PHASE CHANGE MATERIALS (PCMs) – INNOVATIVE MATERIALS FOR IMPROVEMENT OF ENERGY EFFICIENCY OF BUILDINGS

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Summary: *Design of energy efficient buildings is one of the main priorities of the civil engineering research community. During construction of new – energy efficient buildings, the design process and good knowledge of thermal properties of building materials are very important. New materials which have considerable impact on energy efficiency have been emerging on the market. One of the innovative materials are phase change materials (PCMs). Phase Change Materials are ideal products for thermal management solutions. This is because they store and release thermal energy during the process of melting and freezing (changing from one phase to another). When such a material freezes, it releases large amounts of energy in the form of latent heat of fusion, or energy of crystallisation. Conversely, when the material is melted, an equal amount of energy is absorbed from the immediate environment as it changes from solid to liquid phase. The use of phase change material (PCM) in building envelopment can increase the thermal inertia of the wall and decrease the fluctuation of the indoor air temperature, so as to improve the indoor thermal environment. It can also be used with cooling/heating system to storage energy during the night when the electricity price is low, and release energy during the day when the electricity price is high. So the use of PCM in building energy saving is of considerable interest in the last decades. The paper describes the mechanism of phase change materials action, and potential for using them in civil engineering.*

Keywords: *Energy efficiency, innovative materials, Phase change materials, civil engineering, usage*

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1. INTRODUCTION

Buildings are currently consuming 32% of the earth's energy. Regional climates play a large role in the energy consumption behaviors of buildings. A considerable part of this goes to space heating, which is about 60% for buildings in cold climates and 43% for those in moderate and/or warm climates. Fossil fuels are mainly used to meet this demand. This not only increases CO2 emissions that aggravate climate change but also increases concerns of energy security. Saving energy and improving performance are required for more sustainable buildings [1]. Cooling strategies can be classified into three major groups, including active, passive and hybrid. Active strategies cover all conventional heating, ventilating and air conditioning (HVAC). Passive cooling is attributed to the utilization of energy available from the natural environment rather than the consumption of conventional energy resources. As figure 1 demonstrates, passive cooling can be implemented in buildings by means of heat prevention reduction (decreased heat absorption), thermal moderation (modifying heat gains) and heat dissipation (removal of internal heat) [2].

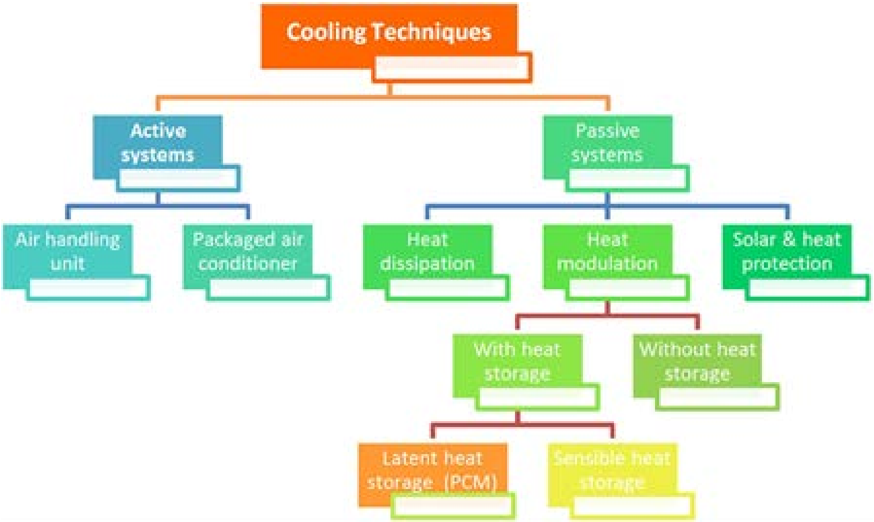

Figure 1. Different types of cooling techniques.

A certain performance of insulation is generally expressed in static terms as the thermal resistance or thermal transmittance of the exterior building envelope, describing the heat flow for a static temperature difference between two faces. However, such a static point of view can be extended by introducing a dynamical term, the heat storage coefficient K ($W/(m^2K)$), to come to the index of inertia. This heat storage coefficient depends on the thermal conductivity, the volumetric heat capacity and the seasonal heat flow wave. As a result, the index of inertia expresses the resisting ability of the building envelope to a periodical heat flow wave. Phase change materials have been addressed and studied widely to influence (i.e. increase) this index of inertia and as such result in a lower energy consumption for buildings [3].

2. PHASE CHANGE MATERIALS

Nowadays thermal energy storage systems are perceived as being environmental impacts such as energy consumption or carbon dioxide production. Thermal energy storage systems using phase change materials (PCM) are an interesting, and increasingly studied, way to attain energy efficiency in buildings. Research has focused on suitable methods to use PCMs in building technology and several methods have been explored. The principle of using a phase change material is simple: when the material changes its phase from solid to liquid heat is absorbed, at a constant temperature until it is completely converted into liquid. Conversely, heat is released when the material changes phase from liquid to solid; again at constant temperature until completely solidified, figure 2 [4].

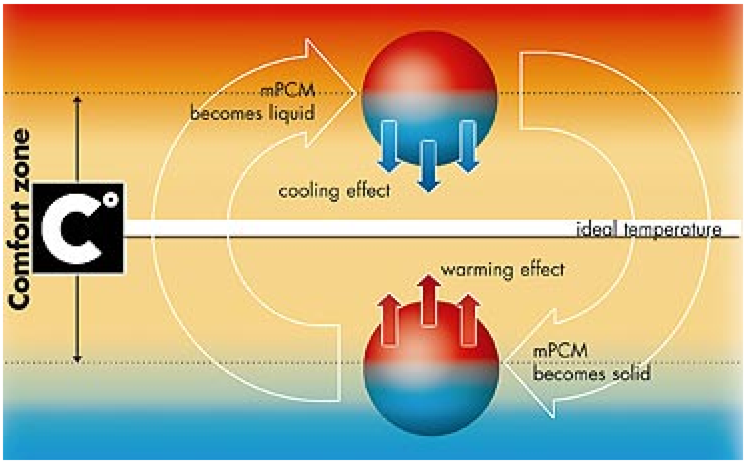

Figure 2. The principle of using a phase change material

3. PCM – CLASSIFICATION BY CHEMICAL TYPE

PCMs are broadly categorized into organic compounds, inorganic compounds, and eutectic mixtures.

Organic PCMs include paraffins, fatty acids, and polyethylene glycol and tend to be chemically stable, non-reactive, and resist sub-cooling. However, they also have a relatively low thermal conductivity, low latent heat storage capability, and may be flammable.

Inorganic PCMs are typically salt hydrates and possess a high latent heat storage capability, high thermal conductivity, and are typically non-flammable. However, they are prone to sub-cooling, segregation, and experience high changes in volume during phase transition.

Eutectics can be mixtures of only organics, only inorganics, or a combination of the two. They tend to have sharp melting points and latent heat storage capabilities that are slightly above organic PCMs, but there is little information available regarding their thermal and physical properties. PCM properties that are desirable for passive building applications include (1) high thermal conductivity, (2) high latent heat of fusion, (3) non-flammability, and (4) a melting point that is approximately equal to room temperature, figure 3 [5].

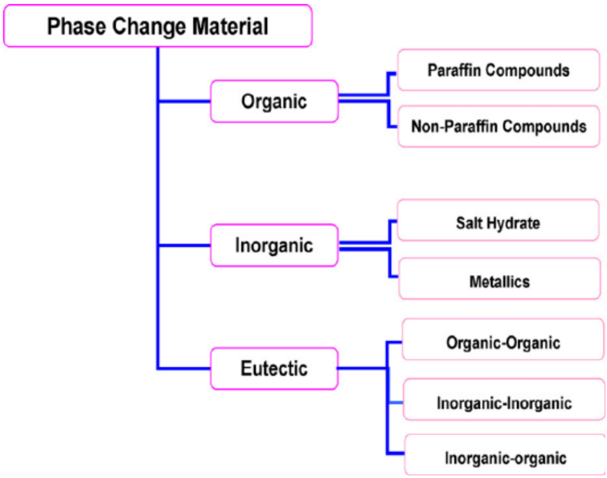

Figure 3. PCM – Classification PCM by chemical type

4. PCMs IN BUILDING APLICATIONS

Including such phase change materials in building constructions, some specific thermal, physical, kinetic and chemical properties are desired:

1. From a thermal point of view, a suitable phase change temperature range, a high latent heat of fusion and a good heat transfer towards the PCM are desired. The desired phase change temperature will depend on climatic conditions and the desired comfort temperature.
2. From a physical point of view, a favourable phase equilibrium, i.e. no phase segregation, a high density and small volume changes at the phase change are desired for easy incorporation in existing building materials or structures.
3. From a kinetic point of view, no supercooling and a sufficient crystallization rate are desired to make optimal use of the properties and possibilities of PCMs. Supercooling, i.e. the process of lowering the temperature of a liquid below its freezing point without becoming a solid, could strongly affect the performance of the PCMs based on the chosen suitable phase change temperature by influencing this temperature.
4. From a chemical point of view, a long-term chemical stability of the PCM despite cycling, compatibility with construction materials, non-toxicity and no fire hazard are desired [3].

4.1 PASSIVE AND ACTIVE COOLING SYSTEMS

Passive systems are generally used in building envelopes. Buildings waste major amount of energy through their envelopes. The amount that escapes may reach 32%, depending on building types and climate. Adding PCM into these envelopes decreases heating and cooling loads by increasing thermal mass. PCMs melt during the day when solar radiation provides heat, thus less heat enters the building. At nighttime, outside temperatures drop, and PCMs freeze and release heat to the building. This passive solar energy may also present homogeneous temperature distribution inside offices and residences. In active PCM systems, solar energy, nighttime air, or any other energy source are stored for sustainable building applications. In contrast to passive systems, active systems use mechanical equipment for charging and discharging of thermal energy of PCM. In active thermal energy storage systems, PCM can be incorporated inside the building (ceiling, floor, and walls), in external solar facades, or in the ventilation system [1].

4.2 PCM INCORPORATION IN BUILDING MATERIALS

There are generally two ways to contain PCMs in building applications: direct impregnation into building materials and encapsulation. Direct impregnation can be accomplished by either dipping porous building materials into a PCM bath or mixing the PCM into the materials during the manufacturing process . Encapsulation involves containing the PCM with another material and can further be categorized into micro- and macro-encapsulation. Micro-encapsulated PCMs are typically contained by microscopic polymeric capsules which form a powder-like sub-stance that can be incorporated into various building materials.
Micro-encapsulated PCMs have been successfully incorporated into wallboard, concrete, insulation and acoustic ceiling tiles, but tend to be costly and can adversely affect structural integrity. Macro-encapsulation contains the PCM in larger pouches, tubes, or panels that interact with other building materials through conduction and convection. Macro-encapsulated PCMs are typically less costly than their micro-encapsulated counterparts, but may not release stored heat as effectively due to solidification of the PCM around the edges of the capsules [5].

4.2.1 PCM ENHANCED WALLBORD

Wallboards are cheap and widely used in building applications, which makes them very suitable for the application of PCMs. Wallboards enhanced with PCMs will provide thermal storage distributed throughout the complete building, enabling passive solar design and off-peak cooling in traditional frame constructions with a typical low thermal mass. The performance of the PCM enhanced wallboards will depend on several factors: the melt temperature of the PCM, the temperature range over which melting occurs, the latent capacity per unit area of the wall, how the PCMs are incorporated in the wallboard, the orientation of the wall, climatic conditions, direct solar gains, etc. However, because not all factors can be taken into account, most studies on PCM enhanced wallboards deal with the choice of the phase change material, the manufacturing methods and the method of testing [3].

4.2.2. PCM ENCHANCED CONCRETE

Another possibility for applying PCMs in building constructions is PCM enhanced concrete or the so-called thermocrete and PCM enhanced clay tiles. Thermocrete is a heat storage medium com-bining an appropriate PCM with a concrete matrix or open-cell cements to produce low cost storage materials with structural and thermostatic properties [3]

Zhang et al.[6] and Mihashi et al.[7] worked on the development of thermal energy storage concrete made from porous aggregates impregnated with liquid PCM. Castell et al.[8] described an experimental set-up to test phase change materials with conventional and alveolar brick for insulated construction under real conditions.

They show that PCM efficiently smooth out the daily temperature fluctuations. Recently, microencapsulated PCM were incorporated with success in the hollows of a lightweight concrete building envelope [9,10]. Hunger et al [11], as for them, tested PCM capsules in self compacting concrete; and studied its influence on strength and thermal properties[4]. It has been shown that increasing PCM dosage lowers thermal conductivity and increases heat capacity. Nevertheless, mechanical strength decreases, and micro-structural analysis indicates that a significant proportion of the capsules are destroyed during the mixing process. Modelling and experiments involving hydration showed that a 5% PCM content could reduce the temperature peak of hydration[3].

Franquet et al.[12] also tested cement mortar containing microencapsulated PCM. In moderate climates, the relatively large thermal mass of the concrete walls and floors can be an advantage, as they store up energy during the day and release it at night, thereby reducing the need for auxiliary cooling/heating.

Therefore, combining PCM and concrete could be useful in construction of buildings; they could maintain interior temperatures close to the PCM melting temperature i.e. below the melting point of the PCM and perhaps avoid temperate variation above this value.

This application looks very promising for buildings such as data centres, which must be cooled to keep a consistent temperature. Generally the incorporation of PCMs would lead to energy savings or the use of air conditioning backup facility [3].

4.2.3. PCM ENHANCED BUILDING INSULATION MATERIALS

Studies on PCM enhanced PU-foam and cellulose have been performed during the last decade. The PCM enhanced open-cell PU-foam was commonly installed in two layers of 6 mm between three low-emittance aluminium foils and installed on top of the mineral wool insulated studs.

Microencapsulated paraffin PCMs have been mixed with con-ventional loose-fill cellulose insulation at a rate of 22 wt% and installed in residential wall cavities without major modifications of the manufacturing or installation processes. The measured results of pilot projects are strongly depending on wall orientation and the location. Nevertheless, clear reductions of both cooling and heating loads are noticed [3].

4.2.4. OTHER BUILDING APPLICATIONS

Other different possible building applications for PCMs have been studied, especially trying to improve the performances of technical installations such as hot water heat stores , pipe insulation , cool thermal energy storage and latent heat thermal storage systems . In addition, the improvement of double facades with PCMs has been studied to achieve a better control of the cavity temperature [3].

5. EXAMPLES

BASF Micronal® PCM is a phase change material, which completes a phase change from solid to liquid within the indoor temperature and human comfort range, i.e. at 21°C, 23°C or 26°C and in doing so can store a large quantity of heat. Micronal® contains in the core of the microcapsule (size around 5 µm) a latent heat storage material made from a special wax mixture. When there is a rise in temperature above a defi ned temperature threshold (21°C, 23°C or 26°C), this absorbs the excessive heat energy and stores it in phase change. When the temperature falls below the temperature threshold, the capsule releases this stored heat energy again [13]. BASF Micronal can be combined cement to form a phase change concrete floor, figute 4.

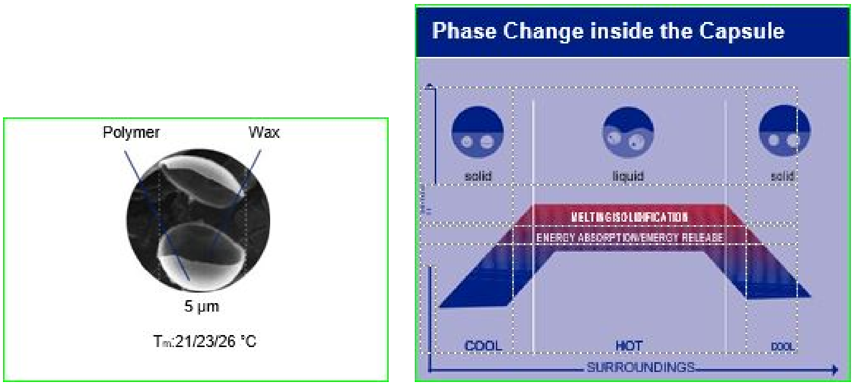

Figure 4. BASF Micronal® PCM

GLASSX (Swiss company GlassX AGis) insulated glass that incorporates a phase change material (PCM) which stores heat energy from the exterior temperatures dramatically reducing the output of building mechanical BOTH heating and cooling systems. An outer insulated glazing unit (IGU) has a suspended prismatic filter (like a Fresnel lens) between the panes of glass that reflects higher-angle sunlight back out while transmitting low-angle sunlight. This offers a "passive" solar-control mechanism for south-facing glass to keep out most of the high summer sun, while benefiting from the lower-angle winter sun. Sunlight that makes it through this outer IGU passes into an inner IGU that is filled with sealed polycarbonate channels into which a translucent salt-hydrate PCM is encapsulated. PCMs store a lot of heat as they change phase from solid to liquid (melt) over a narrow temperature range, then they release that heat as they cool off. The salt hydrate used in GlassX melts and freezes in the temperature range of 26-30 degrees C.
Two separate low-emissivity (low-e) coatings and low-conductivity gas fill in the outer two sealed spaces glass help to push heat from the PCM inward while slowing outward heat loss.Highlights include: an expence reduction on heating/cooling approximately a 1/3 to 1/2 over the year; the interior temperature can be reduced by 4 °C to 6 °C in temperate climates and even up to 12°C in warmer climates during summer months, which contributes to occupant comfort and energy savings through reduction of cooling loads. During winter months PCM has the effect of a "solar tile stove" (more solar gains

than thermal loss) on the inner side of the glass facade, and contributes to a reduction of the heating load by up to 150 – 200 kWh/m² per year. Building energy use when using Glass-X can be reduced by up to 16kwh/m 2 when compared to an opaque wall like insulated brick, concrete or composite panel systems. Plus Glass-X allows for a soft translucent natural light during the day for additional savings on artificial lighting, figure 5[14].

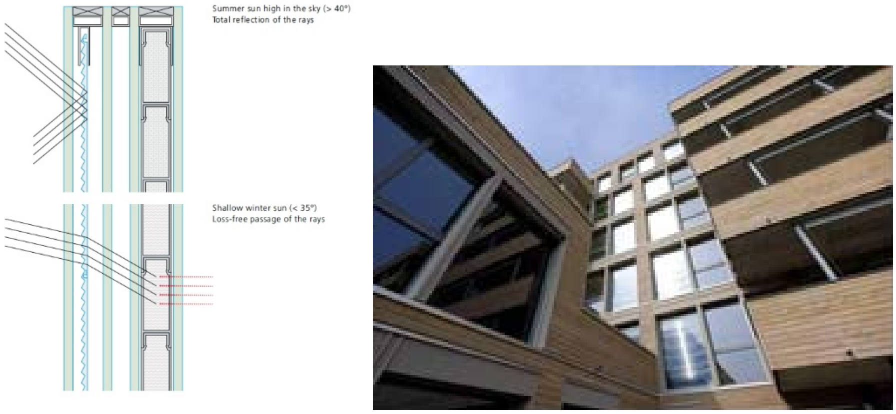

Figure 5. GlassX

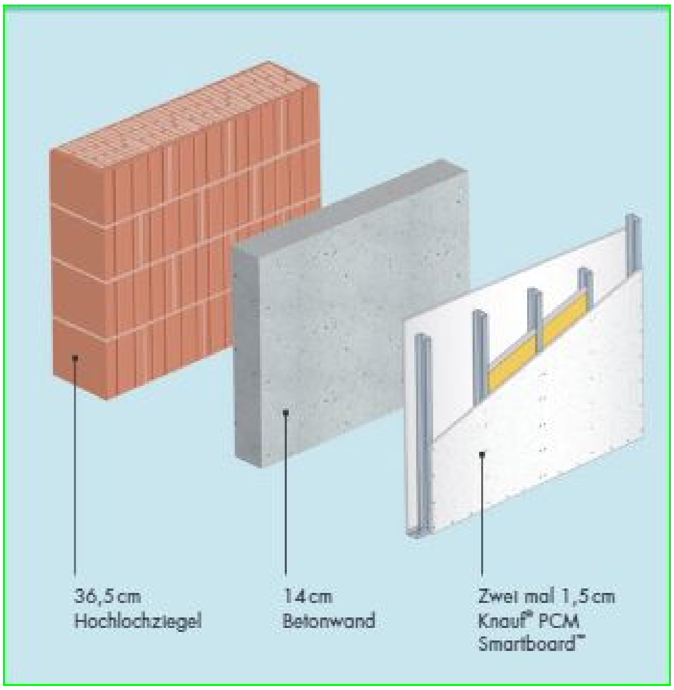

Figure 6. Knauf PCM Smartboard

When Micronal® PCM incorporated in a plasterboard, known as **Knauf PCM SmartBoard™** (figure 6), BASF reckon that 5mm of their product has the thermal mass properties equivalent to “a 140mm thick concrete wall or a 3650mm thick brick wall.” Furthermore, they explain that one of the unique characteristics of Micronal PCM is that 1g of the stuff is equivalent to a surface area of 3sqm. The product has been tested for 10,000 phase changes, without loss of effectiveness, which is said to correspond to a life cycle of about 30 years. Based on such testing, BASF are confident their Micronal PCM is durable for the lifetime of the building [15].
In 2009, Charles Sturt University's Thurgoona campus at Albury (figure 7a) was apparently the first in the world to use phase change materials in their concrete flooring. PCMs were also integrated in the plasterboard ceilings. Such attributes helped the site score six green stars and 'world leader' status from the Green Building Council of Australia. Speaking of six star buildings, the first one in Victoria to rate such a thing for Office Interiors was the offices of architectural firm Umow Lai. They picked up a maximum of five innovation points for their use of phase change materials to control temperatures in a meeting room, without resorting to mechanical cooling and heating systems [16].


Figure 7. a) Charles Sturt University's Thurgoona campus at Albury
b) DuPontTM Energain®

DuPontTM Energain® comes in aluminium-laminated panels, bordered at the edge with aluminium tape, which contain a copolymer and paraffin wax compound. The panels are installed on the interior walls and ceilings of a building, behind the plasterboard lining, together with a mechanical ventilation system, figure 7b.
The wax in DuPontTM Energain® thermal mass panels melts and solidifies at around 22° C and 18°C respectively. As the compound melts heat is absorbed from a room and as it re-solidifies it releases heat back into the room. By absorbing heat, DuPontTM Energain® significantly slows down the temperature increases within a room, reducing temperature peaks by as much as 7°C. As temperatures drop, the absorbed heat in the panels is released, warming rooms and reducing the usage of heating systems[17].
Phase Change Energy Solutions is created with the waste product **BioPCM** derived from the manufacturing process of soy, palm, coconut oi, figure 8. These blended with a nano scale thickening agent made of spherical bits of silica.” The final result is a gel, which is contained within a multitude of pockets in a flexible roll of plastic film.
Control building without BioPCM exhibited a temperature swing of 13°C, compared to only a 3°C variance in the identical structure that otherwise deployed BioPCM.

Architectural firm Positive Footprintsworked with BioPCM for their 9-star reverse brick veneer residential project in Victoria[18].
BioPCM can be installed directly under timber floor boards. In doing so, Phase Change Energy Solutions maintain such flooring delivers more effective thermal mass than concrete, but with just two per cent the weight of concrete.

Figure 8. BioPCM

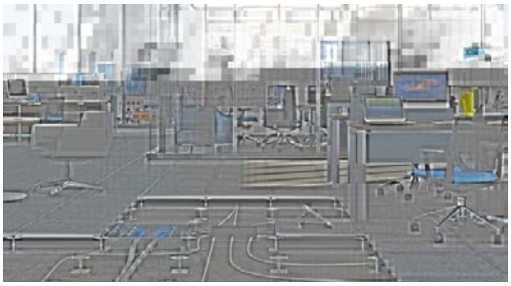

Figure 9. Tate Access Floors

Tate Access Floors also use PCMs in flooring, but with a couple of twists. Firstly their EcoCore panels (figure 9) are used for raised access floors, that allow for an office’s services, like cabling and air conditioning, to be hidden underneath. Secondly, they advocate a perimeter placement of the panels on sunward side of building. As heat enters the office, the phase change materials mixed with structural cement and contained within steel welded shells absorb this increased temperature. Tests performed by Tate suggest their system can reduce air conditioning demand by 17.7 per cent, when contrasted with a typical concrete slab floor[19].

6. CONCLUSIONS

Usage of Phase Change Materials (PCM) in building elements results in considerable energy saves. Phase change materials (PCMs) have a wide variety of uses in buildings including integrated space heating, integrated cooling systems, and integrated combined heating and cooling systems. They are also used in air conditioning, in thermally activated ceiling panels and in incorporation in building materials. PCMs should have a high energy storage density for their successful use. Also, they should be able to charge and discharge the stored energy with a thermal power adapted to the desired application. The transient heat transfer is governed by heat storage and also by heat conduction. Being able to store heat assumes that the heat can be transported by means of conduction to the PCM. The capacity in storing the heat at the proper rate depends on conductivity. Thus, we need to know exactly the conductivity of all materials involved in the heat transfer process [20,21].

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FAZNO PROMENLJIVI MATERIJALI – INOVATIVNI MATERIJALI ZA POBOLJŠANJE ENERGETSKE EFIKASNOSTI OBJEKATA

Rezime: *Projektovanje energetski efikasnih objekata jedan je od glavnih prioriteta istraživačke zajednice u oblasti građevinarstva. Kod izgradnje novih energetski efikasnih objekata, jako je bitan proces projektovanja kao i dobro poznavanje termičkih svojstava građevinskih materijala. Na tržištu se pojavljuju novi materijali koji znatno utiču na energetsku efikasnost. Jedan od inovativnih materijala su i fazno promenljivi materijali (FPM) – Phase change materials (PCMs). Fazno promenljivi materijali su idealni proizvodi za rešavanje toplotnih problema u objektima. Oni skladište i oslobađaju toplotnu energiju tokom procesa smrzavanja i topljenja (menjaju agregatna stanja). Kada se takav materijal smrzava, oslobađa veliku energiju u obliku latentne toplote - fuzije ili energije kristalizacije. I obrnuto, kada se materijal otapa, ista količina toplote se apsorbuje iz neposrednog okruženja dok prelazi iz čvrstog u tečno agregatno stanje. Korišćenje fazno promenljivih materijala (FPM) u omotačima objekata može povećati toplotnu inerciju zidova i smanjiti fluktuiranje temperature vazduha unutar objekata čime se poboljšava njihov toplotni komfor. Takođe se mogu koristiti u sadejstvu sa sistemima za hlađenje i grejanje, tako što akumuliraju energiju tokom noći kada je cena električne energije niža i oslobađaju energiju tokom dana kada je cena električne energije viša. Stoga je upotreba FPM u uštedi energije u objektima u žiži interesovanja poslednjih decenija. U radu je objašnjen mehanizam delovanja fazno promenljivih materijala i mogućnosti njihove primene u oblasti građevinarstva.*

Ključne reči: *Energetska efikasnost, inovativni materijali, fazno promenljivi materijali, građevinarstvo, primena*