Use of Microencapsulated Phase Change Materials in Building Applications

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ABSTRACT

Phase Change Materials (PCMs) have been considered for thermal storage in buildings since before 1980. In the literature, development and testing were conducted for prototypes of PCM wallboard and PCM concrete systems to enhance the thermal energy storage (TES) capacity of standard gypsum wallboard and concrete blocks, with particular interest in peak load shifting and solar energy utilization.

The idea studied here was to integrate a PCM in construction materials and test them in real buildings to check improvements in thermal performance. The first experiment was the inclusion of a microencapsulated PCM in concrete and the construction of a small house-sized cubicle with this new PCM-concrete. A second cubicle with the exact same characteristics and orientation, but built with standard concrete, was located next to the first one as the reference case. The thermal behavior of such cubicles was tested during the years 2005 and 2006. In autumn 2006 a Trombe wall was added in both cubicles and its influence was investigated. The results were very good, since temperature differences up to 4ºC were observed between both cubicles and peak temperatures in the PCM cubicle were shifted to later hours

INTRODUCTION

Phase Change Materials (PCMs) have been considered for thermal storage in buildings since before 1980. With the advent of PCM implemented in gypsum board, plaster, concrete or other wall covering materials, thermal storage can be part of the building structure even for light weight buildings. In the literature, development and testing were conducted for prototypes of PCM wallboard and PCM concrete systems to enhance the thermal energy storage (TES) capacity of standard gypsum wallboard and concrete blocks, with particular interest in peak load shifting and solar energy utilization.

During the last 20 years, several forms of bulk encapsulated phase change materials were marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial products was inadequate to deliver heat to the building after the PCM was melted by direct solar radiation. In contrast, the walls and ceilings of a building offer large areas for passive heat transfer within every zone of the building [Neeper 2000]. Several researchers have investigated methods for impregnating gypsum wallboard and other architectural materials with phase change materials [Salyer et al. 1985, Shapiro et al. 1987, Babich et al. 1994 and Banu et al. 1998]. Different types of PCMs and their characteristics are described. The manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which have been impregnated with phase change materials have been presented and discussed previously [Kudhair and Farid 2004, Zalba et al. 2003 and Hauer et al. 2005].

The PCM must be encapsulated so that it does not adversely affect the function of the construction material. Previous experiments with large volume containment or macro-encapsulation failed due to the poor conductivity of the phase change material. When it was time to regain the heat from the liquid phase, the PCM solidified around the edges and prevented effective heat transfer. With microencapsula-

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tion, the dimensions are so small that this effect does not occur. Microencapsulation also allows the phase change materials to be incorporated simply and economically into conventional construction materials [ISE 2002]. This has been studied by several researchers [Brown et al. 1998, Hawlader et al. 2003] and developed by companies like BASF [Jahns 1999, Schossig et al. 2003]. Both methods of PCM encapsulation in concrete (micro- and macroencapsulation) may have some drawbacks. Plastic or metallic encapsulation of the phase change material is expensive but safe, as the PCM is considered as a individual concrete aggregate, not adversely influencing its primarily functions. Microencapsulation by impregnating the phase change materials in the fresh concrete is very effective, but it may affect the mechanical strength of the concrete as well as it may lead to bleeding during the melting phase of the PCM.

The main objective of this paper is to demonstrate the possibility of using microencapsulated PCM in concrete without loosing any of the concrete initial characteristics, achieving high energy savings in cooling power. The inclusion of PCM in the buildings envelope would influence in thermal gains and losses of the building and also in the thermal inertia. Such a effect, as many of the available passive systems, is difficult to predict and control, so the authors have been experimentally investigating the effects all over the year, during different climate conditions. The effect of ventilation was studied as well, opening and closing windows at a certain time of the day. It should be reminded that the effect of PCM will only be present if the whole cycle takes place, that is, if the PCM is frozen and melted every day. Night ventilation can help in this regard.

EXPERIMENTAL SETUP

The study investigates the inclusion of PCM in concrete, This modified concreted (from now on called PCM-concrete) was then used to build one of the two identically shaped cubicles. The other cubicle was built with conventional concrete for reference [Cabeza et al. 2007]. The cubicles were designed with the help of TRNSYS using the Type developed by the authors for such application, and validated in the laboratory [Ibañez et al. 2005].

The PCM used was a commercial microencapsulated PCM called Micronal®PCM (from BASF) with a melting point of 26ºC, and a phase change enthalpy of 110 kJ/kg. Its mixture and inclusion in the concrete was developed within the European project called MOPCON (2003-2006) and the mechanical strength and thermal behavior was tested [Leppers 2005]. It was found out that the PCM-concrete reaches a compressive strength over 25 MPa and a tensile strength at break over 6 MPa (after 28 days). These values open the opportunity for structural purposes. Also other properties tested give rise to the conclusion that a real use of this new concrete is possible.

The panels for the cubicles were built in Greece, mechanical and thermal tests to evaluate walls behavior were performed in The Netherlands and Spain, and finally they were located in an open area in the countryside, one next to each other, in Puigverd de Lleida (Spain). Lleida represents a typical continental climate in Spain, similar to the one in Madrid, with cold winters and hot and relatively dry summers, and with important daily temperature oscillations between day and night.

The cubicles are apparently identical, built with the union of six concrete panels, but one of them contains about 5% in weight of phase change material mixed with the concrete in three panels (South and West walls and roof) (Figure 1). The dimensions of the cubicles including the envelope thickness are 2.64 x 2.64 x 2.52 m. The panels have a thickness of 0.12 m; the distribution of the windows are the following: one window of 1.7 x 0.6 m at the East and West walls, four windows of 0.75 x 0.4 m at the South wall and a door in the North wall. Only the South wall windows can be opened. It should be highlighted that the cubicles are not insulated, since the initial objective was to test the effect of the PCM alone.

The cubicles were fully instrumented to monitor and evaluate the thermal characteristics: temperature sensors (PT100) in the internal surface of each wall, temperature sensors (PT100) in the middle of the room at a height at 1.2 m and 2.0 m and one heat flux sensor (HUKSFLUX HFP01, with a precision of ± 5%) in the internal surface of the South wall. A meteorological station was installed nearby; this meteorological station measured outdoor temperature and wind speed. Also one irradiation sensor was set on top of each cubicle, giving the irradiation measures, and the possibility of shadows in each one. All the instrumentation is connected to a data logger connected to a computer to work with the data obtained.

During autumn a Trombe wall was added to the cubicles (south wall) with the idea of increasing the wall temperature and activating the PCM effect also in the winter season. A temperature sensor outside of the South surface was connected to investigate the influence of the Trombe wall.

RESULTS

First Results

During the last two years (2005-2006), the behaviour of such cubicles was tested. The results were very good during both summers, since temperatures differences up to 4ºC were observed between both cubicles. Also, the reference cubicle achieved the same temperature as the peak temperature of the PCM cubicle (36 ºC) about 2 hours earlier. In Figure 2 it can be seen that in a given day while the maximum outdoors temperature was 31ºC, the west wall of the cubicle without PCM reached 39ºC, and the west wall of the cubicle with PCM reached only 36ºC, showing a temperature difference of 3ºC. This difference could also be seen in the minimum temperatures where there was a 2ºC difference.

The cubicle with PCM showed higher thermal inertia than the reference cubicle, since as explained above, a given temperature is reached about 2 hours later in the cubicle with PCM than in the cubicle without PCM. This thermal inertia

Figure 1 *View of the concrete cubicles.*

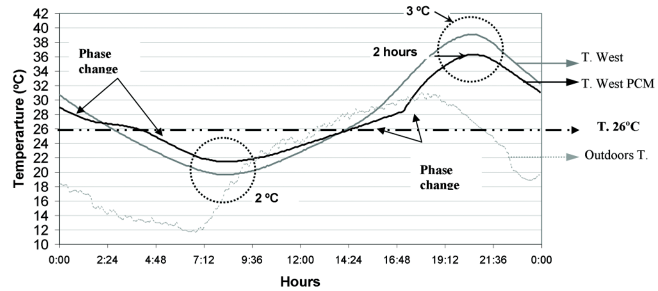

Figure 2 *Outside temperature and temperature of the west wall with and without PCM with closed windows tests in July 2005.*

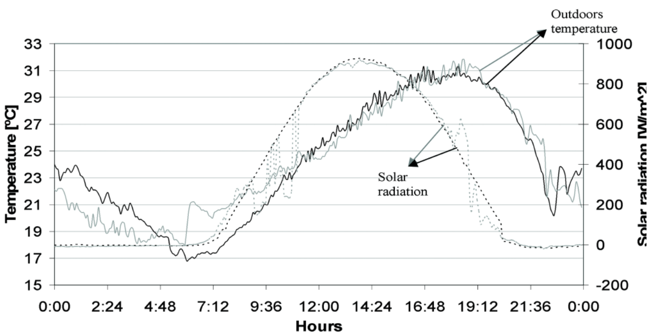

Figure 3 *Two different days (05/07/2006 and 28/07/2006) with similar solar radiation and similar outdoor temperatures.*

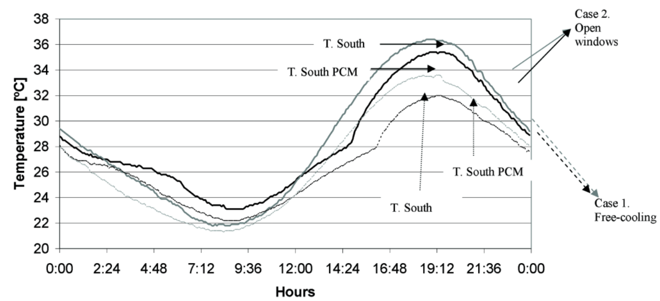

Figure 4 *Comparison of the south wall temperature (with and without PCM) on two different days, 05/07/2006 and 28/07/2006 (Cases 1 and 2, respectively).*

appears early in the morning due to freezing of the PCM and during the afternoon due to the melting of the PCM

Further Experiments

In order to have a real simulation of a building, a sequence of experiments was performed. The analysis of each case has been done for one week each time. The experiments were:

- *Case 1 (free cooling)*: Open windows at night, closed during the day
- *Case 2:* Open windows all day (Only the south wall windows can be opened.)
- *Case 3:* Closed windows all day

In every experiment the results were different, but the better option was the free cooling case, because opening the windows during the night helped the PCM to do its melting-solidification cycle. But for a good comparison between cases it is important to take into account different parameters, such as solar radiation and outdoors temperature.

Figure 3 shows the comparison of the solar radiation and outdoors temperature between two different days of the summer 2006, July 5th compared with July 28th. Both days have the similar outdoor conditions, namely maximum temperatures around 31ºC and minimum around 17ºC, and maximum solar radiation around 900 W/m^2.

The measured temperatures in the south wall of the standard cubicle and the cubicle with PCM here for case 1 (free cooling) and case 2 (open windows) are shown in Figure 4. It can be seen that case 1 is more favorable than case 2 since the maximum temperature reached in case 1 (free cooling) was 33.5ºC (south wall of the cubicle without PCM) and 32ºC (south wall of the cubicle with PCM) and were lower compared to the temperatures of case 2 (open windows), which were 36.5ºC and 35.5ºC, respectively. Due to the higher thermal inertia of the PCM-concrete, the walls with PCM show a delay in its maximum and minimum temperatures of 2 hours (case 2) and 3 hours (Case 1). It is important to highlight also that the night ventilation in both cases facilitate the freezing of the PCM. Minimum south wall temperatures of 22 ºC (Case 2) and 23 ºC (Case 1) are achieved, well below the melting point of the PCM used (26 ºC).

In order to check that all the effects seen (higher thermal inertia, phase change zone) are due to the inclusion of the PCM in the concrete, Figure 5 shows the comparison of the east wall in both cubicles, walls that never contained PCM, where practically the same temperatures were obtained for the same period of time.

Comparing case 3 (closed windows) with the other cases (open windows or free-cooling), one can see that during the afternoon (maximum temperature peaks) case 3 does not presents temperature differences between both cubicles (Figure 6), while in the other cases the cubicle with PCM always reached lower temperature than the cubicle without PCM. On the other hand, during the morning (minimum temperature valley in the plots) the experiments in this case shows the same behavior as before, that is, the temperature of the cubicle with PCM is not as low as the cubicle without PCM. This comparison highlights the importance of night ventilation in summer to achieve complete PCM cycles. Closing windows at night prevents the wall from cooling down below the melting point of the PCM and the next day the PCM does not show any effect as it is already melted.

In the roof (Figure 7), where wind effects are less important, the cubicle with PCM shows even a higher temperature than the one without PCM, illustrating the fact that the melted PCM has lower thermal inertial than the replaced concrete. A slight partial melting and/or the wind effect may have hidden this fact in the south wall.,Again, the importance of opening windows in hot summer nights is observed.

Trombe Wall

During autumn 2006 a Trombe wall was added to the cubicles covering all the south wall with glass spaced 10 cm apart from the wall (Figure 8). Solar radiation passes through the glass and is absorbed and stored by the wall. The same cases as before (changing the sequence of the case 4) were investigated:

- *Case 4 (free heating):* Open windows during the day, closed at night
- *Case 5:* Open windows all day (Only the south wall windows can be opened.)
- *Case 6:* Closed windows all day

The main idea was to see if it is possible to gain heat in the south wall and to reach the melting temperature of the PCM when the outdoors temperature is lower than the melting point of the PCM, and therefore, to take advantage of the PCM in a longer period of time.

Figure 9 shows the results of the experiment of the south wall and outdoors temperature for a free-heating case. Up to now, these experiments were not very successful, because the cubicle with PCM and Trombe wall reached lower temperature than the cubicle without PCM. The authors expect other results given the right weather conditions.

Figure 10 shows the results of the temperatures of the south wall and outdoors temperature for a given period of time with closed windows. In this time of the year (autumn) the outdoors temperatures are lower than 26ºC in Lleida, but with

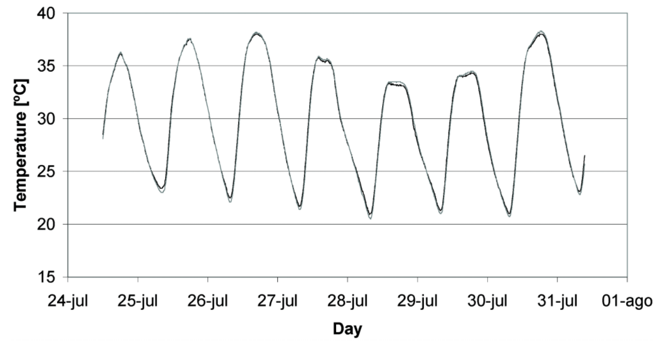

Figure 5 *Temperature of the east wall in both cubicles (July 2006).*

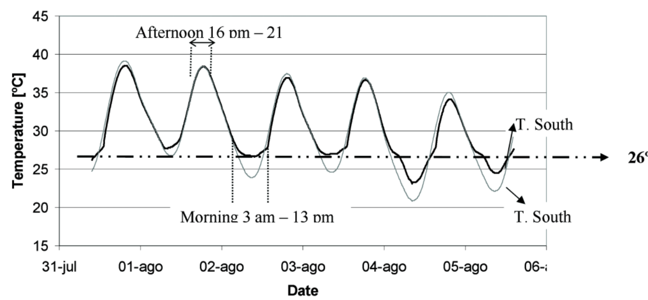

Figure 6 *Temperature of the south wall (closed windows, August 2006).*

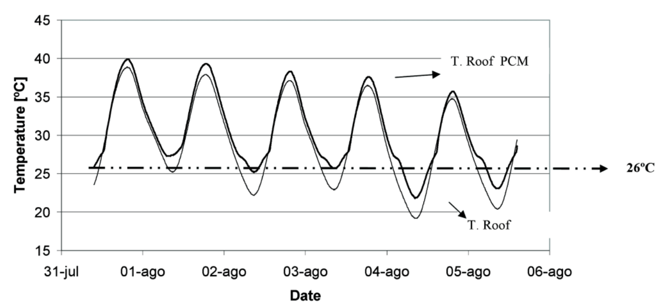

Figure 7 *Temperature of the roof (closed windows, August 2006).*

Figure 8 *View of the cubicles with Trombe wall.*

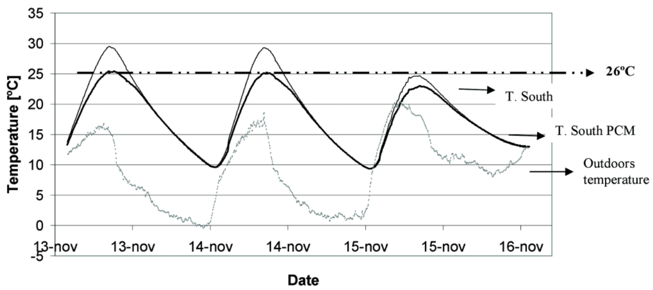

Figure 9 *Temperatures of the south wall and outdoor temperatures with Trombe wall (free-heating) for PCM cubicle and reference cubicle (November 2006).*

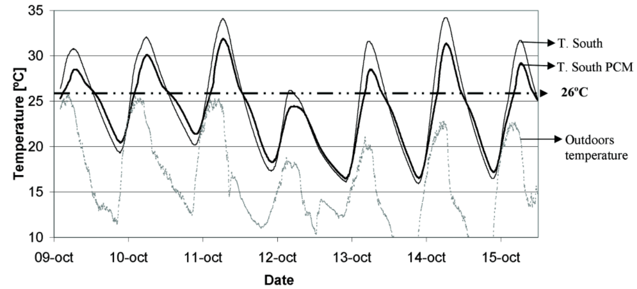

Figure 10 *Temperatures of the south wall and outdoor temperatures with Trombe wall (closed windows) for PCM cubicle and reference cubicle (October 2006).*

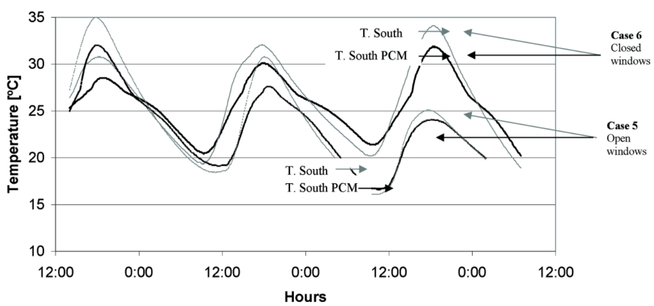

Figure 11 *Comparison between south walls with different cases. Case 6 closed windows (9–12/10/2006) and Case 7 open windows (27–29/10/2006), both with Trombe wall.*

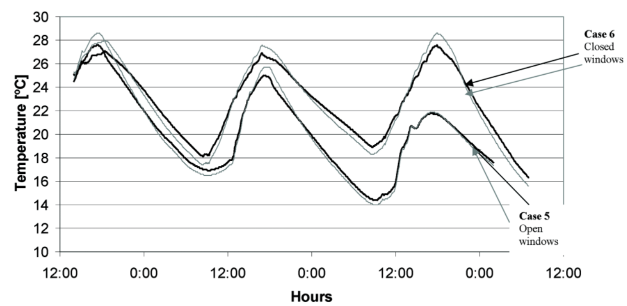

Figure 12 *Ambient temperatures inside of the cubicles at 1.20 m. Case 6 closed windows (9–12/10/2006) and Case 5 open windows (27–29/10/2006), both with Trombe wall.*

the trombe wall it was possible to obtain temperatures up to 26ºC in the South wall and the effect of the PCM was perceptible. The main advantage of melting the PCM in winter season is that the wall minimum temperatures can be increased in 1 or 2 ºC, reducing the thermal discomfort and the heating demand.

To study the effect of the Trombe wall and the PCM it was necessary to find different days with similar climatic data and to compare the measurements of the cubicles with and without PCM. Figure 11 shows the comparison between Case 5 and Case 6, both cases had similar climatic data with outdoors temperatures of 24ºC max. and 11ºC min.and the maximum solar radiation around 700 W/m^2. It can be observed that in case 6 (closed windows) the Trombe wall effect was more effective with temperatures of the walls higher than Case 5.

Figure 12 shows the same comparison (case 5 with case 6), but this graphic shows the temperature inside the cubicles at 1.2 m, and corroborates the conclusions of the Figure 11, because if the effect in the walls is higher temperatures (case 6) the results for the ambient temperature of the cubicles will be higher too.

SUMMARY AND DISCUSSION

The objective of this work was to demonstrate the possibility of using microencapsulated PCM in concrete, achieving high energy savings in buildings. The work here presented is the experimental installation of two real size concrete cubicles to study the effect of the inclusion of a phase change material with a melting point of 26ºC, and a phase change enthalpy of 110 kJ/kg.

The results of this study show the energy storage in the walls by encapsulated PCMs and the comparison with the standard concrete without phase change material. The cubicle with PCM showed higher thermal inertia than the reference cubicle, a given temperature is reached about 2 hours later in the cubicle with PCM than in the cubicle without PCM, for example in Summer this thermal inertia appears early in the morning due to freezing of the PCM and during the afternoon due to the melting of the PCM.

Different experiments were performed in order to have a real behavior of a building. After seeing the results with the different cases and the comparisons among them, it can be concluded that all the cases had their advantages or disadvantages according to the months or seasons. With this experience, for typical continental weather climates such as in Lleida or Madrid (Spain), a sequence of experiments can be recommended in order to take advantage of the improved thermal inertia of the PCM and to achieve better thermal comfort inside the cubicle throughout the year.

During April-June is better to have installed the Trombe wall, reaching higher temperatures and activating the PCM. April and May with the windows closed, and June using the free heating case and the case opening windows. For July it is recommended to remove the Trombe wall and use the free-cooling case, because the change of temperatures between June and July in Lleida is very important. August it is a difficult month in Lleida due to very high peak temperatures (around 40ºC). So, the best option recommended for both cubicles is the free-cooling. However, results with the PCM are not promising, since it cannot be melted in most of the days of this month. In September, our suggestion is to apply the free-cooling during the first 15 days, but the other 15 days using the case with closed windows due to the significant decrease of ambient temperatures in this second half of the month. October is a good month for installing the Trombe wall and, to use it until November or December with the windows closed. The authors are still analyzing which is the best option for winter months.

With the results obtained during these years, the future work will be to quantify the energy savings in a real building using this new PCM-concrete.

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