IOP Conference Series: Earth and Environmental Science

Lifecycle analysis of finishing products enhanced with phase changing materials

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012154 doi:10.1088/1755-1315/323/1/012154

Lifecycle analysis of finishing products enhanced with phase changing materials

Petr Zhuk[1]

[1]Architectural Science of Materials Department, Moscow Institute of Architecture (State Academy), Rozhdestvenka street 11, Moscow 107031, Russia

peter_05@bk.ru

Abstract. Applicability of phase changing materials (PCMs) in buildings by their integration into the structure of finishing materials structure in the form of particles is especially high as a mean of providing heat-insulation during summer. Materials containing particles with phase changing behaviour are successfully applied at objects with large daylight areas, focused on active utilization of sunlight energy, among others. Utilization of PCM components allows saving considerable amount of energy due to possible refusal of air-conditioning while providing heat-insulation during summer.
The paper deals with the lifecycle analysis of gypsum-based finishing products. Main challenges with respect to the lifecycle of products with PCM components are the preservation of their longevity as well as their potential for reuse/ recycling. Through the example of PCM-enhanced plaster covering and gypsum plasterboard factors affecting the preservation of the advantageous thermal properties of PCMs over extended periods were studied, along with options of refining materials and products containing different amounts of PCM components.
The results of the research allow comparing similar materials with the use of PCM components and without them as well as analyzing the life cycle related environmental performance of PCM-enhanced finishing materials.

Introduction

Thermal insulation during summer is an important aspect of energy-efficiency provisioning in buildings for different functions. It can contribute to both primary energy savings and greenhouse gas emissions reductions, along with an improvement of the thermal comfort. On the economy side, not only energy costs can be reduced, but also investment costs for cooling/air conditioning systems can be reduced or entirely avoided.

One way of providing latent heat insulation is utilization of particles with phase-changing components in finishing materials. In this case excessive solar radiation energy is directed to support phase changing within those materials. It is reasonable to compare the effect of construction materials with phase-changing components utilization with that of building conditioning system utilization. This allows energy saving and achieving better level of thermal comfort during cooling period due to refusal of climate control equipment utilization. Climate control equipment is energy-expensive and requires scheduled change of filters, which can accumulate pathogenic flora. At the same time, different phase-changing components can be used in different construction materials, from concrete slabs [1], heat insulation based on cellulosic fibers [2, 3], gypsum boards to finishing materials such as plasters and paints.

An analysis of the lifecycle environmental impact of all of the above-mentioned materials was performed. Introducing phase-changing components somewhat influences material's lifecycle and, therefore, a problem of comparing similar finishing materials' (both with and without PCM) impact during their lifecycle becomes current. As an example of such materials, gypsum boards and gypsum binder based plaster coverings were chosen.

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012154 doi:10.1088/1755-1315/323/1/012154

1. Methods

One of the most important lifecycle aspects in current research is Phase Changing Materials (PCM) operating longevity as components of finishing materials. To assess the longevity, methods harmonized with the Quality Assurance RAL-GZ 896 were used [4]. Results of the research according to this paper suggest defining a number of successfully completed cycles, rating by indicator of cyclic stability as well as data on possible damage situations. During the test it is necessary to exercise control over PCM's functional criteria such as the range of phase-changing temperature and the amount of saved thermal energy. Under the RAL-GZ 896 requirements, definitions of these criteria are made at the start and at the end of the test. During the current research, criteria definition was performed no less than three times, which was necessary to clarify dynamics of PCM's properties change. Changes of samples' mass and thermal conductivity depend on testing samples' size and do not describe properties of a material as a whole. Samples of gypsum plasters and gypsum boards parts with size 20 x 20 cm were tested. Paraffins were used as PCM. Injection of paraffins was performed in two ways: (1) drenching through material's surface and (2) incorporating into finishing materials' structure in the form of microcapsules with diameter from 5 to 10 μm. High-endurance polymeric capsule was used as a shell, which, along with granule size, provides component's stability against different mechanical impacts. Paraffin has the following properties as a PCM: F_p around 25 ^{0}C, ΔH=110 J/g, which substantially corresponds to products under Micronal® trademark. Above-described material's parameters allow reaching maximum environmental thermal energy saving in amount around 110 kJ/kg of material. Under such parameters PCM accumulates excessive environmental thermal energy when its temperature becomes higher than 25 ^{0}C [5]. Incorporation of microcapsules was performed in two ways: (1) through microcapsules' dispersion in tempering water as well as (2) in form of powdered substance, which is mixed with binding agent in form of dry plaster mortar. The amount of granule particles incorporated was similar for both materials. This amount was 3 kg per square meter of finishing's surface. Finally, the lifecycle was defined and analyzed for different production specifications of finishing materials.

As far as the lifecycle analysis is concerned, it was performed using well-recognized methods. In particular, such methods and indicators as CML, Cumulative energy demand, Eco-indicator-99, Ecological footprint, Oekoindex OI3 [6] were analyzed and discussed. For simplicity and due to a limited number of indicators, Oekoindex OI3 method was chosen. The main indicators chosen for conducting an environmental impact assessment during lifecycle were primary energy consumption, global warming potential and acidification. These three criteria are taken into account during the complex Oekoindex OI3 calculation [7].

The important stage during the lifecycle of finishing materials with PCM is the materials' recycling stage at the end of their service life. Different ways of separation gypsum base and paraffin-containing components were considered. The main method being considered was a method of components' separation using moisture. Thermal processing methods proved inefficient due to PCM damage under high temperatures.

2. Results

During materials' functionality testing with regard to heat-insulation during summer, cycling stability was defined. Under this indicator, testing materials corresponded to different classes according to the RAL-GZ 896. In particular, materials with drenching (both plaster mortars and gypsum boards) failed to reach even F-class (from 50 cycles). This was caused by shallow invasion of PCM, wherein plaster mortars survived less temperature load cycles without losing their properties (less than 15), gypsum board samples demonstrated the result of around 20 cycles. Incorporation of PCM granule in form of dispersion or powdered substance showed good results in cycling stability (A-class, more than 10.000 cycles). Testing results are shown in Table 1.

Table 1. Results of cycling stability testing of finishing materials

Name of material with PCM components	Result of test for PCM incorporation as a powder, number of cycles	Result of test for PCM incorporation as a dispersion, number of cycles
Gypsum-based plaster		
Sample 1	12.450	9.500
Sample 2	14.250	7.450
Sample 3	15.150	5.450
Sample 4	20.050	5.500
Sample 5	18.450	8.150
Gypsum board fragment		
Sample 1	22.450	10.650
Sample 2	27.550	12.450
Sample 3	25.350	11.350
Sample 4	23.150	10.600
Sample 5	21.000	11.450

Results shown in Table 1 demonstrate that gypsum board slabs and plaster mortars (with PCM incorporation as a powder) belong to A-class in cycling stability (> 10.000 cycles), while plaster mortars with PCM incorporation as a dispersion belong to B-class (> 5.000 cycles). The cause of low class for this materials group lies in irregularity of PCM components' distribution within the material, including excessive granule proximity to surface. Tests were performed until the loss of ability to consume excessive thermal energy, with a step after every 50 cycles. Supposing that during internal utilization of PCM-containing finishing materials up to 300 phase changings per year can occur (which is approximately 1 changing a day), 10.000 (A-class) provide more than 30 years duration of minimal service life for a PCM-containing material [5]. Plasters with PCM incorporated as dispersion have slightly shorter working life. But working life of such materials with PCM is purely comparable to that of the finishing material itself. Researches show that sometimes results for products (plaster mortars with PCM incorporation as dispersion) slightly differ from results for PCM granule, which is somewhat inconsistent with the RAL-GZ 896 data.

Cycling stability testing results are important for lifecycle analysis because they define, to a great extent, the length of the operation stage. Let's consider production (which in this case will include raw materials preparation), operation and recycling as main stages of the finishing materials' lifecycle. The following discussion will begin from the production stage.

PCM dispersion in tempering water directly during plaster or gypsum board production as well as powder produced by drying this dispersion and added in dry mixes, which are stored in sacks or silos depending on required quantity, can be used in production. Production scheme of dry mix for plaster being researched is shown in Figure 1.

During the production stage energy expenditure for paraffin and granule with PCM should be taken into account. In case of PCM incorporation in form of powder costs of drying under diffusion of dispersion for powder production should be taken into account. In case of PCM incorporation with tempering water as a result of mixing it is impossible to achieve desirable longevity of working life, despite that from the energy capacity point of view this process is less expensive, it is hard to achieve homogeneity in distribution of granule along the gypsum board product or within plaster coating.

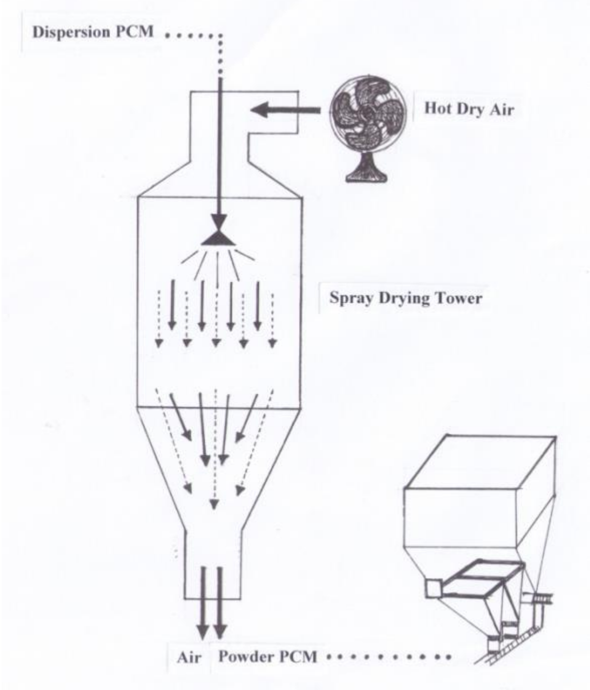

Figure 1. Production scheme for plaster with PCM in form of powder

The assessment results on the basis of the considered indicators for plaster and gypsum board slabs with PCM and without are not a far cry from each other. This proves the efficiency of using PCM components for achieving a passive heat-insulation effect at the material operation stage.

The service life, related to effect of using excessive thermal energy in a room for phase change in granule is different for different finishing materials. Service life depends on a way of granule incorporation into finishing material as well as room composition, window frames size and glaring, environmental conditions of building location, among others. Generally speaking, considerable effect can be achieved during the operation stage by means of rooms' temperature equalization at comfort level, which makes savings on energy cost of climate control equipment possible. Comfortable microclimate can be achieved for certain temperatures without overheating. Furthermore, heat accumulation can be achieved through a certain level of thermal mass or with help of PCM [8, 9 and 10]. Also, paraffin reaction is instant while mass of constructions reacts slowly. Due to PCM components the following phenomenon occurs: an instant significant excessive energy draw-off, PCM concentration close to surfaces of walls and slabs, fast release of energy remains as a result of ventilation. Calculation of microclimate improvement and gain in economic feasibility can be performed with the help of specialized software and programming tools by designing and modeling for certain conditions (for instance, PCM express programs by [5]).

At the final stage it is important to perform a separation of mineral constituent and paraffin granule. In order to do this thermal or moisture related methods can be used. Experience has shown that utilization of thermal methods leads to disturbance of PCM properties related to phase-changing capabilities. Although moisture utilizing methods turn out to be more energy-consuming (even compared to process of recycling finishing materials without PCM), they allow a more thorough recycling. As a result, there are the following indicators of energy consumption and impacts related to global warming potential and acidification (Figure 2). The assumptions and data bases are described below.

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012154 doi:10.1088/1755-1315/323/1/012154

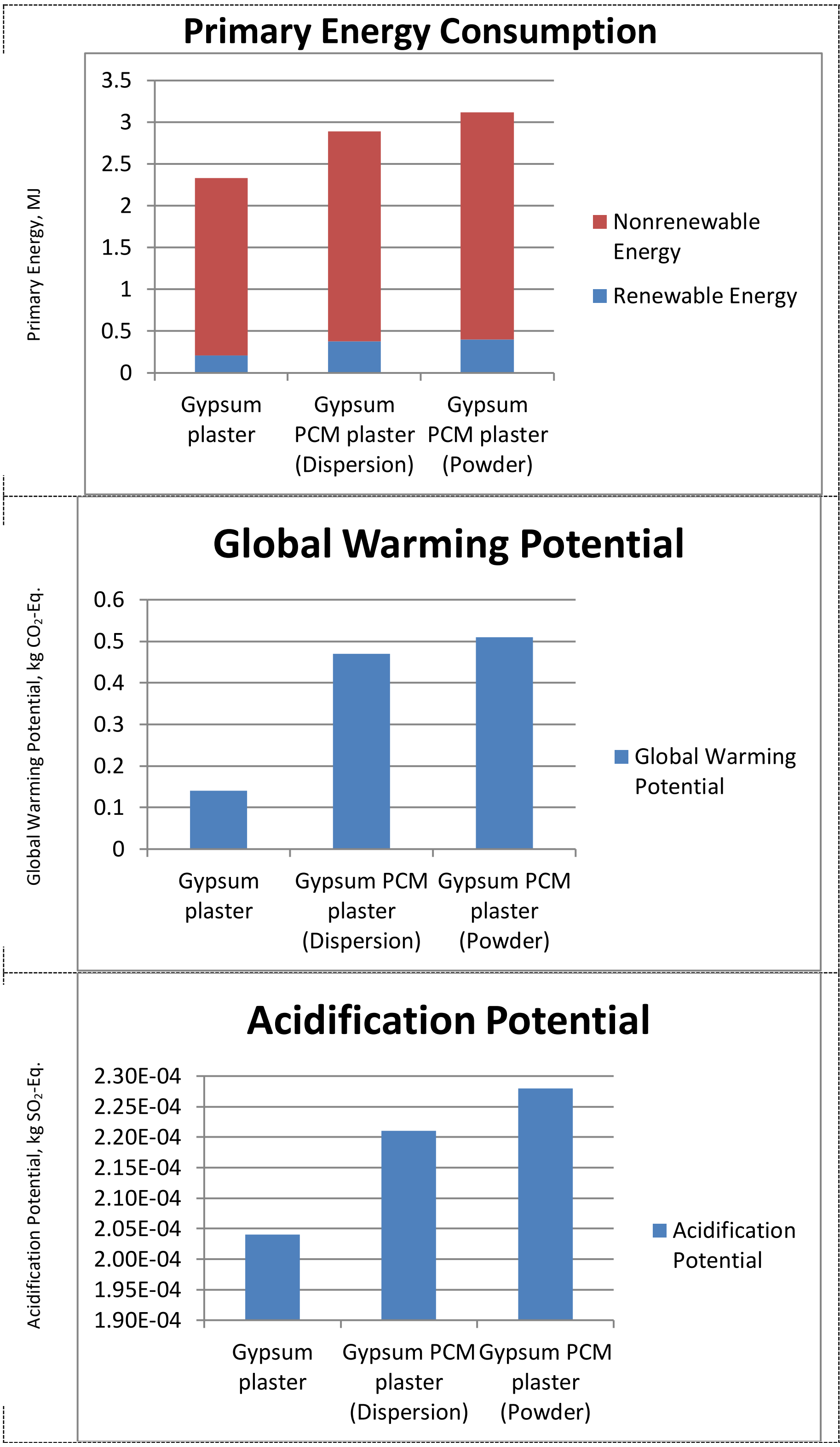

Figure 2. Comparison of three types of plaster based on three environmental indicators. Note: All figures represent the production stage only and are expressed per kg of material

Primary energy consumption during the lifecycle of different technological options is normalized per functional unit, which in case of plaster is 1 kg. Energy consumption during the operation stage was calculated using eco2soft method, developed by the IBO Austrian Institute for Healthy and Ecological Building [7]. Calculations were performed for the lifecycle with the postulated gypsum plasterboard service life of 30 years during operation in Central Europe climate conditions taking into account production and recycling stages. Due to lack of EPD for PCM containing materials a correlation of data received under the given research with the EPD data for similar materials without PCM (in particular, for gypsum plaster) [11, 12].

Taking into account energy saving during the operation stage due to reduction/avoidance of air conditioning energy consumption, which amounted around 100 kWh per annum for a testing room on under roof floor of free-standing residential building (area of surfaces finished with gypsum plaster with PCM was equal to 70 m^2), total energy consumption by lifecycle stages are displayed at the Figure 3.

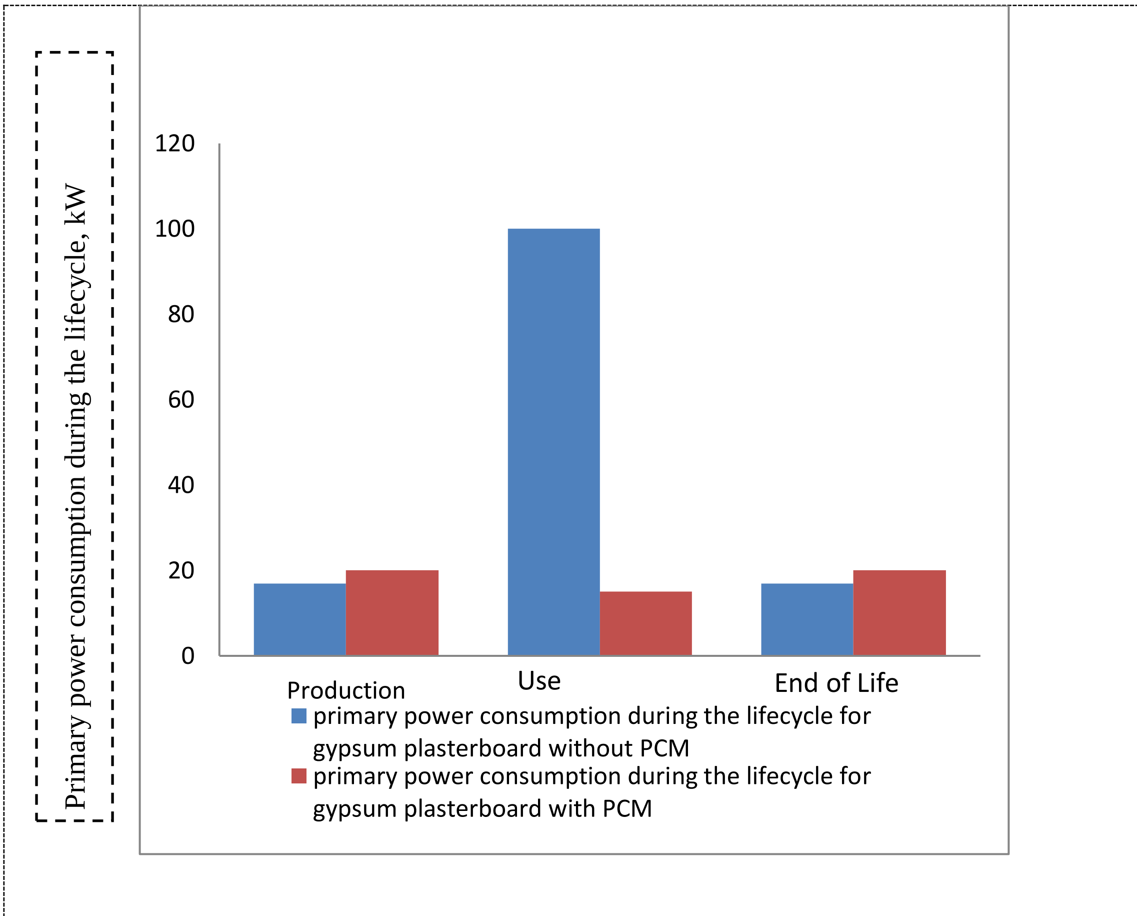

Figure 3. Comparison of primary energy consumption per life cycle stage for gypsum plasterboard with and without PCM

The information presented at the Figure 3 state that saving in energy consumption at the material's operation stage greatly surpasses slightly more high energy consumption rates at production and lifecycle end stages, related to granule with PCM production, incorporation and distribution within plaster structure and problems of components separation during recycling of served-out material. Figure 3 shows the scale of energy consumption that occurs during the lifecycle stages of the plaster, i.e. production, operation and end of life. In addition, it was taken into account that during the operation stage climate control equipment in rooms with the use of PCM can be waived. The figure 3 is a qualitative display of comparative power consumption scales during materials' lifecycles and can be interpreted in such a way that slight increase of expenditures during materials' production and recycling stages a significant effect at the operation stage can be achieved.

A principle, similar to the one used in assessment of B1 (utilization), B2 (maintenance, cleaning) and B6 (power consumption requirement) stages in Environmental Product Declaration (EPD), was used for comparison of primary power consumption values during the lifecycle. Calculation of conditioning costs using simple plaster (without PCM) resulted in approximately 1,5 kW for plastered surface of 67 m^2 [5]. Also the data on plaster consumption for a square meter in kilograms (including the amount of injected PCM) and acceptable original plaster life duration (which is 15-20 years for interior plastering) is known. Therefore, it is possible to make a comparison by functional unit of proceeded surface (1 m^2) or by unit of dry plaster with known consumption (in kilograms). Not only primary power consumption is important for the purpose of accurate comparison, but also other environmental indexes as well as economic and social effects which were not considered in the given research. However, literature sources provide interesting data on these indexes. In particular, CO_2 emission index, calculated through primary power consumption for conditioning of building with gross floor area of 5902 m^2, accounts for more than 100 tons per year [5]. Data on plaster with PCM depreciation life gives indexes ranged from 2 to 5 years, depending on building type, enveloping structures, environmental and other conditions. Based on this data, experts calculate general economic effects occurring on replacement conditioning systems with plaster or other finishing materials modified with PCM.

3. Discussion

Indicator results of environmental impact during the full lifecycle of finishing materials with the use of PCM are generally comparable to indicator results of similar materials without these components [11, 12]. This proves the insignificant environmental impact of PCM production and operation.

Increase of environmental impact can be observed during raw materials preparation (PCM granule production), production of finishing materials with the use of PC components and at the stage of recycling at the end of their operating life. Separation of mineral constituent and granule with organic components provides for higher level of finishing material components recycling.

Considerable environmental impacts can be achieved at all times during the useful life of a building due to significant saving on climate control equipment, because PCM longevity allows calculating for such a long period.

4. Conclusion

Basing on the results of the conducted research the following conclusions can be made:

- one of the most important parameters of finishing materials utilizing PCM is their cycling stability, which, depending on the way of granule incorporation, amounts for decades under given design operation condition and provides for working life of phase changing component comparable to working life of finishing coating as a whole;
- preparation of raw materials (including production of the phase-changing component itself and granule with it), as well as gypsum board and plaster mortars with PCM granule, are associated with a slightly larger environmental impact compared to regular finishing materials;
- at the operation stage due to creation of comfortable conditions in a room without the use of air conditioners and other climate control equipment energy consumption effect is achieved as well as reduction of greenhouse gas emission, expressed as GWP and acidification;
- recycling of finishing materials with PCM requires a higher energy consumption compared to similar regular finishing materials, but this effect is insignificant and does not have a crucial impact on general positive evaluation of finishing materials with PCM lifecycle;
- calculating amount of PCM granule being incorporated in finishing material structure as well as special aspects of their distribution along layers from surface to depths of coating play an important role which allow achieving the most effective heat-insulation during summer.

Utilization of PCM in finishing materials for interiors allows achieving savings when creating a comfort microclimate during summer. This reduction of environmental impact considerably surpasses effects occurring during PCM production, incorporation into material and recycling after the end of the lifecycle, which can last for decades.

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012154 doi:10.1088/1755-1315/323/1/012154

Outlook

The main directions of PCM development and utilization must include lowering energy consumption of paraffin production as well as developing effective product's recycling methods at the end of its lifecycle.

Acknowledgement

The author would like to thank Dr. Maria Balouktsi and Prof. Dr. Thomas Lützkendorf of the Karlsruhe Institute of Technology (KIT) for their cooperation and support in the preparation of this paper.

References:

[1] Niall D et al 2016 Thermal mass behavior of concrete panels incorporating phase change materials *Proc. Int. Conf. Sustainable Built Environment (Hamburg)* (Hamburg: ZEBAU) pp. 1276-1285

[2] Kosny J et al 2007 *PCM-Enhanced Building Envelopes in Current ORNL Research Projects* (Bucyrus, OH: Douglas Leuthold Advanced Fiber Technologies)

[3] Yarbrough D W et al *Use of PCM Enhanced Insulation in the Building Envelope* (Oak Ridge, TN: Building Technology Centre)

[4] Phase Change Materials 2018 Quality Assurance RAL-GZ 896 (Bonn: RAL Deutsches Institut für Gütesicherung und Kennzeichnung e.V.)

[5] Micronal®PCM 2010 Katalog für Architekten und Planer (Lüdwigshafen: BASF SE)

[6] Frischknecht R, Jungbluth N et al 2007 Implementation of Life Cycle Impact Assessment Methods. *Ecoinvent Report No. 3* (Dübendorf: Ecoinvent)

[7] Oekoindex OI3. *The instrument for environmental building optimisation*. IBO Austrian Institute for Healthy and Ecological Building

[8] Kalz D, Fischer M, Schossig P 2008 *Monitoring und modellbasierte Auswertung. Bewertung des Potentials von Phasenwechselmaterialien zur Verbesserung des thermischen Komforts im Sommer in einem Schulgebäude* (Freiburg: Fraunhofer-Institut für Solare Energiesysteme ISE) p 26

[9] Origgi D 2006 *Einfluss von Wärmedämmung und Phasenwechselmaterial auf den Energiebedarf und CO_2-Ausstoss in verschiedenen europäischen Klimata im Auftrag der BASF AG* (Darmstadt: Passiv Haus Institut)

[10] Mehling H, Schossig P, Kalz D *Latentwärmespeicher in Gebäuden. Wärme und Kälte kompakt und bedarfsgerecht speichern* (Karlsruhe: FIZ Karlsruhe GmbH) pp 3-20

[11] Umwelt-Produktdeklaration. *Knauf Gipsputze nach DIN EN 13279-1* (Berlin: Institut Bauen und Umwelt e. V.) pp 1-9

[12] Krogh H, Hansen K, Hoffmann L 1997 Collection and use of environmental data on building materials *Proc Second Int Conf Buildings and the Environment (Paris)* pp149-156