



Determination of Thermo-physical Properties of a Smart Hexadecane Phase Change Material -Gypsum Composite as Building Energy Storage System

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Received: November 20, 2022

Published: December 09, 2022

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Abstract

The depository of phase change material in the macro-capsules utilized for a latent thermal energy storage system considerably improves the thermal performance. Gypsums with improved thermal properties have been obtained using copper tube filled with Hexadecane Phase Change Materials (HPCMs) in order to develop building materials with high thermal energy storage (TES) capacity useful for being applied in high comfort constructive systems.

Firstly, an investigation by means of a differential scanning calorimeter (DSC) was carried out to obtain the latent heat and the transition temperature of HPCMs. Secondly, an additional study was conducted to gauge the improvement of energy storage performance in classical construction material (Gypsum/copper tubes) filled with paraffin developed to improve different properties of PCM and open a wide field of applications to latent heat storage systems. The objective of this research is to use PCM composite as integrated components in a passive solar wall. The proposed composite TROMBE wall allows daily storage of the solar energy in a building envelope and restitution in the evening, with a possible control of the air flux in a ventilated air layer. Experimental investigations of the thermophysical properties of the considered composite (Gypsum/copper tubes) have shown that the material combines a high heat storage potential and an improved heat transfer at the same time. Accordingly, the results showed that the shape-stabilized phase change material prevents the leakage of the molten paraffin during phase transition and proved a good thermal stability.

Keywords: Gypsum; Hexadecane Phase Change Material (HPCM); Thermal Energy Storage (TES); Transient Guarded Hot Plate Method (TGHPM); DSC Analysis

Nomenclature

e Composite Width

t Times

ρ Density Of Composite, $kg.m^{-3}$

T Temperature, °C

C_p Specific Heat Capacity, $kJ / kg.^{\circ}C$

λ Thermal Conductivity, $W.m^{-1}.K^{-1}$

Q Energy Per Mass Stored, J / g or kJ / kg

L Latent Heat of Fusion (kJ/kg)

ϕ Density of Heat Flux, W / m^2

Subscripts

1,2 Lower and Higher Face of the Composite

init Initial Thermal Steady State

end Final Thermal Steady State

sens Sensible

S Solid State

l Liquid State

m Melting

C Crystallization

Introduction

Since a mismatch between energy supply and demand rises increasingly, thermal storage systems designed to reduce it and to save energy in buildings have received correspondingly more and more interest [1]. Under this circumstance, thermal energy storage is the most preferable techniques to be applied in building construction in order to develop the energy efficiency [2]. In particular, latent heat energy storage with phase change material is taken as the most promising method due to its large energy storage capacity and its ability to store thermal energy at relatively constant temperatures [3,4].

Massive kinds of phase change materials (organic, inorganic and eutectic) have been investigated as latent heat thermal energy storage materials. Among them, paraffin is perceived as the best candidate for preparation of smart PCMs in diverse application due to its important heat storage capacity, good thermal and chemical stability, little super-cooling, and low cost [5,6]. The problem of paraffin is its low thermal conductivity and leakage, which can hinder its applications. It extends the period of charging and discharging process of the thermal energy storage and can reduce the rate of storing and releasing energy of PCM.

For over three decades, research projects have investigated frequent techniques for improving the thermal storage of the PCM. The most repeated techniques are:

- Increasing the heat transfer area either by, using heat pipes [7]), application of multitubes heat exchangers [8], or utilization of finned tubes [9].
- Enhancing the PCM thermal conductivity either by dispersing high conductivity particles within the PCM [10,12,13], inserting a metallic matrix into the PCM or utilizing of bub-

ble agitation in the PCM [11] and impregnating a porous graphite matrix with PCM [14,15].

Studies into composite PCM drywall systems principally gypsum board prove that it is relatively recent research topic. Gypsum is an adaptable building material used in partitions, interior walls, ceilings, soil [16], and decoration [17] due to its easy fabrication features, exceptional fire resistance properties and environmental friendliness, esthetics. In addition, it presents low prices and can be carried out in situ or as precast slabs [18]. Therefore, such massive potential has led to past efforts in the direction of the development and the thermal characterization of PCM gypsum board.

For instance, Borreguero., *et al.* [19] evaluated the integration of 15 wt % of microcapsules of PCM into gypsum plaster boards would allow to safeguard 4.5 kWh of energy per operating cycle in a conventional room covered with 1 m³ of this material. J.R. Patel., *et al.* [20] performed the experimental and numerical investigations to assess the influence of the different shaped macro-capsules on the melting and solidification processes. The test's results showed that the triangular capsule exhibits better thermal performance with melting and solidification time of 41 min and 133 min, respectively. In addition, the raise in the heat transfer fluid temperature increased the melting rate. Furthermore, it estimated that the 27% diminution in the capsule size reduced melting and solidification time by 12.19 and 19.17%, respectively. Consequently, the capsule size had more influence on the solidification process compared to the melting process. Bo Zhang., *et al.* [21] estimated the feasibility of applying the (diatomite/paraffin/gypsum) (DP/gypsum) composite in buildings in terms of economic, practical, and environmental aspects. In this way, they developed a gypsum-based PCM composite reinforced with carbon fiber, a kind of structural-functional integrated energy storage building material. The results of this study demonstrated that the flexural strength and thermal conductivity of DP/gypsum containing 1 wt % carbon fibers amplified by 176.0% and 20.3%, respectively. Additionally, revealed that the existence of carbon fibers improved the overall thermal conductivity and enhanced the thermo-regulated performance of DP/gypsum. Multi-scale analysis of cementitious mortar and concrete containing microencapsulated PCM (MPCM) was executed experimentally and using numerical simulations [22]. The results indicated that the effective thermal conductivity is strongly dependent on the volume fraction of PCM. Numerical simulations

of the macro-scale performance of mortar and concrete with PCM for passive thermal storage showed a decrease in the maximum heat flux and time lag effect subjected to diurnal temperature fluctuations. M. Mahdoui, *et al.* [23] evaluated numerically the thermal performance of the hollow brick (extensively used in Morocco construction) impregnated by a PCM using Ansys Fluent software. A parametric study was handled to estimate the influence of endure conditions and PCM thermophysical properties on the thermal response of this building element. They deduced that the employ of PCM in building bricks stabilizes and decreased the indoor temperature variation.

The present work aims at developing new construction material for utilization in high-comfort constructive and to contribute to elucidating our knowledge and understanding of the effects of the PCM incorporated in building material. This material consists of copper tubes filled with HPCM which are regularly spaced and aligned in a gypsum matrix. The prepared composite shows features of high energy storage density, a high thermal conductivity of heat exchange, and an absence of molten paraffin leakage. This paper emphasizes on the experimental investigation of the thermal energy storage properties improvement of a new composite PCM. The melting temperature, latent and sensible specific heat of the PCM was characterized using DSC (Differential Scanning Calorimetry). The thermophysical properties of the elaborated material have been measured using Transient Guarded Hot Plate Method (TGHPM).

Experimental study

Studied material

Two samples of identical dimensions ($200 \times 200 \times 62 \text{ mm}^3$) have been considered.

The first sample is gypsum with empty copper tube. The second one consists of gypsum composite with copper tube containing PCM (hexadecane). Hexadecane is a saturated hydrocarbon of the alkenes family, purchased from Sigma-Aldrich with the purity of 99%. The melting temperature of the HPCM provided by Sigma-Aldrich is 18°C . The reason behind the selection of this PCM in this work is its high latent heat and suitable phase change temperature, which is in the range of human comfort temperature.

Tunisian gypsum was used as a construction material to study the effect of PCM added on the heat storage capacity. IT was se-

lected due to its affordability and its good thermal and acoustic resistance. In addition, Gypsum is frequently found in partition walls and placed in the interior side of wall as a cladding element [24].

The preparation of the PCM composite goes through different steps:

Copper tubes are positioned and aligned in a mold ($200 \times 200 \times 62 \text{ mm}^3$) with an equidistant distribution of 25mm between the tubes (see figure 1-a). By doing so, 1000g Tunisian gypsum was mixed with water and the necessary amount of water was gradually added to the mix and stirred continuously by hand at high speed until a homogenous paste was formed (figure 2). Thus, the necessary quantity of water was not pre calculated, but it was gradually added during the experiment. The paste was poured into the mold, slightly compressed to remove excess of water at an ambient temperature for 48 h before demolding. Then, the samples were dried at 45°C for 4 days to remove the moisture inside the gypsum composites.

Finally, HPCM was melted at a temperature above the melting temperature. After that, all copper tubes were filled rapidly with the molten paraffin wax by using a hermetic syringe. It is worth pointing that the samples of weights have been monitored before and after the tests, and no change in weight was found. Thus for the same volume, the mass of the gypsum with empty tube is 1537.6 g and the mass of the second gypsum composite including PCM is 1637.6 g (Figure 1.b). The chosen form of the sample enables its application as a component of a wall or as an elementary heat storage module in the building sector.



Figure 1a: Model of Composite: gypsum/copper tubes. White spheres represent trigonal C=C (ethene-like) carbon pair.

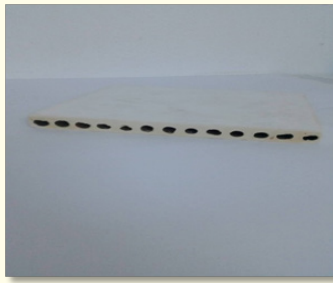


Figure 1b: Composite: gypsum/copper tubes (12 mm outer diameter and 11.2 mm inner diameter).



Figure 2: Pasty mixture (gypsum + water).

Experimental set-up

Figure 3 illustrates an experimental facility used in the present and previous studies by Trigui, *et al.* [25,26]. The facility included two plate heat exchangers of aluminum between them a parallelepiped shaped composite sample ($200 \times 200 \times e$ mm³) was sandwiched. Thermo regulated baths, supplying the plates, allows the heating and cooling needed to simulate diverse thermal conditions. The lateral sides of the studied composite are insulated by expanded polystyrene which reduces the heat transfer into the external ambient condition.

Considering the positioning of the sample between the two plates heat exchangers, an attempt was made to measure heat flux and temperature on each face of the sample. Doing so, heat flux sensors and T-type thermocouples are places on both sides of the sample. All sensors are connected to an USB acquisition device controlled by a Lab view program adapted to measure temperature fluctuations and heat flux exchanged during melting and cooling processes. Experimental data are recorded with regular and adjustable time procedures (6 s).

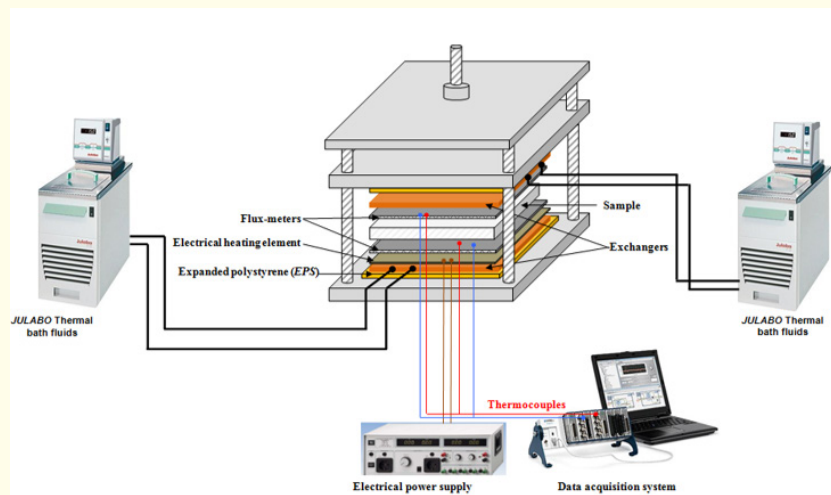


Figure 3: Transient Guarded Hot Plate Method (TGHPM).

Results and Discussion

DSC analysis

This paragraph concerns only the thermal analysis of the paraffin included in the composite PCM. DSC technique was used to analyze the thermal property of the hexadecane. Figure 4 presents the DSC melting and freezing curves of the pure hexadecane at 10°C/min scanning rate and the characteristic temperatures including melting temperature T_m , melting peak temperature $T_{m,peak}$, freezing temperature T_f and freezing peak temperature $T_{f,peak}$. The difference between $T_{m,peak}$ and $T_{f,peak}$ is the supercooling ΔT . It can be noted that the melting/freezing peak temperature is 25.57°C and 14.04°C, respectively, so the supercooling represents 11.53°C.

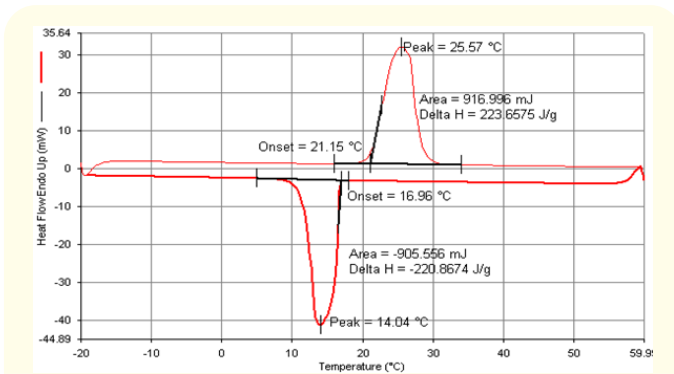


Figure 4: DSC fusion and cooling curves of the pure hexadecane (HPCM) at 10° C/min scanning rate and the characteristic temperatures.

Determination of thermophysical properties of the composite-PCM

This section aimed to provide the determination of various thermophysical properties of the specimen during the solid or liquid state of the PCM.

Apparent thermal conductivity

In order to measure the solid and the liquid thermal apparent conductivity of such sample, several tests were carried out by means of Transient Guarded Hot Plate Method (TGHPM). To be certain that the state of the PCM is solid or liquid; the characterization has been realized far away from the melting temperature. The measures of thermal conductivity are then carried out in the temperature range 10°C -17°C for a solid PCM state, and between 22°C and 30°C for its liquid state. This test is done by imposing a thermal

gradient between the top and bottom sides of the composites until observing a zero heat flux (equilibrium state).

Thereby, the apparent thermal conductivity of the sample is determined via the following expression [27,28]:

$$\lambda_{s,l} = e \cdot \frac{\sum \varphi_{s,l}}{2 \cdot \Delta T_{s,l}} \quad \text{----- (1)}$$

Where e is the thickness of the specimen and $\sum \varphi_{s,l}$ is the sum of measured heat fluxes.

The evolution of heat fluxes and the measured temperatures on both sides of the composite gypsum PCM, when the paraffin is in liquid and solid state are illustrated in figure 5, 6 respectively.

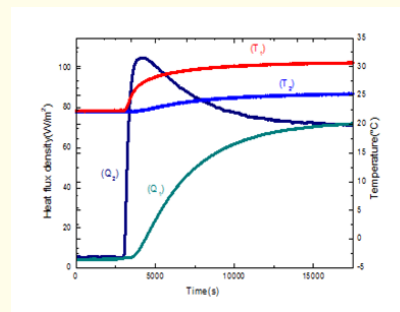


Figure 5: Measurements with thermal variation of the liquid sample (22°C to 30°C) for gypsum/copper tubes filled with paraffin.

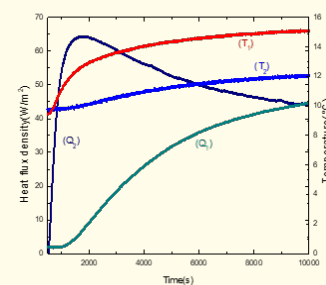


Figure 6: Measurements with thermal variation of the solid sample (10°C to 17°C) for gypsum/copper tubes filled with paraffin

A symmetrical behavior of heat fluxes and temperatures measured on both faces of the composite sample can be observed in figure 5 and 6, which will correspond to the results obtained lately in (figure 7) with a solid material without phase change.

Both figures show that the sample is isothermal at the beginning. Therefore, a thermal gradient was imposed which cause a temperature increase only in the bottom face of the composite up to second thermal equilibrium was established.

Adopting Eq. (1), the thermal conductivity of the composite-PCM could be measured using the value of the temperature difference and the average value of the heat fluxes when a steady state is reached.

Several tests were carried out on the composite material to check the reproducibility of the measurement. The results were found to be satisfactory; they provided an average thermal conductivity of $0.73 \text{ W m}^{-1}\text{K}^{-1}$ for the PCM in solid phase and an average thermal conductivity of $0.83 \text{ W m}^{-1}\text{K}^{-1}$ when the PCM is in liquid phase. And their associated uncertainties when the paraffin is in solid and in liquid phases represent respectively 6.2% and 6%.

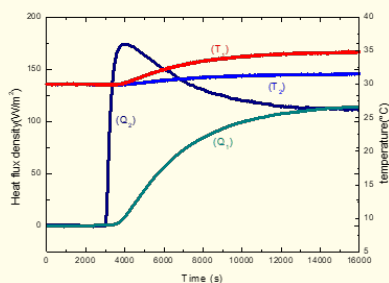


Figure 7: Measurements with thermal variation one side of the solid sample (30°C to 35°C) for gypsum/copper tubes.

The experiences carried out with the composite (gypsum/copper tube without PCM) have yielded its thermal conductivity $0.99 \text{ W m}^{-1} \text{ K}^{-1}$ in the temperature range 31°C – 35°C. So, one can note that a significant decrease in the thermal conductivity of the composite occurs when we added the PCM. Accordingly, the addition of paraffin to the gypsum matrix with copper tube sample reduces the heat transport in the composite, and the HPCM act as a thermal insulator:

The thermal conductivity in the solid state was estimated and decreased from 0.99 W/m/K for 0g of the paraffin to 0.78 W/m/K for 100g of paraffin. In addition, we noted a decrease in the thermal conductivity of the composite with an increase in the mass of the paraffin. Thus, it can be concluded that the higher PCM content is, the higher percentage of decrease of the thermal conductivity. In other words, its diminution is about 25% and 19.27% respectively for solid and liquid state to the sample of gypsum matrix. Thus, the thermal conductivity in the liquid state was slightly greater than that in the solid state. This reduction in the thermal conductivity of the composite was predictable because the thermal conductivity of the Tunisian gypsum increased as the temperature increased [32], and the thermal conductivity of the HPCM in the liquid state was higher than that of the paraffin in the solid state. Moreover, the thermal conductivity of Tunisian gypsum is 0.22 W/m K [32]. According to the results obtained, the following trend can be established in the thermal conductivity: gypsum/copper tubes without HPCM more than gypsum/copper tubes with HPCM. Consequently, the thermophysical properties are really affected by the HPCM's state (liquid or solid). Furthermore, the integration of PCM in the copper tube decreases the thermal conductivity. Henceforth reduction conductivity appears in the thermal conductivity can be an additional advantage. In general, the incorporation of PCM improves the storage ability and the insulation authority of this building element [23,31,32]. So, the subject of the following section is to study the effect on heat storage capacity.

Sensible heat and apparent heat capacity

To measure the specific heat capacity and specific heat of a material, the method used in this work consisted in measuring simultaneously the heat flux $f_{1,ex}$ and $f_{2,ex}$ and the temperatures T_1 and T_2 on the two faces of the sample (T_1 and T_2 are the two thermocouples integrated in the flux sensors). Initially, the exchangers are maintained at a constant temperature until reaching a zero heat flux density on both faces of the sample. Then, the temperature of the exchangers was augmented and maintained until thermal equilibrium. Between these two permanent steady states, there appears a variation of the internal energy of the system, in that it maintains the sample to be stored the quantity of sensible heat to be liberated.

The evaluation of the specific heat capacity is given by the following equation [31]:

$$Q_{sens} = \frac{1}{\rho \cdot e} \int_{T_{init}}^{T_{end}} \Delta\phi \cdot dt = C_p (T_{end} - T_{init}) \tag{2}$$

$\Delta\phi$ represents the cumulated heat rate entering the sample;
 C_p : apparent specific heat capacity composite (kJ/kg.°C); ρ : density of the sample; e : thickness of the sample.

Figure 8 and 9 represent up an example of sensible heat storage in solid and liquid states, respectively. It can be noted that there is a symmetrical behavior of heat fluxes and temperatures measured on both faces of the composite sample. It is also shown that the measured temperatures on the lower (T_1) and the upper (T_2) faces of the material evolve in an asymptotic way toward the target point. In addition, we can note that the flow evolves very quickly at the begging of data collection and then falls to zero, which corresponds to the achievement of a new state balance at the end of the test. This confirms that the lateral thermal losses are negligible. The results obtained for the specific heat capacities and the sensible heat accumulated by the composite when the PCM is in solid or in liquid phases are summarized in table. These values will be helpful for determining the apparent latent heat of the sample.

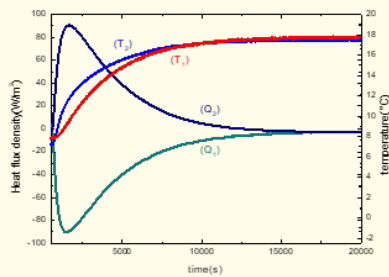


Figure 8: Heat flux and temperatures evolution during the solid phase.

The apparent specific heat of the sample without PCM is calculated according to the temperature solicitations exposed in figure 10.

At the beginning of the test, the sample is maintained at a constant initial temperature T_{ini} 5.8°C. The temperature is then increased to T_{end} = 10.8 °C.

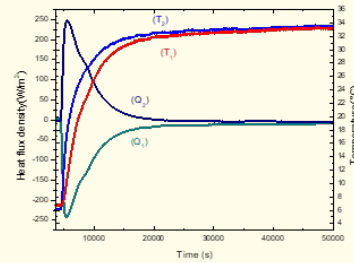


Figure 9: Heat flux and temperatures evolution during the liquid phase.

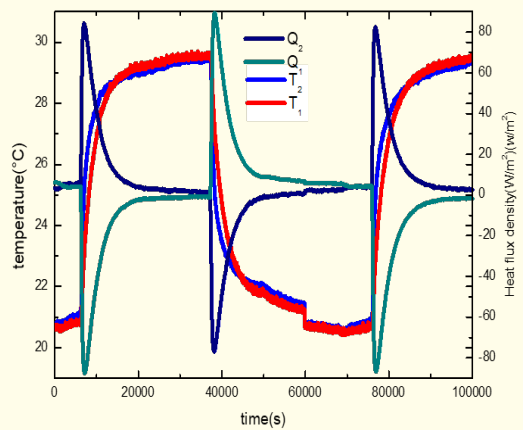


Figure 10: Determination of the apparent thermal capacity: gypsum/copper tube without PCM.

It should be noted that a stabilization time must be allowed after every temperature setting change. This period authorizes the sample to evolve towards its thermal equilibrium state. This occurs (see Figure 10) when the measured heat fluxes are becoming zero. As soon as the sample reaches its equilibrium state, the heat recovery process starts. Finally, the sample ruffled until it reaches the initial temperature. It should be noted that both processes are iterated in order to show the repeatability of measurements. Thus, the average apparent specific heat capacity is calculated from these six values is 880 J kg⁻¹ K⁻¹.

Latent heat
Temperature solicitations

For the main purpose of determining the latent heat of solid/liquid phase change of the different samples in this work and the

phase change temperatures, an experimental process is carried out, in which a slowly progressive temperature deviation have been set on the specimen, has been used. This method consists simultaneously the measurement of heat flux and temperatures on both lateral sides of the sample.

The thermal evolution from 6°C to 33 °C (Figure 12) allowed us to follow the entire melting process, from the solid to the liquid state, during which a large quantity of heat has been stored by the material. The selected temperatures are sufficiently far from the zone of melting point to consider that indeed the material is strictly in one or in the other state.

Regarding to the variation of the flux density between 6 °C and 33°C, where there is phase change, initially, the system is isothermal and then a new thermal balance is reached. Between these two isothermal states, the composite stores sensible and latent heat.

The total amount of energy per mass stored can then be obtained from the following expression:

$$Q = Q_{sens} + L_m = (Cp_s \cdot \Delta T_s + Cp_l \cdot \Delta T_l) + L_m \text{ [kJ/kg]}$$

Cp_s and Cp_l are the average solid state and the liquid state specific heat of the material, ΔT_s and ΔT_l are the temperature variations for the material in solid phase and in liquid phase, and L_m is the

latent heat of melting. By subtraction of sensible heat to the quantity of the total heat accumulated, the latent heat L_m can be evaluated.

Various tests were carried out to ensure the reproducibility of the experiments. To demonstrate the importance of thermal storage by latent heat, the heat flux and temperature evaluations for the temperature differences between the initial and final states are summarized in table 1.

The results presented in table 1, showed that the total and the latent heat stored by the composite-PCM during a melting cycle are strongly affected by HPCM addition, where the total heat is equal to 47.41 kJ and the latent heat is equal 24.16 kJ. This enhance is probable due to the high latent heat of the paraffin.

The heat capacity energy of the gypsum composite PCM is 1.5 times superior to that of the composite material with empty tubes. At the liquid state, the composite gypsum-HPCM stores 63% more energy than sample 1.

Finally, the latent heat of the composite filled with paraffin was 47, 41 kJ/kg, which is a reasonable value for effective heat energy storage. Thus, we believe that the materials under investigation can be used in most applications where traditional gypsum composite systems are used, even with higher affectivities. These results validate our interest in latent heat storage.

Samples	Q_{sens} (kJ)		Cp (kJ /kg. °C)		Q (kJ)	L_m (kJ)
	Solid (7.7-17.5°C)	Liquid (23.5-32°C)	Solid (7.7-17.5°C)	Liquid (23.5-32°C)	Evolution (6.7-32.5°C)	
Gypsum/copper tubes without HPCM	7.89	-	0.88	-	32.9	-
Gypsum/copper tubes with HPCM	10.60	12.65	1.10	1.26	47.41	24.16

Table 1: Quantity of heat stored and specific heat capacity at different state for gypsum/copper tubes composites.

Phase change temperature

Figure 11 shows a model of an experiment counting tow solidification/melting cycles.

At the beginning, the sample was maintained at a constant initial temperature $T_{ini} = 6^\circ\text{C}$ which is lesser than melting temperature. Then, the temperature is augmented to attain $T_{end} = 33^\circ\text{C}$ (higher than melting temperature). This induce a very quick evolution of

the heat flux corresponding to the fusion or solidification of the sample, the heat flux then converge to zero, which corresponds to a new thermal equilibrium state obtained at the end of the test. Finally, the sample was melted until it achieves the initial temperature.

In the light of the results shown in figure, the readers can note that the cooling time of the paraffin is longer than the melting time,

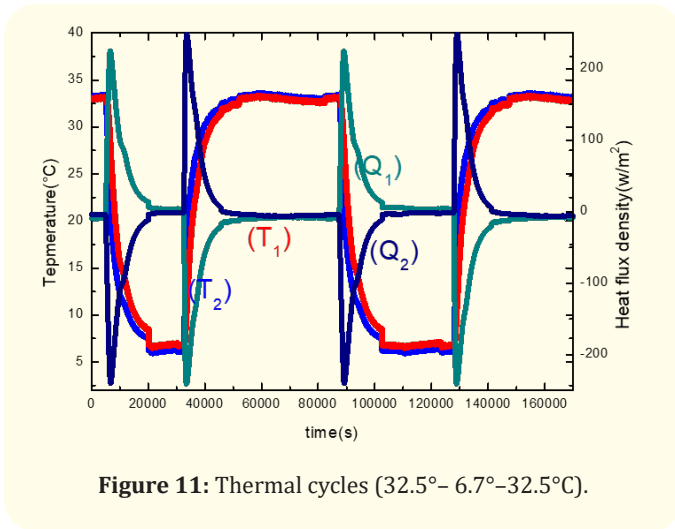


Figure 11: Thermal cycles (32.5°- 6.7°-32.5°C).

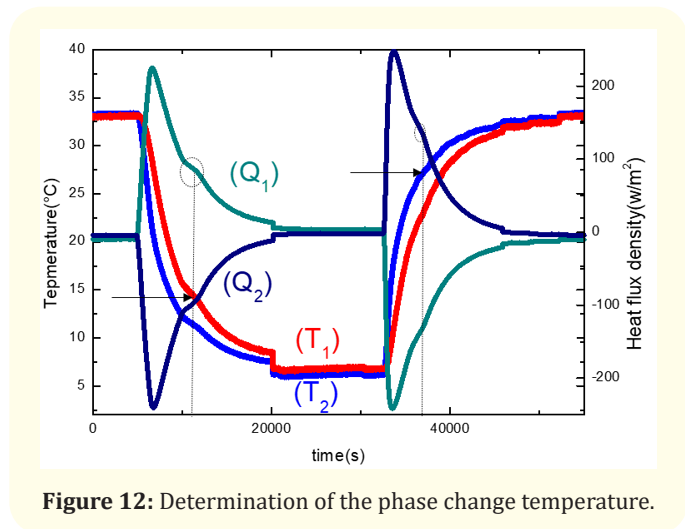


Figure 12: Determination of the phase change temperature.

which can be explained by the construction of layer of solid PCM on the plane surface in contact with the exchanging plate at the start of the solidification process. This layer insulates the liquid phase from the cooling source. The solidification process goes on slowly due to the low thermal conductivities of the solids PCMs.

The composite gypsum-PCM has approximately the same shape of the flux density curve. In the storage state, the maximum value of the heat flux density on both sides of the sample was 250 W/m². Whereas in the release they stood at 245 W/m². So, at the cooling process, the sample supplies nearly the same thermal energy storage during the melting process.

So, according to the results obtained, we can conclude that this composite material possesses a strong thermal stability over various melting/solidification cycles. This result affirms that there is no outflow problem when paraffin is in liquid stat during thermal cycling.

One can also observe the little difference between the amount of energy stored and released in each cycle, this can due to the heat losses during the solidification process

In order to better picture and explication of the behavior of the paraffin the phase change temperature, Figure 12 only focuses on the first heating cooling cycle of figure 11.

Concerning the solidification process, where the temperature evolves from 33°C to 6°C, cooling of the material occurs. Initially, it can be observed a normal evolution of measured heat flux corresponding to the cooling of the liquid phase up to 3.33h. At this moment, it can be observed a discontinuity that occurs when surface temperatures are around 14.04°C (Figure 12). 14.04°C is the solidification point of the HPCM measured by DSC; from this significant moment, the cooling of the samples goes on. The paraffin solidifies slowly and samples cools down until it reaches the prescribed 6°C.

In the melting case, the dynamic thermal behavior is different. The sample stores sensible and latent heat at the same time; its temperature increases and the PCM melts. An inflection point appears in the heat flux curves (t = 10.55h). When the temperatures of surfaces are in the vicinity of 25°C, 25°C is the melting point of the PCM measured by DSC. From this critical moment, the melting of the samples goes on, paraffin melts slowly until it reaches the prescribed temperature of 33°C: Then the samples has reached an equilibrium state.

Conclusion

The main goal of this study has been to carry out an experimental investigation to thermally characterize buildings equipment materials containing copper tube filled with PCM included into gypsum. To intensify our comprehension of thermophysical properties such as apparent thermal conductivity, apparent thermal heat capacity and latent heat, of materials with or without PCM, a suitable method has been established.

In order to point out the importance of including HPCM in building materials, a comparative study has been realized. The results of the current study successfully showed that the investigated composite (Gypsum-copper tubes) with HPCM liquid could offer important advantages for thermal storage systems as well as heat transfer applications.

The obtained results led to the following conclusions of the present work:

- The thermal conductivity results show that the PCM addition produces a reduction in the effective thermal conductivity of the samples. The experimental values show that the following trend can be established in the thermal conductivity: gypsum/copper tubes without HPCM more than gypsum/copper tubes with HPCM
- A gypsum composite PCM stores as much energy as a sample 1. In the solid and liquid phases, the heat storage capacity improved with including HPCM.
- The latent heat and the capacity of storing thermal energy as latent heat determined by transient guarded hot plates method (TGHPM) are a viable approach of the utilization of solar heat, a green source of energy, and the optimization of energy consumption in buildings.

An optimization will to be considered in future studies by introducing conductive particles to increase the thermal conductivity of the PCM.

Thermal conductivity, thermal stability of gypsum-copper tubes composites and the amount of energy exchanged during the variation of the samples thermodynamic states when the boundary temperatures vary will to be investigated numerically in future studies and the results will be compared with the experimental results.

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