Energy Assessment of A PCM–Embedded Plaster: Embodied Energy Versus Operational Energy

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 3210 – 3215

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Energy assessment of a PCM–embedded plaster: embodied energy versus operational energy

Corrado Carbonaro[a], Ylenia Cascone[b], Stefano Fantucci[b], Valentina Serra[b,*], Marco Perino[b], Marco Dutto[c]

[a]*Department of Architecture and Design, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy*
[b]*Department of Energy, TEBE Research Group, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy*
[c]*Vimark S.r.l., Strada Spartafino 2, Cuneo 12100, Italy*

Abstract

Phase change materials (PCMs) are an emerging technology that can be integrated in building envelope components. PCMs are able to stabilise indoor air temperature and increase thermal energy storage especially in lightweight constructions. Within a research activity aimed at developing advanced plasters with improved thermal properties, a plaster which incorporates a microencapsulated paraffin-based PCM was developed. The paper highlights the importance of an overall analysis, facing both operational and embodied energy, since the expected decrease of the energy consumption during the operational stage difficultly counterbalances the high energy impact related to manufacturing processes.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Phase Change Material; plaster; embodied energy; operational energy

1. Introduction

In the latest years, many researches on advanced materials suitable for application in building envelope components have been carried out. Phase change materials (PCMs) are an emerging technology that can be integrated in building envelope components for new constructions as well as for refurbishment. PCMs are capable of stabilising indoor air temperature and increase thermal energy storage especially in lightweight constructions.

* Corresponding author. Tel.: +39-011-090-4431; fax: +39-011-090-4499.
E-mail address: valentina.serra@polito.it

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.782

Even though a lot of research has been carried out to evaluated the effect of PCMs on the energy demand reduction in the operational phase of a building, not much attention is generally given to their embodied energy.

In the present work, within a research activity aimed at developing advanced plasters with improved thermal properties, a plaster which incorporates a microencapsulated paraffin-based PCM was developed. Laboratory measurements were performed in order to assess the thermal conductivity and the dynamic thermal behaviour of the PCM plasters. In addition, an overall analysis of both operational and embodied energy was carried out.

2. Description of technology

The PCM embedded plaster was developed within a research project aimed at identifying new plaster solutions, for both new buildings and energy efficient refurbishment [1]. The new formula was called PCM_005. Several binders were tested in order to find the best combination with the innovative aggregates (PCM) and obtain the highest interrelation with the binding matrix. Eventually, after testing several hydraulic and air-entrained binders, gypsum was chosen as the prevailing binder. Gypsum allows a great volume of light-weight PCMs to be embedded within the premixed product. Optimal properties of mechanical resistance, product workability, applicability of thick layers and limited possibility of crazing formation were still guaranteed.

As a result, PCM_005 is an experimental natural mineral plaster which comes as a ready to use premixed powder based on calcium sulphate, PCMs and lightweight mineral expanded aggregates. It is suitable for manual application on indoor walls and, due to its composition, it is specifically fit for realising internal surfaces with a high thermal regulation capability. It can be applied on every kind of traditional internal brickwork due to its characteristics as both substrate and finish plaster. The product complies with the requirements of the EN 998-1:2010 standard and it is classified as a "General purpose rendering/plastering mortar (GP)".

For the experimental analyses, three different plaster samples were used as reported in Table 1. They consisted in two PCM-embedded plasters (PCM_005-V1 and PCM_005-V2) and a plaster sample without PCM used as reference (Base Plaster).

Table 1. Experimental results.

Plaster name	Code	Description	PCM melting temperature
Base Plaster	Rif.	Natural hydraulic lime, gypsum, calcium carbonate, flakes, additives	-
PCM_005	V1	Natural hydraulic lime, incapsulated PCM (14%), gypsum, calcium carbonate, flakes, additives	26°C
PCM_005	V2	Natural hydraulic lime, incapsulated PCM (14%), gypsum, calcium carbonate, flakes, additives	23°C

3. Thermal characterisation

Laboratory measurements were performed on three plaster samples. The measurements were carried out to assess both the thermal conductivity λ and the dynamic thermal behaviour of the three samples. The experimental tests were carried out by means of a Lasercomp FOX600 single sample guarded heat flow meter apparatus according to EN 12667:2001 [2]. The apparatus was adjusted to allow for thermal tests in dynamic conditions.

The thermal conductivity measurements were performed at three different average temperatures (6 °C, 21 °C and 36 °C) while the temperature difference between the two plates was fixed at 10 °C.

To avoid any additional surface resistance due to the plaster surfaces discontinuity, all the specimens were sandwiched between two rubber sheets with a thermal conductivity of 0.136 W/(m K) and 2 mm of thickness.

Moreover, swinging transient measurements of exchanged heat fluxes were performed with the adjusted experimental apparatus. For the swinging test, the lower surface was maintained at the constant temperature of 23 °C, while the upper surface temperature was subjected to a controlled swinging in the range of 23 °C ± 5 °C with a periodic cycle of 24 h (test durations were at least 48 h. Nevertheless, only the last stabilised 24 h cycles were considered for the time lag calculations). The time lag φ_t, as defined according to EN ISO 13786:2007 [3], was determined as the time difference between the peak of the lower surface temperature on the transient plate side and the maximum heat loss density measured on the steady state plate side.

Table 2. Experimental results.

Sample name	code	Density ρ (kg/m^3)	$\lambda_{6°C}$ (W/mK)	$\lambda_{21°C}$ (W/mK)	$\lambda_{36°C}$ (W/mK)	φ_t (min)
Base Plaster	Rif.	1090	0.337	0.340	0.349	11
PCM_005	V1	940	0.109	0.112	0.112	39
PCM_005	V2	1302	0.180	0.181	0.184	17

Table 2 reports the results of the guarded heat flow meter measurements for both steady state and transient tests. The specific heat of the reference plaster and of the PCMs were retrieved by literature values. The specific heat as a function of temperature of the PCM-embedded plasters was estimated as an average of the PCMs and plaster specific heats weighted on their respective mass concentrations. The resulting latent heat of the PCM-embedded plaster was approximately 15 kJ/kg. This value is in agreement with those reported in [4] for similar PCM plaster products.

4. Embodied vs operational energy

4.1. Operational energy

The operational energy was evaluated for a residential case study by means of numerical simulations which were performed with EnergyPlus 8.0.0 [5]. The case study was a 5 x 5 x 2,7 m room (internal size) with a 2,1 x 1,4 m window facing south. A parametric analysis was performed by varying plaster type (Reference, V1 and V2), plaster thickness (2 cm, 5 cm and 10 cm), and number of surfaces facing the external environment (from one to three, either south façade, south and east façades or south and east façades plus roof).

The case study was located in Turin, Italy, and the thermal characteristics of the envelope components were chosen in order to comply with the standards for this location. The vertical opaque envelope was composed by an external layer of Autoclaved Aerated Concrete (AAC) with variable thickness and an internal layer of plaster. The U-value was set to 0,33 W/(m^{2}K) when the surfaces faced the external environment. The horizontal envelope was considered either as a flat roof or a floor slab dividing the room from the upper floor. It was composed by an external tiled floor, a slab, an insulation layer with variable thickness and an internal layer of plaster. The U-value was set to 0,30 W/(m^{2}K) when the surface faced the external environment. A U-value of 0,8 W/(m^{2}K) was set for walls and roof when these surfaces were adiabatic. The transparent envelope was composed by a low-e double glazing whose gap was filled with 90% Argon. The U-value of the window was 1,0 W/(m^{2}K) and the g-value 0,7.

Internal gains deriving from people activity and lights/electric equipment were chosen according to ISO 13790:2008 [6]. A constant average value of 9,0 W/m^2 was scheduled. Natural ventilation strategy was adopted. The ventilation rate was set to 0.3 air changes per hour. The space was treated as a single thermal zone. Heating and cooling set point temperatures were respectively set to 20 °C and 26 °C during the whole year.

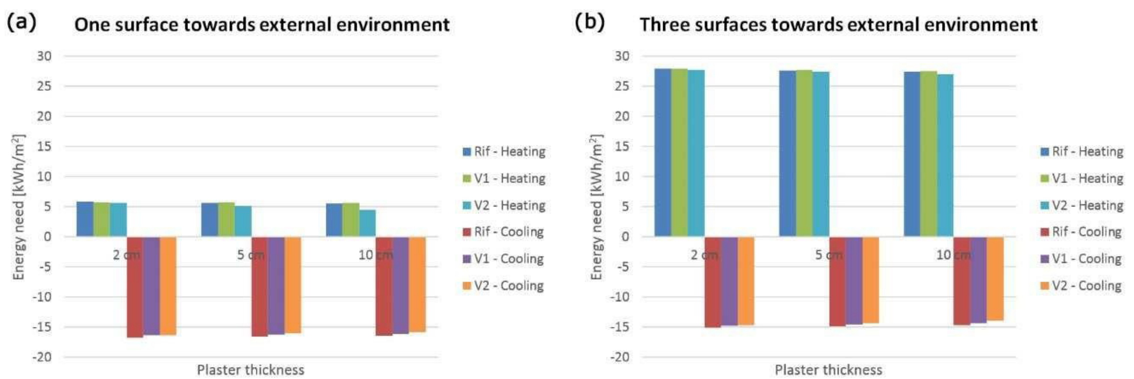

Fig. 1. Energy need for heating and cooling: (a) one surface towards external environment; (b) three surfaces towards external environment.

For brevity, only the results of the energy need for heating and cooling for the cases of one and three non-adiabatic surfaces are reported in Fig. 1. Even though different PCM-embedded products are analysed, these results are not as promising as those reported in [7]. In the present study, the effect of the PCM in the reduction of the energy need for heating and cooling was not very significant due to the low PCM concentration and, consequently, to the low latent heat of fusion of the PCM plaster.

The greatest energy reduction was achieved with the use of the PCM_005-V2 plaster, whose PCM melting temperature of 23 °C lies within the free running range.

The advantages in the use of PCM-embedded plasters would be far greater if the thermal comfort during summer could be guaranteed without the need for a cooling system. For this to be possible, a higher PCM concentration together with the adoption of passive cooling criteria would be advisable in terms of operational energy. However, this target may not be achievable in all the climates.

4.2. Embodied energy

The environmental impacts were evaluated with the Life Cycle Assessment methodology defined by the UNI EN ISO 14040/44 [8]. The life cycle analysis was aimed at developing and improve a range of experimental prototypes of plaster with PCM and to evaluate the effectiveness of the PCM embedded in the plaster in relation to embodied energy and operational energy. The LCA method was developed in three progressive steps. The first one was the analysis of the raw material in order to support the design phase, the second step was the comparison between the prototypes and the Base plaster (benchmark), and the third one was the evaluation of the Embodied Energy in comparison with the Operational Energy obtained by means of numerical simulation for a case study. The Functional Unit for the former two steps was kWh/kg, while the Functional Unit of the last analysis was kWh/m^2 related to the net floor area of the simulated case study.

The system boundary – covering cradle-to-gate – included all the processes from the extraction of raw materials, transports, up to the plant processes of manufacturing and packaging. The Life Cycle Inventory was based both on indirect and direct data. The indirect data of the raw materials (natural hydraulic lime, gypsum plaster, calcium carbonate, flakes and additives) were retrieved from the database Eco-Invent v.2.0. The inability to retrieve direct data for the production processes determined the choice to study the PCM through the analysis of its two component materials, i.e. paraffin and polymethyl methacrylate. The scientific literature data on the encapsulated PCM was adopted; 60 wt. % of paraffin and 40 wt. % of polymethyl methacrylate are reported in [9]. The data on transport route and plant processes related to the manufacturing of the experimental thermal plasters were gathered directly from the companies involved in the research project.

Results of the LCA analyses of plasters are shown in Fig. 2 where the non-renewable and renewable energies were evaluated with the CED method v. 1.06. The comparison between 1 kg of plaster's raw materials, based on adaptation of data from Ecoinvent, highlights the high environmental impact of phase change materials in relation to the binders and other aggregates (Fig. 2).

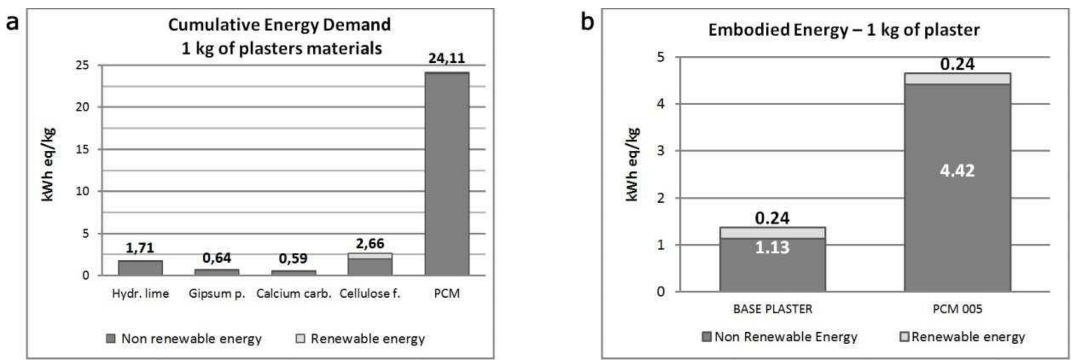

Fig. 2. Cumulative Energy demand of (a) plasters materials; (b) Base and PCM plasters.

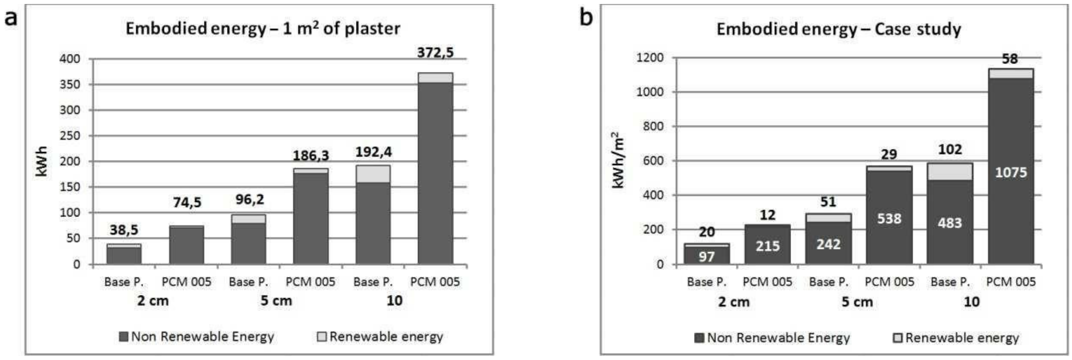

Fig. 3. Embodied Energy in: a) 1 m^2 of plaster; b) all plastered surfaces of the simulated room normalized on the net floor area.

The environmental and energy analyses on the material emphasise the high environmental cost of PCMs. The highest the amount of PCM, the highest the embodied energy that needs to be properly counterbalanced by the energy demand reduction in the operational phase (Fig 2.a). The analysis carried out on the thermal plasters highlights also a ratio of 1:4 on the cumulative energy demand of the Base plaster with respect to the PCM_005 plaster (Fig. 2.b). These results are in accordance with the embodied energy data reported in the Inventory of Carbon & Energy (ICE) realised by SERT of Bath University and in previous studies on plasters[10, 11].

To compare the embodied energy of construction powder products, the study of the consumption of product per surface unit in the installation phase is fundamental. The bulk density of materials in the blend and the concentration of aggregates affect the final weight of powder used per square meter. The amount of powder consumption per square meter can vary between 2.5 and 15-16 kg depending on the plaster characteristics. In this research, PCM_005 had a consumption of 8 kg per m^2 per cm of thickness, which is much lower than the basic plaster (14 kg per m^2 per cm of thickness). The differences between Base plaster and PCM_005 are quite evident (Fig. 3), but could be greater if a higher concentration of PCM product was used during plaster preparation. The embodied energy in the application of three thicknesses of PCM plaster (2 cm, 5 cm, 10 cm) on one square meter of wall highlights the big differences between Base and PCM plasters. In particular, the embodied energy in 5 cm of PCM plaster resulted very similar to that in 10 cm of Base plaster (Fig 3.a). To compare the embodied energy with the operational energy data, the embodied energy was calculated and normalised on the net floor area (25 m^2) of the simulated room, whose surfaces were all plastered with the exception of the floor. These results are shown in Fig 3.b.

5. Results and discussion

The comparison between embodied (EE) and operational energy (OE) for the investigated case study is shown in Fig. 4. Results were normalized on the net floor area of the simulated room and are reported in terms of yearly difference, over a period of 50 years, between PCM plasters and Base plaster with equal thickness. The value referred to total energy (ΔTE) resulting from the sum of yearly difference for both embodied and operational energies is also presented. The benefits in terms of operational energy for the analysed case study did not balance the high embodied energy content. From these results, the importance of analysing both EE and OE of PCM materials is highlighted. The adoption of PCM plasters could potentially be profitable when the highest reduction of OE can be achieved with the lowest amount of PCM. However, in the presented case study this condition was not met even using the PCM plaster only on the perimetral walls. A balance may be achieved in locations whose climate is similar throughout the year with a suitable optimisation of the PCM type, properties, quantity and position, and through a proper integration between building envelope and building services [12, 13]. In addition, an issue that would need further investigation is the durability of the PCM. The effect on the operational energy reduction resulting from alteration of the thermophysical properties of the PCM due to thermal cycling should be taken into account for properly evaluating the time frame of the analysis.

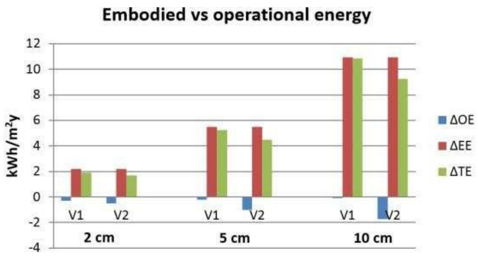

Fig. 4. Yearly difference of embodied energy (ΔEE), operational energy (ΔOE) and total energy (ΔTE) between the PCM plasters and the Base plaster with equal thickness, over a period of 50 years.

6. Conclusions

In the present work, a plaster which incorporates a microencapsulated paraffin-based PCM was developed. Laboratory measurements were performed on three plaster samples to assess their thermal conductivity and dynamic thermal behaviour in terms of time lag. In addition, an overall analysis of both operational and embodied energy was carried out. The operational energy was evaluated for a residential case study by means of numerical simulations.

Results addressed the importance of analysing both embodied and operational energy of PCM materials. For the analysed case study, the high embodied energy content of the PCM plaster was not counterbalanced by the benefits in terms of operational energy reduction. The effects of thermal cycling should be also taken into account.

In order for PCM plasters to become competitive materials from a global energy point of view, efforts should be made by the manufacturers to reduce their embodied energy.

Acknowledgements

The project was developed in cooperation with DAD_Politecnico di Torino, DENERG Politecnico di Torino, VIMARK s.r.l., AGRINDUSTRIA s.n.c., CLUSTER s.r.l., ARTI E MESTIERI, ATC Torino. In the framework of the POLIGHT projects “SI2 – Sistemi isolanti innovativi”

References

[1] Bianco L, Serra V, Fantucci S, Dutto M, Massolino M. Thermal insulating plaster as a solution for refurbishing historic building envelopes: First experimental results. Energy Build 2015; 95:86-91; doi:10.1016/j.enbuild.2014.11.016.
[2] EN ISO 12667. Thermal Performance of Building Materials and Products – Determination of Thermal Resistance by Means of Guarded Hot Plate and HeatFlow Meter Methods – Products of High and Medium Thermal Resistance; 2001.
[3] EN ISO 13786. Thermal performance of building components - Dynamic thermal characteristics - Calculation methods; 2007.
[4] Karkri M, Lachheb M, Albouchi F, Ben Nasrallah S, Krupa I. Thermal properties of smart microencapsulated paraffinplaster composites for the thermal regulation of buildings. Energ Buildings 2015;88:183-192.
[5] U.S. Department of Energy. EnergyPlus Engineering Reference. Office of Energy Efficiency and Renewable Energy, United States; 2014.
[6] EN ISO 13790. Energy performance of buildings - Calculation of energy use for space heating and cooling; 2008.
[7] Ascione F, Bianco N, De Masi RF, de‘ Rossi F, Vanoli GP. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. Appl Energ 2014;113:990-1007.
[8] EN ISO 14040/44. Environmental Management – Life cycle assessment; 2006.
[9] Menoufi K, Castell A, Navarro L, Pérez G, Boer D, Cabeza LF. Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase. Appl Energ 2012;92:534-544.
[10] www.bath.ac.uk/mech-eng/sert/embodied.
[11] Carbonaro C, Dutto M, Thiebat F. Eco-design approach for Innovating building product. In: Proceeding in LCA case study Symposium; 2013 Nov 11-13; Rome. Italy.
[12] De Gracia A, Rincón L, Castell A, Jiménez M, Boer D, Medrano M, Cabeza LF. Life Cycle Assessment of the inclusion of phase change materials (PCM) in experimental buildings. Energ Buildings 2010;42:1517-1523.
[13] De Gracia A, Navarro L, Castell A, Boer D, Caveza LF. Life cycle assessment of a ventilated facade with PCM in its air chamber. Sol Energy 2014;104:115-123.