The feasibility of phase change materials in building structures for saving heating energy in the Nordic climate

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The feasibility of phase change materials in building structures for saving heating energy in the Nordic climate

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Abstract. The study is based on a nearly two-decade research at the Department of Civil Engineering at the Tampere University of Technology (Finland). The purpose of the current study is to find out the structural solutions for the thermal storage of solar radiation in buildings. A significant effect of solar gains was noticed in massive external walls as well as roof structures in sunny days from March until September. However, modern lightweight materials lack the thermal inertia to store energy. An idea to utilize the latent heat of phase change materials (PCMs) inside the insulation of a light-weight roof structure enables to overcome this problem. The idea is supported with a principal example of the diurnal performance of a metal sheet roof structure as well as comparative calculation of the energies consumed and gained. The results of the current study show that PCMs have potential in the future application of light-weight roof structures. In general, efficient solar solutions still need to be developed in order to store energy in summer and to release it in winter.

Key words: 10-year data, temperature distribution within a structure, calculation of heat losses and gains, phase change materials (PCMs).

INTRODUCTION

Nowadays, the construction industry is constantly evolving. An increasing amount of modern lightweight materials and glass surfaces are applied in the facades of buildings. Still, these materials lack thermal inertia i.e. their thermal capacity is insufficient to store energy. Thermal storage is an efficient way of energy conservation possible by incorporation of latent heat (concealed heat) storage in building materials and structures. A hot-air floor system has been designed to accumulate the excessive heat from the fireplace (Kic, 2013). Energy storage in the walls, ceiling and floors of buildings may be enhanced by applying suitable phase change materials (PCMs) within these surfaces to capture solar energy directly and increase human comfort by maintaining the temperature in the desired interval for a longer period of time.

Latent heat storage such as using a phase change material (PCM) has gained growing attention recently due to its ability of storing significant thermal energy within a small volume, making it one of the most promising technologies for developing energy efficient buildings. PCMs absorb and release heat when the material changes from one phase to another. Solid-liquid phase change is the main phase change of interest since other types, such as the liquid-gas phase change materials, are generally not practicable for most energy storage applications. As a matter of fact, the liquid-gas phase changes involve large changes in volume or pressure when going from the liquid to the gas phase, which prevent effective implementation. Some materials exhibit solid/solid phase changes, in which the crystalline structure is changed at a certain temperature. These are available in limited temperature ranges (Tekes 2010).

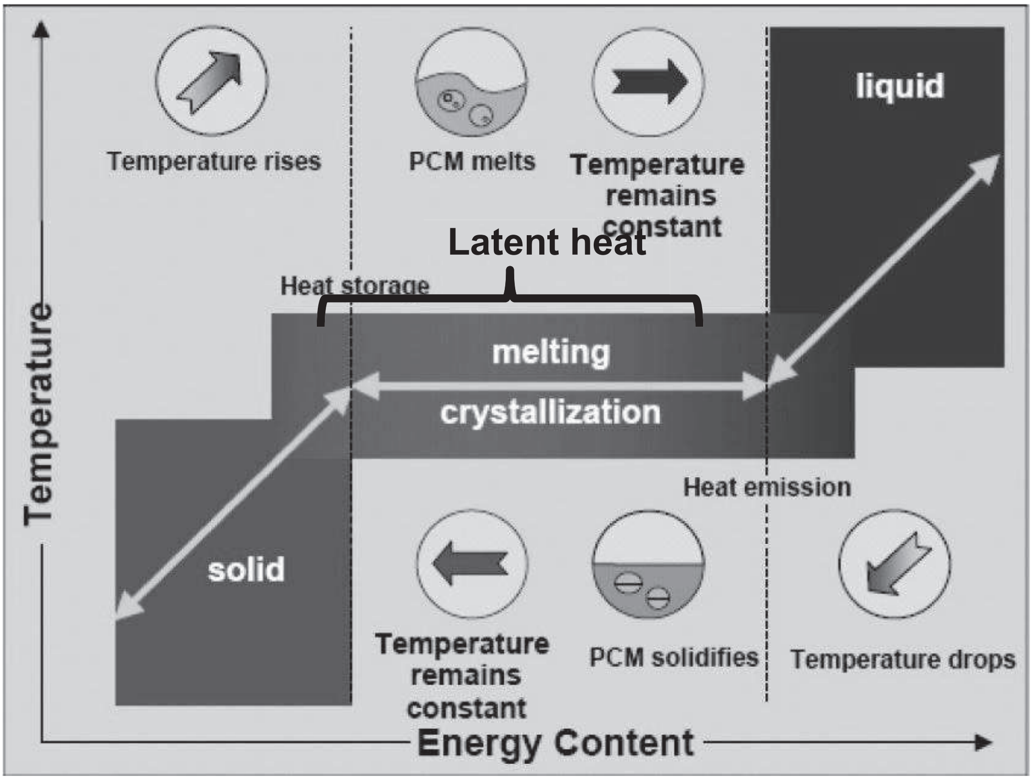

Figure 1. Material phase change (Tekes 2010; Minux 2012).

Initially, unlike conventional energy storage materials, when solid-liquid PCMs reach the temperature at which they change phase (their melting point), they absorb large amounts of heat without a significant rise in temperature. Despite the heat input, the temperature of the material stays relatively constant while the phase change is taking place (Fig. 1). Storage of latent heat means storing heat in a material which undergoes a phase change. When the temperature around a liquid material falls, the PCM solidifies and releases its stored latent heat (Tekes 2010). As no temperature increase can be observed over a long period of time, despite the application of heat, the heat stored during the phase transition is called ‘latent heat’. For a solid-liquid phase transition, the latent heat is equal to the heat of melting or crystallization of the storage material.

Phase change materials can be divided into different subcategories based on their chemical composition. Three groups are commonly formed: (i) organic compounds, (ii) inorganic compounds, and (iii) inorganic eutectics or eutectic mixtures. The group of organics can be divided into paraffins and non-paraffins. Each group has its typical range of melting temperatures and its range of melting enthalpies.

Commercial paraffin waxes (i) or $CH_3(CH_2)_nCH_3$ are inexpensive and have a reasonable thermal storage density of 120 kJ kg^{-1} up to 210 kJ kg^{-1}. Paraffins are available in a wide range of melting temperatures from approximately 20°C to up to about 70°C. However, paraffins have a low thermal conductivity of about 0.2 W $(m\,K)^{-1}$ which limits their application (Farid et al., 2004), and have a large volume change during the phase transition (Hasnain, 1998). The non-paraffin organics (ii) include a wide selection of organic materials such as fatty acids, esters, alcohols, and glycols. Generally, they have excellent melting and freezing properties, but are about three times more expensive than paraffins (Hasnain, 1998). The most commonly used fatty acids are divided into 6 groups: caprylic, capric, lauric, myristic, palmitic, and stearic.

Inorganic PCMs in general have a rather high heat of fusion, good thermal conductivity, are cheap, and non-flammable. However, most of them are corrosive to most metals, undergo supercoiling, and undergo phase decomposition. Most common inorganic PCMs are hydrated salts (EPIC-HUB 2014).

Eutetic mixtures or eutetics have, in general, sharp melting points and their volumetric storage density is slightly higher than that of organic compounds. However, limited data are available on their thermal and physical properties. Eutetics may be divided into 3 groups according to the materials of which they consist: (i) organic-organic, (ii) inorganic – inorganic, and (iii) inorganic – organic eutetics (EPIC-HUB 2014).

Since the late 19th century, PCMs have been used as a medium for thermal storage applications. Kuznik et al. (2011) reviewed the history of PCMs in buildings based on the published journal articles. The first studies were dated from the 1980s. These dealt with methods for impregnating gypsum wallboard, concrete, and other architectural materials with phase change materials (Salyer et al., 1985; Shapiro et al. 1987; Banu et al., 1998). Then, during the period between 1980 and 1990, only very few articles were published. From 1990 to 2000, the number of publications increases to about 1 publication per year. After 2003, an increase in the number of publications occurred (reaching up to 14 articles). Almost 80% of the studies have been carried out over the past 10 years which have seen the development of new encapsulation technologies and new energy standards.

Baetens et al. (2010) have performed a review of phase change materials for building applications. The principle of latent heat storage can be applied to any porous building material, but research so far has primarily concerned on gypsum wallboards and boards, concrete and insulation materials. For example, Zhang et al. (2012) have studied the thermal performance of gypsum boards incorporated with microencapsulated PCMs for thermal regulation. Gypsum boards incorporated with 50 wt% micro-PCMs were found to have a good potential for thermal energy storage purpose in buildings (Zhang et al., 2012). Ling & Poon (2013) reviewed the use of phase change materials for thermal energy storage in concrete. PCM-concrete has some useful characteristics, such as better latent heat storage and thermal performance. PCM-concrete also has some undesirable properties, such as lower strength, uncertain long-term stability, and low fire resistance. These undesirable properties, however, can be minimized if appropriate PCM types and means of incorporation are employed.

Tyagi et al. (2011) have performed a review of phase change materials based on microencapsulation technology for buildings. Microencapsulation was found to be one of the well-known and advanced technologies for better utilization of PCMs with building parts, such as walls, roofs and floors, and within building materials.

Sharma et al. (2013) also dealt with development of phase change materials for building applications. Specifically, eutectics based on commercial grade fatty acids i.e. capric acid (CA), lauric acid (LA), myristic acid (MA), palmitic acid (PA), and stearic acid (SA) were developed with different weight percentages. The melting temperature and latent heat of fusion of these developed eutectics were measured by using the differential scanning calorimetry (DSC) technique. The DSC showed that the melting temperatures and latent heat values of the developed PCMs were in the range of about 20–30°C and 100–160 J g^{-1}. It was concluded that if CA mixed with any other lower melting temperature PCM, a desired eutectic can be developed for building applications.

Also, the practical application and development of PCMs in the construction industry is gaining interest. An overview of industrial research projects on Energy-efficient Buildings (EeB) can be found on the European Commission/CORDIS/FP7 web page. EeB consists of a financial envelope of € 1 billion to boost the construction sector. For example, important developments were achieved within the project: New Advanced iNsulatiOn Phase Change Materials (NANOPCM; from 2010-06-01 to 2013-05-31). The objective of NANOPCM was the development, implementation, production, and demonstration of low cost and improved Phase Change Materials for new high performance insulation components in existing buildings. The project aimed to reduce the cost of nanotechnology-based insulation systems and make their wide scale commercial application feasible.

MATERIALS AND METHODS

The Department of Civil Engineering at the Tampere University of Technology (RTEK/TUT) has been studying the energy consumption and thermal performance of building structures. Ten years (Sept. 1997–Aug. 2007) of measuring data from six test buildings have been gathered. Also, six years (Apr. 2001 – Aug. 2007) of data from additional two test buildings is also available at the RTEK/TUT. The test buildings were identical-sized, having different external wall structures. Detailed description of test buildings, their structures and data collection can be found in Lindberg et al. (2004) and Kiviste et al. (2013). The temperatures at various depths of external wall structures were monitored in order to determine the temperature distribution. The temperatures were measured with calibrated semiconductor sensors and copper–constantan thermocouples. Multiplexers were used to collect the data from the sensors so that readings from each channel were recorded in a computer after every 20 s. Analogue-to-Digital and Digital-to-Analogue (ADDA) cards were used for data collection and conversion. The minimum, maximum, and average values from the values measured in every 20 seconds were saved to a computer hard disc in every 30 min. The level of detail (200 sensors in each building), the huge amount (after each 20 seconds), long-term (measuring period of six and ten years), and coherency (measured at the same time in the same conditions) makes that data unique in Finland as well as in Europe.

RESULTS AND DISCUSSION

Through the analysed period from September 1998 to May 1999, the heat losses through the external walls of the test buildings were up to 50% smaller than calculated (Lindberg et al., 1998). Three main reasons for the difference were found: (1) the material properties from which the U-values are calculated, (2) the areas of the walls, and (3) the solar radiation energy stored in the external part of the exterior walls (Lindberg et al., 2008).

The influence of solar gains was found to be significant to the thermal performance of some massive external wall structures during sunny days from (late February) March until September. The heat storage capacity of Autoclaved Aerated Concrete (AAC) (Lindberg & Leivo, 2005) and insulated brick external walls (Lindberg et al., 2012) was remarkable.

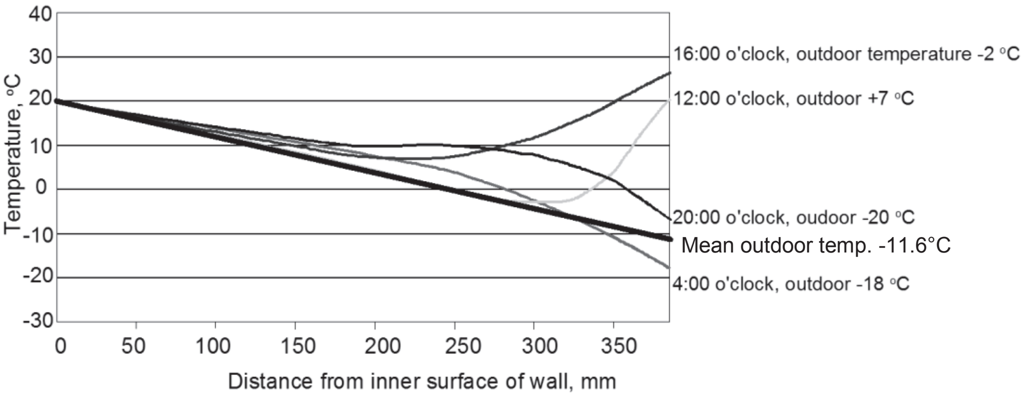

Figure 2. Temperature distribution in the Autoclaved Aerated Concrete (AAC) south wall on 11.3.1998 (Lindberg & Leivo 2005).

Fig. 2 shows the influence of solar radiation to the outer parts and surface of a AAC south wall. The thick line is showing the well-known stationary temperature distribution, based on average indoor and outdoor temperatures. In the morning, the sun starts to heat up the outer parts of the AAC wall. At noon, the temperature of the outer surface has increased to 20°C, while the outdoor air temperature was 7°C. In the afternoon (16:00 o'clock), the outer surface temperature has reached 27°C, while the outdoor air temperature has decreased to -2°C. In the evening, it is freezing cold outside (-20°C), but the outer half of the AAC wall still stays relatively warm (from -7°C at the outer surface up to 10°C in the mid-part), due to its heat storage capacity. Only at night (4:00 o'clock), the outdoor temperature is about the same as the surface temperature (both about -18°C), being rather similar to stationary temperature distribution.

The effect of solar gains was found to be greater in the massive roof structures. During the winter of 2002–2003 the temperatures in the Autoclaved Aerated Concrete (AAC) roof structure of a Finnish factory were constantly measured. A rough summary of the measurement results is shown in Fig. 3. The thickness of the reinforced AAC elements was 300 mm, and it had roofing felt glued on top.

The average daily temperature at the moment of examination was 0°C and the indoor air temperature +20°C. Fig. 3 has a curve representing the stationary temperature distribution. Fig. 3 shows how the solar radiation striking a dark felt roof affects the temperature of the structure below it. It is known that the effect can be substantial, even tens of degrees. At night, the felt cools, but the heat storage capacity of AAC keeps the elements warm. The end result is that the external surface of the AAC roof remained above the mean outdoor air temperature even during the night.

The diurnal temperature distributions of massive and lightweight wall structures of the test buildings have been carefully compared at the RTEK/TUT. It has been found that due to the lack of thermal storage capacity, the effect of solar radiation is almost lost in conventional light-weight wall and roof structures.

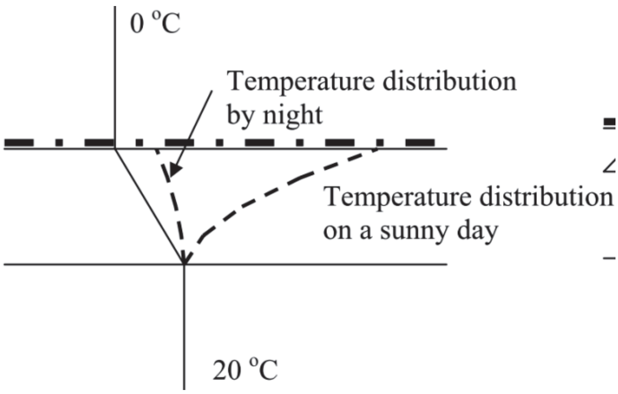

Figure 3. Rough summary of the typical diurnal thermal performance of an AAC roof structure (Lindberg et al., 2008).

The situation could be improved considerably if PCMs could be effectively applied inside insulation, thus enabling energy storage and release in light-weight structures as well. Fig. 4 shows the principal idea of applying PCM inside an insulation of a light-weight flat roof structure. Metal sheet roof cover is applied in Fig. 4, however, the principle would be similar in case of dark bituminous roof cover.

The width of the air gap or use of an attic in Fig. 4 could be optimized to achieve the maximum efficiency of thermal storage of solar radiation. As mentioned before, the thermal storage principle in Fig. 4 is fully effective only in a sunny day and from early spring to autumn. A small but still noticeable effect of thermal storage could be found even on the days with less sun radiation (cloudy days); therefore, a considerable amount of daylight is necessary.

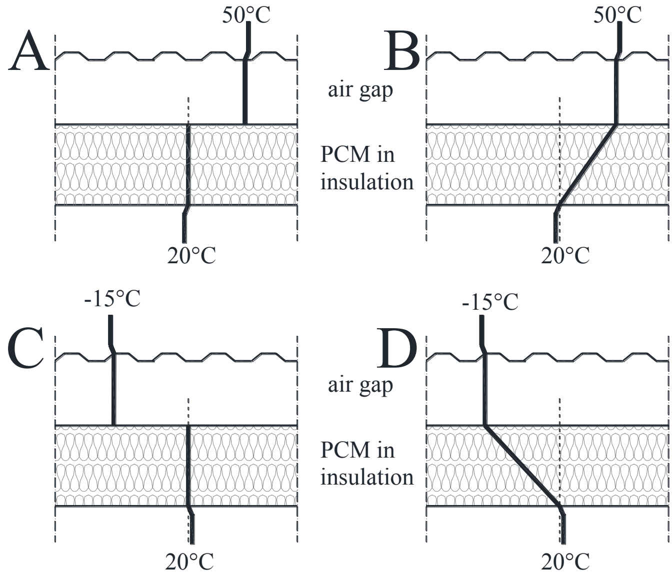

Figure 4. Principal idea of the daily temperature distribution of a metal sheet roof structure, where PCM is applied inside insulation. A. In the morning and at noon (e.g. 7 a.m. – 12 noon) the sun heats up the metal sheet and air-gap, therefore the PCM starts to store latent heat while changing phase (melting). The temperature of the PCM does not change. B. In the afternoon (e.g. 12 noon – 19 p.m.), the air-gap is very hot and, after phase change, the temperature inside insulation becomes stationary. C. In the evening and at night, the air-gap cools down and freezes. During that phase, the PCM solidifies and releases its stored latent heat, thus saving heating energy of the building. D. At night, the air-gap is cold and the PCM has given away its latent heat (become solid).

The conduction heat losses (*Q*) of a building could be calculated with the following formula:

$$Q = \sum A \cdot U \cdot \sum \Delta t \cdot t, \tag{1}$$

where: A is the area of enclosing structures, m^2; U is thermal conductivity (U-value) of a structure, W $(m^2K)^{-1}$; Δt is temperature difference between indoor and outdoor air, K; t is duration, hours.

In case of a typical one-family (15 × 10 m) dwelling, the area of the enclosing structures would be around 460 m^2 (roof 160 m^2, floor 150 m^2, walls including windows and doors 150 m^2). If a U-value of 0.2 W $(m^2K)^{-1}$ and a temperature difference of 18° K (average indoor air temperature 20°C, average outdoor temperature 2°C). According to the FMI (Finnish Meteorological Institute), the annual average temperature in Finland varies from +5.9°C (Southern coastal area) to -0.4°C (Lapland). Generally, +2.0°C is recommended, which is suitable for large areas in Southern Finland. Therefore, the conduction heat losses could be calculated as follows: $Q = 460 \cdot 0.2 \cdot 18 \cdot 24 = 39{,}744 Wh \approx 39.7 kWh$.

Sharma et al. (2013) recommended that capric acic (CA) mixed with any other lower melting temperature PCM could be developed for the building applications. For example, eutectic capric-myristic acid (CA-MA) PCM has a melting temperature 21.7°C and a heat of fusion 155 kJ kg^{-1} (Karaipekli & Sari, 2008). 3,600 kJ equals to 1 kWh. Therefore, 8 kg m^{-2} of CA-MA inside insulation could store/release energy $\frac{155}{3{,}600} \cdot 8 = 0.34$ kWh $(m^2)^{-1}$. Based on the previous example of a one-family building, CA-MA applied in roof structures would absorb/release $0.34 \cdot 160 = 54.4$ *kWh*. Therefore, the amount of energy stored by PCM would cover the average heat losses of 39.7 *kWh*. Previous calculations serve the purpose of explaining the principle. Due to the high variability of factors, a rather conservative approach was taken by the authors in conductive heat calculations. The comparisons of heat losses and gains show that PCMs have a potential in the future application of light-weight roof structures. Although, for example, Estonia is a relatively solar-poor country, the solar radiation to the horizontal surface is still 990 kWh $(m^2 \text{ year})^{-1}$. 63.5% of it could be stored in summer, 30% in spring and autumn together, and only 6.5% of the annual solar radiation is available at winter (Masso, 2012).

In future studies at the RTEK/TUT, dynamic calculations and simulations are needed to further understand and describe the process. Additional proof in still necessary before initiating extensive and expensive tests with PCMs inside building structures at the RTEK/TUT.

Mankind still needs solar energy storage solutions to store energy in summer and release it in winter. Although solar panels are becoming cheaper and thus more affordable, solar cells are still too expensive for wide-spread solar energy storage in buildings structures.

CONCLUSIONS

The current paper is presenting an idea of storing and utilizing the latent heat of phase change materials (PCM) in building structures. Some examples of nearly two decades of research results at the Department of Civil Engineering at the Tampere University of Technology (RTEK/TUT) are presented in that sense. The effect of solar gains was found to be significant to the thermal performance of massive (AAC and insulated brick) external wall structures during sunny days from March until September. That effect was found to be greater in massive (AAC) roof structures. However, even modern lightweight wall and roof structures lack the thermal inertia to store energy. Effective application of PCMs inside the insulation of a light-weight roof structure enables to overcome this problem. A principal example of the daily temperature distribution of a metal sheet roof structure as well as the comparative calculation of energies is demonstrated. These findings show that PCMs have potential in the future application of light-weight roof structures. As energy accessibility (from early spring until September) and demand (heating season, especially in winter) do not match, long-term thermal energy storage and release plays a crucial role in taking full advantage of solar radiation in buildings.

REFERENCES

Baetens, R., Jelle, B.P. & Gustavsen, A. 2010. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings* **42**, 1361–1368.

Banu, D., Feldman, D., Haghighat, F., Paris, J. & Hawes, D. 1998. Energy-Storing Wallboard: Flammability Tests. *Journal of Materials in Civil Engineering* **10**(2), 98–105.

EPIC-HUB deliverable D1.1. 2014. D1.1: Operational Scenarios Requirements. EPIC-HUB – Energy Positive Neighborhoods Infrastructure Middleware based on Energy-Hub concept. Collaborative project: FP7 NMP-ENV-ENERGY-ICT EeB. (http://www.epichub.eu/documents/37010/37341/D1.1+Operational+scenarios+requirements), 304 p.

Farid, M.M., Khudhair, A.M., Razack, S.A.K. & Al-Hallaj, S. 2004. A review on phase change energy storage: materials and applications, *Energy Conversion and Management* **45**, 1597–1615.

Hasnain, S.M. 1998. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management* **39**(11), 1127–1138.

Karaipekli, A. & Sari, A. 2008. Capric–myristic acid/expanded perlite composite as form-stable phase change material for latent heat thermal energy storage. *Renewable Energy* **33**(12), 2599–2605.

Kic, P. 2013. Hot-air heating of family houses with accumulation of energy in the floor. *Agronomy Research* **11**(2), 329–334.

Kiviste, M., Lindberg, R. & Leivo, V. 2013. Improving the calculation of building energy consumption based on ten year measured data. In Malinovska, L., Osadcuks, V. (eds): *Engineering for rural development. The 12th International Scientific Conference. Volume 12.* Latvia University of Agriculture, Jelgava, 451–455.

Kuznik, F, David, D., Johannes, K. & Roux, J.-J. 2011. A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews* **15***,* 379–391.

Lindberg, R., Binamu, A. & Teikari, M. 2004 Five-year data of measured weather, energy consumption, and time-dependent temperature variations within different exterior wall structures. *Energy and Buildings* **36**, 495–501.

Lindberg, R., Keränen, H. & Teikari, M. 1998. The influence of external wall structures to the energy consumption of a building (Ulkoseinärakenteen vaikutus rakennuksen energiankulutuksen). Tampere University of Technology, Publications 90, Tampere, 33 p. (in Finnish).

Lindberg, R., Korpi, M. & Vinha, J. 2008. Factors affecting energy consumption of buildings. In*: Building Enclosure Science and Technology. The BEST 1 conference*, National Institute of Building Sciences, Canada, 8 p.

Lindberg, R. & Leivo, V. 2005. Building Energy Consumption and Thermal Performance of the Autoclaved Aerated Concrete (AAC) Exterior Walls, In: Limbachiya and Roberts (Eds.). *Autoclaved Aerated Concrete*. Taylor and Francis Group, London, 519–523.

Lindberg, R., Rantala, J., Leivo, V. & Kiviste, M. 2012. Effect of massive outer leaf of an insulated cavity brick wall on heat loss. *Journal of Building Physics* **36**(2), 198–211.

Ling, T.-C. & Poon, C.-S. 2013. Use of phase change materials for thermal energy storage in concrete: An overview. *Construction and Building Materials* **46**, 55–62.

Masso, T., 2012, *ABC of building physics (Ehitusfüüsika ABC*), Ehitame publishing, Tallinn, 172 pp. (in Estonian).

Minux website. 2012. http://www.minux.es/materiales-de-cambio-de-fase-pcm/ (San Juan de Ortega 16, 09007 Burgos, Spain, Phone 947 24 30 80, comercial@minux.es)

Salyer, I.O., Sircar, A. K., Chartoff, R.P. & Miller, D.E. 1985. Advanced phase change materials for passive solar storage applications. In *Proc. of the 20th Intersociety Energy Conversion Engineering Conference*, Warrendale, PA, USA, pp. 699–709.

Shapiro, M., Feldman, D., Hawes, D. & Banu, D. 1987. PCM thermal storage in drywall using organic phase change material. *Passive Solar Journal* **4**, 419–438.

Sharma, A., Shukla, A., Chen, C.R. & Dwivedi, S. 2013. Development of phase change materials for building applications. *Energy and Buildings* **64**, 403–407.

Tekes tori webpage. 2010. PCM - Phase Changing Materials. (Source: Super Sustainable City), Tekes – the Finnish Funding Agency for Innovation. http://tekes.dicole.net/blogs/show/482/0/14727/PCM_%2528Phase_Changing_Materials%2529_%2528Super_Sustainable_City%2529 . News added 02.08.2010 at 10:28.

Tyagi, V.V., Kaushik, S.C., Tyagi, S.K. & Akiyama, T. 2011. Development of phase change materials based microencapsulated technology for buildings: A review. *Renewable and Sustainable Energy Reviews* **15**(2), 1373–1391.

Zhang, H., Xu, Q., Zhao, Z., Zhang, J., Sun, Y., Sun, L., Xu, F. & Sawada, Y. 2012 Preparation and thermal performance of gypsum boards incorporated with microencapsulated phase change materials for thermal regulation. *Solar Energy Materials and Solar Cells* **102**, 93–102.