998)	Paraffin-based PCM	The phase change wallboard containing 20% by paraffin mass	A prototype IEA building located in California climate condition was selected	28% of the peak cooling load was expected to be reduced	Simulation
(Turnpenny, Etheridge, & Reay, 2000)	Ventilation cooling with LETES		Heat pipe/PCM unit in a controlled environment,	Ventilation with heat pipes embedded in PCMs for	Simulation

			measurements of heat transfer rate and melting times	improving the air conditioning in buildings	
(Turnpenny, Etheridge, & Reay, 2001)	Ventilation cooling with LETES	PCM with a phase-change temperature of 20°C	Installing fan at the center of the system above the heat pipe, and preventing from overheating in the summer	Heat pipes embedded in phase change material	Experimental
(Takeda, Nagano, Mochida, & Shimakura, 2004)	Ventilation using granular PCM		Experimental ventilation system that features direct heat exchange between ventilation air and granules containing a phase change material (PCM)	The outlet air temperature was fixed and stayed within the phase change temperature range	Simulation
(Nagano et al., 2006)	Floor supply air-conditioning using granular PCM	Combination of two kinds of industrial paraffin wax, hexadecane ($C_{16}H_{34}$) and octadecane ($C_{18}H_{38}$),	new floor supply air conditioning system	A 30 mm thick packed bed of the PCM could store 89% of the daily cooling load during the night	Experimental and simulation
(Castellón, Castell, Medrano, Martorell, & Cabeza, 2009)	PCM inclusion in building envelopes	A Trombe wall with PCM	Assessing the energy consumption and thermal comfort for nine test rooms with different envelopes	Temperature were reduced by up to 4°C4°C through the use of PCM	Experimental
(Fang, Wu, & Liu, 2010)	Cool storage air-conditioning with spherical capsules	Water	Experimental system on cool storage air-conditioning with spherical capsules packed bed	This system showed a better thermal performance than the conventional air-conditioning	Experimental
(Parameshwaran, Harikrishnan, & Kalaiselvam, 2010)	PCM-based variable air volume air-conditioning	Encapsulated PCM	Achieving enhanced energy conservation for space conditioning	Energy savings of 38% and 42%	Exprimental
(de Gracia et al.,	Ventilated	Macro-	Test stands	Achieving	Experimental

2013)	facade with PCM	encapsulated salt hydrate SP-22 from Rubitherm.	located in Puigverd de Lleida (Spain) with ventilated facades	average energy conservation around 28% and 47% per day by employing DCV and ECV modes, respectively	
(Hichem, Noureddine, Nadia, & Djamila, 2013)	Brick filled with PCM	Paraffin 52-54	Heat flux through the wall	Reducing the inner temperature, and the heat flux, entering the building, around 3.8 °C and 82.1%, respectively	Simulation and experimental
(Labat, Virgone, David, & Kuznik, 2014)	PCM in air heat exchanger storage for ventilation	Paraffin based, commercial Microtek 37D	Heat exchanger prototype containing PCM material	Energy stored and released is higher than 2 kWh	Experimental
(Jaworski, 2014)	PCM ceiling panel	Gypsium panel with microencapsulated PCM (Micronal DS-5008X, made by BASF).	A Ceiling panel containing mixture of PCM and gypsum mortar as night ventilation was applied	Substantial dumping of daily oscillations of air temperature	EXperimental
(Real et al., 2014)	Heat pump-based HVAC with PCM	PCM tank	improvement the performance of a heat pump based HVAC system	Cold accumulation and heat dissipation with high COP of HVAC system, increasing the energy savings around 18.97%	Simulation and experimental
(Lin, Ma, Sohel, & Cooper, 2014)	Ceiling ventilation with PVT collectors and PCM		Performance evaluation of a novel ceiling ventilation system integrated with solar photovoltaic thermal (PVT) collectors and phase change materials (PCMs	Improving the thermal comfort in a building even without air-conditioning units, with a maximum air temperature rise of 23.1 °C from the PVT collectors	Simulation
(Mannivannan & Jaffb arsathiq Ali, 2015)	Concrete roof with PCM	Chloride hexahydrate ($CaCl_2 6H_2O$)	Building concrete roof with vertical cylindrical hole of 0.5 ×	Improving the thermal comfort and reducing the internal temperature	Simulation and experimental

			0.5 m and array of 3 × 3 filled with phase change material (PCM) was considered for analysis	fluctuations around 4 °C	
(Chaiyat, 2015)	Air-conditioner with packed ball bed of PCM	Macrocapsulated Rubitherm20 (RT-20)	Concept of using phase change material (PCM) for improving cooling efficiency of an air-conditioner	Increasing the electrical power, stored by the modified system, around 3.09 kWh/d more than the basic one	Simulation and experimental
(Lee et al., 2015)	Plug-and-play walls (PPW)	Thin boards of polymeric compounds saturated with PCM and laminated with aluminum foil on both sides and around the edges	Existing institutional research building	Decreasing the daily heat transfer and delaying the time of peak heat fluxes for the south and west facing walls around 27.4% and 10.5%, respectively	Experimental
(Jamil, Alam, Sanjayan, & Wilson, 2016)	PCM in the room ceiling,	Macro-encapsulated BioPCM™ Q25, polyfilm encapsulated fatty-acid based organic PCM	Existing house in Melbourne Australia	Rescuing the thermal discomfort hours around 34%. Night ventilation is requested	Simulation and experimental

1.3. Selected materials and methods

1.3.1. "DuPont Energain"

"DuPont Energain" is PCM thermal mass panel laminated with protective aluminum foil, consisting of mix of copolymer and paraffin wax, the polymer ensures that the panel remains rigid while the paraffin is in liquid form.

The solidification/melting temperatures of "DuPont Energain" can be seen in Fig.1.17. As the temperatures rise over 22 °C paraffin wax melts as the phase change takes place, and heat is absorbed into panels. As the temperature lower, reaching 18 °C, the wax solidifies and releases stored heat back into room environment[2].

[2] http://www.edsl.myzen.co.uk/downloads/misc/DuPont%20ENERGAIN(r)%20PCM%20Guidebook_December%202010.pdf

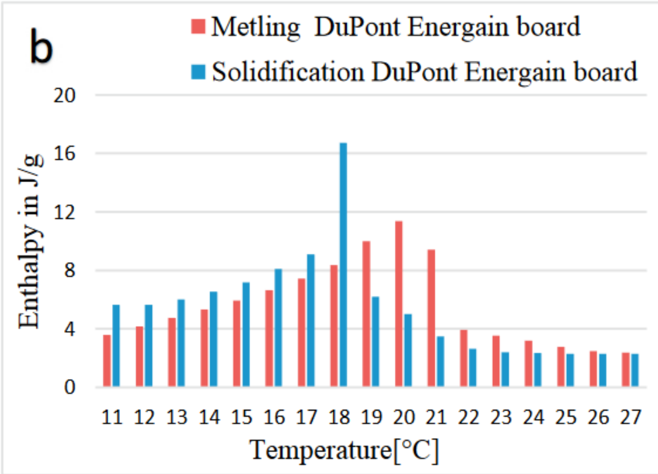

Figure 1.17. *DuPont Energain melting/solidification temperatures*[3]

“DuPont Energain” panels can be easily installed, they can be cut or sawn, and edges should be closed using aluminium foil tape (Fig. 1.18.). Can be attached by dry lining or gluing, can be covered with plasterboards or left uncovered as the foil functions also as protection.

Figure 1.18. *DuPont Energain panel (left)*[4] *and application to ceiling (right)*[5]

1.3.2. “Ilkazell Ilkatherm”

For production of “Ilkazell Ilkatherm” panels BASF “Micronal PCM Smartboards” is used and integrated in the cooling system. This system consists of sheet metal coating (1), PU rigid foam (2), capillary tube mat (3) and Micronal PCM (4)[6].

To increase energy efficiency and reduce peak temperatures in lightweight buildings, PCM (Phase Change Materials) can be used and integrated in various building elements like underfloor (Devaux & Farid, 2017), walls (Chhugani, Klinker, Weinlader, & Reim, 2017) and ceilings (Weinläder, Klinker, & Yasin, 2016). This system uses PCM

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[3] http://www.edsl.myzen.co.uk/downloads/misc/DuPont%20ENERGAIN(r)%20PCM%20Guidebook _December%202010.pdf
[4] https://www.e-architect.co.uk/products/dupont-energain
[5] https://www.e-architect.co.uk/products/wealdon-district-council
[6] https://www.ilkazell.de/fileadmin/wireframe/redaktion/downloads/Prospekte_en/en_prospekt_ilkatherm. Pdf

cooling ceilings (Fig. 1.19.). The goal of PCM cooling ceilings is to reduce cooling peak loads and shift cooling loads from day into the night when it is more efficient to produce the cool air, thus improving the efficiency of cooling system and helping PCM to solidify and regenerate.

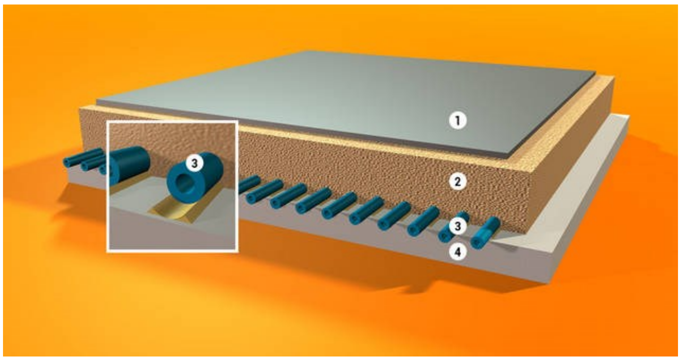

Figure 1.19. *“Ilkazell Ilkatherm” panel*[7]

Table 1.2. *Ilkazell Ilkatherm makeup (see Fig.19.)*[8]

Insulation	80mm PU rigid foam, CFC-free, foamed-in
Specific cooling performance	approx. 80W/m² at 10K below-temperature and 16°C cold water temperature
Capillary tube mats	Polypropylene-capillaries, at distance of 10mm,
	Size of capillaries: 3,4 x 0,55mm

1.3.3. “BioPCM”

“BioPCM” is a plant based PCM (Fig. 1.20.) with melting temperature +25 °C, latent heat 200 kJ/kg, thermal conductivity 0,2 W/m*K. Its properties remain unchanged in artificial aging of more than 87 years. The used raw materials (soy and palm oil) for production of “BioPCM” is complexly treated and all fatty esters are removed, so rodents have no interest in this material.[9]

[7] https://www.ilkazell.de/en/climate-systems/ilkatherm-ceiling-and-wall.html
[8] https://www.ilkazell.de/en/climate-systems/ilkatherm-ceiling-and-wall.html
[9] http://phasechange.com.au/product#toggle-id-7

Figure 1.20. *"BioPCM" based PCM material*

1.3.4. Knauf "Comfortboard"

Knauf Ltd uses the same PCM technology as Ilkatherm production "Comfortboard" – BASF "Micronal". The plasterboard of "Comfortboard" is made from FGD gypsum, a synthetic product derived from flue gas desulphurization and a waste by- product from coal-fired power plants (post-industrial recycled content). The paper liner is made primarily (>97%) from recycled paper".[10]

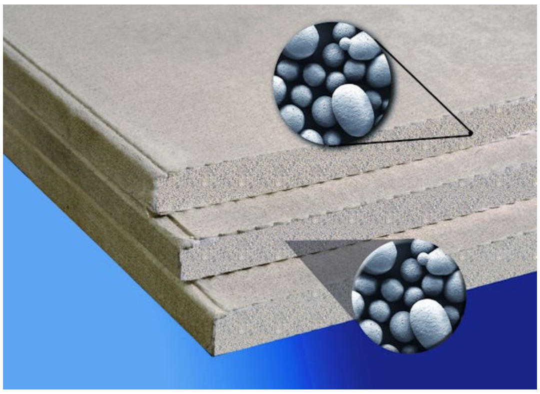

Figure 1.21. *Knauf "Comfortboard"*[11]

[10] http://www.knaufplasterboard.com.au/uploads/resource-documents/KNAUF_DESIGN_GUIDE_COMFORTBOARD_MAY_2016.pdf
[11] http://www.bine.info/en/publications/publikation/latentwaermespeicher-in-gebaeuden/baustoffe-stabilisieren-raumklima/

Table 1.3. *Summary of the reviewed PCM properties*

Properties and testing methods	Unit	DuPont Energain	Ilkazell Ilkatherm	BioPCM	Knauf Comfortboard
Thickness	mm	5.26	105	-	12.5
Width	m	1	625	-	1250
Length	m	1.2	2600	-	2000
Area weight	kg/m^2	4.5	28	3.57	11
Melting point	^{o}C	21.7	23/26	25	18-23
Heat storage	kJ/m^2	515	330	200	300

1.3.5. Description of experimental research of Knauf "Comfortboard" and DuPont Energain® board

In order to increase energy efficiency and thermal comfort in lightweight buildings, PCMs (Phase Change Materials) can be integrated within building components like finishing materials for walls or ceilings.

Materials will used in research:

- Knauf Comfortboard-23® which contains 80% gypsum and 20% microencapsulated paraffin[12]. The wallboard has a thickness of 12.5 mm and a heat storage capacity of 200 kJ/m2. The enthalpy-temperature graph is shown in Fig. 1a; the latent heat storage occurs between 18 °C and 23 °C (melting enthalpy in Fig. 1.22. a). In this temperature interval, the phase change from solid to liquid takes place and the PCM stores a high amount of heat. It can be seen from the partial enthalpies during solidification (blue bars in Fig. 1.22 a) that Knauf Comfortboard-23 shows nearly no subcooling. Solidification starts at 23 °C, and PCM becomes perfectly solid at 18 °C.
- DuPont Energain® board with a thickness of 5.26 mm; it is a compound of paraffin and copolymer, containing 60% paraffin[13]. Due to the percentage of paraffin, this board is flammable. Hence it is compulsory to apply a fire-resistant coating on the surface of the wallboard that faces the room for fire safety reasons. As Fig. 1.22 b shows, the melting range of this wallboard is between 17 °C to 21 °C, which is derived from the experiments at the ZAE Bayern and the latent heat storage capacity is 515 kJ/m2[14]. However, this board shows significant subcooling. As can be seen from the solidification in Fig. 1.22 b, the solidification slowly starts at 21 °C but the biggest part of the stored heat is only released below 19 °C.

Thermal conductivity is another parameter that influences the thermal performance of a PCM. The thermal conductivity of both wallboards is 0.23 W/mK .

[12] Knauf Comfortboard-23 data sheet. www.knauf.de/wmv/?id=13573.
[13] Kosteru, DuPont™ Energain® PCM guidebook, December 2010: new
[14] Kosteru, DuPont™ Energain® PCM guidebook, December 2010: new thermal mass solution for low inertia buildings

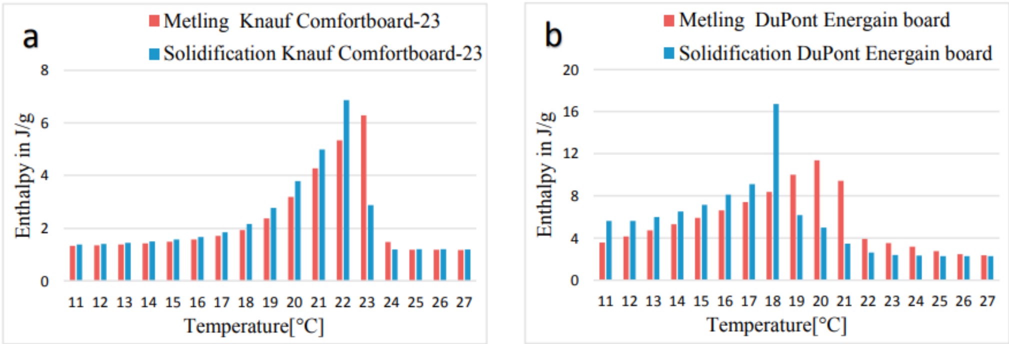

Figure 1.22. *a and 1.22 b Enthalpy-temperature graph (a) Knauf Comfortboard-23 [2]; (b) DuPont Energain board*

Short description of the experience of B. Chhungani: the aim of B. Chhungani team's research was to investigate the thermal behavior of two different PCM wallboards, the Knauf Comfortboard-23® and the DuPont Energain® Board (Chhugani et al., 2017). These wallboards were equipped in the office rooms of the Energy Efficiency Center of ZAE Bayern in Würzburg, Germany. The experimental results show that PCM wallboards can provide passive cooling powers of around 8 W/m2 under typical office room conditions. The experiments prove that PCM wallboards can almost store twice as much heat compared to conventional gypsum boards and can provide a passive cooling power which is comparable to a concrete wall with a thickness of 15 cm. However, the regeneration behavior of PCM wallboards plays a major role in its efficiency. The results reveal that Knauf Comfortboard-23 shows a better regeneration behavior than the DuPont Energain board. Still, the average regeneration rate of the Comfortboards-23 during the summer months in the offices of the Energy Efficiency Center was found to be below 20%. The regeneration of the DuPont Energain board was nearly impossible being 1% in average.

The conclusion is that a sufficient regeneration of PCM wallboards is an issue which has to be addressed to improve the thermal performance. However, PCMs are still well suited to achieve thermal comfort for lightweight buildings in moderate climate zones (e.g. Germany); the room temperature is mostly kept between 22°C to 26°C during summers.

Given materials were selected to follow experience of Chhungani et al. and to evaluate effectiveness of them in Latvia climate. Experimental plan will be developed and selected materials will be investigated during that project.

1.3.6. Doubts concerning to the economic and environmental evaluation of DuPont Energain® board done by A.L.S. Chan

In additional to the investigation on the thermal and energy performance of PCM integrated in finishing materials, economic evaluation is an essential process for assessing the applicability of PCM in buildings ("Energy and environmental performance of building façades integrated with phase change material in subtropical Hong Kong," 2011). Both capital cost of PCM and electricity tariff are crucial factors affecting the successful application of PCM integrated façade with respect to economic return. Through information collection from the supplier and contractor, it is found that the material and installation cost of PCM wallboard *Energain*® is USD 70/m^2. In Hong Kong, there is no differential pricing system for peak and non-peak periods in the tariff structure for domestic consumers. The electricity charge for domestic users is USD 0.122/kWh. By comparing the base case to the one with west-facing PCM integrated façade in the living room of a residential flat, an annual saving of 72 kWh in the cooling energy of A/C unit was determined in the previous section. The area of the PCM incorporated into the external wall of the living room is 11.4 m^2 in this study. Disregarding the time value of money, the simple payback period was estimated as 91 years. From this calculation, it indicates that the payback period is much longer than the average life span (60 years) of a residential building in Hong Kong. Obviously, the high capital cost of the PCM wallboard is the most significant disincentive to the successful application of PCM integrated façade in residential flats in Hong Kong, with respect to economic feasibility.

The embodied energy for manufacturing of PCM is commonly expressed as energy consumed per unit area (kWh/m^2) or per unit weight (kWh/kg). In this study, a value of 148 kWh/m^2 was used as the embodied energy of the *Energain*® PCM wallboard[15]. Based on an annual electricity saving of 72 kWh in A/C unit estimated for the application of PCM integrated external wall (area 11.4 m^2) in the living room of a residential flat, an energy payback period of 23.4 years was determined. This is an encouraging finding that the net energy saving over the remaining 36.6 years (i.e. no. of years after the energy payback period) has a significant implication on protecting the environment. Taking an emission factor of 0.7 kg/kWh for CO_2 average content[16] , the saving in electricity consumption of A/C unit can give a reduction of GHG emission of 1.84 tones of CO_2 equivalent per flat. The analysis shows that the energy saved can surpass the embodied energy of the PCM wallboard and contribute to mitigation of GHG emission over the life span of the building.

1.3.7. Chilled ceilings with integrated PCM

The aim of Kośny`s (Kośny, 2015) 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. 12, 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

[15] Kosteru, DuPont™ Energain® PCM guidebook, December 2010: new thermal mass solution for low inertia buildings

[16] Guidelines to account for and report on greenhouse gas emissions and removals for buildings (commercial, residential or institutional purposes) in Hong Kong, 2010 Edition, Electrical and Mechanical Services Department and Environmental Protection Department, The Government of Hong Kong Special Administrative Region

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.

1.3.8. Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system

Phase change materials are used with various building materials in order to increase their thermal mass. This research is on the application of phase change material in the form of DuPont Energain® wallboards in combination with an underfloor heating system incorporating phase change materials. An experimental study was carried out using two identical test huts at the Tamaki Campus, University of Auckland(Barzin, Chen, Young, & Farid, 2015).

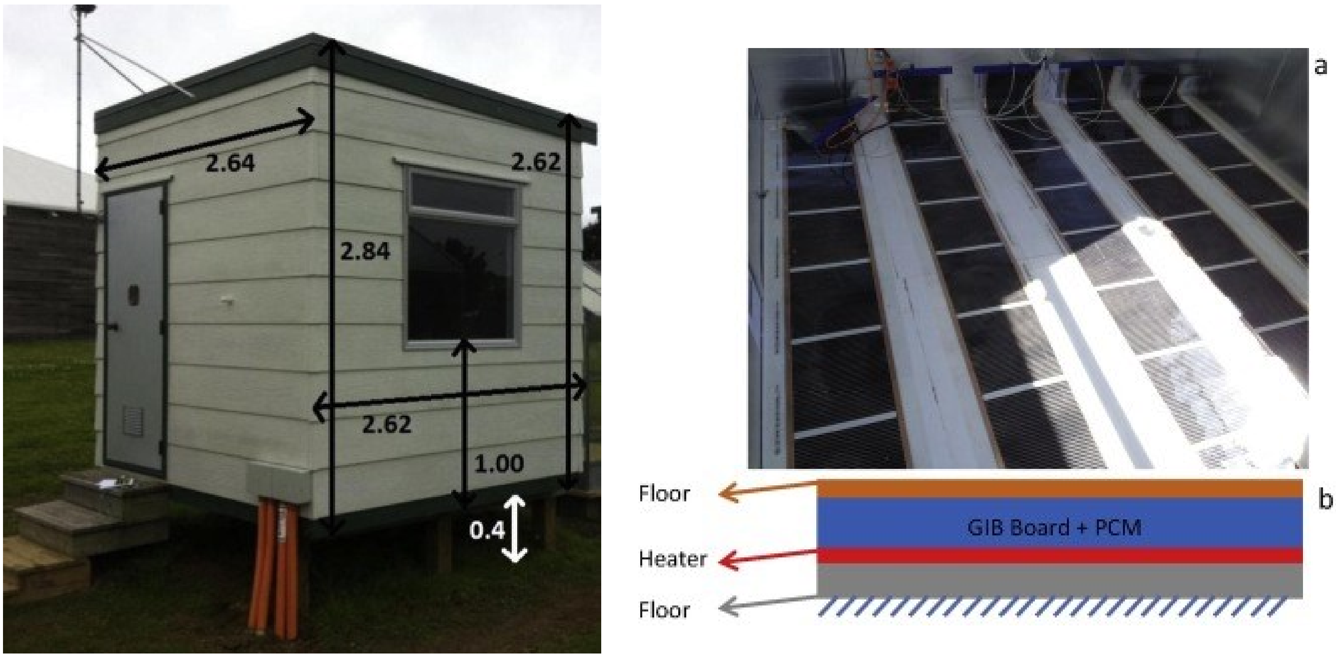

Figure 1.23. *(left) Experimental hut at Tamaki Campus; (right) The underfloor heating system used*

A series of experiments were conducted in two identical test huts at the Tamaki Campus, University of Auckland. A price-based control method was tested initially using a PCM underfloor heating system, which showed a successful morning peak load shifting. However very little improvement was observed during the evening peak load period. DuPont Energain® wallboards were installed on the interior walls in order to provide energy storage for evening peak. Experimental results showed that the application of the underfloor heating system in combination with PCM wallboard, enables very efficient energy usage. A total energy saving and electrical cost saving equal to 18.8% and 28.7%, respectively, were achieved over a period of five days. The highest energy saving achieved during this period was 35%, with a corresponding cost saving of 44.4%.

1.3.9. Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building using BioPCM

In a study, a newly constructed passive house duplex was thoroughly instrumented to monitor indoor environmental quality metrics and building energy use. One unit of the duplex was outfitted with 130 kg of PCM while the other unit served as a control. The performance of the PCM was evaluated through analysis of observed data and through additional computer simulation using an EnergyPlus whole-building energy simulation model validated with observed data (Sage-Lauck & Sailor, 2014). The used PCM was BioPCM described above.

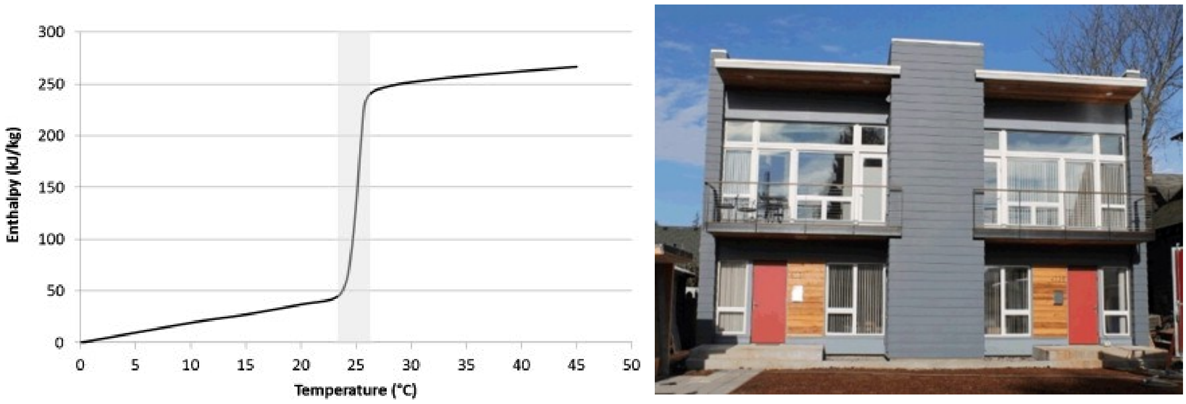

Figure 1.24. *(left) Enthalpy curve for BioPCM25™ Standard; (right) The passive house duplex home is divided into two mirror-image apartments with a party wall on the north–south axis*

The results of the corresponding building energy simulations indicate that the incorporation of 0.9 kg/m^2 floor area of PCM with a melt temperature of 25 °C is capable of reducing the zone hours overheated by about 50%. The simulations indicate that reducing the melt temperature of the PCM below 25 °C may have an adverse effect on thermal comfort. Finally, changing the location of the PCM from behind the drywall to the interior wall surface resulted in a reduction of zone hours overheated by more than 60% compared with a building with no PCM. While this type of surface application is not directly practical, this finding clearly demonstrates the value of maintaining good thermal coupling between the PCM and the interior air(Sage-Lauck & Sailor, 2014).

Conclusions

In this review passive elements with adaptive features to essentially increase the thermal inertia for nearly zero energy buildings in climate with a great diurnal temperature variation were reviewed.

One of the widest used such passive elements are Phase change materials which uses a principle of latent heat thermal energy storage. General overview of the PCM`s indicate, that although there has been extensive experimental work done in last decade, widespread commercial application of these materials is still developing. There are complex reasons behind this slow commercial adaption, but the main points are complicated installation and operation systems, economic justification and in general lack of know-how.

PCM`s can reduce overheating and can effectively be used as passive cooling elements, following main requirements should be met:

- Appropriate PCM for the particular application should be chosen – melting point, heat storage capacity and thermal conductivity is the main properties in question;
- Correct placement of PCM in overall construction that greatly influences the effectiveness of the material;
- Additional cooling systems should be used to maximize the effect of PCM`s and to provide increased thermal comfort.

For the testing and experimental phase three PCM`s were chosen – DuPont Energain, Knauf “Comfortboard” and BioPCM. These materials have demonstrated their effectiveness in in-situ experiments and their commercial availability could allow for more widespread commercial use, also in nearly zero energy buildings.

For additional cooling systems for PCM`s capillary ceiling cooling tubes were chosen for further experiments, as they have demonstrated good compatibility with other PCM`s and their reduced size allows for space saving solutions to be realized.

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