Phase Change Materials as a solution to improve energy efficiency in Portuguese residential buildings

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Abstract. The buildings sector contributes to 30% of annual greenhouse gas emissions and consumes about 40% of energy. However, this consumption can be reduced by between 30% and 80% through commercially available technologies. The consumption of energy in the dwellings is mostly associated with the heating and cooling of the interior environment. One solution to reduce these consumptions is the implementation of technologies and Phase Change Materials (PCMs) for Thermal Energy Storage (TES). So, the aim of this work is to analyse the advantages, in terms of decreasing energy consumption, associated with the application of PCMs in Portuguese residential buildings. For this, eight PCMs with different melting ranges were analysed. These materials were analysed through a dynamic simulation performed with EnergyPlus software. The results achieved, showed that the materials studied allow to reduce up to 13% of the heating needs and up to 92% of the cooling needs of a building located in the North of Portugal, at an altitude higher than 100m.

1. Introduction
Progressive global energy demand is an increasingly important issue in terms of climate change and energy supply. The world consumes large amounts of fossil fuels by driving climate change and reducing fossil fuel reserves faster. One method to benefit the use of energy is to increase the building’s energy efficiency. The European construction industry is responsible for about 40% of energy consumption [1]. This consumption is mainly associated with the heating and cooling of the indoor environment, in order to obtain the best users thermal comfort. One solution to reduce these consumptions is the implementation of phase change materials (PCMs) and technologies for TES.

PCMs can be used to store energy or control energy balances over a specific period of time. The use of this kind of material for buildings heating and cooling has demonstrated to have a good performance [2]. The phase change from solid to liquid occurs when there is an increase of temperature. The PCM absorbs heat in an endothermic process and changes phase. Furthermore, the phase change from liquid to solid arises when the temperature decreases and the PCM release heat in an exothermic process and returns to its solid phase [2]. Through latent heat phase change, PCMs control temperatures in a specific range of time [3]. Since the phase change temperature is close to the desired comfort temperature, the energy used to change the phase of the material will lead to a more stable and comfortable indoor environment. The use of PCMs also allows reducing peak cooling and heating periods and, consequently, energy consumption spikes [3].
Over the last few years, several studies have been carried out in this area. Some of these are intended for the analysis of different mixtures of mortars with direct incorporation of this type of materials [4]–[9]. On the other hand, other authors dedicated themselves to the experimental and numerical analysis of constructive solutions with an application of a layer of PCMs [10]–[12].

Portugal is one of the countries in Europe where there are a large number of cold deaths [13], [14]. For this reason, it is important to analyse solutions that can reduce the energy consumption of Portuguese buildings and improve the indoor environmental quality of life. However, Portugal is also one of the countries with the highest rate of energy poverty [15], [16]. For this reason, a cost-benefit analysis of the application of PCMs will be carried out in a building located in the North of Portugal.

2. Methodology
The present study was carried out through the comparative analysis of the energy needs of one residential building located in the North of Portugal. This analysis compared the energy performance of this building with and without the application of a layer with different PCMs. It was considered the application of macro encapsulated PCMs on the inner face of the exterior walls and on the inner face of the roof. In total, the construction area, where the PCM was simulated, is 213 m².

For the analysis of the energy needs, the comfort temperatures recommended by the Portuguese thermal regulation [17] were considered: 18 ºC for the heating season and 25 ºC for the cooling season.

The building energy needs were calculated by using the EnergyPlus software and the conduction finite differences heat balance algorithm.

Some authors [18], [19] had already performed the model validation and verification of this software regarding the analysis of PCMs implemented in building walls and ceilings using the condition finite differences heat balance algorithm. These authors have used a similar approach as dictated by ASHRAE Standard 140 [20], which consists of analytical verification, comparative testing, and empirical validation. According to these studies this model can be used with acceptable monthly and annual results [18].

We analysed eight different PCMs commercialised by Rubitherm company [21]. These PCMs were selected because they have a melting point close to the comfort temperatures of the heating and cooling seasons: RT15, RT18, RT21, RT22, RT24, RT25, RT26 and RT28. The technical characteristics of these materials are presented in Table 1.

| Table 1. PCMs properties [21]. |
|-------------------------------|
| Melting area (ºC)              |
| RT 15                         | 10-17 | 17-19 | 18-23 | 20-23 | 21-25 | 22-26 | 25-26 | 27-29 |
| Heat storage capacity (kJ/kg)  |
| RT 15                         | 155   | 260   | 155   | 190   | 160   | 170   | 180   | 250   |
| RT 18                         | 0.88  | 0.88  | 0.88  | 0.76  | 0.88  | 0.88  | 0.88  | 0.88  |
| RT 21                         | 0.88  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |
| RT 22                         | 0.77  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |
| RT 24                         | 0.77  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |
| RT 25                         | 0.77  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |
| RT 26                         | 0.77  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |
| RT 28                         | 0.77  | 0.77  | 0.77  | 0.7   | 0.77  | 0.76  | 0.75  | 0.77  |

2.1. Case Study
The case study selected to perform the parametric analysis is a detached single-family house located in the North of Portugal. Portugal has around 3,500,000 buildings and the North is the geographic zone with the largest number of buildings (around 1,200,000 buildings and 1,800,000 dwellings) [22]. Detached houses are one of the most common types of constructions in Portugal and the vast majority of buildings (90.7%) [22].

The choice of the case study took into account the aim of simulating a building that was representative of the constructive reality of the North of Portugal. However, it was attempted that the geometry of the building was as simple as possible to facilitate dynamic simulation. In this way, we selected a family house with two bedrooms and 110 m², located in the North of Portugal, at an altitude
of 100 m. According to the Portuguese legislation, the climatic region of this building is I1, V2 (the most severe for winter and between the most severe, V1, and the mildest, V3 to summer).

In Figure 1 the geometry of the analysed building is presented. The living room (LR) and kitchen (KIT) are facing south.

![Figure 1. Case study geometry.](image)

Table 2 presents some details of the case study building geometry.

| Room     | Orientation | Room area (m²) | Glazing area (m²) |
|----------|-------------|----------------|-------------------|
| Kitchen  | South / East| 12             | 4.5               |
| Living room | South / West  | 28             | 9                 |
| WC1      | North       | 5              | 0.3               |
| Bedroom 1 | North / West | 16             | 4.5               |
| Bedroom 2 | North /East | 20             | 4.5               |
| WC2      | East        | 9              | 0.3               |
| Hall     | West        | 17             | -                 |

The building constructive solutions are presented in Table 1 and correspond to the typical constructive solutions existing in Portugal between 1960 and 1990 (construction period of time to which the largest number of existing buildings in Portugal corresponds). In the case of the exterior walls and the roof, it was adopted an inner coating with plasterboard to ensure that the only difference between simulations was the type of PCM applied.

It was also considered that the building was air conditioned through mobile heating and cooling equipment with an efficiency of 100%.
Table 3. Construction solutions of the case study building elements.

| Building element | Construction solution                                                                 | U (W/m².ºC) |
|------------------|---------------------------------------------------------------------------------------|-------------|
| Exterior walls   | Single masonry Wall with 22cm with 2 cm of plaster in the outside and coated with a gypsum plasterboard (1,3cm) | 1.76        |
| Interior walls   | Single masonry Wall with 22cm with 2 cm of plaster both sides                          | 1.76        |
| Roof             | Lightweight slab with false ceiling                                                   | 2.8         |
| Ground Floor     | Concrete slab covered with ceramic tile                                                | 1.65        |
| Glazing          | Single glazing (6 mm) and wooden frame                                                | 4.1         |

2.2. EnergyPlus Model

In order to perform the dynamic simulations some approaches and considerations were made. The simulation run period was considered to be one year and annual results were obtained. Regarding the occupancy schedules, it was admitted that building was occupied during all day in the weekends and from 7pm to 8am in the weekdays. When in the building, it was considered that people spend 15% of their time in the WCs and hall and 85% of the time in bedrooms, kitchen and living room.

Additionally to the fixed shading in the South faced, it was considered that the windows have a movable shading device (blind). This shading devices were considered to be open from 8 am to 7pm in winter and 30% open in the same period during summer.

Table 4 present the lighting and electric equipment level and functioning schedules that have been considered in the numerical model.

Table 4. Lighting and Electric Equipment design levels and functioning schedule.

| Design level (W) | Lighting | Electric Equipment | Functioning Schedule | Lighting | Electric Equipment |
|------------------|----------|--------------------|----------------------|----------|--------------------|
| Kitchen          | 18       | 100                | Until 7am            | 0,05     | 0,1                |
| Living room      | 47       | 150                | Until 8am            | 0,3      | 0,3                |
| WC1              | 12       | 50                 | Until 7pm            | 0        | 0,1                |
| Bedroom 1        | 24       | 80                 | Until 8pm            | 0,6      | 0,6                |
| Bedroom 2        | 30       | 80                 | Until 11pm           | 0,8      | 0,8                |
| WC2              | 13       | 50                 | Until 12pm           | 0,4      | 0,4                |
| Hall             | 20       | 40                 |                      |          |                    |

Concerning the ventilation, the building was considered to be ventilated only by natural ventilation by 1 air change per hour. This situation is common in the Portuguese residential buildings.

The acclimatization systems were modeled considering the EnergyPlus Ideal Load Air System. The HVAC set points were defined to be 18ºC for heating and 25ºC for cooling.

3. Results

3.1. Energy Needs

Figure 2 presents the case study heating needs without PCM (Reference) with and without the applications of the PCMs.

In the north of Portugal, either due to the weather or because of commonly used building solutions, the heating needs of buildings are usually much higher than cooling needs. By analysing the heating energy requirements, it was possible to verify that all PCMs analysed allowed to reduce the heating needs by at least 10% of their initial value. The PCM that presented better results was the RT22 because
the application of this material allowed to reduce the heating needs in 8.22 kWh/m².year, which corresponds to a decrease of 13.2% in relation to the reference solution.

Figure 2 shows that the initial cooling needs of the building were already relatively low. However, the application of PCMs allow to greatly reduce the cooling needs. There were great advantages in the application of the PCMs to the cooling station. The application of this type of material allowed to reduce the cooling needs by at least 53% of its initial value. However, considering the best-performing solution (RT28), there was a reduction in the energy consumption for cooling of 3.88 kWh/m².year. Taking into account the initial cooling needs, this value corresponds to an improvement of 92.2%.

Regarding the total energy needs it is concluded that the application of this type of technology leads to a significant reduction on these index. Observing the situation where the PCM produced fewer effects (RT15), it is possible to highlight that the energy needs decreasing its initial value by 11%. The solution that allowed to obtain a greater reduction of the energetic necessities was the application of RT24. This material allowed to reduce the energy needs in 10.65 kWh/m².year, which corresponds to a percentage decrease of 13.4%.

Other authors [10], [11], [23], [24] [25] have performed similar numerical analysis by incorporating PCMs in walls and ceilings in buildings located in Porto. Although some of these authors have been focused in different outputs (internal temperature variation, heating and cooling degree days), the results can be compared. Regarding the energy consumption, these studies have also found advantages in the incorporation of PCMs in buildings elements.

3.2. Optimized Solution
Taking into account the results obtained, a simulation was carried out in which the effects of PCMs were maximised. So, it was tested one situation in which the PCM with better behaviour in the heating station (RT22) was applied on the building roof and the PCM with better performance in the cooling station (RT28) was applied on the exterior walls. However, it was verified that the improvement over the situation with the best performance in terms of total energy needs was not significant (a decrease of only 0.01 kWh/m².year was achieved).
3.3. Economic Profitability
In 2010, Markets and Markets have launched a report called Advanced Phase Change Material Market: Global Forecast (2010–2015)” [26] stating that the increasing demand for energy-saving and environment-friendly technology is driving the growth of the global PCM market. After analysing the energy savings, it was developed an analysis to understand if the application of PCMs presents economic viability compared to the reference solution. As presented in Equation 1, the building’s LCC was assessed according to the method proposed by the European Commission Delegated Regulation No. 244/2012 of 16 January 2012 [27].

\[
C_g(r) = C_I + \sum_j \left[ \sum_{i=1}^T \left( C_{a,i}(j) \times R_d(i) - V_{f,r}(f) \right) \right]
\]

(1)

Where:
- \( r \) - Period
- \( C_g(r) \) - Global cost over the calculation period
- \( C_I \) - Initial investment cost for the measure \( j \)
- \( C_{a,i}(j) \) - Annual cost during year \( i \) for measure \( j \)
- \( R_d(i) \) - Discount rate for year \( i \)
- \( V_{f,r}(f) \) - Residual value of measure \( j \) at the end of the calculation period

A discount rate (inflation) of 3% was also taken into account, as well as the evolution of the energy costs. The energy prices predicted in EU energy trends to 2030, published by the European Commission in 2009, were considered for the period between 2013 and 2030 [28]. The prices forecasted in the Energy Road Map 2050 were used for the period between 2030 and 2046 [29].

Investment costs for the reference solution are estimated based on market analysis. The investment costs for PCMs were provided by the manufacturer [21]. The PCM solution studied in the economic analysis was the one with the best energy performance results.

| Table 5. Economic analysis. | Investment Costs | Operational Costs | Life Cycle Costs |
|-----------------------------|------------------|-------------------|-----------------|
| Reference                   | €11,654          | €40,228           | €51,881         |
| PCM (RT22 roof + RT28 wall) | €36,882          | €34,822           | €71,704         |
| Difference                  | + €25,229        | - €5,406          | + €19,823       |

Table 2 presents that the initial investment that needs to be made in the solution with PCMs is more than three times higher than the investment for the reference solution. In terms of operational costs, it is possible to highlight that the solution with PCMs allows obtaining a reduction of about 13% in the energetic invoice. However, regarding life cycle costs, it is clear that, for now, the decrease in operational costs is not sufficient to cover the high initial investment.

Other authors have performed an analysis on the economic viability of incorporating PCMs in building walls and ceilings [30], [31]. The results are greatly influenced by the type of PCMs, the encapsulation technique, the building characteristics and use and mainly by the climatic conditions of the building location. However, in Portugal and specifically in the North region, other authors [32] have already come to the conclusion that, for now the pay-back time is still too long.

Nevertheless, although the incorporation of PCMs in buildings is still an expensive technology, it could contribute for reduction in peak demand and potential reduction in energy consumption and savings for buildings customers [33].

4. Conclusions
The application of PCMs has been discussed as a solution to reduce the high-energy building’s consumption. In this work, eight different PCMs with melting points ranging from 15 °C to 28 °C were
analysed. This analysis was carried out through the dynamic simulation of the energy performance of a building located in the North of Portugal with and without the application of this type of materials.

It was found that the materials studied led to a reduction of 13% in energy requirements for heating, 92% of energy requirements for cooling and 13% of total energy requirements. However, an analysis of the economic profitability of this type of solution was carried out and it was verified that the high initial investment is not compensated by the decrease in the operational costs, nowadays. Although significant energy savings have been observed in the cooling station, they do not lead to economic profitability. One of the reasons for this is related to the fact that the energy needs of the Portuguese buildings located in the North, at an altitude higher than 100m, derive mainly from heating and not from cooling needs.

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