CONTRIBUTIONS to SCIENCE, **3** (4): 501–510 (2007)
Institut d'Estudis Catalans, Barcelona
DOI: 10.2436/20.7010.01.26 ISSN: 1575-6343 **www.cat-science.cat**

research article

Thermal energy storage with phase change materials in building envelopes

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Resum

Els materials de canvi de fase (PCM) han estat considerats per a l'emmagatzematge tèrmic en edificis des de 1980. Amb la inclusió dels PCM en plaques de guix, guix, formigó o altres materials que s'utilitzen per a cobrir les parets, l'emmagatzematge tèrmic pot ser part de les estructures fins i tot en edificis lleugers. Les noves tècniques de microencapsulació han obert moltes possibilitats en aplicacions per a edificis. El treball que es presenta és el desenvolupament d'un formigó innovador mesclat amb PCM microencapsulat, amb un punt de fusió de 26 ºC i una entalpia de canvi de fase de 110 kJ/kg. El primer experiment va ser la inclusió del PCM microencapsulat dins del formigó i la construcció d'una caseta amb aquest nou formigó-PCM. Es va construir una segona caseta al costat de la primera amb les mateixes característiques i orientació però amb formigó convencional que serveix com a referència. Durant els anys 2005 i 2006 es va analitzar el comportament d'ambdues casetes i més tard es va edificar un mur Trombe a la paret sud de totes dues per investigar la seva influència durant la tardor i l'hivern.

Paraules clau: evolvent d'edifici, sistemes de gestió d'energia, emmagatzematge d'energia tèrmica, materials de canvi de fase, microencapsulació

Abstract

Phase change materials (PCM) have been viable for thermal storage in buildings since before 1980. With the advent of gypsum board, plaster, concrete or other wall covering materials containing PCM, thermal storage can be part of the building structure even for lightweight buildings. New microencapsulation techniques offer many possibilities in building applications. The work we present here uses an innovative concrete that contains a commercial microencapsulated PCM with a melting point of 26ºC and a phase change enthalpy of 110 kJ/kg. First we introduced the microencapsulated PCM into the concrete, and then we constructed a small house-sized cubicle from this new PCM-concrete. A second cubicle with the exact same characteristics and orientation, but built from standard concrete, was located next to the first as a reference system. We tested the behaviour of the cubicles in 2005 and 2006. Later, a Trombe wall was added to the cubicles to study its effect during autumn and winter.

Keywords: building envelope, energy managing systems, thermal energy storage, phase change materials, microencapsulation

Energy is becoming one of the most important issues in our society. The shortage of primary energy, the cost of fossil fuels, and environmental concerns are the main factors that have prompted research into new and more efficient energy systems. Thermal energy storage has become a key technology. Storing thermal energy enables supply to be matched to demand even when they do not occur at the same time, and to match different loads of supply and demand.

Thermal energy from any source (renewable or non-renewable) can be stored, but solar energy is most commonly considered [4, 5, 14]. Solar energy is only available for a few hours a day, therefore only thermal energy storage can ensure a continuous supply of this energy source; matching supply and demand. Domestic hot water heated by solar collectors also absorbs the varying power production of the solar collector field over many hours of the day to meet the demand of a hot bath that is filled in only a few minutes.

The thermal energy storage technology usually used today is sensible heat storage, which acts by increasing the temperature of a material such as water or rocks. However, advanced technologies also require an improved energy density, the stabilization of temperatures and improved energy efficiency. This has led to research into other thermal energy storage technologies such as latent heat storage (using phase change materials, PCM) or chemical storage [1, 3, 8, 9, 10, 13]. All heat storage examples could also be described in terms of cold storage.

In this paper, we consider the use of PCM in building envelops. In this application, thermal energy storage is not used to meet an energy demand, but to reduce the energy demand of a building. The construction sector in Spain faces one of its

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biggest ever challenges from the new technical building regulations (*Código Técnico de la Edificación*, CTE), which state that all new buildings must have dramatically decreased energy demands and use solar energy.

The main objective of this paper is to demonstrate the possibility of using microencapsulated PCM in concrete without losing the desirable characteristics of normal concrete, thus achieving high energy savings in cooling power. The inclusion of PCM in the building envelope would influence the thermal gains and losses of the building and also the thermal inertia. Such effects, as with many of the available passive systems, are difficult to predict and control, so we experimented with the effects throughout the year, in different climate conditions. We also studied the effect of ventilation; opening and closing windows at certain times of the day. PCM will only have an effect if the whole cycle takes place, that is, if the PCM solidifies and melts every day. Night ventilation can help this to occur. We further performed modified experiments adding a Trombe wall in front of the south wall. Our results include the increase in the number of hours that the cubicle with PCM is within the comfort zone (defined by the American Society for Heating, Refrigerating and Air-Conditioning Engineers – ASHRAE) compared to a cubicle without PCM.

Figure 1. Micronal PCM.

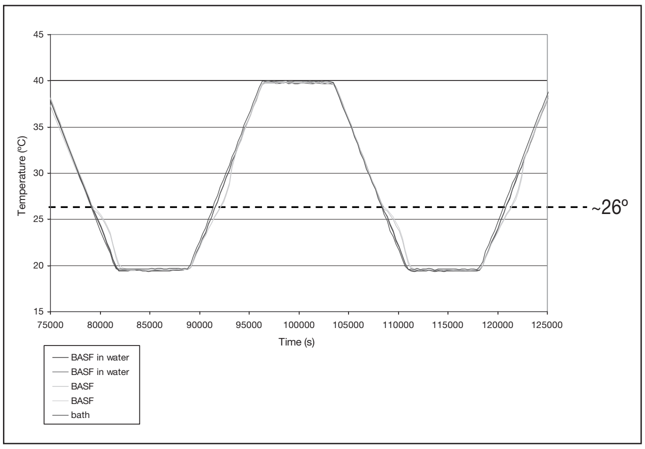

Figure 2. Micronal®PCM, after about 100 cycles.

Materials and method

Materials

In any application of PCM, the election of the material to be used is essential; organic or inorganic. Table 1 shows the advantages and disadvantages of each.

Many materials have been considered as PCM, but only a few are commercially available [15]. The PCM we use here is a commercial microencapsulated PCM called Micronal®PCM (from BASF) with a melting point of 26ºC, and a phase change enthalpy of 110 kJ/kg (Figure 1).

Samples of the microencapsulated PCM were placed in test tubes (some with water, others without) and inserted in a thermostatic water bath programmed to vary between 20ºC and 40ºC. Figure 2 shows the results of temperature versus time for over 100 heating and cooling cycles. No changes were observed in the behaviour of the microencapsulated PCM. The melting point clearly appears at ~26ºC for the samples without added water, but no phase change was seen for the PCM with water. It is important for the designer (engineer and/or architect) to select a PCM with a suitable melting temperature from the materials available, and one that has a melting enthalpy that is as high as possible. It is therefore very important to use a reliable method for testing these properties. Differential scanning calorimetry (DSC) and the T-history method are normally used [11, 16].

The microencapsulated PCM we used was analyzed by DSC. DSC determines the amount of heat absorbed by a sample upon temperature change [6]. The evolution of the temper-

Table 1. Comparison of organic and inorganic materials for heat storage

	Organic	*Inorganic*
Advantages	Not corrosive Low or no undercooling Chemical stability	Greater phase change enthalpy
Disadvantages	Lower phase change enthalpy Low thermal conductivity Inflammability	Undercooling Corrosion Phase separation

Table 2. Melting point (ºC) results obtained with DSC at different heating/cooling rates and different sample masses

Heating rate	*0.2[ºC/min]*		*0.5[ºC/min]*		*2[ºC/min]*		*5[ºC/min]*	
	5 mg	10 mg	5 mg	10 mg	5 mg	10 mg	5 mg	10 mg
Micronal	25.64	25.32	25.26	25.24	25.36	25.37	25.49	25.45
Micronal cycled 100 times	25.84	–	25.31	–	25.38	–	25.46	

Table 3. Density values of concrete with and without PCM

Sample	*Weight* *kg*	*Weight average* *kg*	*Volume* m^3	*Density* kg /m^3
With PCM	1.0885	1.07385	5.28*10-4	2030.44
	1.0592			
Without PCM	1.2386	1.2486	5.28*10-4	2360.86
	1.2586			

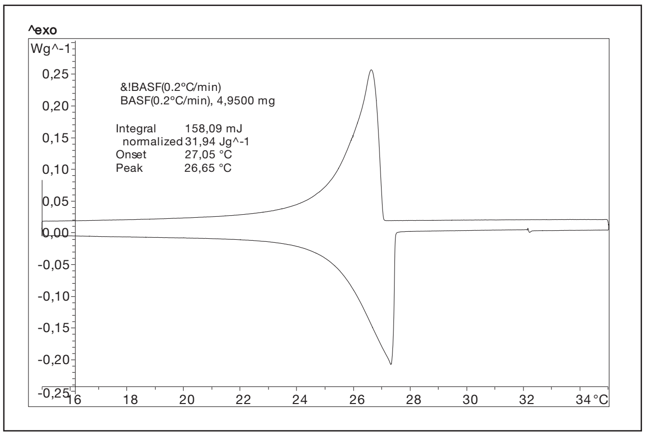

Figure 3. DSC graph for the Micronal®PCM.

Figure 4. Compressive strength of the PCM-concrete.

ature of the sample in a furnace is compared to that of a reference system in a symmetric position. We took measurements for different sample masses (5 mg and 10 mg) and different heating/cooling rates. The melting point of the samples was determined before and after the experiments. Figure 3 and Table 2 show the DSC melting point results. Changing the sample mass hardly affects the results. The PCM results before and after the experiments were as expected.

The innovative PCM-concrete [2, 12] was found to reach a compressive strength of over 25 MPa and a tensile splitting strength of over 6 MPa (after 28 days) (Figure 4). These values are appropriate for structural purposes and other tested properties show that a real use of this new concrete is possible.

One important parameter is the density of the concrete used in the experiments. This allows us to calculate the amount of PCM in the concrete, but furthermore, using the real density in the simulations produces more reliable results. To measure the density of the concrete, two cylindrical samples were taken from each cubicle. To minimize disturbance, the samples were taken from the north side of the roof. The samples were weighed and the volume measured, and the densities calculated (Table 3). The new PCM-concrete had a density 14% lower than the reference concrete. This may be due to air trapped in the concrete, but it is most probably due to the amount of PCM in the concrete, which we calculated as about 5% wt.

Experimental set-up

We built two identically-shaped concrete cubicles; one with conventional concrete, the other with the modified PCM-concrete. The cubicles were designed with the help of the Transient Energy System Simulation tool (TRNSYS) using the Type (program module) developed by the authors for such applications, and validated in the laboratory [7]. Each consisted of the union of six concrete panels and they were apparently identical. One of them contained about 5% (by weight) PCM mixed in with the concrete in three of the six panels: the south and west walls, and the roof (Figure 5). The cubicles were 2.6 x 2.6 x 2.5 m. The walls were 0.12 m thick. The openings were distributed as follows: one, 1.7 x 0.6 m window in each of the east and west walls, four

Figure 5. View of the cubicles.

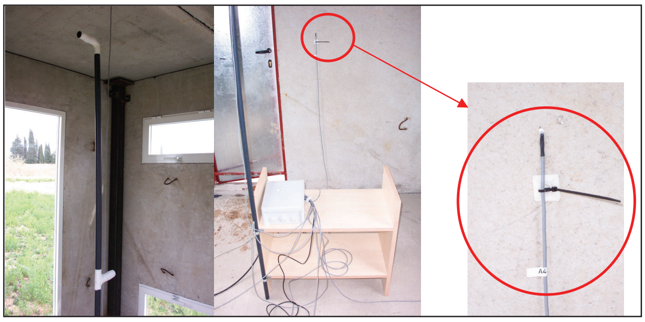

Figure 6. Instrumentation inside the cubicles.

Figure 7. Meteorological station.

Figure 8. View of the cubicles with Trombe wall.

0.75 x 0.4 m windows in the south wall and a door in the north wall. No insulation was added, to test only the effect of the PCM.

The cubicles were fitted with temperature sensors on the inner side of every wall, as well as one on the outer side of the south wall and sensors in the middle of the room at heights of 1.2 m and 2.0 m. A heat flux sensor was installed on the inside of the south wall (Figure 6). A meteorological station was installed nearby (Figure 7) to measure outdoor temperature and wind speed. Furthermore, a radiation sensor was set on top of each cubicle, providing sunshine measurements and the amount of shade for each one. All the instrumentation was connected to a computer via a data logger.

In autumn, when the outdoor daytime temperature is lower than the melting point of the PCM, a Trombe wall was added to the cubicles (Figure 8). It consisted of covering the outside of the south wall with glazing. Sunlight passing through the glazing generates heat. The temperature of the air between the glazing and the south wall was measured with a temperature sensor. This warm air could be channelled by natural convection into the cubicle to allow the use of the PCM over a longer period.

Experiments performed

Initial experiments

The first experiments were performed in summer 2005. The following sequences were performed:

- **Case 1. Windows closed** all day
- **Case 2. Windows open** all day (only the windows in the south wall could be opened)
- **Case 3. Free cooling**: windows open at night, closed during the day.

Each experiment was performed for a week. Temperature differences of up to 4ºC were observed between the two cubicles and peak temperatures in the PCM cubicle were reached later due to the increased thermal inertia. This thermal inertia is apparent early in the morning due to the solidification of the PCM, and during the afternoon, due to it melting.

Further experiments

During 2006 the following experimental sequences were also carried out:

- **Case 4. Free cooling**: windows open at night, closed during the day.
- **Case 5. Windows open** all day (only the windows in the south wall could be opened).
- **Case 6. Windows closed** all day.

They were the same as in summer 2005 in order to compare the results.

Trombe wall

In autumn 2006 a Trombe wall was added to the cubicles (south wall) and the measurements followed the same sequence as in summer 2006.

- **Case 7. Free heating** windows open during the day (only the windows in the south wall could be opened) and closed at night.
- **Case 8. Windows open** all day (only the windows in the south wall could be opened).
- **Case 9. Windows closed** all day.

Thermal Comfort Analysis

To quantify the results from the experiments without the Trombe wall, we evaluated the thermal comfort of the cubicles at different moments. The thermal comfort analysis is performed by calculating the operative temperature [ASHRAE]:

$$t_o = \frac{h_r \cdot t_{rm} + h_c \cdot t_a}{h_r + h_c} \qquad \text{Eq. 1}$$

Table 4. Percentage of time within the comfort zone

Month	*Case*	*Percentage of the time within the comfort zone, cubicle with PCM*	*Percentage of the time within the comfort zone, cubicle without PCM*
April 2006	Windows closed – Case 6	36%	28%
July 2006	Free cooling – Case 4	24%	23%
July 2006	Windows open – Case 5	27%	25%

where t_o is the operative temperature, h_r is the linear radiative heat transfer coefficient, h_c is the convective heat transfer coefficient, t_{rm} is the mean radiant temperature, and t_a is the ambient air temperature.

Results

Initial results

The first results from the field tests were obtained from March 23rd to April 1st, 2005. Figure 9 shows that the temperature of the south wall of the cubicle without PCM was 2ºC higher at midday than that of the cubicle with PCM. This means that the PCM acts as insulation.

Measurements were taken with the windows of the cubicles closed (case 1). Figure 10 shows the temperature over two weeks for the walls containing PCM in one of the cubicles. Differences between the two cubicles are evident. These temperature differences offer the opportunity of saving energy and of maintaining the comfort temperature for a longer period.

To provide more details, the measurements for the south wall over two days are presented in Figure 11. This illustrates three important points:

- The maximum temperature of the cubicle without PCM is 1ºC higher than that of the cubicle with PCM, and its minimum temperature is 2ºC lower.
- The maximum temperature of the wall containing PCM appears about 2 hours later than that of the corresponding wall without PCM: the thermal inertia of the PCM wall is higher.
- The thermal inertia appears in the afternoon due to the melting of the PCM, but also earlier in the morning due to it solidifying.

The effect of thermal inertia is very interesting in commercial buildings, such as office buildings. A delay of 2 hours in the heat peak would mean a decrease in the electrical consumption due to air conditioning.

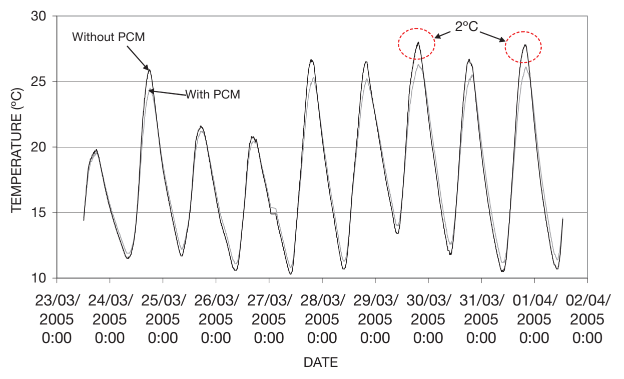

Figure 9. Temperature of south wall in both cubicles.

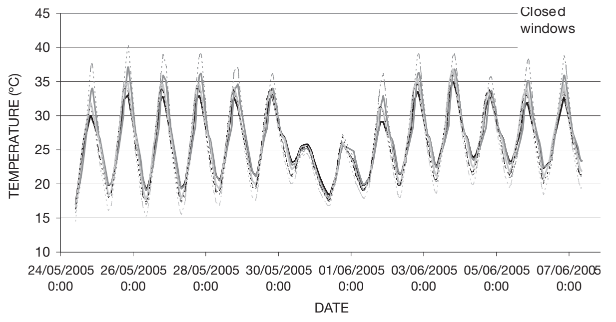

Figure 10. Temperature of the walls with and without PCM (south, west and roof walls) over two weeks. Windows closed (case 1).

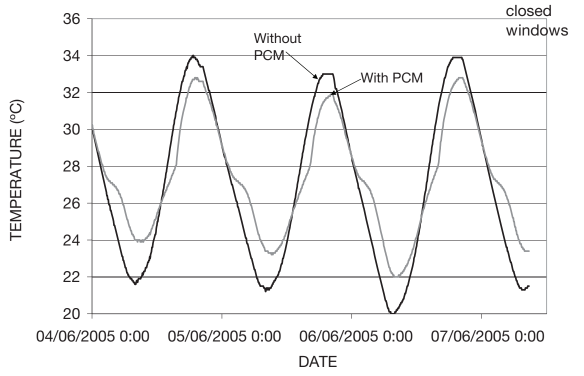

Figure 11. Detail of the temperature of the south wall with windows closed (case 1).

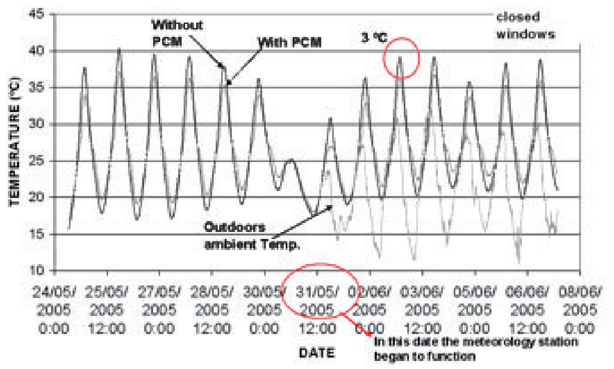

Figure 12. Comparison between west wall temperature in both cubicles and outdoor ambient temperature. Windows closed (case 1).

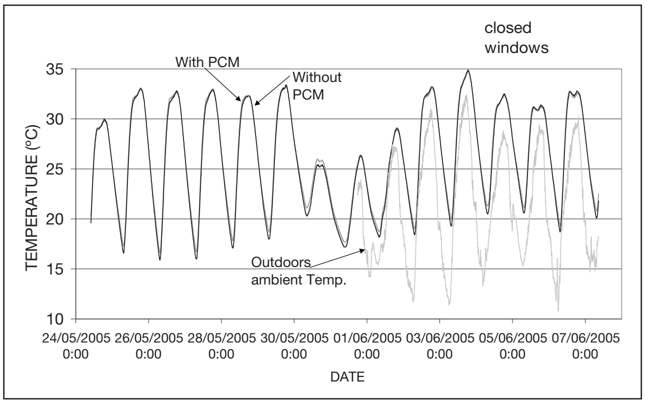

Figure 13. Comparison between east wall temperature in both cubicles and outdoor temperature. Windows closed (case 1).

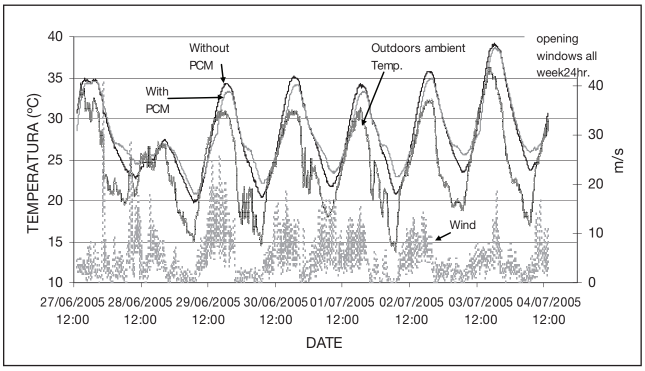

Figure 14. Comparison between south wall temperature in both cubicles, outdoor ambient temperature, and outdoor wind. Windows open (case 2), June 2005.

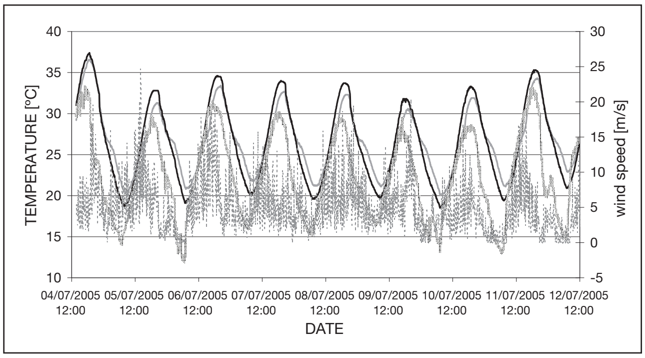

Figure 15. Comparison between south wall temperature in both cubicles, outdoor ambient temperature, and outdoor wind. Free cooling (case 3).

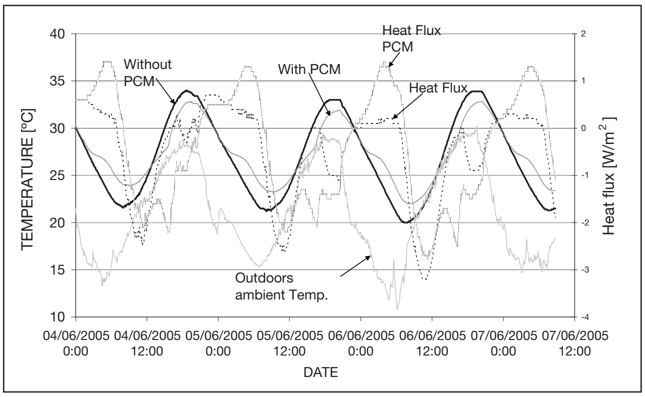

Figure 16. Comparison between south wall temperature in both cubicles, outdoor ambient temperature, and heat flux. Windows closed (case 1).

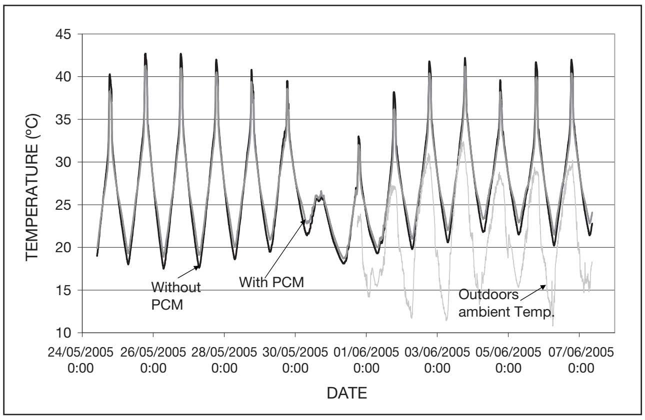

Figure 17. Comparison between indoor temperature at 1.2 m height in both cubicles and outdoor ambient temperature. Windows closed (case 1).

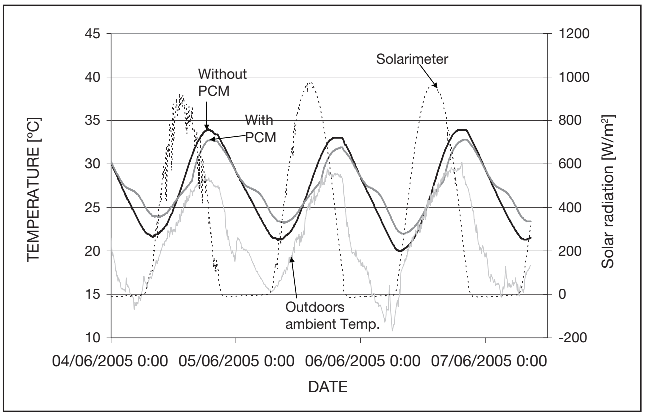

Figure 18. Comparison between south wall temperature in both cubicles, outdoor ambient temperature, and solarimeter signal. Windows closed.

Figure 12 shows that while the maximum outdoor temperature was 32ºC, the west wall of the cubicle without PCM reached 39ºC, and the west wall of the cubicle with PCM reached only 36ºC. This difference can also be seen in the minimum temperatures. The temperature difference between day and night is so high because the cubicles had no insulation. Figure 13 confirms the reproducibility of the measurements in the cubicles, since the east wall does not contain PCM in either cubicle. Figure 14 shows the results for case 2, and case 3 (where the outdoor cold is accumulated during the night and released indoors during the day) is reflected in Figure 15.

The measurements of heat flux in the south wall, outdoor wind speed and solar irradiation are presented in Figure 16. As expected, the heat flux shows the same tendency in both cubicles when the PCM is out of its melting/solidifying zone, but changes its tendency totally when there is a phase change. That is, the heat flux increases in the morning when the cubicle walls heat up. As soon as the wall with PCM reaches the melting temperature and the temperature shows the plateau of the phase change, the heat flux decreases drastically, and increases again when the phase change finishes. The heat flux decreases again when the walls are at their maximum temperature and increases again when they start to cool down (negative flux). However, as soon as the wall with PCM reaches the melting temperature, the heat flux increases much more in this wall. As soon as the phase change finishes, the heat flux decreases similarly in both cubicles.

In these experiments the indoor temperature always showed a peak of 5ºC at noon. However, this peak was due to the sun shining directly on the sensor (Figure 17).

Finally, the south wall temperatures in both cubicles were compared with the solarimeter signal. With consistent solar irradiation, and therefore, consistent outdoor ambient temperature, the temperatures measured in the south wall of the cubicles were also very consistent (Figure 18).

Further experiments

The results were different for each of cases 4, 5 and 6. The best option was free cooling (case 4) because having the windows open during the night helped the PCM complete its melting-solidification cycle. When comparing cases, it is important to take into account different parameters, such as solar radiation and outdoor temperature.

Figure 19 shows the solar radiation and outdoor temperature on two different days in summer 2006: July 5th and July 28th. Outdoor conditions were similar; maximum temperatures around 31ºC and minimums around 17ºC, and maximum solar radiation of around 900 W/m^2.

The temperatures in the south wall of the standard cubicle and the cubicle with PCM for case 4 (free cooling) and case 5 (open windows) are shown in Figure 20. Case 4 is preferable to case 5, since the maximum temperatures reached in case 4 (free cooling) were 33.5ºC (south wall of the cubicle without PCM) and 32ºC (south wall of the cubicle with PCM) both of which are lower than in case 5 (open windows); 36.5ºC and 35.5ºC, respectively. Due to the increased thermal inertia of the PCM-concrete, the walls containing PCM show a delay in their maximum and minimum temperatures of 2 hours (case 5) and 3 hours (case 4). Night-time ventilation facilitates the solidification of the PCM in both cases. Minimum south wall temperatures of 22 ºC (case 5) and 23 ºC (case 4) were reached; well below the melting point of the PCM used (26 ºC).

Figure 21 shows the temperature of the east wall in both cubicles. Neither of these walls contained PCM. Practically the same temperatures were recorded in the two cubicles, demonstarting that the higher thermal inertia and phase change zone observed in the south walls were in fact due to the inclusion of the PCM in the concrete.

One can see that during the afternoon (maximum temperature peaks) for case 6 (windows closed) there is no temperature difference between the two cubicles (Figure 22), whereas in the other cases (windows open or free-cooling) the cubicle with PCM always reached a lower temperature than the cubicle without PCM. However, during the morning (minimun temperatures) the temperature of the cubicle with PCM is not as low as that of the cubicle without PCM. This highlights the importance of night ventilation in summer to achieve complete PCM cycles. Having the windows closed at night prevents the wall from cooling down below the melting point of the PCM and so the next day the PCM has no effect as it is already liquid.

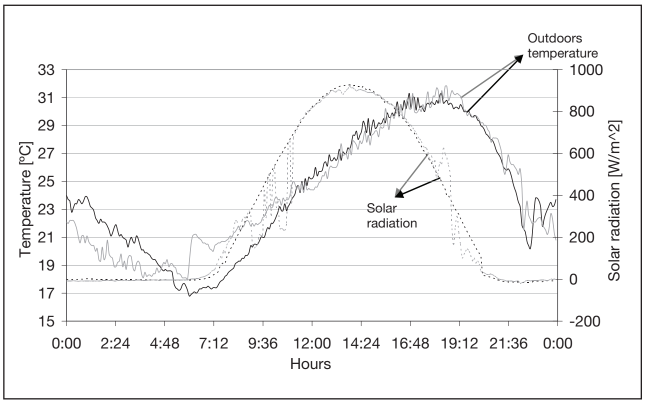

Figure 19. Two different days (05-07-2006 and 28-07-2006) with similar solar radiation and similar outdoor temperature.

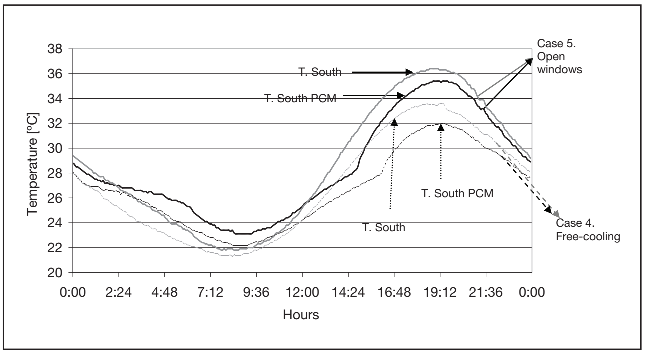

Figure 20. Comparison of the south wall temperatures (with and without PCM).Two different days 05-07-2006 and 28-07-2006; case 4 and case 5 respectively.

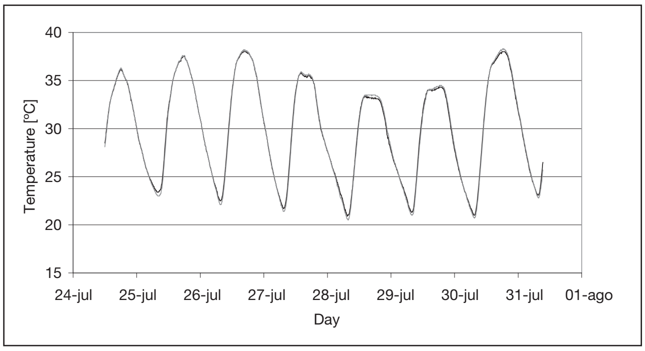

Figure 21. Temperature of the east wall in both cubicles. July 2006.

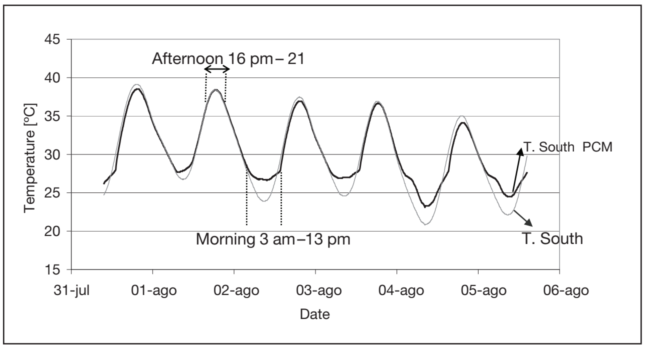

Figure 22. Temperature of the south wall (windows closed – case 6). August 2006.

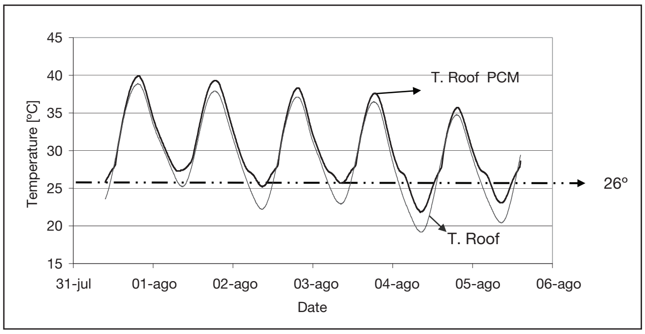

Figure 23. Temperature of the roof (windows closed – case 6). August 2006 .

In the roof (Figure 23) where wind effects are less important, the cubicle with PCM has an even higher temperature than the one without PCM, illustrating the fact that the molten PCM has lower thermal inertia than the concrete it replaces. Partial melting and/or wind effects may have hidden this fact in the south wall. Again, the importance of opening windows in hot summer nights is observed.

Experiments including a Trombe wall

Figure 24 shows the results for the south wall and the outdoor temperature for free heating (case 7). These experiments have not proved very successful, because the cubicle with PCM and a Trombe wall reached a lower temperature than the cubicle without PCM. Given adequate weather conditions, we expect to see different results.

Figure 25 shows the temperature of the south wall and the outdoor temperature for a given period of time, with windows closed in autumn. The outdoor temperatures are below 26ºC in Lleida, but with the Trombe wall it was posible to reach temperatures of up to 26ºC in the south wall and the effect of the PCM can be observced.

To study the effect of the Trombe wall and the PCM we compared the measurements for the cubicles with and without PCM on different days with similar climate data. Figure 26 shows case 8 and case 9 with similar weather data; outdoor temperatures of 24ºC max. and 11ºC min. and maximum solar radiation around 700 W/m^2. Case 9 (windows closed) was more effective, with the temperatures of the walls higher, than case 8.

Figure 27 shows the temperature inside the cubicle at a height of 1.2 m for the same comparison (case 8 with case 9) and corroborates the conclusions drawn from Figure 26; if the walls are reaching higher temperatures (case 9) the ambient temperature of the cubicles is higher too.

Results of the thermal comfort analysis

Table 3 shows the results at different times of the year for both cubicles with no Trombe wall. During winter the PCM-concrete has no effect on the operative temperature. However, from April to November the addition of PCM has a positive effect increasing the comfort time inside of the cubicle.

Conclusions

The objective of this work was to demonstrate that the use of microencapsulated PCM in concrete can produce high energy savings in buildings. The work we present here involves the experimental installation of two real-size concrete cubicles to study the effect of the inclusion of a PCM with a melting point of 26ºC, and a phase change enthalpy of 110 kJ/kg .

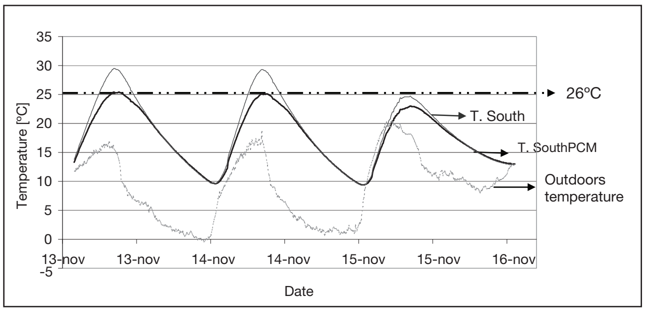

Figure 24. Temperatures of the south wall and outdoor temperatures with Trombe wall (free-heating – case 7). November 2006.

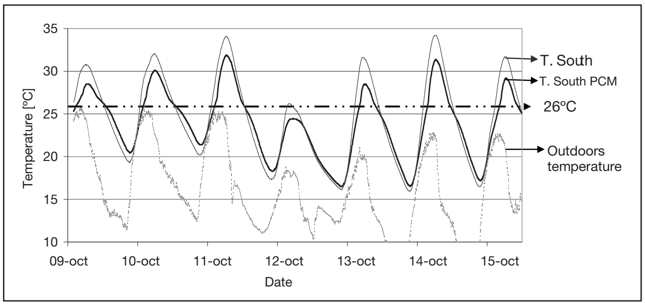

Figure 25. Temperatures of the south wall and outdoor temperatures with Trombe wall (windows closed – case 9). October 2006.

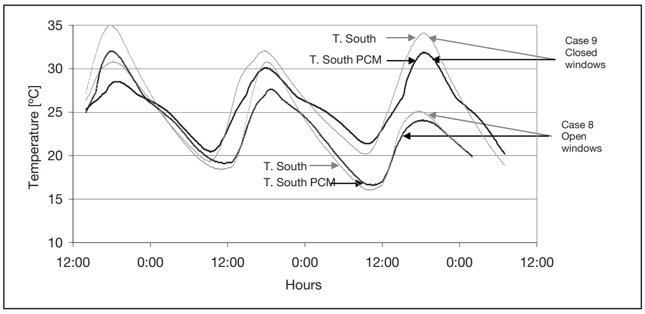

Figure 26. Comparison between south walls in different cases. Case 9 windows closed (9-12/10/2006) and case 8 windows open (27-29/10/2006), both with Trombe wall.

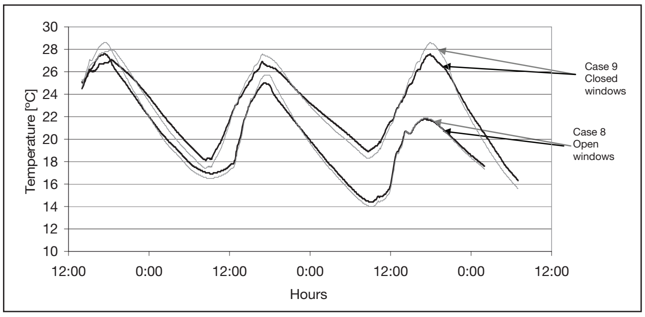

Figure 27. Ambient temperature inside the cubicle at 1.2 m. Case 9 windows closed (9-12/10/2006) and case 8 windows open (27-29/10/2006), both with Trombe wall.

Accurate knowledge of the thermophysical properties of the PCM is crucial for the correct design of commercial products; therefore, different thermal and mechanical properties were tested with the microencapsulated PCM alone and with concrete-PCM mixture.

Our results demostarte energy storage in walls by encapsulated PCM compared to standard concrete without PCM. The cubicle with PCM:

- had higher thermal inertia than the reference cubicle,
- reached peak temperatures about 2 hours later than the cubicle without PCM,
- showed the effects of increased thermal inertia early in the morning (due to the PCM solidifying) and during the afternoon (due to the PCM melting).

Our results show different ways of saving energy, adding only PCM and using a Trombe wall to benefit from the PCM over a longer period of time.

We conclude that all the different cases studied in the experiments had their advantages and disadvantages, depending on the month or season. For typical continental climates, such as those of Lleida or Madrid (Spain), we can recommend a sequence of conditions to take advantage of the increased thermal inertia of the PCM and to achieve better thermal comfort inside the cubicle throughout the year. From April to June it is better to have the Trombe wall installed, thus reaching higher temperatures and activating the PCM. In April and May it is best to have the windows closed, and to adopt the free-heating case, and to have the windows open in June. The Trombe wall should be removed for July, and the free-cooling case adopted, because the change in temperatures between June and July in Lleida is very important. August is a difficult month in Lleida due to the very high peak temperatures (around 40ºC). So, the best option for both cubicles is the free-cooling case. However, the PCM is not promising, since it cannot be solidified most days of the month. In September, our suggestion is to apply free cooling during the first 15 days, and to use the case with the windows closed the other 15 days, due to the significant decrease in ambient temperatures in the second half of the month. October is a good month for installing the Trombe wall and it should be used until November or December with the windows closed. We are still analysing the best option for the winter months.

Acknowledgements

The authors wish to acknowledge the contribution of all the partners of the MOPCON project (EU CRAFT ref. G5ST-CT-2002-50331): Aspica Constructora (coordinator, Spain), University of Lleida (Spain), Inasmet (Spain), BSA (Spain), Medysys (France), Prokel (Greece), and Intron (The Netherlands).

The work was partially funded by the project ENE2005-08256-C02-01/ALT (Ministerio de Educación y Ciencia). M. Medrano would like to thank the Spanish Ministry of Education and Science for his *Ramon y Cajal* research appointment.

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