



2013 ISES Solar World Congress

Design of a prefabricated concrete slab with PCM inside the hollows

Lidia Navarro^a, Alvaro de Gracia^a, Albert Castell^a, Servando Álvarez^b, Luisa F. Cabeza^{a*}

^a*GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001, Lleida, Spain*

^b*Grupo de Termotécnica, Universidad de Sevilla, Escuela de Ingenieros Camino de los Descubrimientos s/n. 41092, Seville, Spain*

Abstract

In the recent years, the integration of heat storage systems inside building components has been applied for heating and cooling purposes. The implementation of the thermal energy storage inside the building is used to manage and smooth the peak demand. An innovative constructive system including heat storage has been designed to reduce the energy consumption of the HVAC systems, during both heating and cooling periods. It consists of a prefabricated concrete slab with macro-encapsulated PCM inside its hollows. An installation of air ducts allows the air to be forced through the inside of the slab and therefore enhancing the heat exchange with the PCM. The operational mode during summer lies in solidifying the PCM during the night time and using the cold stored as a cooling supply during the day. Moreover, a solar air collector is installed for the winter mode, where the heat from the solar radiation is used to melt the PCM and cover part of the heating demand. The objective of this study is to analyse the benefits of this new system and to quantify its potential in reducing the energy consumed both for heating and cooling.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Selection and/or peer-review under responsibility of ISES.

Keywords:

1. Introduction

It is well known that energy consumption in the building sector has become an important issue to take into account for the global energy consumed in Europe, as it means 40% of the total. A significant part of the energy consumed in buildings is due to the heating and cooling systems. Moreover, the comfort parameters are getting stricter especially under summer conditions. In the recent years a rise in the number of air-conditioning systems has been observed in European countries [1]. The European directive on the

* Corresponding author. Tel.: +34.973.00.35.76; fax: +34.973.00.35.75.

E-mail address: lcabeza@diei.udl.cat.

energy performance of buildings (EPBD) suggests that all the EU member states should approve national plans and targets in order to promote the inclusion of very low and close to zero energy buildings. Hence, it is critical to reduce the energetic consumption of the building.

Improvements in buildings envelope have high potential in energy demand reduction. An important amount of literature regarding the building envelope performance is related to the thermal insulation layer as it is considered by Papadopoulos [2] the most effective protection from the external conditions. In addition, most of the building regulations, such as the Spanish one [3], are focused on the insulation thickness to achieve a proper thermal resistance of the building components. However, these design restrictions have to be not only focused on the thermal resistance but in the thermal inertia, as well.

In recent years, the incorporation of latent heat storage materials in building envelopes as a passive system has been widely studied. These materials change their phase at a certain temperature, in the case of building applications ambient temperature is desired (18 °C to 27 °C), providing high heat storage capacity within the comfort range. Therefore, the thermal inertia of the building is improved by the phase change materials (PCM). Different applications have been studied for PCM incorporation such as in gypsum board for thermal mass enhancement of the walls [4]; in prefabricated concrete walls for thermal inertia increase and lowering peak internal temperatures [5]; and in blinds for solar heat gain reduction [6]. Moreover, in Castell et al. [7] the macro-encapsulated PCM was placed in the constructive system of the building facade as passive cooling system and 15% of energy consumption reduction was registered.

Furthermore, the use of PCM in active systems was also studied in several applications. Takeda et al. [8] implemented the PCM in a ventilation system with a direct heat exchange between the exhaust air and the PCM and demonstrate that the cooling load can be reduced by their ventilation system. Wang and Niu [9] used a PCM slurry tank for a cooled-ceiling system and they observed a decrease on the daytime electricity demand by about 33%. On the other hand, Koschenz and Lehmann [10] presented a thermally activated ceiling panel with PCM for retrofitted buildings and showed that a 5 cm thickness gypsum panel with PCM is enough to maintain a comfortable room temperature in office buildings. Most of these studies included the PCM in the HVAC equipment, in the air handling unit or in storage tanks.

In this study the PCM is implemented inside a building component and it is designed as storage and supplying system to reduce the cooling and heating consumption of the HVAC systems. The design of a concrete slab with PCM is described. The system will reduce the energy consumption during summer and winter periods. The objective of this paper is to define the characteristics of the active slab, the operational principle and to calculate the thermal energy storage capacity of the system in order to cover the energetic demand during heating and cooling seasons.

2. Experimental set-up

2.1. Description of the experimental set-up

An experimental set-up was built in Puigverd de Lleida (Lleida, Spain) to evaluate different constructive systems for building energy efficiency. This installation consists of several cubicles (Figure 1), simulating real buildings and operated under real conditions. The experiments are going to be performed under continental Mediterranean weather conditions, where five different weather periods can be defined:

- Severe winter: Very low temperatures (-5 °C to 10 °C) and mild solar radiation (800-900 W/m²).
- Mild winter: Low temperatures (5 °C to 20 °C) and mild solar radiation (800-900 W/m²).
- Severe summer: Very high temperatures and solar radiation (25 °C to 35 °C, and 1000-1100 W/m²).
- Mild summer: High temperatures and solar radiation (18 °C to 30 °C, and 1000-1100 W/m²).

- No demand: Temperatures and solar radiation are mild; therefore there is no need for cooling or heating.



Figure 1. Experimental set-up in Puigverd de Lleida, Spain.

Two of those cubicles are used in this project to test the incorporation of PCM in a prefabricated concrete slab. These two cubicles were built based on the alveolar brick constructive system and have exactly the same roof constructive system. Both roofs consist of a 25 cm concrete slab made of precast beams. To overcome thermal bridges, 3 cm of polystyrene were placed above the slab and a roof slope of 3% was created with lightweight concrete. A double asphalt membrane is located to protect from water infiltrations and a gravel layer of 5 cm thickness is placed on the top.

Their internal dimensions are 2.4 x 2.4 x 5.1 m, so the internal height of the cubicle allows the authors to simulate two a store cubicle with different internal slabs. One of these cubicles contains the active slab, while the other one is used as a reference having a standard internal slab.

2.2. Description of the active slab

As previously said, one of the cubicles is equipped with an active slab composed by a prefabricated concrete plate of 30 cm thickness, which is located at medium height of the cubicle. The internal concrete slab of the cubicle is used as a storage component which is charged and discharged through an air duct installation. The incorporation of a mesh of metallic tubes filled with PCM inside the hollows (Figure 2) enhances the heat exchange between the PCM and the air. Therefore, the air can flow through the channels and take advantage of the phase change for heating and/or cooling purposes.

The PCM used in this application is RT-21 macroencapsulated in the aluminium tubes, and their thermo-physical properties are presented in Table 1.



Figure 2. Prefabricated concrete slab filled with PCM tubes.

In order to provide versatility to the system, six different openings are located in the air ducts that allow the set up to work with different modes. Figure 3 describes, in a simplified scheme, where the gates are placed. A control system was programmed to run the operational mode of the storage system according to the different temperatures registered.

Table 1. Storage technology in active slab

Storage media – PCM	Paraffin RT-21	Manufacturer data
		$T_{PCM} = 18\text{--}23\text{ }^{\circ}\text{C}$
		$h_{PCM} = 134\text{ kJ/kg}$
		Macroencapsulated in aluminium tubes of 115 mm height and 25 mm of diameter.
Target		Heating and cooling/Energy savings

2.3. Instrumentation and control

In order to analyse the thermal behaviour of both cubicles, different data was registered at five minutes intervals:

- Internal wall temperatures (east, west, north, south, roof and floor) measured with Pt-100 DIN B.
- Internal ambient temperature and humidity (at a height of 1.5 m) measured with ELEKTRONIK EE21.
- Electrical consumption of the HVAC systems using an electrical network analyser (MK-30-LCD).

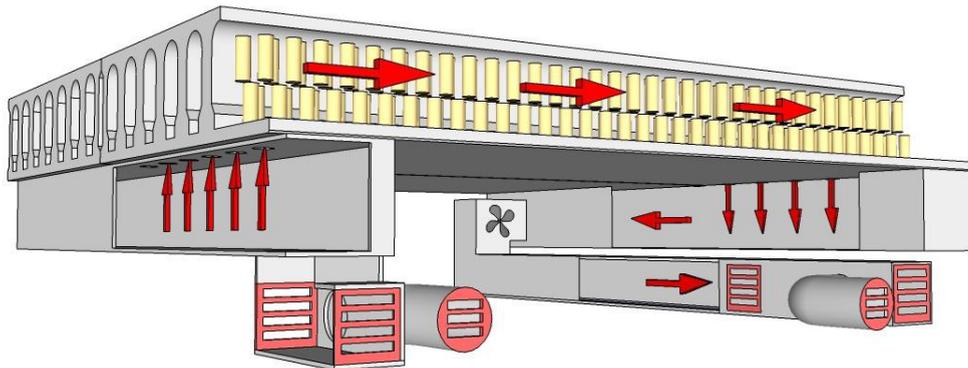


Figure 3. Scheme of the active slab and air duct operation.

Moreover, in order to analyse the thermal response of the active slab with PCM, the following data was measured:

- Air temperature inside the hollow of the slab at the inlet and outlet (Pt-100 DIN A).
- Air velocity of the cavity at different locations (4 hot wire sensors KIMO CTV 210).
- Pressure drop across the cavity (KIMO CP 200).
- Temperature of the PCM at different locations (Pt-100 DIN A inserted in the aluminium tubes).
- Air temperature of the inlet and outlet of the solar air collector (Pt-100 DIN A).

In addition, the weather data was also registered every 5 minutes. Two Middleton Solar pyranometers SK08 were used to capture the horizontal and vertical global solar radiation, the outside air temperature and humidity were measured using an ELEKTRONIK EE21 with a metallic shield to be protected against radiation, and finally the wind speed and direction was provided by a DNA 024 anemometer.

A control system was installed so different operational modes can be executed depending on the weather conditions, the internal ambient, and the internal conditions of the slab.

3. Operational principle

3.1. Winter mode

In the winter season (Figure 4), the system works as a heating supply having stored the solar energy from the solar air collector. During the day time, the PCM is melted and the heat stored in the internal slab is used to cover the heating demand of the cubicle. In order to melt the PCM, a solar air collector is installed in the South facade of the cubicle, where the outside air is heated by the solar radiation and then injected to the inside of the slab. When a heating demand is needed, the air of the internal ambient is pumped through the hollows of the slab and the heat exchange with the PCM provides the heat needed to cover the demand.

Due to the versatility of the system, the heat can be supplied either during the melting process, taking advantage of the temperature of the air at the outlet of the slab, or in later hours using the storage capacity of the PCM in the slab. Furthermore, several cycles of charging and discharging of the PCM could be done during the same day and, therefore, increasing the storage potential of the system.

Moreover, a recirculation mode could be programmed to inject the air coming from the outlet of the slab to the air collector. Thus, the air could achieve a higher temperature and it could provide a good solution for days with low solar radiation values.

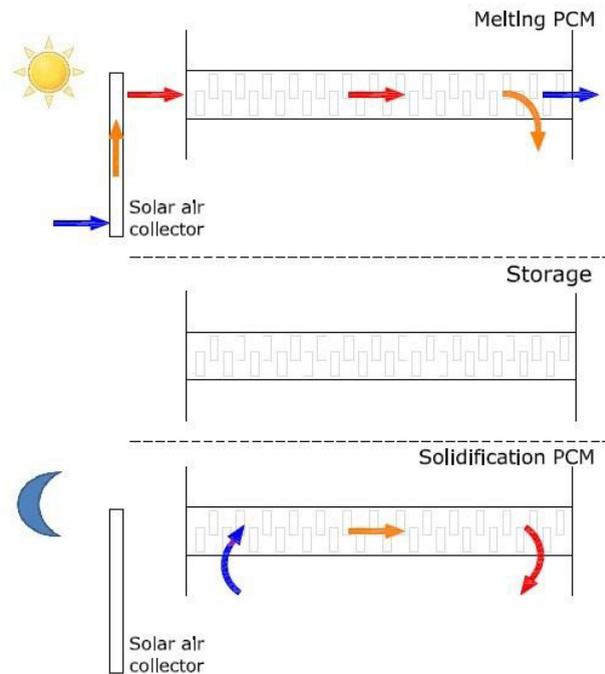


Figure 4. Operating principle of the active slab with PCM during winter.

3.2. Summer mode

On the other hand, the operational mode in the summer season (Figure 5) is based on night free cooling. When the external temperatures are below the phase change temperature (20 °C) the outside air is injected inside the slab and the PCM is solidified. The storage period starts when the temperatures start to rise up and the PCM is completely solidified. During the day, when a cooling demand is needed, the internal ambient air from the cubicle is pumped through the slab and cooled down till 20 °C due to the heat exchange with the PCM, covering part of the cooling loads.

At night and during the solidification process of the PCM, the air could also be used to cool down the internal temperature of the cubicle. Unlike in winter mode, during the summer season the PCM can only provide one cycle of cold storage a day.

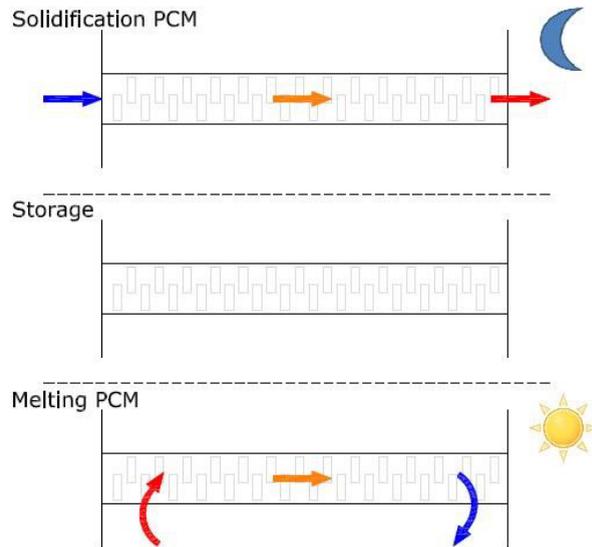


Figure 5. Operating principle of the active slab with PCM during summer.

4. Energy storage capacity

Before starting the experimentation under real conditions, a previous thermal evaluation of the potential of including PCM inside the concrete slab was done. The thermal properties considered in this analysis for the RT-21 (Table 2) were provided from the technical datasheet of Rubitherm.

In a previous work, a ventilated facade with PCM [11] was tested in the same experimental set-up and compared with the same reference cubicle used in this study. The energy consumption from the HVAC system of the whole year was registered for the reference cubicle, and is now used to determine the heating and cooling load required. The climatic conditions defined in section 2 have influence in the energy consumption and the average daily consumption, so different values were distinguished for severe and mild conditions (Table 3).

Table 2. Thermal properties of RT-21.

Typical values for RT-21		
Melting area	°C	18 – 23 (typical being 21°C)
Congeeing area	°C	22 -19 (typical being 22°C)
Heat storage capacity (temperature range 15 °C to 30 °C)	kJ/kg	134
Density solid	kg/l	0.88
Density liquid	kg/l	0.77
Heat conductivity	W/m·K	0.2

In the concrete slab and with the designed distribution, the maximum quantity of PCM that can be put in the aluminium tubs is 49.39 kg. The energy stored in the phase change of the RT-21 was calculated for

winter and summer conditions depending on the ΔT that the PCM is supposed to be subjected to (Table 2).

During the cooling season, a ΔT of 5 °C (from 18 °C to 23 °C) for the PCM was fixed and the energy stored is 1.53 kWh. As seen in Table 3, in a typical mild summer day, the active slab is able to cover and even exceed the energetic demand, while in the severe summer the PCM storage could deal with a 65% of the energy needs.

In the winter period, a theoretical ΔT of 15 °C (from 15 °C to 30 °C) was defined and the latent and sensible energy stored within this thermal gradient is 1.84 kWh. If this value is compared to the energy demand, it just covers 45 % of the daily consumption during mild winter and 21% during severe winter. However, during winter it should be taken into account that the PCM could be melted and solidified more than once in a day having two or even three times the energy described before. Moreover, some direct heating from the air solar collector can also be available, therefore, the PCM may only need to cover a part of the heating load.

Furthermore, the slab used as a storage component is made of concrete which is a material with high thermal inertia. The maximum theoretical energy stored by the concrete slab is estimated and presented in Table 3, but the authors know that this estimation is not realistic, since the ΔT of 15 °C will hardly ever be achieved (having 15 °C in an indoor environment is not realistic).

Table 3. Energy consumption of the cubicle and energy supplied by the PCM.

		Daily heating and cooling loads (kWh/day)	Energy stored by:			PCM Improvement (%)
			PCM (kWh/day)	Concrete slab (kWh/day)	Concrete slab with PCM (kWh/day)	
Winter	mild	4.08	1.84	19.83	21.67	9.27
	severe	8.69	1.84	19.83	21.67	9.27
Summer	mild	0.85	1.53	6.61	8.14	23.20
	severe	2.33	1.53	6.61	8.14	23.20

5. Conclusions

The design of a prefabricated concrete slab with PCM was presented in this paper. The implementation of a thermal storage system inside a building component, as the internal slab in this case, has high potential for energy savings in the HVAC systems. The incorporation of phase change materials would provide more energy storage capacity and would allow the system to be used for cooling and heating purposes.

The energy saved with the active slab was theoretically calculated and the results show an important amount of energy demand covered by the PCM storage. In the summer season, the system can provide 66% of the cooling demand during the severe conditions, while in the mild period the whole energetic demand of the cubicle is covered by the active slab and no cooling devices are needed. On the other hand, in the winter period the results present less energy covered by the PCM storage, 45% during mild conditions and 21% in severe period. However, this energy was calculated for one cycle of melting and solidification, but at least two cycles a day are expected to happen, as well as some direct heating from the air solar collector.

The experimentation under real conditions will be carried out during summer and winter 2013. The energy savings of the active system will be measured and compared with the energy storage capacity calculated in this study.

Acknowledgements

This work was supported by the “Corporación Tecnológica de Andalucía” by means of the project “MECLIDE-Soluciones estructurales con materiales especiales para la climatización diferida de edificios” with the collaboration of DETEA. The work partially funded by the Spanish government (ENE2011-28269-C03-01 and ULLE10-4E-1305). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2009 SGR 534).

References

- [1] Directive 2010/31/eu of the European parliament and of the council of 19 May 2010 on the energy performance of buildings. Available from: <http://www.epbd-ca.eu>.
- [2] A.M. Papadopoulos. State of the art in thermal insulation materials and aims for future developments. *Energy and Buildings* 37-1 (2005) 77-86.
- [3] Spanish building regulation, Código técnico de la Edificación, Documento básico HE ahorro de energía.
- [4] Mandilaras I, Stamatidou M, Katsourinis D, Zannis G, Founti M. Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls. *Building and Environment* 2013;**61**:93-103.
- [5] Cabeza LF, Castellon C, Nogues M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. *Energy Build* 2007;**39**:113–9.
- [6] Alawadhi E.M. Using phase change materials in window shutter to reduce the solar heat gain. *Energy and Buildings* 2012;**47**:421–429.
- [7] Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings* 2010;**42**(4):534-540.
- [8] S. Takeda, Nagano K, Mochida T, Shimakura K. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. *Solar Energy* 2004;**77**:329–338.
- [9] Wang X, Niu J. Performance of cooled-ceiling operating with MPCM slurry. *Energy Conversion and Management* 2009;**50**(3):583–591.
- [10] Koschenz M, Lehmann B. Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. *Energy and Buildings* 2004;**36**:567–578.
- [11] de Gracia A, Navarro L, Castell A, Ruiz-Pardo A, Álvarez S, Cabeza LF. Experimental study of a ventilated facade with PCM during Winter period. *Energy Buildings* 2012; **58**:324-332.