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Laboratory test cells for evaluate the real performance of precast concrete façade with PCM.

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Abstract

The Inphase project proposes the development of a precast concrete façade with incorporated Phase Changing Materials (PCMs) for residential buildings' envelopes, taking advantage of the latent thermal storage capacity of the latter in order to improve the overall performance of the building. The solution is based in layers of mortars and slurries for incorporation in precast building components actively controlled by means of an integrated hydronic radiant system.

In order to evaluate the performance of different solutions, an experimental infrastructure was developed with laboratory test cells with increasing amounts of microencapsulated PCM (0%, 9%, 19%, 24% and 32%) proportions in relation to the total volume of PCM containing concrete. The temperature of the system is modified and controlled through an active water installation and measured at different points of the testing blocks and pipes, providing an in-depth analysis of the dynamic response of the system.

The idea is to be able to activate or control the thermal inertia of the material at will for the development of the experiment as well as future applications. The models were devised to be monitored in order to obtain a detailed study of their thermal properties and performance, such as temperature profiles, heat flux, dampening or phase shift. This information will later be used to validate the simulation model, which enables the digital analysis of a building with these materials incorporated as part of its envelope.

Keywords: Phase Change Material, Thermal energy storage, Thermally Activated Building Systems, Radiant wall.

1. Introduction

Buildings represent an important percentage of energy consumption, at around 30-40% of the total. This has resulted in several new legislations that intend to minimize the energy requirements when it comes to the performance of a building [1], [2]. The objective is to achieve comfortable conditions that allow people to develop their activities in a healthy and adequate environment with the lowest energy demand possible.

The current situation is an opportunity to develop new techniques that could be implemented in buildings, both new construction and already existing ones. The main focus is set on the façade, because it's the part of the building that interacts with inside and outside conditions. But this could be extended to other elements, even the structure itself.

One of the main concerns regarding energy is its storage, given that more often than not it's only available at a certain time and needed at a different one. With renewable sources a possible solution is batteries, which allow the time gap to be solved. The same concept can be applied to buildings thanks to Thermal Energy Storage. TES through sensible heat has traditionally been the way to a more comfortable interior. It works particularly well in areas where temperature varies significantly from day to night, although a possible downside is that it requires a large amount of mass to work, which can't always be achieved. To solve this, TES can be combined with Thermally Activated Building Systems (TABS), enabling a broader control over the thermal performance of the building when needed [3], [4], [5].

Nevertheless, systems based on sensible heat are limited by the amount of material used for the construction of the building and the depth of surface material that usefully exchanges energy with its environment. This is where materials with high energy storage capacity in smaller volumes come into play. Phase Changing Material, with their latent heat, stand out as an interesting element to consider and research. Several of them can potentially be implemented in construction, although the research hasn't provided with a fully suitable solution yet. On the contrary, it still allows for further analysis and development.

With all this in mind, an experiment has been developed under the INPHASE project. The main objective is to research the possibilities of the incorporation of PCMs into a precast concrete façade and how heat transfer could be controlled through an active water system.

2. Inphase solution

Considering the growing relevance of efficiency in energy-related sectors, the INPHASE project develops a precast concrete façade which partly incorporates microencapsulated Phase Changing Materials with the objective of enhancing the thermal properties of this material. This new technology enables the storage of renewable energy, such as the sun, when it's available and its use when necessary in order to achieve thermal comfort in the interior of buildings. As part of this research, an experiment is studied to analyze the sensible and latent thermal energy storage capacity and the dynamic response of the proposed system. PCMs are included at variable percentages in several testing blocks, providing information about how the amount of PCM improves the thermal performance of the different models. The temperature of the system is modified and controlled through an active water installation and measured at different points of the testing blocks and pipes, providing an in-depth analysis of the dynamic response of the system. The measurements obtained with this study are used to calibrate the simulation model for future analysis of buildings which will include PCMs in their envelope.

The experiment is based on a series of thermal batteries which are monitored to allow tracking the dynamic response of the system. The idea is to analyse the heat storage capacity of concrete and PCMs combined and how they perform while actively charging and passively discharging.

As part of the INPHASE project, microencapsulated PCMs were incorporated to mass concrete as an additive. Initial laboratory research was needed to understand the compatibility of both materials and how the increasing amount of PCMs affected the concrete mortar properties. This is of significant importance, given that, depending on the use and placement of the PCM-containing concrete, certain qualities and characteristics must remain at a certain level when compared to basic concrete.

The final experiment consisted of a total of 15 cells with different percentages of PCMs in relation to the total volume: 0%, 9%, 19%, 24% and 32%. For each of these five dosages, three testing blocks were developed, ensuring enough data for a correct interpretation on the results.

3. Laboratory test cells

Each cell consisted of a 0.38 m x 0.30 m block with a 0.12 m base of pure concrete and 0.04 m layer of concrete with microencapsulated PCMs. *Figure 1* shows the basic scheme followed for the development of the testing cells.

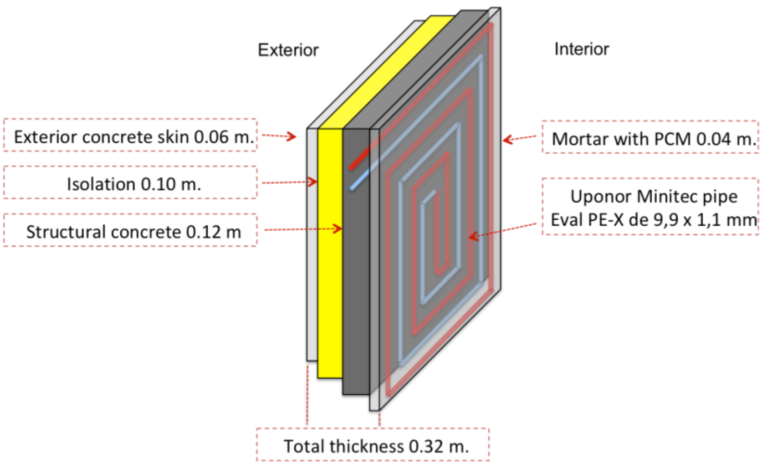

Figure 1: Panel scheme

These cells are connected with a parallel piping installation (*Figure 2*). Water is used to distribute heat throughout the system, with the required temperature achieved and controlled through a boiler system and valves. For reliable results and minimal energy loss the entire installation is insulated, including the blocks and the pipes. For the monitoring, a series of thermocouples were distributed and connected to a Data Logger that saved all the information for future analysis.

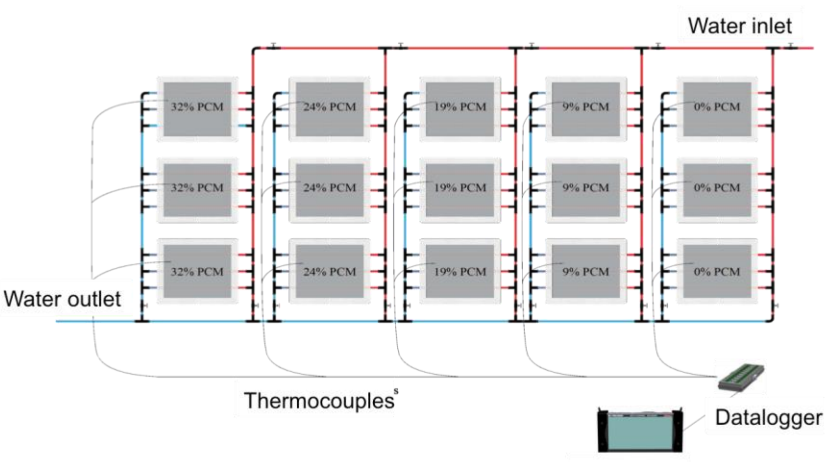

Figure 2: Installation for the experiment

For a correct measurement and study of the experiment, 100 thermocouples were placed all over the system, both within the testing cells and at different locations on the pipes. Temperature is monitored at 10 locations at the supply and return pipes, before and after heat is transferred to the blocks. The remaining 90 thermocouples are placed within the cells, either superficially or internally. *Figure 3* shows the exact locations of the thermocouples:

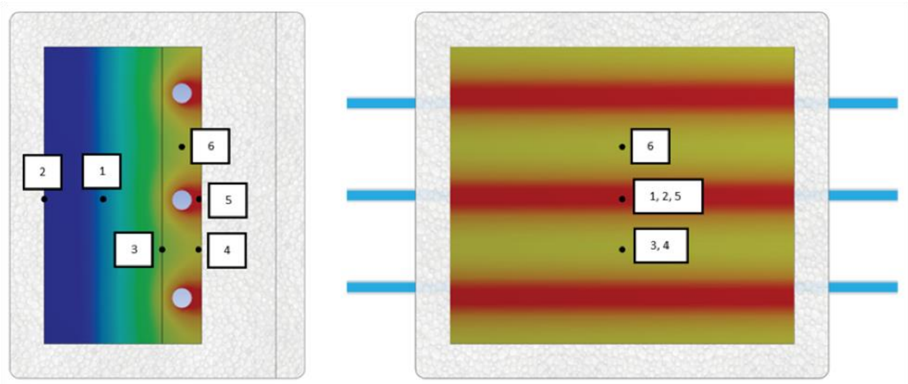

Figure 3: Testing cell and thermocouple locations

For the development of the experiment, the entire installation is provided with water at 15 °C, which can be controlled thanks to the thermocouples. Once every block reaches this temperature the boiler system brings it up to 38 °C and is then turned off, leaving the cells to cool down on their own until they go as low as 15 °C. This experiment is repeated in cycles, measuring the response of the system as it charges and discharges.

Once this information has been recorded in the Data Logger it's processed and organized with the use of a computer to fully understand and organized the obtained data.

4. Results and discussion

The experiment and its monitoring not only allow understanding the behavior of the system in dynamic conditions, but also the possibility to use it as a reference for future research. It serves as a base to calibrate the simulation models, which will then be used for further a priori studies. The values obtained are not representative by themselves, because they refer to the specific conditions of the experiment. Instead, they provide a general idea of how the materials behave and give an approximate order of magnitude for similar situations.

For the scientific test, the system is actively charged and passively discharged. This emulates the actual situation where a building could be thermally charged during a certain time, while that energy would then be released slowly over time depending on the environment and its needs. The idea is to extend and expand the thermal inertia of the building, making it last for more than one day and reducing the time spacing between the required charges.

Energy stored, used to evaluate thermal battery performance, is defined as Eq.1 :

$$E_{\text{Stored}} = m_{\text{PCM}} \cdot \lambda + \int m_{\text{Concrete}} \cdot Cp\ (T + 273)\ \mathrm{d}T \qquad (1)$$

The temperature range for the experiment is T_{min} = 15 °C and T_{max} = 38 °C. This range is also limited by the charging time of the battery. Therefore, energy stored is defined as Eq.2:

$$E_{\text{Storage}} = m_{\text{PCM}} \cdot \lambda + \int m_{\text{facade}} \cdot Cp \, (T_{\max} - T_{\min}) \, \mathrm{d}T \quad (2)$$

Where m_{PCM}, $m_{façade}$ and λ are PCM mass, façade mass and latent heat, respectively.

Table 1 below includes the properties of the different PCM-concrete dosages for the PCM layer.

Table 1. Properties of the INPHASE façade developed containing different PCM amounts

Vol. % PCM	**% PCM [kg/kg]**	**Density [kg/m³]**	**Thermal conductivity k [W/m·K]**	**Specific heat Cp [kJ/(kgK)]**
0%	0%	2100	2.50	1.0
9%	5%	2000	1.75	1.0
19%	11%	1750	1.25	1.1
24%	14%	1650	1.20	1.2
32%	20%	1450	1.00	1.4

Density of concrete layer: 2300 kg/m³

To simplify and given that the experimental result is intended to be approximate, two types of temperatures are considered according to their location: the temperature of concrete without PCMs is obtained from thermocouples #1, #2 and #3; on the other hand, thermocouples #3, #4 and #6 provide the temperature for the PCM-containing concrete. Thermocouple #3 is used for both situations given that it is located right in between the two layers. On the other hand, thermocouple #5 has been ignored because its proximity to the pipe and the hot water within alter the value considerably. (Please refer to *Figure 3* for the exact location of each thermocouple in the test cells).

This information, properly organized and filtered, results in the analysis of the charging and discharging capabilities of the testing blocks under the conditions established for the experiment. One of the interests is to see and compare the effect of the energy storage capacity as opposed to the thermal conductivity.

Another object of study is the total amount of energy that can be stored in the materials during a charging period of 30.000 seconds (approximately 8 hours). The following Figures show the temperature increase while the system is supplied with water at a controlled temperature. Each line represents a specific PCM-concrete dosage, with the final temperature calculated through the average value from the three corresponding test cells.

Figure 4 reflects the graph of time and temperature for the concrete containing PCMs, obtained from thermocouples 3, 4 and 6. *Figure 5* represents the same graph for the base concrete layer, in this case from thermocouples 1, 2 and 3.

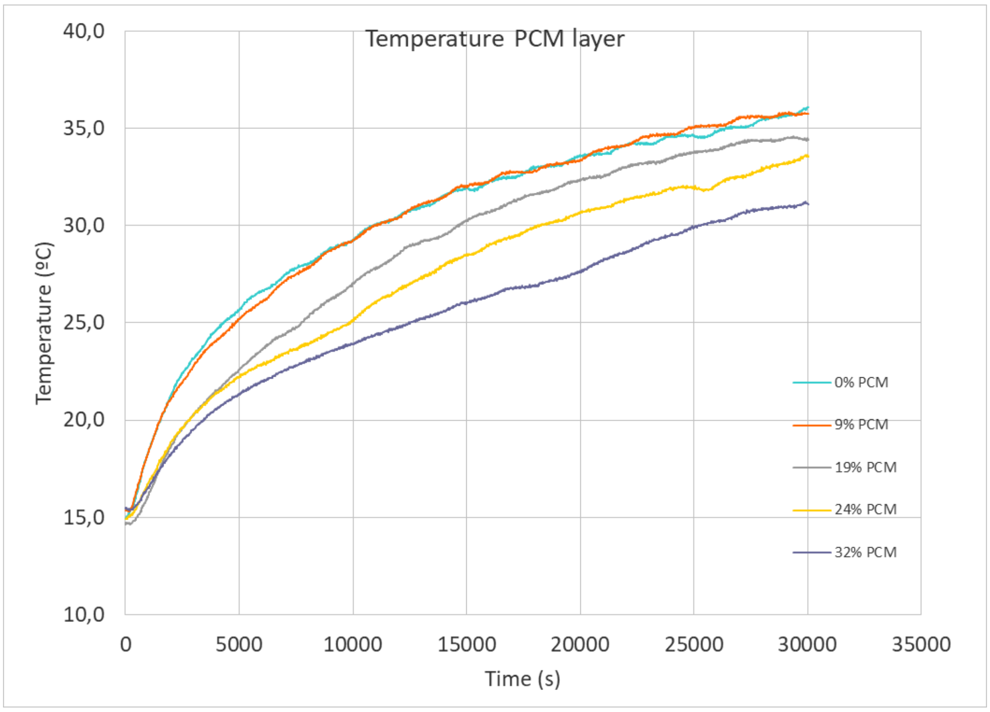

Figure 4. Time-Temperature graph for the PCM-containing concrete layer for 0-30.000 seconds - Charge.

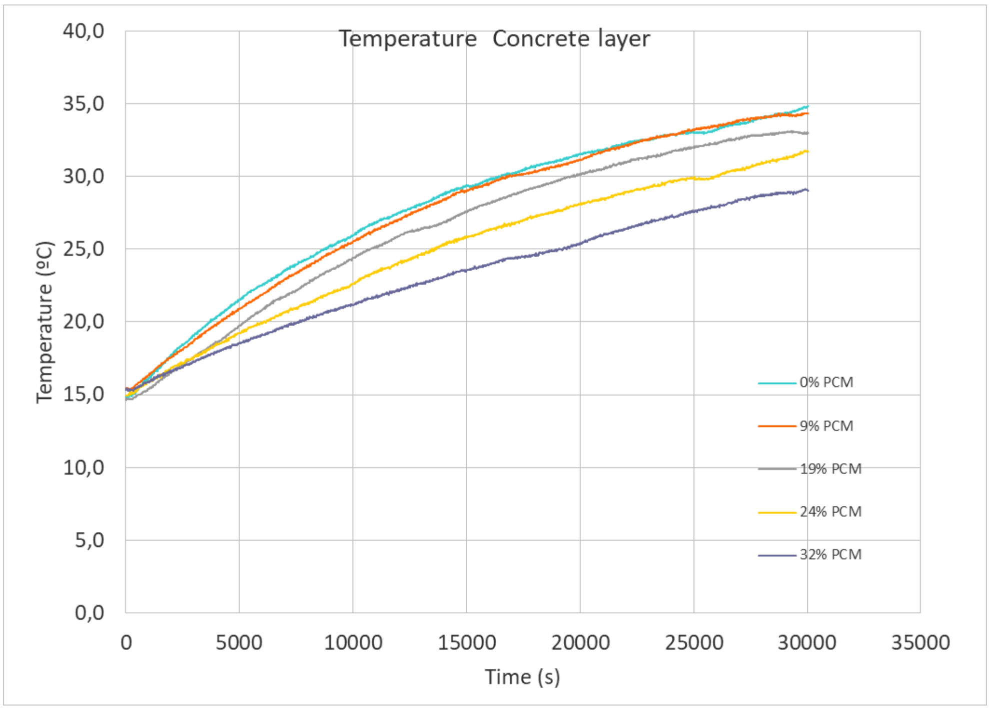

Figure 5. Time-Temperature graph for the mass concrete layer for 0-30.000 seconds - Charge.

Looking at the graphs, one piece of information that can be extracted is the time required for the system to increase the temperature from 20ºC to 30ºC. These two values represent interesting lowest and highest temperature levels for the standard use of a building. In all the analyzed examples, both PCM-containing concrete and mass concrete, test cells with lower amounts of PCM prove to demand less time to reach 30ºC. On the contrary, cells containing higher levels of PCM take longer to achieve the same increase in temperature. This is directly related to the thermal conductivity of the materials. The higher amount of PCM in the concrete, the lower the conductivity is, therefore producing a slower energy exchange.

When a 30.000 second limit is set for the charging process, the test cells with higher amounts of PCM haven't reached their full thermal potential. This shows that they could be charged at a higher temperature in order to achieve the desired temperature in a shorter period of time.

While temperature is a significant value to understand the system and its response, it is also useful to translate this information into the amount of energy stored in the materials, both sensible and latent. *Table 2* provides the breakdown of the energy capacity in the mass concrete and the PCM-containing concrete layers from 0 to 30.000 seconds, with an initial temperature of 15ºC.

Table 2. Energy stored in the façade

Vol % PCM	Energy stored, structural layer (Sensible range) [kJ/m2]	Energy stored, PCM layer (Latent heat) [kJ/m2]	Energy stored, PCM layer (Sensible range) [kJ/m2]	Total energy stored [kJ/m2]	Percentage in relation to 0% PCM (%)
0%	5464,8	0,0	1352,4	6817,2	100,00
9%	5326,8	440,0	1264	7030,8	103,13
19%	4995,6	847,0	1116,5	6959,1	102,08
24%	4636,8	1016,4	1077,12	6730,3	98,73
32%	3891,6	1276,0	909,44	6077,0	89,14

Initial temperature: 15ºC

Looking at the values from the table, it can be deduced that increasing the amount of PCM has a non-sequential effect in the thermal properties of the materials. Smaller amounts of PCM (9% and 19%) increase the total energy stored, while the higher amounts (24% and 32%) are lower.

As far as discharging is concerned, the system was let to cool down by itself after reaching 30.000 seconds of charging. Thermocouples measured the cooling process and evolution of the different test cells, and the results were monitored and recorded as well.

Figures 6 and 7 show the discharge progression of the system, considering as the initial time (T=0) the instant T=30.000s from the beginning of the experiment. Once again, this information has been divided into two graphs, one for the PCM-containing layer (*Figure 6*) and one for the pure concrete (*Figure 7*). In order to obtain a comparable result between the different PCM-concrete dosages, one specific temperature was set as a starting point. This temperature was the lowest among the highest of the average for the test cells, being 33.9 ºC for the PCM-containing layer and 32.7 for the mass concrete layer. This allows to compare the response of the different test cells.

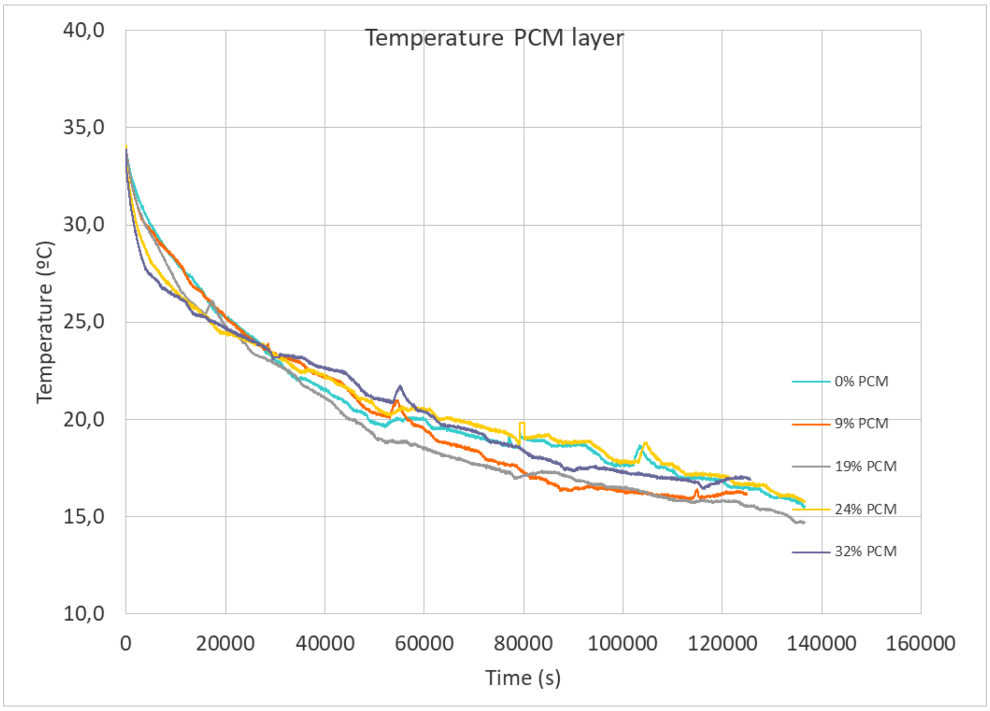

Figure 6. Time-Temperature graph for the PCM-containing concrete layer after 30.000 seconds - Discharge.

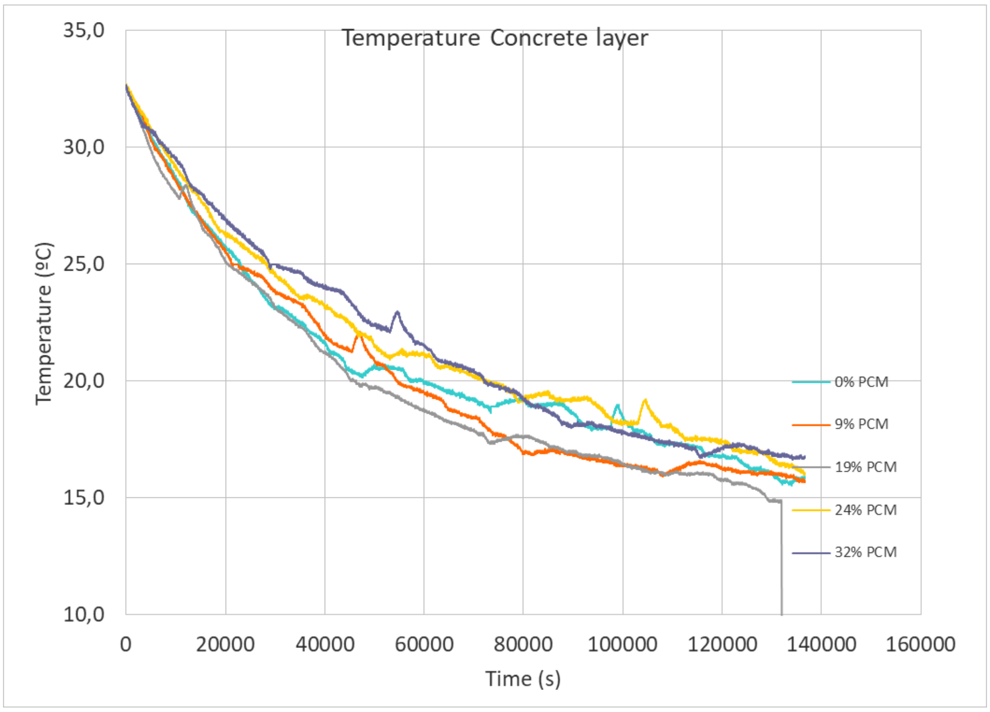

Figure 7. Time-Temperature graph for the PCM-containing concrete layer after 30.000 seconds - Discharge.

5. Conclusions

The experiment was developed to ascertain the heat transmission of the materials and work as a base for the calibration of models. Nevertheless, it also provides information in relation to the results regarding its behaviour over time while charging and discharging and the effect that PCMs have in the overall performance.

As foreseeable, the solution with integrated PCMs requires longer periods of time for the charge and discharge of the test cells. The energy density is logically much higher for the higher PCM dosages, but requires more time to be accumulated.

The lower thermal conductivity of the test cells with higher amount of PCM affects the charging process more than the discharging, which opens up the possibility to store energy with higher temperatures. This is not always convenient due to the reduction of energy performance, for example with pumping heat.

On the other hand, the reduction in thermal conductivity doesn't affect as much as could be expected. The concrete layer is still effective in the test cells with high PCM dosages.

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