Behaviour of a concrete wall containing micro-encapsulated PCM after a decade of its construction

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Abstract

Today, our society has the duty of reducing the energy consumed in the building sector. A promising technology to achieve this goal is the implementation of thermal energy storage (TES) solutions in buildings envelope. Lately, much literature dealing with the effect of the inclusion of latent heat storage materials in construction materials to provide higher thermal inertia has appeared, mostly focusing on the evaluation of the thermal properties, density, or porosity of these new materials. However, few of them evaluated the long stability properties of the materials with embedded PCM when included in a building, very much needed since the lifetime of a building is about 50 years. Therefore, in this study, an evaluation of a house-like cubicle of concrete with micro-encapsulated PCM after a decade of its construction is carried out. The results are compared to the tests done in 2005 concluding that the thermal performance of this cubicle presented no degradation in the PCM effect.

Keywords: building; energy efficiency; thermal energy storage; long lasting performance

1. Introduction

Buildings use 32% of global final energy demand, and generate 30% of energy-related CO_2 emissions, and approximately one-third of the black carbon emissions. Over 60% of residential and almost 50% of commercial buildings use thermal energy, with higher contribution from water heating in residential buildings and from cooling in commercial ones. The drivers of the heating and cooling energy demand in buildings show a clear tendency where the decrease of the energy demand is a need [1].

Thermal energy storage (TES) is one of the highlighted technologies to achieve energy demand decrease in buildings. It is well known that improvements in the building envelope have high influence in the energy demand reduction. The use of phase change materials (PCM) in the building envelope has been widely studied to take profit of the latent heat stored during the phase change. The implementation of PCM as a passive system became a way to provide thermal inertia to the building at a specific temperature, in this case the comfort building temperature range [2].

Different methodologies can be used to insert PCM in buildings. Direct incorporation, immersion, vacuum impregnation, encapsulation, shape-stabilisation, and form stable composites are the identified methods. However, when including PCM into a construction material during the mixing process, such as concrete or cement mortar, the one that prevents the leakage problem is using micro-encapsulation PCM. This method consists in encapsulating PCM in small particles (1 μm - 1000 μm) with a thin solid shell which is made from natural and synthetic polymers [3]. More details can be found in Marani and Nehdi, 2019 [4].

Several studies have been also dedicated to the performance analysis and enhancement of composites made by cement or concrete based components and PCM based inclusions in a variety of ways and for different uses. Most of them are aimed at improving building thermal inertia, since the PCM contribution is able to dampen down thermal waves entering and exiting the building envelope at reasonable cost, as recently demonstrated [5,6]. PCM can be effectively integrated into structural and non-structural elements, which is the reason why several experiments and case studies concern their characterization in walls, ceilings, roofs, windows [7]. In this regard, the reduction of mechanical properties of concrete when PCM is added should be considered; the literature reports a reduction of up to 51% [8]. More details can be found in Berardi and Gallardo, 2019 [9]. Very little research is done in also evaluating the durability of the mortars or concrete after the addition of PCM [10].

The most typical PCM materials are organic or inorganic. Organic PCM are usually paraffin and fatty acids, while inorganic PCM are usually salt hydrates. This second material are frequently associated to high volume change rates during the thermal transitions and large subcooling, which compromises both their effect and the quality of prediction models which are elaborated in order to better predict their field behaviour, after inclusion into the cement based matrix. Therefore, organic PCM (paraffin mainly) are the most acknowledged from the scientific community and the practical field of application nowadays [11]. Since the large majority of these investigations concern microcapsuled PCM or aggregated microcapsulated PCM, they have been gaining a massive success thanks to a variety of experimental data, now available for verification. In details, several studies have been focused on the variability of concrete mechanical behaviour with varying the quantity of PCM or its thermal performance analysis associated to structural and microstructural reliability of the material. Since microcapsulated additives may be responsible for new voids and possible cracking effects, resulting in the material weak sections. In general, a PCM content higher than 3% may be responsible for more than 50% reduction in the original strength capability (i.e. compression and bending strength) which for sure needs to be taken into account when designing structural components [12,13]. At the same time, given the PCM capability to absorb released heat, they may be helpful in reducing curing-related cracks due to their function of hydration heat absorber. Such promising function may be achieved by means of a relatively smaller quantity of PCM, i.e. less than 2% [14]. Therefore, PCM inclusions may be seen as a promising way to produce lightweight concretes with enhanced thermal mass by improving both the mechanical and thermal performance of building envelope. To ensure durability of the system, the breakage of the microcapsules during concrete production needs to be avoided; to achieve this goal, robust microcapsules have been developed [15].

All these analyses were also confirmed by large scale experiment in test-buildings or prototype rooms, also named as cubicles [16,17]. This experiment configuration allowed to estimate the TES capability of composite solutions even when applied to building envelope components and energy systems in operating conditions, with varying climate and occupancy boundaries [18,19]. In this panorama, Cabeza et al. (2007) [13] published an experimental study about two cubicles made of prefabricated concrete panel, one of them was constructed with a conventional concrete and the other one had 5wt.% of micro-encapsulated PCM. Both cubicles were tested under real summer weather conditions. Results showed that the cubicle with PCM provided more stable temperature conditions in the internal ambient and a delay of the maximum peak temperature. Time-zero experiments are becoming popular for the reasons explained above, i.e. to demonstrate the effect of TES incorporation in more real conditions, e.g. in full scale continuously monitored buildings. At the same time, durability assessment is still missing while studying the scientific literature of the sector, since those few studies concerning TES or PCM performance during the course of the time are pretty focused on TES-materials in particular, and not on the composite system when integrated into building envelope or HVAC system [20]. That is the reason why this paper wants to fill this gap by investigating the long-term behaviour of TES-doped system represented by a concrete ceiling slab with PCM-incorporation aimed at stabilizing indoor air temperature, energy saving and improving indoor comfort conditions, following the work presented by Cellat et al. [21]. Therefore, in this paper, the durability of building materials with PCM and the behaviour of the micro-capsules inside these matrixes are investigated, since they are not usually taken into account in most of the published studies so far.

However, these properties are considered of significant interest for builders, architects and building engineers, to achieve better acceptance on these new materials. Therefore, the experiment of this study represent a follow up of a previous experiment carried out more than one decade before, in summer conditions, with the precise purpose to observe any evidence of difference or degradation in the concrete with PCM cubicle. Additionally, a critical comparison between the initial performance of the concrete with PCM system and the current status is presented.

2. Experimental set-up

In the experimental setup of Puigverd de Lleida (Spain), two house-like cubicles made of prefabricated concrete panels of 0.12 m of thickness were used in this study. These cubicles were built in 2005 within a European project framework (MOPCON). Both cubicles have the same dimensions (2.4×2.4×2.4 m) and orientation (N-S, 0°), but one of them have conventional concrete, and the other one 5wt.% of micro-encapsulated PCM in the concrete matrix (Figure 1). This fact allows the authors to evaluate and compare the effect of PCM incorporation in these construction systems. The windows are also distributed with the same pattern in both cubicles, having one at the east and west wall, and four windows in the south wall, as well as the metallic door located in the north facade. The monitoring of the cubicles is continuous and it is evaluated evaluating the data in a weekly basis; the results are shown for selected weeks that allow showing the performance of the cubicles in different periods of the year.

Figure 1. Construction of the cubicles with prefabricated concrete panels in 2005 at the experimental setup of Puigverd de Lleida (Spain)

In this application, the PCM was implemented as a passive cooling system to avoid indoor overheating in summer conditions. For this reason, just three panels of concrete with PCM were installed in the southern and western walls, and in the roof. The selected PCM was a commercial micro-encapsulated (Micronal DS 5001) with a melting point of 26 °C, and a phase change enthalpy of 110 kJ/kg [22].

The cubicles were instrumented to be able to measure and analyse their thermal performance in terms of temperature of internal wall surfaces (East, West, North, South walls, roof and floor) and also external South wall temperature, and indoor temperature and humidity of the cubicle. Moreover, the meteorological station registered outdoor temperature and humidity, global solar radiation over the horizontal plane, wind velocity and direction. All the data were collected every 5 minutes and memorized in dedicated data loggers of the facility.

In order to analyse the performance of the concrete with PCM system after a decade of the cubicle construction, the same experiments from Cabeza et al. (2007) [13] were performed in the facility. During the summer period, the evaluation of both concrete cubicles was done in free floating conditions, where no cooling system was operating, hence the evolution of the temperatures can be compared. On the other hand, the compressive strength was tested in 2005 once the concrete was hardened, following the European standard UNE-EN 12390-3 and UNE-EN 12504-1.

Figure 2. Concrete test samples extracted from both cubicles

The same mechanical tests were performed to compare the properties of the concrete with PCM after a decade. Therefore, two cylindrical specimens were extracted from the field installation, i.e. one from the conventional concrete cubicle, and the other one from the concrete with PCM cubicle (Figure 2).

3. Results

3.1. Thermal analyses comparison

In the experiments performed during summer, as previously mentioned, free floating conditions were tested in both cubicles. From the whole experimental campaign, key representative results are showed in this study to demonstrate the thermal performance of the concrete with PCM system after a decade.

The internal air temperature profiles collected in both the cubicles are reported in Figure 3. Since the free floating conditions experiments do not have active cooling supply, both cubicles present difficulties to maintain the ambient temperature inside the comfort zone. However, the internal ambient temperature of the concrete with PCM cubicle is always dampened down thanks to the PCM inclusion and its peaks are always below the ones in the conventional concrete cubicle. In fact, the daily fluctuation of air temperature in the cubicle with PCM is never higher than 4°C and its thermal peaks are lower than the reference cubicle by about 2°C.

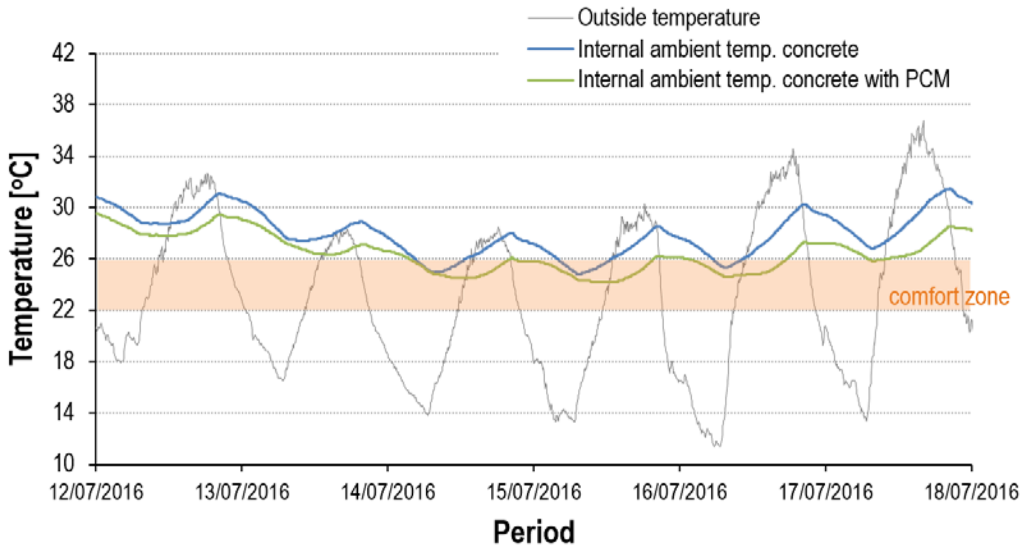

Figure 3. Outside and internal ambient temperatures in both cubicles in 2016

By looking at the external surface temperature from the South wall, big differences can be also seen between the two cubicles (Figure 4). Conventional concrete cubicles present relatively higher temperature peaks compared to the concrete with PCM case. Maximum temperatures achieved in the South external surface wall in conventional concrete cubicle are between 34 °C and 39 °C, while in the one with PCM mostly are around 28 °C. Figure 4 shows the very clear PCM effect, which is able to store the heat coming from high temperature peak hours and postpone the thermal peaks and decreasing temperature wave by about 4-6 hours (on July 13th, 14th and 17th). The results corroborated the behaviour of PCM when included in a building material. As stated by several authors [23,24], the phase change temperature of a PCM depends on the heating and cooling rate, therefore in Figure 4 some peaks show that the melting of the PCM is not exactly at 26 ºC as expected, but it appears at the range between 26 ºC and 28 ºC.

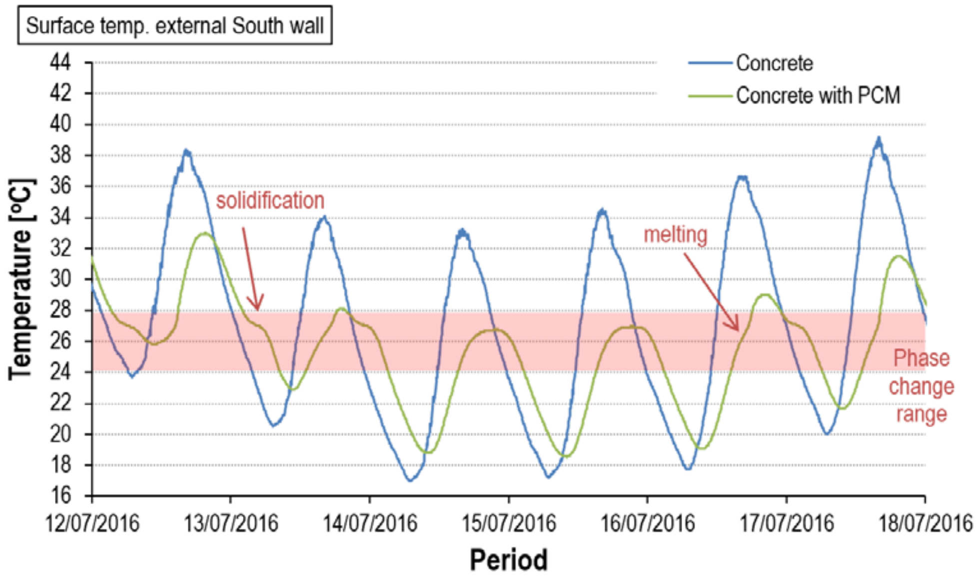

Figure 4. Surface temperature from the external South wall of conventional concrete and concrete with PCM cubicles (12 – 18 July 2016)

Another example of the PCM effect can be observed in Figure 5, where the solidification and melting process are clearly reported for both studied periods. Additionally, a delay on the maximum peak temperature is observed in the concrete with PCM cubicle compared to the conventional concrete cubicle, e.g. by about 4-5 hours. From these experiments authors observed that the PCM incorporated in the concrete matrix is correctly working, storing the heat from daily peak hours and releasing it later, once the outdoors temperature is dropping down. When comparing both studied periods, summer 2005 and summer 2016, both periods had similar solar radiation (reaching 1000 W/m^2 every day), but the external temperature was higher in 2016 (reaching 32-36 ºC during the day and dropping to 10-16 ºC during night) than in 2005 (reaching 26-32 ºC during the day and dropping to 12-16 ºC during night). Therefore, the indoor temperature was higher also in 2016. This is why, the difference between the cubicle with PCM and that without PCM was 1-3 ºC in 2005 and reached 5-7 ºC in 2016. These results show how the effect of the PCM is higher with more extreme weather conditions.

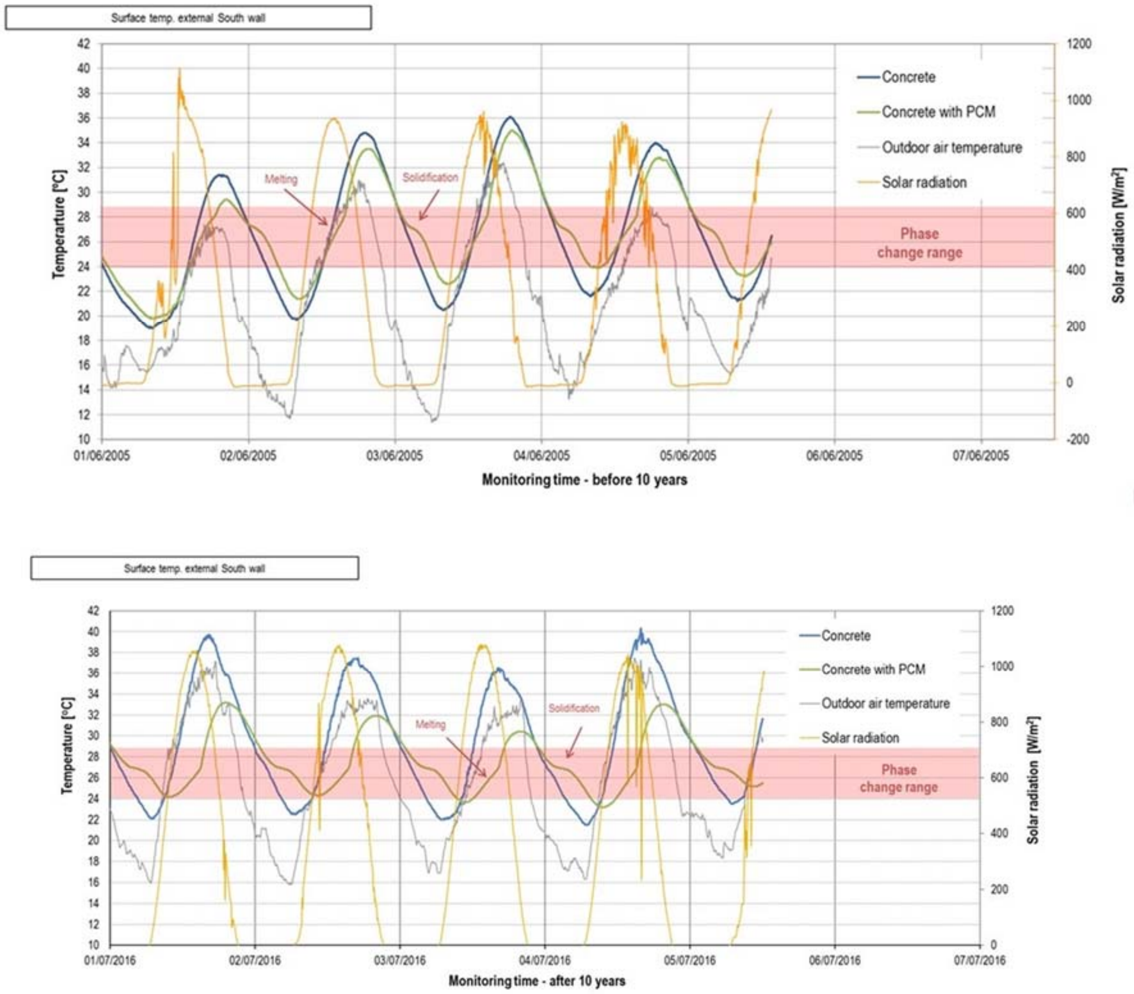

Figure 5. External surface South wall temperature in both cubicles in 2005 and 2016

The results from the experiments presented in this study were compared to the ones published in the study of Cabeza et al. (2007) [13]. The effect observed in experiments performed in 2005 were the same as the ones seen nowadays. As an example, the external surface temperature of the south wall in the concrete with PCM cubicle shows lower peaks compared to the conventional concrete. Also, the solidification and melting process of the PCM added in the concrete are clearly reflected in the external surface temperature. In addition, the authors in Cabeza et al. (2007) [13] concluded that the effect of PCM included in the concrete matrix contributed to a temperature reduction in the internal ambient of the cubicle.

3.2. Mechanical tests comparison

Besides the thermal performance of the cubicles, the same compressive strength tests done in 2005 were performed for this study. The samples obtained from the cubicles with and without PCM had the same dimensions and the test followed the same European standards. Results presented no significant differences between the values obtained in 2005 (Table 1), hence in this aspect concrete with PCM has not experimented any change or degradation.

Table 1. Results from the compressive strength test of concrete samples with and without PCM, in 2005 and nowadays

Test samples		Compressive strength (N/mm^2)
Concrete + PCM (1)	In 2005	15.12
Concrete + PCM (2)		12.86
Concrete + PCM	Nowadays	14.93
Concrete (1)	In 2005	31.76
Concrete (2)		31.33
Concrete	Nowadays	23.00

4. Conclusions

Different aspects about the use of phase change materials in buildings have been widely studied in different aspects, such as thermal properties, density, and porosity, among others. However, when including these materials in buildings there is no literature about their long-term performance. Within this framework, the aim of this study was to evaluate the thermal performance nowadays of two house-like cubicles built in 2005. Both cubicles were built with prefabricated concrete panels, but one of them have conventional concrete, and the other one 5wt.% of microencapsulated PCM was added to the concrete matrix.

Based on the summer experimental campaign performed in 2005, this study replicates the same tests and the results are compared. The effect of PCM was observed in the experiments presented in this study. Surface temperatures of the facades with embedded PCM were reduced, and consequently it was reflected in the delay of the peak temperature in the internal ambient and the smoother temperature fluctuations between day and night. With these results authors can conclude that the cubicle with PCM showed the same thermal response obtained in 2005, observing no degradation in the thermal response of the PCM. Moreover, the mechanical performance of the concrete with microencapsulated PCM was the same after ten years.

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