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Phase change materials and energy efficiency of buildings: A review of knowledge

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ABSTRACT

Nowadays, the energy efficiency of buildings is one of the biggest preoccupations, due to the high negative impacts in the environment, economy and society. The utilization of phase change materials (PCM) in construction industry was been developed by several authors around the world. In this study, the connections between the PCM, energy efficiency and energy poverty are presented. The main PCM characteristics and an exhaustive description of the PCM application in buildings, more specifically in walls, floors, ceilings and glazed areas, are also presented.

1. Introduction

The rapid economic growth in the world has led to an increase in energy consumption. Fossil fuels dominate the world energy market, with a share of about 81%. However, fossil energy sources are running out and their exploitation entails rather high environmental and economic costs. Its exploitation is associated with the emission of harmful gases into the environment, which increases the environmental concerns of society [1]. Thus, the efficient use of energy and the possibility of using renewable energy are increasingly important.

Currently, the high growth rate of urban areas and the increased comfort parameters have been caused an increase in energy consumption, making it one of the biggest concerns of today's society. This problem is due to the excessive use of energy from non-renewable sources, which causes serious impacts on the environment. The large part of the electric energy consumption in the residential sector is associated with heating and cooling. Thus, it is urgent to implement solutions aimed to increase the energy efficiency of buildings.

Every year, energy of about 5×10^{24} J is supplied by the sun and reaches the entire land surface. This amount of energy is about 10000 times higher than the actual energy consumption per year around the world. So, the need to find a way to take advantage of this natural resource along with the demand for an improvement in the quality of the built environment is enormous. In this way, the scientific community has now made efforts to combine the use of solar energy and functional building materials, which allow limiting the energy consumption in buildings [2].

The ability to reduce and relocate the energy consumption, combined with the use of phase change materials (PCM), enhances their use in construction products as a solution to improve the energy efficiency of buildings, demonstrating social, economic and environmental benefits, with large contribute to the different dimensions of sustainable development.

The enormous surface area covered by building materials is now a promising solution in the exploration of solar energy, thanks to technological improvements in the energy and environmental fields. On the other hand, combining the low thickness achieved with the use of phase change materials and flexible construction solutions is possible to obtain solutions with a greater capacity to adapt to the life cycle assessment of the buildings, moving towards a more sustainable construction. Therefore, it is necessary that the construction industry stops being traditionally conservative and starts focusing on innovative solutions that provide the problems solution with several years.

The storage of thermal energy and phase change materials has been a relevant research topic in recent years, attracting the interest of several researchers around the world, in the most diverse areas, due to its ability to reduce energy needs, based in the solar energy.

The incorporation of PCM in construction materials led to the publication of several articles in the last years. According to Fig. 1 it was possible to observe an increase in the publication of this issue after 2011, which meets the major concerns about the sustainable construction, energy consumption and energy efficiency in the scientific community. This growth in the number of published papers related to phase change materials is also associated with the goals of the 2020 Horizon and the 2030 Agenda for Sustainable Development, which ensure the access to affordable, reliable, sustainable and modern energy

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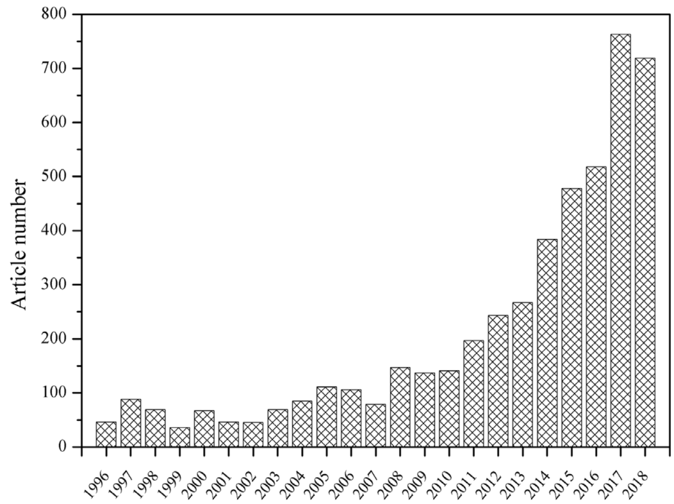

Fig. 1. PCM publication between 1996 and 2018.

for all as one of the main concerns of the scientific community.

2. Energy efficiency

The growing demand for energy throughout the world is one of the main reasons for the unsustainable development of our planet [3]. This increase in energy consumption is justified by the increase in world population and also by the fact that more people have access to electricity.

The high energy consumption and greenhouse gas emissions are a serious problem in the exploitation and consumption of non-renewable fossil fuels with high impact to the environment. It is known that energy production is the largest emitter of greenhouse gases, representing approximately 75.2% [3, 4].

In recent decades, there has been an international discussion on climate change mitigation through the reduction of energy consumption. In 2012, the EU adopted a target of reduce energy consumption and emissions of greenhouse gases in 20% until 2020 compared to 1990 values. However, more recently, 2017 data, indicate that this target will not be met, even though there was recommended an increase in the targets for 2030, with a reduction of around 27% for energy consumption and 40% for greenhouse gas emissions [4]. In this way, an additional effort is required to achieve these objectives.

Portugal is still an energy dependent country since it imports much part of the consumed energy. However, in recent years there has been an enormous effort to combat this problem, reducing not only the imported energy but also the burning of fossil fuels. Currently, in Portugal, the production of renewable energy in wind power plants, photovoltaic and small hydroelectric power plants accounts for about 42% of electricity consumption and exportation.

Buildings are responsible for a large share of final energy consumption in the European Union, about 38.9%, higher than the transport and industry, with approximately 33.1% and 23.3%, respectively [4]. Thus, it is easy to understand that this is a sector with high potential and huge urgency of intervention.

The Portuguese housing stock is aging, with about 15% of Portuguese buildings predate 1945 and approximately 70% were built before 1990, period of time when there was no regulation regarding to the buildings thermal performance [5].

One of the measures to reduce energy consumption is the modernization of buildings in order to reduce their low energy efficiency. On the other hand, the energy rehabilitation of buildings is one of the measures and objectives of sustainable development of the United Nations until 2030 [4]. In recent years, measures have been taken to increase the energy efficiency of buildings, and the most significant improvement was observed after the 1990s, due to the implementation of strict regulations in the construction sector. Thus, it was found that residential buildings built in 2002 show a decrease in energy consumption of around 24%. However, estimates of annual building renovation rates in Europe currently stand between 0.5% and 2.5% of real estate stock [4]. These numbers are quite small, so the implementation of new functional construction materials, with capacity for thermal regulation is a fundamental way to solve this problem.

3. Energy poverty

Energy consumption in the construction industry is present in all stages of the development of a building, i.e. energy spent for the extraction and production of raw materials, construction of the building and the maintenance costs of buildings during their life time. Thus, there is already the concept of energy poverty, which is related to the fact that families do not have conditions or spend more than 10% of their monthly budget to ensure comfort conditions inside their buildings. The main causes of energy poverty in Portugal are related to the poor quality of buildings, high energy prices and very low family incomes [6]. It is also known that in Portugal about 29% of the families are in this situation, thus resulting in the need to intervene quickly [6–8]. Families easily give up thermal comfort over energy bill savings and hence their monthly budget. The fight against energy poverty has to counteract and try to eliminate its causes. In this sense, given the inability to reverse the prices of fossil fuels or the low incomes of Portuguese families, the focus is mainly on improving the thermal conditions of buildings. This improvement can be achieved through measures that promote energy efficiency and the use of cheaper and more sustainable energy sources, such as the use of functional materials with thermal storage capacity.

4. Phase change materials

4.1. Operation principle

It is generally known that all materials interact with the environment. However, the most part of the materials does not have the ability to change its properties according to the characteristics of the environment in which they are applied.

The PCM operating principle consists in change their status, according to the environment temperature. The PCMs absorb and store energy, suffering a change from a solid state to a liquid state, while temperature increases. On the other hand, the material possesses the capability to release the previously stored energy when the temperature decreases, suffering in this case a change from a liquid state to a solid state.

There are different processes of phase change. The phase change materials may have a transition from the solid phase to the liquid phase, from the solid phase to the solid phase and from the solid to gaseous phase by evaporation [9]. The phase change by evaporation has a high enthalpy. However, it presents some application problems, such as a high volume and pressure variation during the phase transition. The solid-liquid transition is preferred for thermal energy storage, since they do not present significant volume change during the phase transition [9–11]. Finally, the solid-solid transition has characteristics very similar to the solid-liquid transition, but with a significantly lower energy storage capacity [11].

4.2. PCM classification

There is a wide variety of PCM's with different melting points, which are divided into three categories. In 1983, the first classification of the substances used for thermal storage appeared, classifying the PCM as organic, inorganic and eutectic mixtures [12].

4.2.1. Organic PCM

The organic phase change materials may be paraffinic or non-paraffinic. Normally, they have a congruent fusion without degradation during the time. They consist of a chain of carbon and hydrogen atoms. Pure paraffins, for example, generally contain from 14 to 40 carbon atoms and paraffin waxes from 8 to 15 carbon atoms. Its melting point is greater as the number of carbon atoms gives rise to the chain [13].

Paraffins are safe, reliable, predictable, non-corrosive, low cost, chemically inert and stable materials below 500°C and exhibit slight volume variations. The congruent melting process and good nucleation properties are once again seen as advantages in their use. However, they also present some disadvantages such as low thermal conductivity and high flammability [13-14].

The main advantages of this PCM type are based on the availability of a wide range of temperatures, high latent heat of fusion, low liquid phase undercooling capability, congruent phase change, auto-nucleation properties, low segregation, high nucleation rate, thermal and chemical stability, non-reactive, non-corrosive, compatible with construction materials and recyclable. On the other hand, the main disadvantages of these materials are the low enthalpy, low thermal conductivity, low density, flammable, significant volume variation and high cost [13,14].

4.2.2. Inorganic PCM

The inorganic phase change materials are classified as hydrated and metal salts. The hydrated salts have been extensively studied for their use in thermal storage systems. Its most attractive properties are the high heat of fusion per unit volume, high thermal conductivity (almost double the paraffin) and small changes of volume during the phase transition. In addition, the hydrated salts are non-corrosive, compatible with plastics and non-expensive. Some of its disadvantages are the formation of salts inconsistently and lower nucleation rate [13].

Metal salts have not yet been seriously considered for thermal storage due to their weight. However, they have some potential related to reduced volume changes and high heat of fusion and thermal conductivity [13].

Summary, the advantages of the inorganic PCM are the high enthalpy, low cost, easily available, high thermal conductivity, Nonflammable, low volume change, compatible with plastic containers and low environmental impact. Their main disadvantages are the liquid phase subcooling problems, low nucleation properties, incongruent phase change, low thermal stability, material separation problems during phase transition, decomposition, incompatibility with some construction materials, corrosive to metals and slightly toxic [13,14].

Comparing with organic PCM, it is possible to conclude that inorganic materials have a higher thermal conductivity, reduced flammability and lower acquisition costs [14].

4.2.3. Eutectic mixtures

The eutectic mixtures result from the combination of two or more compounds of organic, inorganic or both PCM, thus these present a transition temperature closer to the existing needs, compared with the individual compounds. The two or more components of the mixtures should crystallize congruently [13,14].

The main disadvantage of these materials is the high cost, about two or three times higher than the organic or inorganic PCM's, limited thermophysical properties and strong odor. The main advantages may be the suitable transition temperature, high enthalpy and congruent phase change [13,14].

4.3. PCM properties

The thermal performance of the phase change materials depends on the melting temperature, thermal conductivity and energy storage density. Among the different types of PCM suitable for thermal energy storage, the most suitable material is one with a fast melting and solidification point [15].

Not all existing PCM's can be used for thermal storage. An ideal PCM must have some desirable thermophysical, kinetic, chemical, environmental and economic properties [16,17].

Regarding the thermophysical properties it is necessary that the selected PCM has [14, 16,17]:

- Transition temperature in the desired operating temperature range, in order to guarantee the heat storage and release;
- High heat of transition per unit of volume, in order to store the maximum energy incorporating the minimum amount of PCM;
- High sensitive heat, translated by its heat capacity, in order to increase its energy storage capacity;
- High thermal conductivity in both the solid and liquid states to easily promote heat transfer;
- Reduced volume variation during the phase transition, in order to reduce the problems related to its containment;
- High density;
- Consistent fusion;
- Long term thermal stability;
- Absence of segregation during phase change.

Regarding the kinetic properties, the PCM must have a high growth rate of the crystals, in order to prevent the sub-cooling liquid phase and respond to requests of the surrounding environment [14, 17].

Concerning to the chemical properties the phase change materials should not be degraded after a large number of cycles, non-corrosive to construction materials, non-flammable, non-toxic and non-explosive, for environmental and safety reasons [14, 17].

From the point of view of the environmental properties the phase change materials must have low energy consumption, ease of separation from other materials, high recycling potential and low environmental impact [16].

Finally, regarding the economic properties, the PCM should be abundant, available and with a low acquisition cost, in order to become a competitive solution with other constructive systems [14, 17].

4.4. Problems in the application of PCM

Even making a rigorous selection of the phase change material to be applied, sometimes it cannot meet all the requirements. The more frequent problems in the application of phase change materials can refer to phase separation, supercooling and fire resistance.

4.4.1. Phase separation

Phase separation is a problem that can lead to malfunction of phase change materials. In an ideal situation, a solid substance when transits to the liquid phase maintains its homogeneous composition, consequently when it returns to the solid phase maintain the same composition and homogeneity of the material, always presenting the same enthalpy and transition temperature, during the life cycle [18].

Regarding to the eutectic mixtures, it is important to verify that the phase transition happens at the same temperature, otherwise it may happen that one of the constituent materials is still in the solid state and the other in the liquid state, causing the phase separation. Thus, the original composition of the material ceases to exist and the material does not exhibit the initial transition properties [18]. The application of thickening materials increases the viscosity of the mixture, maintaining the various constituents together [14].

4.4.2. Supercooling

Supercooling consists on the material solidification at a temperature below the phase transition temperature [14]. Basically during heating the phase change material has a good behavior, however in the cooling it cannot release the stored energy. Thus, it is necessary that the outside temperature decrease significantly for the material completes its operating cycle [18].

This problem is more frequent in inorganic phase change materials. The organic phase change materials mostly based on paraffins do not exhibit supercooling. However, one way to mitigate this problem is to add a nucleating agent [14, 18].

4.4.3. Fire resistance

In recent years there has been growing the concern about fire resistance in order to protect buildings from fire hazards. Organic phase change materials, in particular paraffin waxes, present some flammability hazards which raise some concerns about the fire resistance of products where this material is applied. One solution that has been studied is the introduction of a stabilizer material with flame retardant properties, such as magnesium hydroxide and silica [14, 18,19].

4.5. Improving PCM performance

Often, the application of phase change materials to plates, tubes or other elements with low thermal conductivity can compromise the efficiency of the material [18]. There are some ways to improve the performance of phase change materials such as the addition of nucleating agents and thickeners, incorporation of high thermal conductivity additives, fire additive, contact surface increase, porous matrix impregnation and use of multiple PCM [14, 18].

The use of multiple PCM is to put into operation several PCM with different transition temperatures. In this way, the thermal storage system can remain active and have a higher profitability over a wider temperature range. Mosaffa et al. [20], evaluated through numerical simulations the efficiency of a refrigeration system employing multiple phase change materials, observing a good performance of the refrigeration system. Shaikh and Lafdi [21], perform several numerical simulations to analyze the impact of using different configurations with various PCM types on slabs. It was possible to verify a significant improvement in energy storage, in terms of the total stored energy rate. The numerical results also indicated that energy costs can be reduced by using multiple phase change materials compared to the use of a single PCM.

The impregnation of porous matrices of high thermal conductivity with phase change materials, allows increasing the conduction of heat. Since thermal conductivity decreases with increasing porosity, it can be said that there is an optimum matrix porosity value for the impregnation, without compromising the thermal conductivity. Mesalhy et al. [22], carried out a study in which they impregnated a graphite matrix with PCM, having verified that the presence of the porous matrix has a great effect on the rate of heat transfer and energy storage of the PCM. The decrease in the porosity of the matrix increases the melt speed. It has also been found that the best technique to increase the storage efficiency of PCM is the use of a solid matrix with high porosity and high thermal conductivity.

4.6. PCM incorporation techniques

The PCM can be incorporated in construction materials through different methods, such as direct incorporation, immersion, encapsulation and stabilization [1].

The most commonly used PCM incorporation technique is the encapsulation (Fig. 2), due to the possibility of using microencapsulation and macroencapsulation. It is important to note that the use of microencapsulation is about 70% of the work done using the encapsulation technique, while macroencapsulation is about 30%. On the other hand, the direct incorporation and shape-stabilization are the techniques with less number of developed works, however they are quite promising techniques.

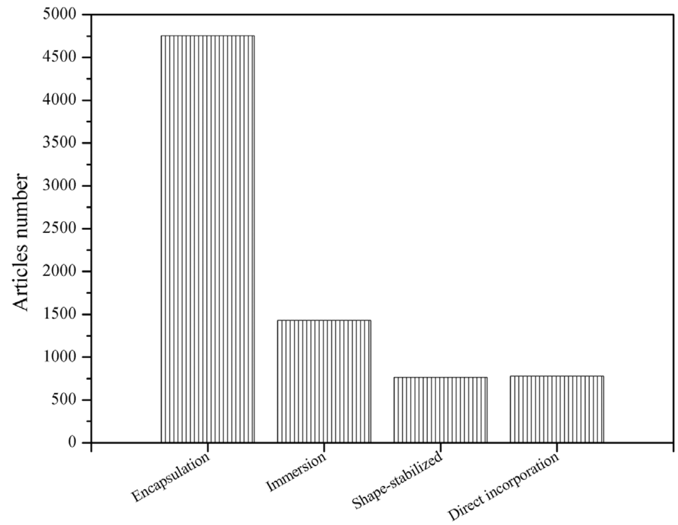

Fig. 2. Utilization of PCM incorporation techniques.

4.6.1. Direct incorporation

Direct incorporation is the simplest and most economical method for using PCM, and the material is directly mixed with the construction materials during its production. However, it is assumed to exhibit some disadvantages such as the affectation of the hydration products, decrease in bond strength between the binder paste and aggregate, decrease the mechanical properties and durability [23].

Until recently it was thought that the direct incorporation of PCM in construction materials led to material losses, since it could be freer to move from where it was initially applied. Aguiar and Cunha [24], developed work and are holders of a patent in which they show that the use of this technique is quite efficient and there is no PCM losses. The authors developed significant work incorporating free PCM in mortars and evaluating their behavior at different temperatures, in order to observe the PCM behavior in liquid and solid state. It was possible to observe that the PCM mortars showed always a lower water absorption capacity compared to the mortars without PCM addition [25].

4.6.2. Encapsulation

In this technique the PCM is encapsulated before its incorporation in construction products, ensuring that it does not move from the place where was applied during the liquid phase. The PCM containment must meet the requirements of mechanical strength, flexibility, corrosion resistance and thermal stability, as well as acting as a protective barrier. It should also have sufficient surface area for heat transfer, structural stability and easy handling of the material [26].

There are two main forms of encapsulation: microencapsulation and macroencapsulation [14].

The macroencapsulation is based on the introduction of PCM into tubes, panels or other large containers, usually containers higher than 1 cm of diameter. In this technique it is possible to place a significant amount of PCM in a single container. The main advantages of this method are the easy transport and handling, possibility of the encapsulation being designed specifically for the intended application, better compatibility with the material and reduction of external volume changes [1, 14]. The disadvantages are the low thermal conductivity, need of protection containment elements against the destruction and possibility of PCM solidification in the corners and edges, reducing the heat transfer [1].

The macroencapsulation is a great method to incorporate PCM into prefabricated walls and roofs. In this method the PCM is not mixed with the basic materials (concrete, mortar, etc) avoiding the decrease of the mechanical characteristics of the basic materials. One of the applications for PCM macroencapsulation is the panel-shaped containers. For better thermal performance it is important that these containers have high thermal conductivity, such as metal containers [27].

Shi et al. [28] used steel containers for PCM macroencapsulation in concrete sandwich panel walls. Their results indicate a significantly decrease in the maximum indoor temperature and an increase the minimum indoor temperature, which reduce the indoor temperature variations. Navarro et al. [29] studied the thermal performance of PCM macrocapsules in an active hollow core concrete slab. It was possible to conclude that the proposed PCM-concrete slab could perform the charge/discharge process of PCM in almost 70% of summer and winter days.

Generally, the performance of the PCM macroencapsulation greatly depends on several factors, such as the location of the PCM macrocapsule, microclimate conditions, configuration of the building element, thermal properties of the building material and PCM type [27].

Microencapsulation consists of placing a small molecular mass in small particles coated with high performance polymers. The microcapsules may be spherical or asymmetrical, with a diameter inferior to 1 cm. However, the preferred diameter is between 1 and 60 μm. The advantage of this encapsulation process is the improvement of heat transfer through its large specific surface area [14, 26, 30,31]. The PCM microcapsules may be obtained in powder or aqueous dispersion. The microcapsule denomination depends essentially on its nucleus. These may be mononuclear, microcapsules which contain a shell having a single nucleus; polynuclear, microcapsules with many nucleuses inside the same shell and a matrix in which the nucleus is homogeneously distributed inside the shell [29].

Microencapsulation methods are basically divided into chemical, physical-chemical or mechanical processes [30].

Chemical processes are essentially polymerization and polycondensation processes in which the wall of the microcapsule is formed in-situ. Physical-chemical methods are those in which walls are formed by preformed polymers by processes such as solvent removal. Mechanical processes include a variety of spray processes, fluid deposition coating processes and micronization. One of the most widely used methods for PCM microencapsulation is the dispersion of PCM droplets in an aqueous solution and the formation of polymer walls around the droplets using techniques such as coacervation, interfacial polycondensation and other in situ polymerization processes. The capsule may be manufactured from a variety of materials, such as polyurea, polyurethane, polymethylmethacrylate, polyvinylacetate, polystyrene or urea-formaldehyde resins, melamine-formaldehyde or gelatin-formaldehyde [17, 30].

The choice of the microencapsulation process as well as the material for capsule formation is of particular relevance because its subsequent application depends on its chemical, physical and mechanical stability. A potential problem associated with the PCM microcapsules incorporation is the microcapsule breakage during mixing process or loading of concrete, as evidenced by SEM images in various studies [32–35]. Pomianowski et al. [35] conducted cryo-scanning electron microscopy study in order to investigate the final microcapsules state after the mixing process. The obtained results indicated some damage in the PCM microcapsules. For example, Sun [36] studied the compressive strength of PCM microcapsules based on melamine-formaldehyde. The microcapsules, with diameters between 1 and 12 μm, were subjected to compression between parallel faces, compressed and released, and compressed until rupture. The results showed that the capsules had an elastic extension of about 19% and bursting thereof to an extent of about 70%. Later Sun et al. [37] compared the mechanical resistance of microcapsules of melamine-formaldehyde, urea-formaldehyde and gum arabic-gelatin. The different capsules tested showed an elastic behavior up to 19% for melamine-formaldehyde and 17% for urea-formaldehyde. The arabic-gelatin capsules were subjected to a 50% extension, exhibiting only elastic behavior.

The microencapsulation has advantages, such as increasing the possibilities of incorporation in various construction materials, high heat transfer rate per volume unit, due to its larger surface area, greater resistance to volume variation during phase transition, chemical stability and improved thermal reliability. The disadvantages of this technique are related to the decrease of the mechanical properties of the construction materials and the higher cost [1].

Generally, PCM microcapsules are used directly in the mixing process of the construction materials, mostly as partial replacement for aggregates. Cunha et al. [38] developed a study with the aim to evaluate the influence of two different PCM microcapsules in lime-gypsum mortars. It was possible to verify that the use of different PCMs microcapsules provides different characteristics in the mortars, which is related to the type of polymer used for the construction of the wall of the microcapsules and also to their size.

4.6.3. Immersion

In the immersion method, the construction products are dipped in liquid PCM in order to absorb the material by capillarity. However, the PCM can interfere with the hydrating products of the construction materials and affect the mechanical properties and durability [23].

Usually, this technique is used for incorporate PCM into porous lightweight aggregates. In recent years several researchers proposed various porous aggregates impregnated with PCM, using different impregnation methods (vacuum impregnation and direct impregnation), and various coating and supporting materials (expanded clay, recycled crushed concrete block, expanded vermiculite) [39–41]. The porous structure of lightweight aggregates is ideal for containing the PCM in concrete. However, these materials need to have adequated characteristics, such as porosity, pore size, aggregate size and surface area.

Aguayo et al. [42] study four different types of lightweight aggregates (pumice, perlite, expanded shale/clay, and expanded slate). It was possible to conclude that porosity and pore diameter can affect the PCM absorption capacity of these materials. Kheradmand et al. [43] indicates that the aggregate size can impact the PCM absorption capacity since the absorption capacity of the smaller aggregates was higher.

4.6.4. Shape-stabilization

Taking into account the risk of PCM leakage in its liquid state, several researchers have proposed a new technique the shape-stabilization [44–47].

In this technique, the PCM and support material are melted and mixed at an elevated temperature followed by cooling until the mixture becomes solid. Stabilization of PCM is carried out using high density polyethylene, styrene and butadiene. The main advantages of this method are high specific heat, adequate thermal conductivity and maintenance of PCM stabilization during the phase transition process, without the need of a container [1].

The selection of the supporting material and the fabrication shape-stabilized PCM form are crucial factors with great impact in the thermal characteristics. The most suitable materials for fabricating shape-stabilized PCM are porous structures with high thermal conductivity, such as graphite, silica fume, bentonite and diatomite [27].

4.7. PCM contribution to sustainable construction

The PCM incorporation in construction materials allows the thermal regulation, increasing the thermal comfort and energy efficiency of buildings. The utilization of these materials contributes significantly to the sustainable construction, based to their contribution in the three dimensions of the sustainable development: social, economic and environmental [38].

The PCM contribution to the social dimension is associated with the decrease of heating and cooling needs, due to the PCM thermal storage capacity. The temperature inside the buildings keep constant, or at least with less significant variations, during a longer period of time.

Regarding to the environmental dimension the PCM contribution is related to the decrease in the utilization of non-renewable energy sources, since this technology is based in the solar energy. On the other hand, the decrease in the climatization needs leads to a decrease in the use of air conditioning equipment, which also reduces the emission of polluting gases into the atmosphere.

Finally, the economic dimension concerns to the decrease in the maintenance costs of the building, more specifically in the costs related to energy consumption. It is also important adapt this technology and their implementation costs that should be easily supported and amortized by the building users.

5. Application of PCM in buildings

There are large urban areas with serious thermal deficiencies, presenting both a challenge and an opportunity for the construction and rehabilitation sector. Any solution for both new buildings and rehabilitation operations should have a contribution to reduce energy consumption and improve the living buildings conditions.

The use of phase change materials for thermal energy storage in buildings predates 1980. The first studies on this material for heating and cooling applications were carried out by Telkes [48,49] and Lane [50].

Currently, the storage of thermal energy has aroused much interest in society and the scientific community, since its applications for heating and cooling have become increasingly attractive. Thus, thermal storage plays an important role in increasing thermal comfort in buildings by reducing the frequency of indoor temperature fluctuations and keeping the temperature closer to the desired temperature for a longer period of time [51–54]. The application of thermal storage techniques is particularly interesting in buildings with significant energy needs and electric energy tariffs that allow thermal storage to be competitive with other ways of obtaining energy [55].

Some of the advantages associated with this technology are:

- Uniformity in the request of the energy of the network, reducing the load and eventual collapse of the supply systems;
- Cost decrease related with the electric bill, by the temporary relocation of the energy consumption for periods of emptiness;
- Contribution to the increase of thermal comfort inside buildings, storage and use of heat associated with solar energy (in particular for winter heating) and cooling associated with natural ventilation (in particular for cooling during the summer) thus reducing the use of air conditioning systems [21, 56].

Between all PCM applications in buildings, the most interesting is their incorporation into building materials with the aim of changing their thermal properties. There are a number of possibilities: PCM can be incorporated into the floor, wall or ceiling and can also be part of the more complex thermal system, such as heat pumps and solar panels [57]. The great advantage of incorporating PCM in buildings is the vast area they offer for storage and heat transfer.

The wall applications have a higher publications number (Fig. 3). It should be noted that the walls are the building element with the largest area of influence in a building, which justifies the greater interest of the scientific community in this constructive element.

Regarding to the construction products with PCM incorporation (Fig. 4) it is important to observe that the panels, bricks, concretes and mortars show to be the most used, with a greater number of publications. This situation can be justified by the fact of these materials can be used in different building constructive elements and possibilities of use different techniques for PCM incorporation.

5.1. Temperature transition and PCM content selection

The electricity consumption varies significantly during the day and night, according to the demand of industrial, commercial and residential activities. This variation leads to a differentiated pricing system, so a better energy consumption management provides

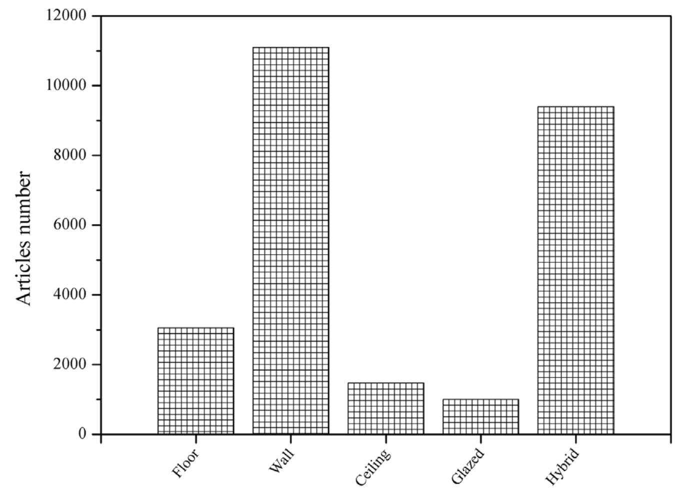

Fig. 3. Publication according PCM incorporation in the different building elements.

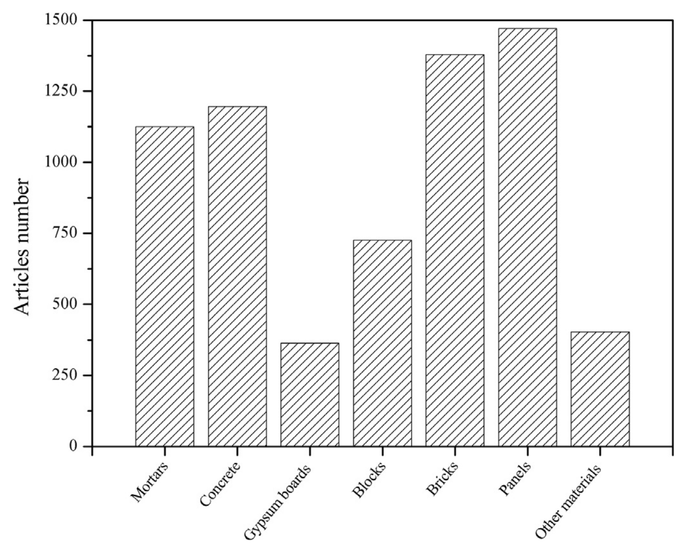

Fig. 4. Publication number according PCM incorporation in the different construction materials.

significant economic benefits, which can be achieved if part of the peak load is reduced and transferred to the empty period, which can only be achieved through thermal storage [52].

The importance of the adequacy of the PCM transition temperature and the atmospheric temperature is an extremely important factor for the high functionality of the solution. It is important to note that the PCM works thought the ambient temperature variation. Thus, the bad selection of the PCM transition temperature may prevent it from operating or does not charge/discharge energy to the environment. Castell et al. [56] showed the suitability of several PCMs for incorporation into gypsum boards. However, even though a large thermal storage capacity, the PCM used did not work correctly, due to the PCM transition temperature did not coincide with the comfort temperature range.

It is also important to choose a suitable enthalpy in order to increase the PCM performance. On the other hand, the amount of PCM incorporated into building materials should be evaluated to be the largest possible. Lai et al. [58] carried out a study that allowed evaluating the contribution of several PCM contents incorporated in gypsum boards. It has been possible to conclude that the thermal storage capacity increases with the presence of a higher PCM content in the constructive product.

The understanding of the PCM potentialities led some authors to make comparisons between the performance of a particular solution with PCM and a conventional solution. For example, Sharma et al. [13] studied thermal storage on walls using calcium chloride hexahydrate, with temperature transition of 29°C as a phase change material. The obtained results allowed concluding that a wall containing PCM with 8.1cm of thickness has better thermal performance than a masonry wall with 40 cm of thickness.

The PCM location in the constructive solution is extremely important, since the PCM needs to sense the ambient temperature variations so that it can become operational. Jin et al. [59] developed a study aiming to find out the most efficient state of PCM and its ideal location in order to take full advantage of this technology. The results showed that the proximity of the PCM to the interior of the spaces is more efficient. With regard to the state of the material it is known that PCM has three distinct states: solid, partially liquid (transition state) and totally liquid. It was possible to observe that the PCM state had great effects on the performance of the constructive solution. When the PCM was in the partially liquid state, it was able to release the latent heat faster. Schossig et al. [60] carried out a study in projected gypsum with PCM incorporation, evolving to a new way of applying the phase change materials. For their experience the authors constructed two test cells coated with gypsum with and without PCM incorporation. Two different solutions were studied: gypsum with 6 mm of thickness and 40% PCM and a second solution with gypsum layer of 15 mm thickness and 20% PCM incorporated. During the monitored time period, it was possible to observe that the solution with 6 mm of thickness kept the temperature inside the cell about 4°C lower. The PCM contribution to the thermal comfort was so significant that for three weeks the temperatures were above 28°C for about 5 h in the PCM cell versus about 50 h in the reference cell. Thus, it was possible to conclude that the PCM location had significant effects on its state, on the PCM phase change performance and on the thermal performance of the building walls.

5.2. Walls applications

The PCM application into the walls is the preferred solution for exploiting the PCM potential. The incorporation of PCM into gypsum boards has been the subject of several studies, due to its low cost and variety of application. However, the principles of latent heat storage can be applied in different building materials [13].

5.2.1. Mortars

Mortars are a very important material in buildings, since they are used in the coating of the most varied surfaces, being able to have compositions very different and adapted to new construction or rehabilitation operations.

Recently, mortars based on different binders (gypsum, aerial lime, hydraulic lime and cement) have been studied with different PCM microcapsules contents (0%, 20%, 40% and 60%). The studies carried out showed a decrease in the mechanical behavior of the PCM mortars, due to the presence of a higher quantity of water, which also increase the porosity [61,62]. The same authors carried out a study regarding the durability of PCM mortars based on different binders, observing that the PCM presence leads to mortars more susceptible to be attacked, which is related to the ease penetration of aggressor's agents, due to the increase of porosity. However, during the development of their work all mortars showed a satisfactory behavior. It was also possible to note that the cement based mortars presented a better performance when doped with PCM. On the other hand, lime based mortars showed a greater sensitivity to the incorporation of PCM microcapsules [63]. The thermal behavior was also evaluated, based on temperature laws representative of each season of the year for the Portuguese climate [64]. Based on this study, it was possible to verify that the use of PCM microcapsules resulted in a decrease in maximum temperature, an increase in minimum temperature, a significant time lag delay of extreme temperatures and a reduction in heating and cooling needs. In the spring season, it was possible to eliminate the cooling needs and in the autumn season, it was possible to eliminate the heating needs.

The mortars exposures to high temperatures were also evaluated by the same group of researchers. It was observed that the incorporation of PCM in mortars decreases their mechanical performance in all studied temperature ranges (20°C, 200°C and 600°C). The cement based mortars presented a lower sensitivity to exposure to high temperatures, and consequently presented better performance. On the other hand, aerial lime based mortars showed a greater deterioration, presenting a more sensitive behavior. This behavior was similar to the reference mortars [65]. It also can be concluded that in terms of high temperatures the incorporation of microcapsules of PCM did not affect the mortars behavior.

The utilization of microencapsulated PCM involves high costs due to the treatment that material suffers during the encapsulation. Thus, the use of PCM in free form, i.e. non-encapsulated, through its direct incorporation into mortars was studied, since this technique allows the development of mortars with a capacity for thermal regulation at a low cost. It should be noted that the use of a non-encapsulated PCM causes a decrease in the production cost of the mortars since it is possible to purchase this raw material at a lower cost and the production process of the mortars can be simplified. Cunha et al. [25] developed a study in cement based mortars with direct incorporation of non-encapsulated PCM, observing that the incorporation of non-encapsulated PCM did not cause significant changes in the main properties of the mortars. On the other hand, it was still possible to observe that the PCM did not move from the interior of the mortar, being contained in the pores.

5.2.2. Gypsum boards

Since 1990 several studies have been developed regarding the addition of PCMs in gypsum boards. Some of them were focused on physical characterization [25, 66,67], while others were centered on the numerical calculation of the heat capacity [68–70]. The gypsum boards are very used do to their availability, profusion in construction, and mainly its position in construction systems. The gypsum boards are usually used in partition walls in the interior side as a lining element, which guarantees the use of most of the thermal inertia [71].

The incorporation of PCM in gypsum boards leads to a decrease in the extreme temperatures inside the buildings and also a saving in energy consumption from non-renewable sources. For example Athienitis et al. [68] carried out an experimental and numerical study based in gypsum boards with PCM incorporation applied into the building walls. This study allows observe a decrease in the maximum temperature of about 4°C. A few years later Shilei et al. [69] also carried out studies with PCM gypsum boards with 9.5 mm of thickness and 26% of PCM, with a transition temperature of 17.9°C to 20.3°C. The investigation allowed verifying a lower temperature oscillation in the test cells coated with PCM gypsum boards. Later, the same authors [72] also developed gypsum boards incorporating a PCM for application in the surface of a common wall in a test room decrease the cooling load. Comparing the room with the PCM wall and the reference room, it was verified that the PCM application was effective in the use of cooling systems. Other authors developed an experimental and numerical study with the objective of evaluate the external temperature and the irradiated flux in a test room with and without gypsum boards incorporating PCM under the same conditions, on a summer day. The results showed that the application of PCM into the walls reduced the air temperature oscillations and increased the thermal comfort [73].

Due to the great possibility of PCM incorporation in gypsum boards Darkwa et al. [74] investigated the behavior of two PCM solutions. In one face it was used a PCM gypsum board with 12 mm of thickness, in order to compare directly with a simple gypsum board with 10 mm of thickness coated with 2 mm of laminated PCM. The amount of PCM incorporated in both cases was 17%. The results demonstrated that the use of laminated PCM is more efficient since it contributed to an increase of about 17% in the minimum temperature. These results are also connected with the thermal inertia increases.

5.2.3. Concrete, blocks and bricks

The incorporation of PCM into building elements such as blocks, bricks and other conventional materials, besides gypsum boards and mortars, was also studied. Cabeza et al. [75] constructed and monitored the behavior of concrete test cells with and without incorporation of 5% of PCM microcapsules. The concrete with PCM incorporation was used in the roof and in the South and West walls. During the summer it was observed a difference of about 3°C in the maximum temperature surface in the west wall with a time lag delay of 2 h. Later, Bahrar et al. [76] studied the incorporation of PCM microcapsules in textile reinforced concrete panels, observing an increase in the heat storage capacity and thermal inertia.

The PCM incorporation in bricks result in increased thermal mass, increasing the thermal resistance and reducing the heat flow. The PCM acts as a thermal capacitor [77]. The phase change materials can be incorporated using a macroencapsulation solution by filling the empty areas of the bricks. An experimental study for the application of macroencapsulated PCM in conventional and alveolar bricks for passive cooling of buildings was carried out by Castell et al. [56]. Several test cells were constructed with the both materials and with and without PCM incorporation. The results showed that the PCM presence can reduce the maximum temperatures and soften daily fluctuations. In addition, in the summer of 2008, the electric consumption was reduced in 15% in the compartments with PCM. These energy savings have resulted in a reduction in CO_2 emissions of around 1 to 1.5 kg/year/m^2. Saxena et al [77] studied the impact of PCM incorporation in bricks for the climatic conditions of Delhi. They evaluated two different PCMs (Eicosane and OM35) observing a temperature reduction of 5-6 °C across the bricks with respect to conventional brick and a reduction in heat flow by 8% and 12% for Eicosane and OM35 respectively.

5.2.4. Panels and other materials

The incorporation of PCM into panels has also attracted the interest of several researchers. Ahmad et al. [78] investigated a new type of PVC alveolar panels with 25 mm of thickness and incorporating 20 kg of PCM, with transition temperature between 21-25°C. The panels were used in the construction of a test cell, which behavior was compared to a reference test cell. During the summer period the amplitude of the temperature inside the cell with PCM was decreased of about 20°C. In winter, the presence of the phase change material prevented the negative internal temperature from being lower than -9°C, demonstrating the beneficial effect of the PCM incorporation in the temperature regulation inside buildings. Other study performed by Santos et al [79] evaluated the thermal performance of a panel designed to encapsulate PCM, comparing with a commercial PCM panel solution. They produced two different specimens, one traditional constituted by 9 panels and other with 7 PCM panels. The new design panel has 17.5 kg more PCM than the existing one, resulting in 30% more material than the existing module. The results showed that the new panel leads to an increase in time to melt and solidify the PCM compared to the existing panel, due to the additional PCM material.

As shown, there are numerous PCM applications in conventional building materials. However there are also applications in materials whose application in the construction industry is not so frequent. For example Jin et al. [80] developed aluminum foil pouches filled with PCM in order to incorporate these bags into the buildings walls. The results obtained showed that the use of this material reduced the peak charge time.

5.3. Floor applications

Several authors have been investigating constructive solutions with phase change materials incorporation in floors. These solutions can be very varied. Since the constructive solution can be constituted by the application of a single layer with incorporation of PCM [81], a multilayer solution of different materials and different types of PCM [82], solutions with capillary channels for PCM circulation [83,84] and even their integration into more complex systems with the use of heat pumps [85].

Entrop et al. [80] carried out an investigation in concrete for floor application with PCM addition. Four test cells were performed, with a south facing window through which solar radiation could enter. The PCM selected for the experimental application was a paraffin mixture with melting point of 23°C, supplied by BASF and designated by Micronal DS5008X. It was possible to conclude that the application of the PCM solution caused a decrease in the maximum temperature of 16% and an increase in minimum temperature of 7%.

Nagano et al. [82] developed a system with PCM incorporation in the floor. The system consisted of a permeable PCM layer with 3 cm of thickness, with a transition temperature of 20°C, applied under the floor and resting on a concrete slab with an air box. The results showed that the phase change of the PCM occurred between 17°C to 22°C, with an enthalpy of 31 kJ/kg. In this way, it was possible to maintain the internal temperature between 1.5-2.1 times longer compared to a reference solution, as well a daily energy storage of 1.79 MJ/m^2.

Lin et al. [83] developed an electric underfloor system incorporating polyethylene boards impregnated with PCM, with a temperature transition of 52°C. The tests were performed in a test cell equipped with an electric heating system, active between 23:00 and 08:00, of each day. During the monitored period an external temperature of 13.6°C and an internal temperature of 20°C were recorded. It was also verified that about 3.3 kW/h of the electric energy consumed was transferred to hours of emptiness, corresponding to 54% of the consumption.

Another possibility of using PCM is its prior incorporation in the raw material constituting the construction products. For example Kheradmand et al. [43] studied feasibility of light aggregates impregnation with phase change materials for floor constructive solutions. The obtained results confirm that the PCM impregnation method in aggregates is effective, due to the high density of thermal energy storage and may be suitable for applications in which the PCMs cannot be incorporated directly.

5.4. Ceiling applications

The application of solutions with PCM in ceilings has also been an area of study by several researchers [86–93]. There are some solutions of ceiling panels with capillary networks for PCM circulation [86,87]. For example Koschenz et al. [86] has developed a panel for application in ceiling, consisting of a steel board through which circulates a web of capillary tubes filled with a gypsum plaster doped with PCM microcapsules. The panel has 5 cm of thickness and contains about 13 kg of PCM in each m^2, which represents about 23% of the total mass of the panel, with a transition temperature of 22°C. Subject to a heat load of 40 W/m^2, the melting process has a duration of about 7.5 h, stored 290 Wh/m^2. This result is significant since it allows to an operation period near to the work schedule, contributing to the interior temperature regulation. Griffiths et al. [87] used a microencapsulated PCM in aqueous suspension, developed by BASF, with a transition temperature of 18°C. The PCM was applied in a ceiling cooling solution, in which, taking into account the small diameter of PCM microcapsules in suspension, it was easily pumped in roof heating and cooling circuits using commercially available pumps. The data obtained showed that a concentration of 40% of PCM in aqueous suspension can be used as a heat transfer fluid in a constructive solution.

Other solutions were also developed regarding the incorporation of PCM in celling solutions, such as their incorporation in the concrete slab [89] and a solution of macroencapsulation in a metallic panel [90]. Pasupathy et al. [89] evaluated the influence of a 2.5 cm PCM panel, located on the roof, between two slabs, the lower one in concrete with 12 cm of thickness and the upper one in brick and mortar with 10 cm of thickness. It was used a PCM with a temperature transition of 26-28°C and latent heat of 188 kJ/kg. The differences recorded were 2°C and 3°C, respectively in the maximum and minimum surface temperature. Chou et al. [90] developed a new metallic celling containing PCM in about 48% of their area. The main objective of the study was to use the PCM to absorb the heat flux of incident solar radiation and release through external convection during the night. The obtained results allowed verifying that the new design effectively reduce the thermal flow through the building and the cooling load.

Constructive solutions based in the shape-stabilized PCM have also been attracting the interests of the researchers.Zhou et al. [88] studied the behavior of a room coated with panels incorporating PCM in the ceiling and walls, with a transition temperature of 21°C. The results show that it is possible to save about 47% of the energy during the daytime period, corresponding to a total saving of around 12%, during the heating season.

5.5. Glazed applications

In the last years, also solutions with PCM integration for apply in the glazed areas have been developed, since there is an increasing use of glazed areas in buildings. The glazed units are essential parts of a building, such as window, glazed façade and roof. The use of glazing allows vision, air ventilation, passive solar gain and day-lighting. However, compared with other components, their thermal performance are poor and significantly affects the energy demand of buildings [94]. Thus, the PCM application in the glazed unit is an effective method to reduce energy consumption in the buildings, and allow visible light transmit to indoor environment for daylighting [95,96].

Several researchers have developed work in this area, through the PCM incorporation in the glazing unit [57, 94, 97]. Ismail and Henriquez [97] carried out a study with the aim to verify the thermal efficiency of a single and a double glazed with air box filled with PCM. During the experiment the PCM was kept in a liquid tank, being pumped and later solidified in the space between the glasses, thus preventing the dissipation of heat through the window and keeping the interior temperature substantially constant. A total reduction of 55% in transmitted energy was reached when the space between glasses was completely filled by PCM. Liu et al. [94] studied the optical and thermal performances of a PCM-glazed based in the influence of solar irradiance, melting temperature and PCM layer thickness in three different parameters (transmittance, temperature difference between upper and bottom surfaces, and the interior surface temperature of the glazed unit). It was possible to conclude that the thermal performance of glazed unit filled with PCM is improved since the transmittance of glazed unit is 50% when the PCM is liquid. The solar irradiance and PCM layer thickness also affects the thermal performance of glazed unit, since the PCM thickness increase leads to a decrease in the heat loss.

Other researcher developed work in glazing protection systems [13, 98]. For example Silva et al. [96] developed a shutter system with phase change materials incorporation for apply in the exterior part of the glazed. During the day this system remains open, being exposed to the solar radiation, allowing the heat absorption. During the night, the system is closed, started to radiate the heat to the interior of the rooms. This solution allows increasing the internal temperature of about 2°C.

5.6. Hybrid PCM applications

There are very severe weather conditions, with different cold and hot seasons, where the use of a single PCM may not allow the utilization of the maximum thermal storage capacity. Thus, constructive solutions have emerged with the incorporation of two or more types of PCM, with different characteristics, in order to obtain a solution capable of operating in a wider temperature range, the hybrid solutions. Pasupathy and Velraj [99] developed a study in order to investigate the thermal performance of a double layer hybrid PCM solution applied on the building roof. The results allowed verifying a decrease in the internal temperature fluctuations and an increase in the thermal comfort.

The study of floor solutions with integration of two PCM layers was carried out also by Jin and Zhang [100] in which the different PCM layers had a different transition temperature, working in the high and low temperatures. The results showed a reduction in the fluctuation of the surface temperature and heat flows. The system has also been able to provide thermal energy after the interruption of the operation of the heat pump or cooler coupled to the system for an extended period of time. Comparing with the standard solution, without PCM incorporation, it was found that the energy released by the floor with PCM in the peak period will be increased by 41.1% and 37.9% during the heating and cooling period, respectively.

The use of this type of solution in walls was developed by Kheradmand et al. [101]. The authors used three different phase change materials (PCM hybrid solution) for interior coating mortars. The thermal performance of the mortars added with the hybrid PCM solution was evaluated experimentally based on realistic temperature laws. The prototype realized with the hybrid solution of PCM allowed observing a higher attenuation of the thermal amplitudes, compared to reference situations (without PCM and single PCM). It was also possible to conclude that the combination of several PCMs with distinct melting points, which cover a wider temperature range, allows this solution to be advantageous compared to classical approaches of a single PCM, which tends to have a more limited influence. On the other hand, the bad temperature transition selection of the different PCM may even induce a worse behavior than would be expected in a traditional mortar.

Table 1 summarizes the main information about the various works presented earlier. Regardless of the location of the PCM in the building, transition temperature and incorporation technique, the use of PCM has shown in all studies to be an effective measure for improving the energy efficiency of buildings. This improvement of the buildings energy efficiency is based on the increase of the minimum temperature, decrease of the maximum temperature and decrease of the temperature variation inside the buildings, killing them significantly more constant. Thus, it is also possible to achieve a reduction in the heating and cooling needs of buildings, which translates into a decrease in the use of HVAC equipment, energy consumption from non-renewable sources and negative impacts on the environment.

6. Conclusions

The world's high energy consumption has been primarily responsible for high greenhouse gas emissions to the atmosphere and energy consumption from non-renewable sources, contributing to global warming and the depletion of fossil fuels.

In recent years, a more stringent legislation has been implemented for the energy efficiency of buildings. Even though there was a positive influence on the implementation of these measures and policies, they were not sufficient to substantially reduce the problem of high energy consumption in buildings. In this way, the use of building materials responsible for lower energy consumption is currently an area of relevant importance and urgency.

Currently there are several thermal insulation materials on market, however they have several disadvantages in terms of toxicity and efficiency. Thus, phase change materials emerge as a very promising technology due to their potential to attenuate the temperature inside buildings.

It should be noted that the correct use and achievement of the maximum efficiency of the PCM is related to the adequacy of its transition temperature to the environment in which it will be applied and the enthalpy associated with the phase change. On the other hand, the

Table 1
Summary of experimental studies.

Study	Study Type	Construtive solution localization	Constructive Solution	PCM incorporation technique	PCM temperature transition	Main Results
Cunha et al. [64]	Experimental	Wall	Mortars	Microencapsulation	24°C	Decrease the maximum, increase the minimum temperature, decrease the heating and cooling needs and lag time delay.
Shilei et al. [69]	Experimental	Wall	Gypsum Boards	Immersion	20°C	Decrease the maximum, increase the minimum temperature.
Shilei et al. [72]	Experimental	Wall	Gypsum Boards	Immersion	50°C	Reduction of energy cost related to the HVAC systems and transference to the electric power peak load.
Kuznik et al. [73]	Experimental	Wall	Gypsum Boards	Microencapsulation	22°C	Lower temperature variations
Darkwa et al. [74]	Numerical	Wall	Gypsum Boards	-	18°C	The PCM presence near to the gypsum board surface showed a better performance, increasing the minimum temperature.
Cabeza et al. [75]	Experimental	Wall	Concrete	Microencapsulation	22°C	Reduction in the air temperature and lag time delay.
Bahrar et al. [76]	Numerical/ Experimental	Wall	Concrete	Microencapsulation	25°C	Increase the heat storage capacity and thermal inertia.
Castell et al. [56]	Experimental	Wall	Brick	Macroencapsulation	25°C	Reduce the maximum temperature, daily temperature fluctuations and electric consumption.
Saxena et al. [77]	Experimental	Wall	Brick	Macroencapsulation	35°C	Reduction the temperature and heat flow.
Ahmad et al. [78]	Experimental	Wall	Panels	Macroencapsulation	21°C	Decrease the temperature amplitude.
Santos et al. [79]	Experimental	Wall	Panels	Macroencapsulation	30°C	Higher energy storage capacity.
Jin et al. [80]	Experimental	Wall	Bags	Macroencapsulation	34°C	Decrease the peak charge time.
Entrop et al. [81]	Experimental	Floor	Concrete	Macroencapsulation	23°C	Decrease the maximum temperature and increase the minimum temperature.
Nagano et al. [82]	Experimental	Floor	Concrete	Macroencapsulation	20°C	Constant temperatures for longer period of time.
Lin et al. [83]	Experimental	Floor	Boards	Shape-stabilization	52°C	Increase the indoor temperature without increase the temperature difference.
Koschenz et al. [86]	Experimental	Ceiling	Metallic panels	Macroencapsulation	22°C	Good interior temperature regulation.
Griffiths et al. [87]	Experimental	Ceiling	Panels	Microencapsulation	18°C	Reduction of volume flows.
Pasupathy et al. [89]	Experimental/ Numerical	Ceiling	Concrete	-	26°C	Decrease the maximum temperature and increase the minimum temperature.
Chou et al. [90]	Experimental	Ceiling	Metallic panels	Macroencapsulation	46°C	Reduction of the thermal flow and cooling load.
Zhou et al. [88]	Experimental	Ceiling	Ceiling	Shape-stabilization	21°C	Energy saving during the daytime period.
Ismail and Henriquez [97]	Experimental/ Numerical	Glazed	-	Macroencapsulation	-	keeping the interior temperature substantially constant
Liu et al. [94]	Experimental	Glazed	-	Macroencapsulation(Hybrid solution)	18°C, 26°C and 32°C	Increase the thermal performance of the glazed unit filled with PCM.
Silva et al. [98]	Experimental/ Numerical	Glazed	Shutter system	Macroencapsulation	-	Increase the internal temperature.
Pasupathy and Velraj [99]	Experimental	Ceiling	Metallic panels	Macroencapsulation(Hybrid solution)	26°C and 28°C	Decrease the internal temperature fluctuations and increase in the thermal comfort.
Jin and Zhang [100]	Experimental	Floor	Panels	Macroencapsulation(Hybrid solution)	14°C, 16°C, 18°C, 20°C, 22°C, 30°C, 34°C, 38°C, 42°C and 46°C	Reduction in the fluctuation of the surface temperature and heat flows.
Kheradmand et al. [101]	Experimental	Wall	Mortar	Microencapsulation(Hybrid solution)	10°C, 24°C, 26°C and 28°C	Higher attenuation of the thermal amplitudes.

PCM properties have a direct impact on their thermal performance and consequently on human comfort. Therefore, PCM selection must be based on its thermal, physical, kinetic, chemical, economic and environmental properties.

There are several possibilities of PCM incorporation in construction materials. However, the selection of the incorporation technique should take into account the type of material to be doped, its application in buildings and the cost of development and implementation.

The incorporation of PCM in construction elements can be carried out on walls, ceilings and/or floors, thus offering numerous possibilities of use. It should also be noted that in all the analyzed studies it was always possible to conclude by the beneficial effect of the PCM incorporation in the thermal performance of buildings. There has been a reduction of extreme temperatures and lower temperature fluctuations, resulting in an effective energy saving, since in a real situation the operating time of the air conditioning equipment in a building would be substantially reduced. Thus, phase change materials show a very promising technology in reducing the high energy consumption of buildings and their negative impacts to the environment.

There are still some research needs in this area, namely with regard to the use of direct incorporation and shape-stabilized techniques, applications for the exterior building elements and development of low cost construction materials doped with PCM.

Declaration of Competing Interest

None

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