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Research Paper

Integration of phase change materials in building walls: Passive cooling

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ABSTRACT: *This paper focuses on new passive cooling techniques through the integration of phase change materials, known as PCMs, in the building sector. Various experimental and numerical studies in the literature show that with the use of phase change materials, room temperature fluctuations can be significantly reduced while improving the thermal comfort of the inhabitant.*
KEYWORDS: *Phase change materials, thermal comfort, Building, Storage of thermal energy, Passive cooling.*

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I. INTRODUCTION

The energy transition is an ecological objective on a global scale. This issue mainly consists in reducing the global energy consumption of the different sectors of activity. The building sector represents about 44% of the total energy consumption of residential and tertiary buildings in France [1], and about 32% of the energy consumption in the European Union [2] as shown in figure 1.

In France, governmental actions have contributed to the implementation of several thermal regulations. The RT 2012 (RT2012) came into force in 2000, has brought a clear improvement in the building with an energy consumption of about 40 to 60 kWh/primary energy/square meter/year in 2013 instead of 150 - 450 kWh/primary energy/square meter/year in 2005. In order to meet the objectives defined by this regulation, to control and minimize the energy demand and the carbon footprint in this sector, the observations and results of numerous studies have led to the development of new and more sustainable building technologies such as the Zero Energy Building (NZEB) [3-4], the integration of insulating materials with good thermal performance, or intelligent materials. This solution is of interest to the majority of builders who wish to control the indoor temperature range while respecting the well-being of the inhabitants and the requirements of the thermal regulations. Great attention has been paid to the use and choice of phase change materials, to respond to the increasing demand for energy. Indeed, the addition of this material in the building presents a way to store thermal energy and reuse it in order to control temperatures in a specific range and therefore, improve the thermal comfort of the inhabitants.

Previous research has been done on the integration of PCMs for thermal storage as well as its application in the building [5 -11]. Thus, it would be interesting to see all the desirable properties for the selection of PCMs, advantages, disadvantages of these materials and different experimental/numerical studies in the field of construction, especially in the building sector. The objective of this study is to draw up a bibliographical study on the various tests carried out on the application of PCMs, mainly in the building wall.

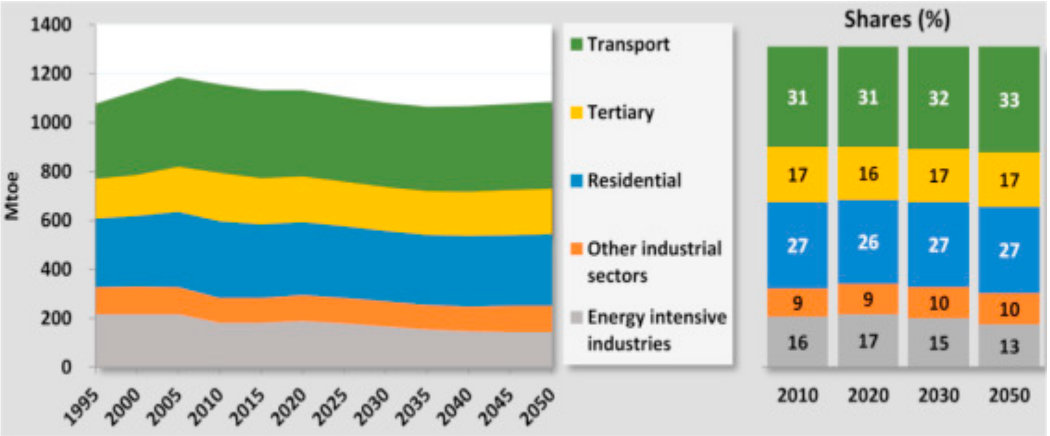


Figure1: Energy consumption by sector in the European Union [2].

II. PHASE CHANGE MATERIAL

Energy storage is defined as the storage of energy from a source in a specific form for a later use. This physical phenomenon is at the heart of current issues, with the aim of optimizing a maximum of energy while limiting losses. More specifically, thermal energy storage (TES) can take different forms [9]. Two types of storage are often used in the field of civil engineering: storage by sensible heat and by latent heat. Figure 2 illustrates the different modes of thermal energy storage.

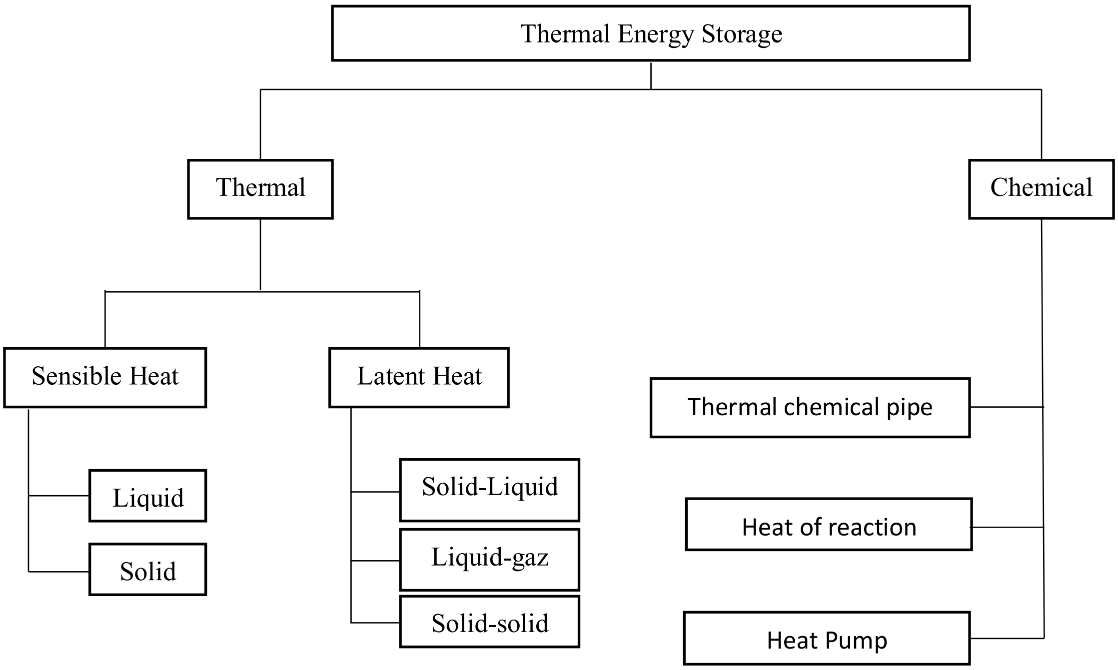


Figure2: The different modes of thermal energy storage.

The storage of energy by latent heat allows to store energy at a constant temperature corresponding to the temperature of change of physical state. The mass energy absorbed by the material is written as follows [12]:

$$\boxed{E_{m,lat} = \Delta H_{latent} = \int C_{app}\ dT} \quad (1)$$

Where ΔH_{latent} is the mass enthalpy of transformation, C_{app} is the apparent heat capacity and T is the temperature.

This type of storage generally requires the use of a material with the ability to change physical state, such as a phase change material. Indeed, this material is perfectly adapted to this type of thermal energy storage. The energy is often absorbed during melting and then released during solidification. It is generally a transition material (solid-liquid) which allows to exploit the stored energy with a surplus of energy in the form of sensible heat, and to reuse it later in several fields such as electronics, textile and building.
Figure 3 [13] highlights the storage capacity of the phase change material compared to other building materials. It is noted that the capacity of PCM is about six times that of concrete and sixteen times that of wood.
There are different phase change possibilities: solid-solid, solid-gas and liquid-gas. However, the solid-liquid transition is the most widely used, offering the greatest number of applications because of its low volume change. Most of the other transitions generally involve a large volume or high pressure to perform the storage.

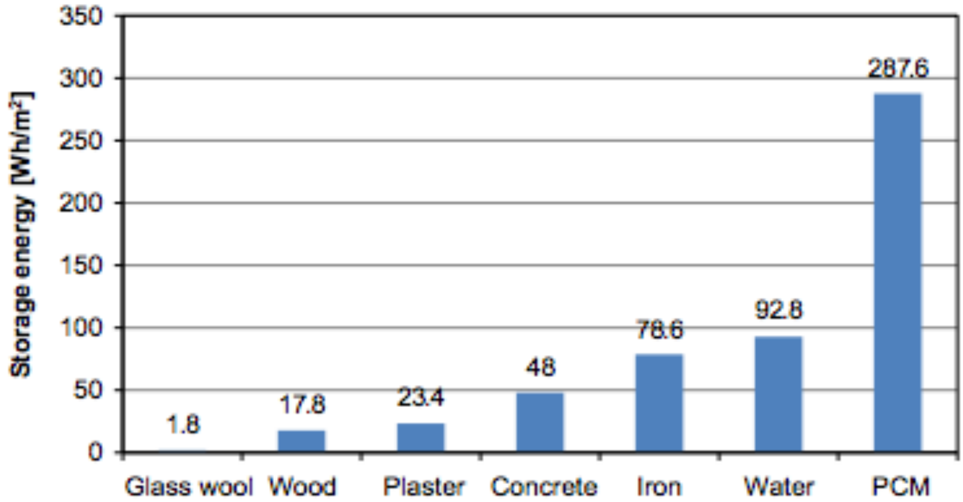


Figure3: Storage capacity of some building materials [13].

PCMs used for latent heat thermal energy storage can be classified into three categories [14]; [11]: organic, inorganic and eutectic, as shown in Figure 4. These categories have different melting enthalpies (Figure 5).

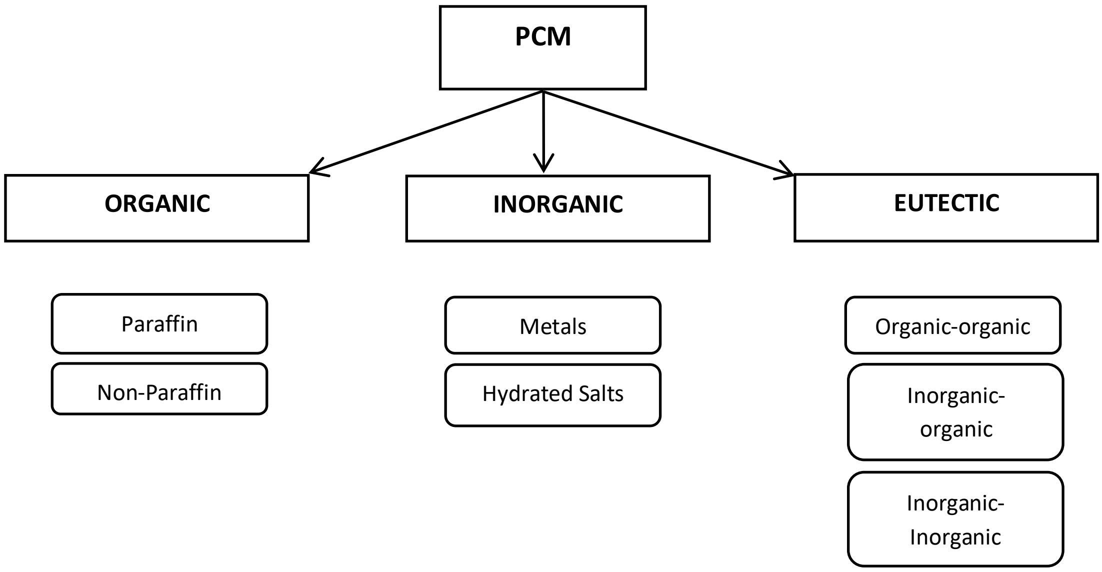


Figure4: The different categories of PCM [11], [14].

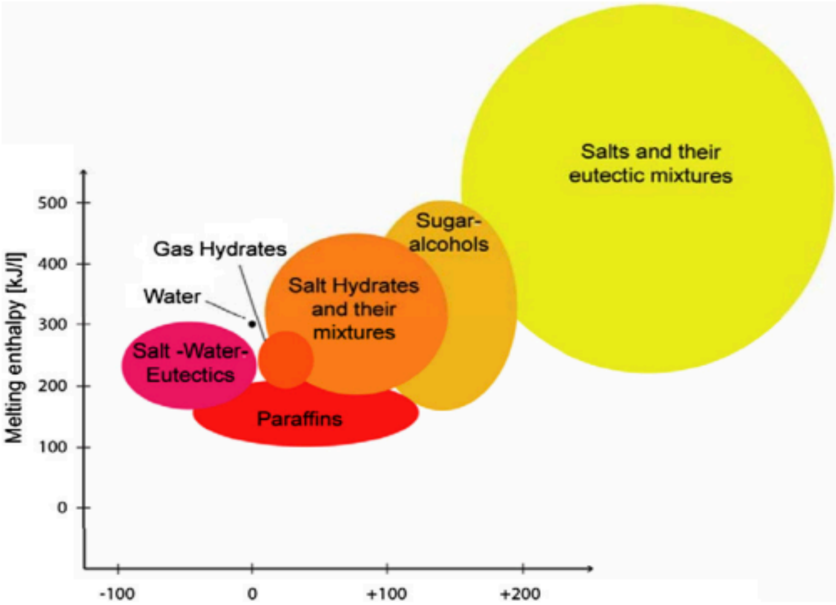


Figure5: Latent heat as a function of melting temperature (Dieckman) [15]

- Advantages and disadvantages

Many researches [12], [16-19] have highlighted that each PCM has advantages and disadvantages as shown in Table 1.

Table1: Advantages and disadvantages of PCMs (organic, inorganic, eutectic) [20]

ORGANIC		INORGANIC		EUTECTICS	
Advantages	Drawbacks	Advantages	Drawbacks	Advantages	Drawbacks
No supercooling; No phase segregation; Low vapor pressure; Large temperature range; Self-nucleating; Compatible with conventional construction materials; Chemically stable; Recyclable; High heat of fusion	Flammable; Low thermal conductivity; Low volumetric latent heat storage capacity	High volumetric latent heat storage capacity; Higher thermal conductivity than organic PCMs; Low cost; Non-flammable; Sharp phase change	Corrosive to metals; Supercooling; Phase segregation; Congruent melting; High volume change	Sharp melting points; Properties can be tailored to match specific requirements	Limited data on thermos-physical properties for many combinations; High cost

It should be noted that organic PCMs (paraffins and non-paraffins) have various advantages over inorganic compounds (hydrated salts), such as chemical stability, compatibility with building materials etc.
According to Schroder and Gawron [21], the choice of a PCM may depend on the many properties listed below:

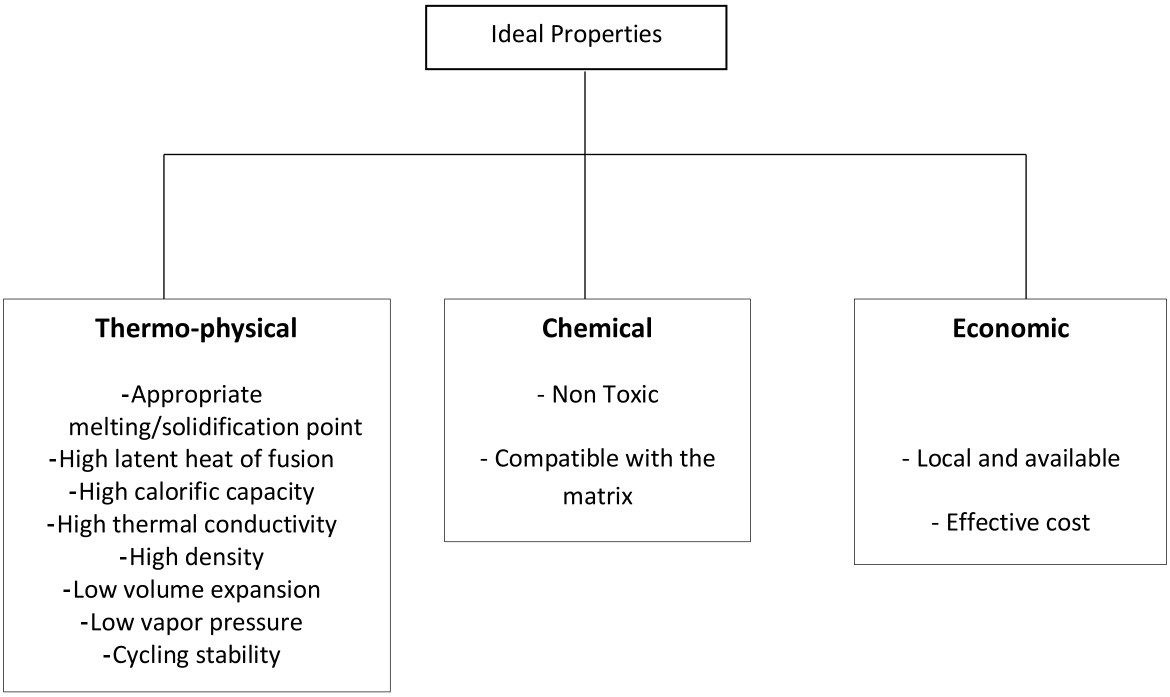


Figure6: The different ideal properties for PCM selection.

The majority of PCMs used in the construction industry are subject to the physical melting/solidification change of state. To avoid leakage problems, it is therefore necessary to encapsulate the phase change material. Indeed, there are different methods of encapsulation of phase change materials: direct incorporation or impregnation, macro-encapsulation and micro-encapsulation

- Microencapsulation

In order to reduce the reactivity of the PCM with its environment and to control its volume during the phase change, micro-encapsulation [22-24] is an interesting solution. This technique overcomes the problem of low thermal conductivity, while increasing the surface-to-volume ratio and the heat transfer rate due to the large exchange surface.
This method consists in enclosing the material in a microscopic capsule.
The microcapsules are usually in the form of powder, which is then integrated into the building material or a compatible matrix.
A particular choice must be made regarding the capsule in order to avoid any chemical reaction between the capsule and its matrix. The PCM is thus confined and can no longer escape.
In 2005, Shossig [25] presented the new method of micro-encapsulation of PCMs, which solves several problems faced by these materials. This technology also improves and facilitates the incorporation of these materials in the building sector. This study presents the resulting advantages following the experimentation of micro-encapsulated PCM: easy application, good heat transfer and good protection against PCM leakage [25].
It should be noted that encapsulation can only be used in new buildings to be constructed and not for renovation.
There is also a promising method in the construction sector: macro-encapsulation.

- Macro-encapsulation

Macro-encapsulation is another method in which the phase change material is packaged in a capsule with dimensions ranging from decimeters to meters. As shown by Sonnick and Erbelk [26], who tested a hydrated salt-based PCM in sealed waterproof bags (Figure 7). It was then, placed in a prefabricated wooden house. The results of this experimental study showed that the integration of PCMs increases energy savings and reduces the interior temperature of the room (up to 4°C).
Today, macro-encapsulation and microencapsulation are two methods that are becoming increasingly common in the construction industry. One of the main differences between these two forms of PCM integration is the shape/size of the capsules.

Figure7: Macro-encapsulated PCM [26]

III. APPLICATION OF PHASE CHANGE MATERIALS IN THE BUILDING

The integration of PCMs for passive cooling/heating has attracted the interest of several researches so far. In the last few years, the research on the use of these materials in the building sector has been increasing, as shown in Figure 8. This is particularly advantageous for lightweight buildings, which are subject to temperature fluctuations, especially in periods of overheating caused by low thermal inertia. An overview of experimental studies conducted on the energy performance of nano-PCMs within the building was presented by A.Kasaeian [6]. This overview is based on the passive cooling and heating of the room while increasing the energy savings and comfort of the inhabitants. Similarly, M. Saffari [7] exposed various numerical studies on the addition of these smart materials in construction.

This section mainly describes on different experimental and numerical studies on the influence of PCMs integrated in the vertical wall, on the passive cooling of the building.

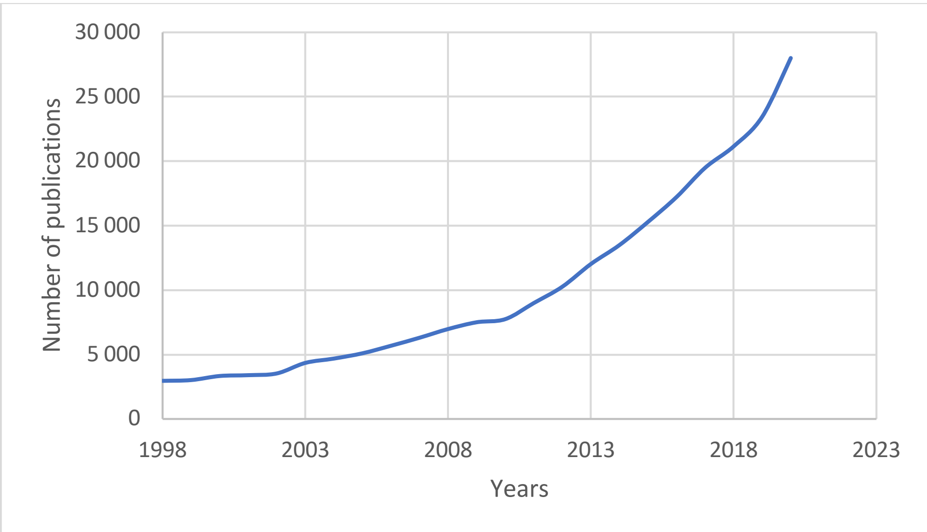
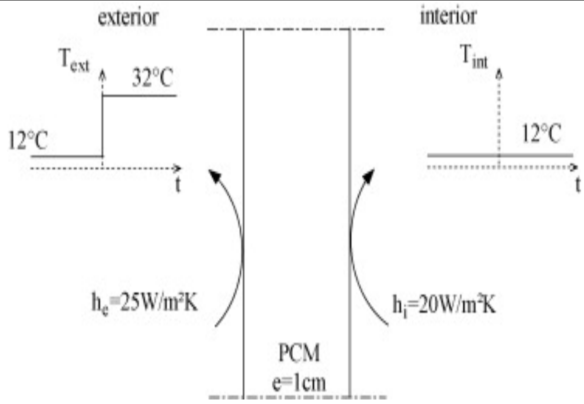
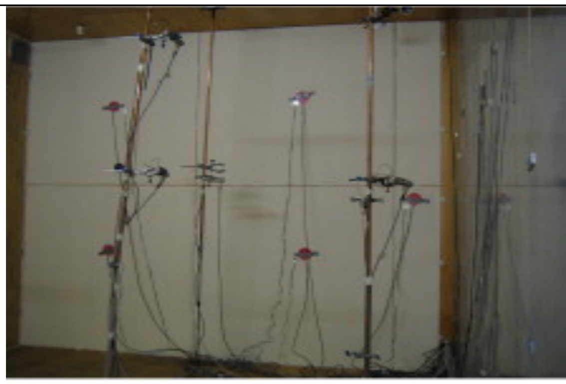
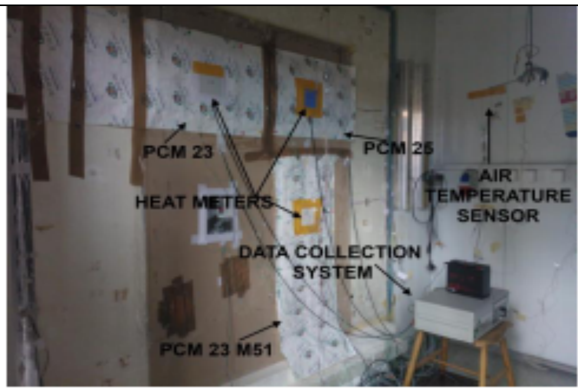


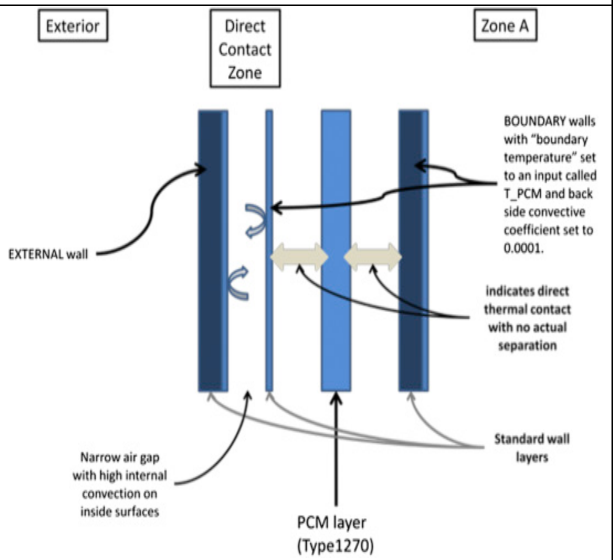
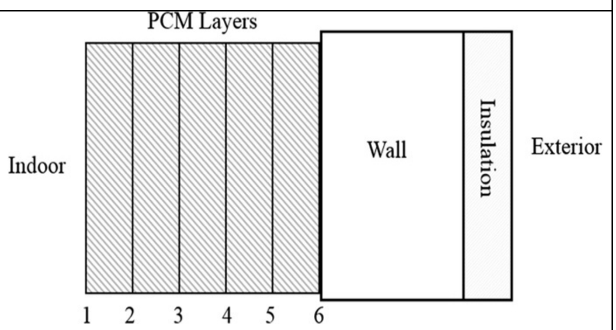
Figure8: Evolution of the number of scientific publications.

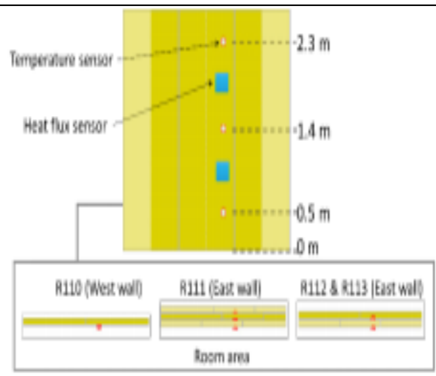
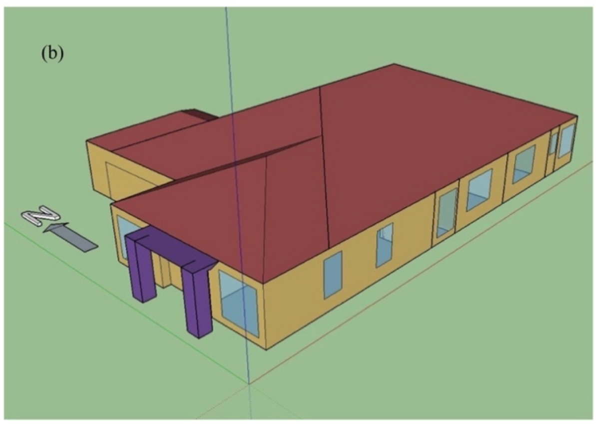
- Wall panels incorporating commercialized PCMs

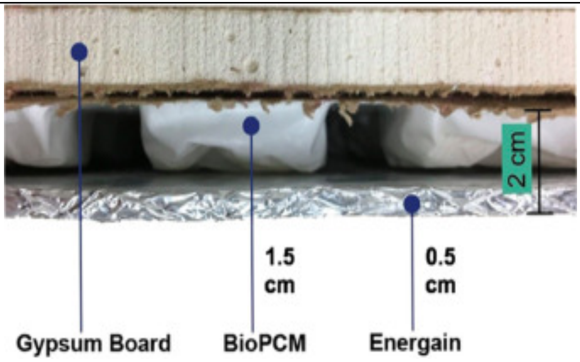
Throughout the last few years, some companies have become interested in this topic and have started to market panels with phase change materials in different forms. Manufacturers can produce their own material or incorporate commercially available PCMs from Rubitherm GmbH [27] or BASF [28]. The table below includes multiple experimental and numerical researches on the inclusion of commercial panels in the building, in chronological order.

Table2: Some commercialized PCM panels.

Authors	Description and Results	Illustrations
Kuznik [29]	Experimental study of a wall integrating a PCM wall panel in a climatic chamber in Lyon during the summer. The wall is made of a wooden plate, plaster and polystyrene. The integration of the PCM panel allowed to reduce the indoor temperature by 3°C.	
Hazim Awbi [30]	An experimental study was conducted in a climate chamber equipped with PCM panels. The presence of PCMs affects the heat peak and reduces the indoor temperature by 3°C.	
Cabeza [31]	An experimental set-up was carried out to study the thermal performance of incorporating PCMs in conventional and cellular brick in a Mediterranean climate. The inclusion of phase change materials in this type of building material had a significant impact on the reduction of Interior temperature and on energy savings (55%).	
Rumin [32]	An experimental study in which a comparison of three Bio PCMs with different melting temperatures was performed in a continental climate (Poland). The Bio PCM25 with a melting temperature of 25 °C, is the most effective in reducing indoor temperature fluctuations.	

Tor A Vik [33]	An experimental analysis of a test cell incorporating PCM panels was conducted to study its impact on the thermal performance of the building. The addition of the PCM wall panel resulted in a decrease in interior temperature of approximately 3.3°C.	
Panayiotou and Kalogirou [34]	A numerical study was performed on TRNSYS to evaluate a test cell in Cyprus in which a PCM panel is applied. The integration of the PCM resulted in energy savings of 28.6% without thermal insulation and a decrease of the interior temperature by 3-5°C.	
Nighana and Tarika [35]	An experimental and numerical study was conducted for a comparison of two buildings with and without BioPCM, under the same climatic conditions. The addition of the PCM reduced wall and indoor air temperature fluctuations and heating energy demand in winter.	
Franceso Guarino [36]	This study analyzes the thermal performance of PCM integrated in the building under a cold climate. This material had an impact on the interior temperature variations: A decrease of 10°C was recorded with a reduction of heating loads (40%)	

Umberto Berardi [37]	A comparison of two Bio PCMs was studied numerically with different melting temperatures: M51Q25 and M182Q25. The percentage reduction (cooling demand and heating demand) is higher when M182Q25 is applied.	
B.Chhugani [38]	An experiment highlights the thermal performance of adding PCM in offices in Germany, in which a comparison was made between two PCM panels. Compared to the Energain panel, the Knauf panel achieved better heat storage.	
Ramakrishman [39]	A numerical study of a PCM integrated within the exterior wall of a house was performed on EnergyPlus to evaluate its effect on energy performance. The results showed a 65% reduction in the period of discomfort.	
A. Mourid & M.El Alami [40]	An experimental study was conducted to evaluate the thermal behavior following the application of the Energain panel in test cells in a Mediterranean climate. This experiment showed that the addition of the panel was able to reduce the interior temperature by 6.5°C.	

Umberto Berardi [41]	An experiment carried out with a combination of Energain panels and BioPCM illustrated its effect on thermal energy storage in the building: A decrease in indoor temperature of 6.7°C was recorded.	
M. Sinka [42]	PCM panels were evaluated in experimental trials in a continental climate with the objective of increasing the thermal mass of lightweight buildings. Several panels were integrated and showed significant effectiveness in reducing the interior temperature (3 to 4°C lower)	

According to the studies presented in the table above, the application of PCMs shows significant results in terms of energy savings. The improvement of energy efficiency and thermal comfort of buildings has been studied in different climatic conditions such as Europe [29,30,38,42], North Africa [40], North America [37, 41], Australia [39], etc.

These commercialized panels are usually integrated in the building construction as an insulation in different places such as wall, roof and floor. These boards have been developed and are mostly available in a wide range of melting temperatures. Some research has looked at the comparison of boards supplied by the same company with different melting temperatures and found distinct results. This demonstrates the impact of the choice of thermal properties of a phase change material panel on the energy consumption of a building in a specific climate. The use of the panel shows optimal results in the summer period. Therefore, its application is quite limited: it is effective and active only during a particular season in which the outside temperature reaches the melting temperature of the panel in question. As a result, some companies have decided to stop their production in recent years due to lack of demand.

- Plasters

The use of smart materials such as phase change materials is primarily aimed at improving the heat storage capacity, stabilizing the temperature inside the building and thus improving thermal comfort.

One of the possible solutions is to integrate these PCMs into building materials such as plasters.

Plaster, obtained from gypsum, is a material used in the construction sector, mainly in the building industry because of its many advantages such as its facility of preparation, its lightness, its resistance to fire and its capacity of adhesion to cement. It has been shown that the thermal insulation capabilities of gypsum board can be improved by 18.4% by incorporating a phase change material [43].

An experimental study was conducted to incorporate a microencapsulated paraffin-based PCM into plaster and evaluate its impact on reducing the ambient temperature of a test room in Germany [31]. Having a melting temperature between 25 and 28°C, this composite has the ability to mitigate temperature fluctuations with 4°C difference between the room with and without PCM. Similarly, Shossig [25] studied a paraffin-based PCM with a melting temperature of 25°C mixed with plaster. Following instrumentation of a real room equipped with the composite. The addition of the latter succeeded in lowering the interior temperature of the room by 2°C. Hawes [44], in turn, evaluates a butyl stearate phase change material incorporated into a gypsum board. Thirteen PCM panels were attached to existing panels in the test room (Figure 9). Using an experimental and numerical study, he presents the following results: the installation of these panels significantly reduced the room temperature (-4°C) during the day.

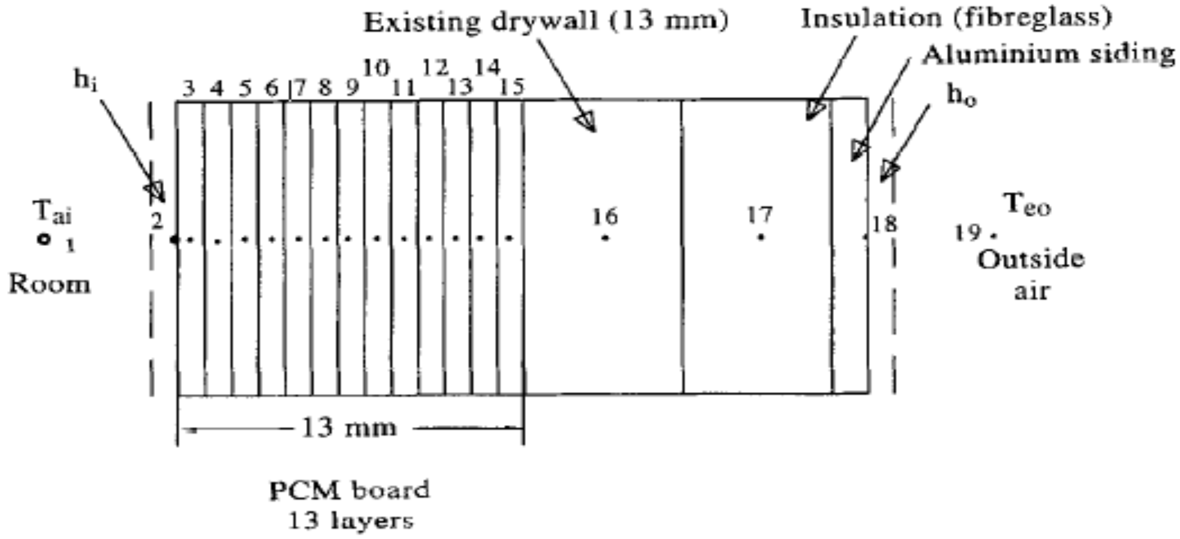


Figure9: Test room wall with Phase Change Materials [44].

A new board was studied in China [45] and was prepared by mixing PCM RT 20 produced by Rubitherm GmbH [27] with montmorillonite, which was then incorporated into a plasterboard. Compared to conventional gypsum, a reduction of the interior room temperature was found (-9°C). Similarly [46], the same mixture was compared to the following composites: Butyl Stearate/Montmorillonite and Dodecanol/Montmorillonite. Following the characterization of the latter, the RT20/MMT composite was more attractive for construction applications due to its appropriate melting temperature and high latent heat. Another composition was studied in Montreal [47] based on butyl stearate and butyl palmitate with the proportions of 50% and 48%, respectively. This mixture was then impregnated on a plasterboard. The results of this experimental study show the impact of this mixture on the interior temperature which was reduced by 1.5°C. In another study [48], it was shown that the application of gypsum boards impregnated with phase change materials in a passive solar building results in a total energy saving of 31%.

Shilei et al [49], in turn, conducted an experimental study to evaluate the integration of PCM gypsum boards in a passive solar building in winter (Figure10). It was concluded that indoor temperature fluctuations were mitigated and that due to the small variation in outdoor temperature, little savings could be obtained. Ana Vas Sa [50], characterizes a new building material that consists of adding BASF's Micronal DS5008x PCM [28] into a plaster mortar. After several tests including different attempts revealing cracking problems, the composite was obtained with 50% PCM with a melting temperature range between 23°C and 25°C. Two test cells were constructed with and without PCM (Figure 11). This highlighted the influence of this composite on the thermal comfort of the building by decreasing the ambient temperature of the room with PCM. Sumin Kim [51] characterized two gypsum-cement panels in which he incorporated n-octadecane and beeswax. A numerical simulation was then performed for four different cities (Los Angeles, Phoenix, Miami and Chicago) and presents a very interesting result in terms of energy reduction due to its appropriate phase change temperature.

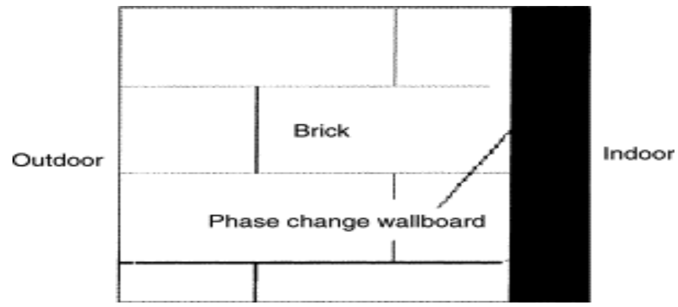


Figure10: Position of the PCM panel within the wall [49].

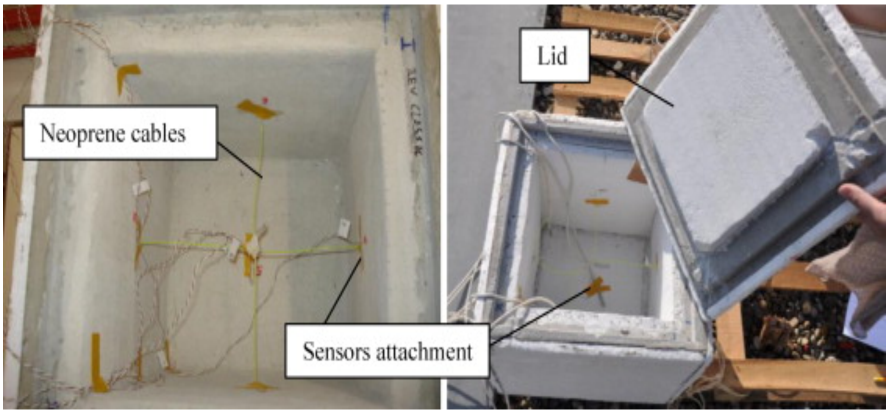


Figure11: Test cells constructed for the experimental study [50].

- Concrete and cementitious materials

Concrete is a building material that is omnipresent in construction due to its strength and durability. there are several researches in concrete integrating the phase change material in order to improve its energy properties. Figure 12 states that a wall incorporating 1.5 cm thick PCMs has the same thermal storage capacity as a 9 cm thick concrete wall and a 12 cm thick brick wall [52].

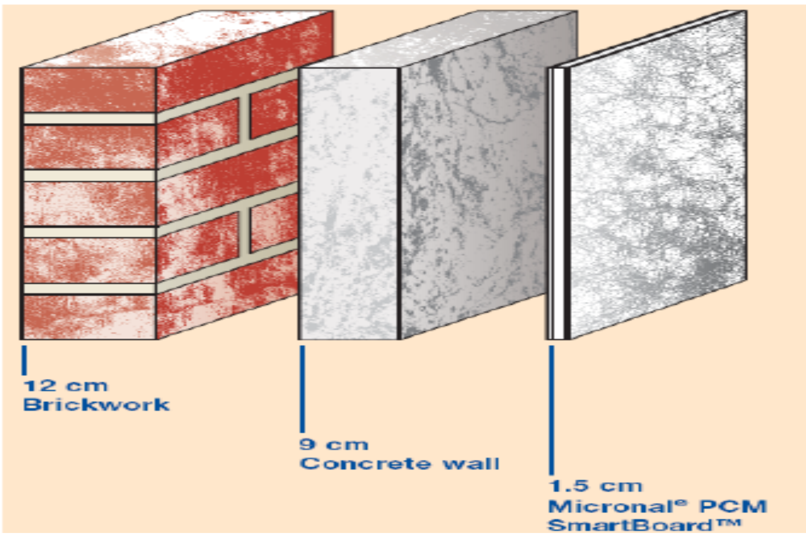


Figure12: Comparison between a PCM wall and a concrete and brick wall [52].

An innovative concrete has been developed in Spain [53] with a melting temperature of 26°C. This concrete was integrated in one of the two cabins built to evaluate the influence of this concrete on the energy consumption of the building. Compared to the reference cabin, the PCM concrete shows a significant improvement of the thermal inertia with a reduction of 2°C on the interior temperature of the test room.

Another study [54] was done for a hollow concrete block in which a PCM (commercial paraffin) is incorporated in a molten state and vertical ventilation tubes for room air control (Figure 13). The results confirm that the addition of the phase change material combined with ventilation results in a gain in thermal inertia and a reduction in room temperature of approximately 3.4°C [55].

R. Stropnik [56] presented a mixture of fatty acid impregnated in concrete developed at Çukurova University, to form a wall panel. To evaluate the thermal performance of this wall, a test cabin was constructed and demonstrated the impact of the composite panel on the reduction of interior temperature.

A diurnal thermal analysis of a wall incorporating micro-encapsulated PCMs was performed in the United States [57] and showed that energy savings are optimal when the melting point of the composite is close to the interior room temperature, and limited or low in excessively hot or cold climates.

Figure13: Concrete block with PCM and ventilation tubes [54].

On the other hand, Palomba [58] carried out the characterization of a composite based on a mortar and a phase change material. Samples of the latter were studied and showed that the addition of PCM in a cement mortar can improve the thermal comfort by about 15% compared to a pure cement mortar. A second cement mixed with parafin was presented by Tao Xu [59]. Different proportions of PCM were studied (10%, 15%, 20%, 25% and 30%) and show that the application of this phase change material effectively improves the heat storage capacity, delays heat transfer and reduces the interior temperature.

According to the studies presented, concrete proves to be an efficient construction material in terms of thermal performance when a PCM is added to it. In fact, the combination of concrete and cementitious materials with PCM has allowed to obtain optimal results on the thermal behavior of walls.
On the other hand, this combination can sometimes cause a real decrease in mechanical properties [60]. It would therefore be recommended that more attention be paid to the mechanical properties in addition to the thermal performance of the composite walls.
It has also been shown that the thermal conductivity of a cement-based composite is associated with the pore structure at the microscopic scale [61]. This should be taken into consideration for better thermal performance and ease of integration of the PCM into its matrix core.

- Other Matrixes

The integration of phase change materials in the construction field can also be done in other types of matrix such as recycled materials, presented by L. Boussaba [62]. Coconut fat was used as a bio-integrated PCM in a matrix based on natural clay and cellulose fibers formed from recycled cardboard, previously used in the industrial sector.

In addition, M. Ahmad [63] presents the performance of a wall panel containing PCMs. To improve the efficiency of the latter, a vacuum insulation panel (VIP=vaccuum insulation panel) was combined with the phase change material board. The chosen solution is a commercial polyvinyl chloride (PVC) gypsum board with the following PCM: polyethylene glycol 600 (PEG 600) with a wide temperature range (21°C-25°C). This new structure allowed to reduce the wall thickness compared to traditional walls and to improve thermal inertia and energy storage.

Medina and Xing [64] thought of incorporating a phase change material based on organic paraffine with a proportion of 10% in small plastic bags with thermal resistance in a wall. After several tests, it was shown in this study that the optimal location for the PCM layer is within the first insulation layer on the inner side of the room.

A new phase change material was studied [65] based on eutectic hydrated salt. Expanded perlite (EP) was chosen as the supporting matrix and was prepared by the vacuum impregnation method. An experimental study was conducted to evaluate the thermal performance of the composite and showed that it has the ability to significantly reduce the peak temperature during the melting process.

Another work was also conducted on the incorporation of a PCM in the form of a wall panel with parafin and expanded perlites as support [66]. Through a numerical simulation on TRNSYS software, it was shown that the application of this panel in an office building of 4000 m2 leads to a decrease in indoor temperature of about 9 K on average during working hours (7 am to 6 pm). This result highlights the addition of this phase change material panel to improve thermal comfort and well-being in the tertiary sector.

Medina [67] studies in turn, the application of a new construction technology for residential and tertiary buildings. This is the structural insulated panels (SIPs): a simple assembly consisting of an inner core (insulation) and two outer skins (plywood or OSB) in which a paraffin-based PCM is added (Figure 14). The use of this composite wall presents a reduction of the thermal flow and would be more interesting for the geographical zones with a big difference of temperature characterized by a high temperature in daytime and a lower temperature in night.

In addition, there are studies, today, that are of particular interest on Trombe walls incorporating PCMs. A work [68] was carried out using TRNSYS software to evaluate the thermal performance of this wall in Wuhan, China. The results of this study highlight the use of the Trombe wall with phase change materials due to its ability to improve thermal comfort and reduce the cooling/heating load throughout the year.

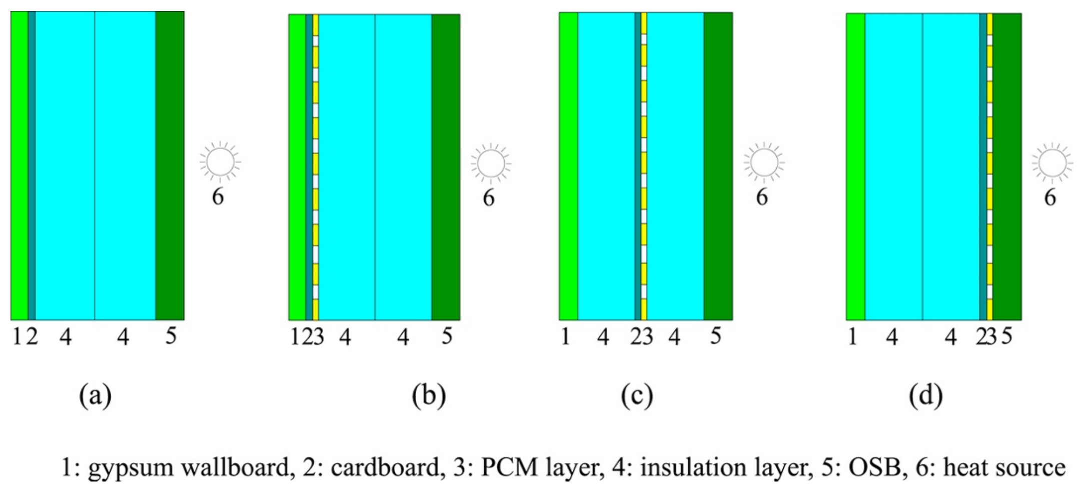


Figure14: Location of the PCM panel in the wall [67].

IV. SOFTWARE

Several studies of the integration within the building envelope have been carried out by means of numerical simulations. This type of study allows to model the physical phenomenon and to analyze the behavior of the building integrating phase change materials subjected to boundary conditions that are as close as possible to real climatic conditions.

Various softwares have been used in the context of the addition of PCMs within the building in order to perform numerical studies based on different methods.

These simulations are often performed with the following software: TRNSYS, ANSYS Fluent, EnergyPlus and COMSOL Multiphysics.

4.1TRNSYS

TRNSYS is considered a world reference in dynamic thermal simulation of buildings based on the FORTRAN language. This tool allows solving complex thermal systems applied in several fields including the building industry while integrating variables such as building materials constituting the different walls, heating/cooling systems, etc. It is also possible to add other components by integrating external functions in FORTRAN, C, C++, etc. The software is a tool to globally evaluate the influence of systems including phase change materials in the building energy balance [69]. Some studies [70,71,72] have used TRNSYS Type 56 in combination with other types for the study of the thermal behavior of the building including phase change materials, the analysis of energy performance and heating and cooling requirements from the total energy consumption.

Figure 15 illustrates the program used on TRNSYS for building simulation with PCM. To do this, the user calls on several types of the software library such as Type 9 for reading boundary conditions and Type 16 for integrating solar flux [69]. In the studies of [73], the use of this software allowed the evaluation of the thermal and energy performance of a new wall panel including PCMs. The numerical results were then compared with the results of a realized instrumentation and allowed to underline the coherence with the experimental.

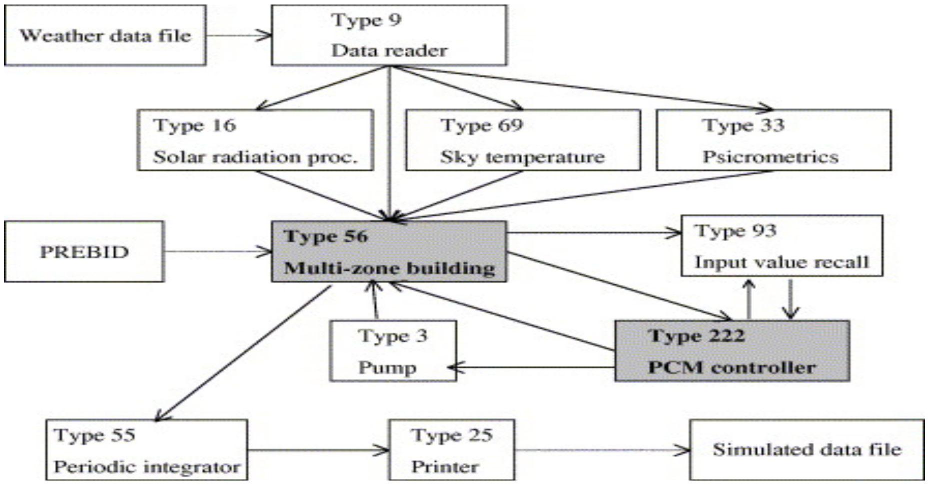


Figure15: Location of the PCM panel in the wall [69].

4.2 Ansys Fluent

Ansys FLUENT is a numerical fluid dynamics tool that allows the study of the local heat transfer of different components of a building integrating phase change materials. Its code is based on the finite volume method (FVM).

A discretization of the equations is carried out by dividing the model domain to be studied into several control volumes and carrying out the mass, momentum and energy balances on each of them [74]. This leads the user to solve a system of algebraic equations in an iterative way [75]. After the geometry of the model has been realized, a mesh must be made which has an impact on the computation time and the accuracy of the desired result. Once the mesh is validated and exported to Fluent, the configuration is performed for the whole model such as the nature, the thermo-physical properties of the different materials, the choice of the boundary conditions etc. In the context of the integration of phase change materials on ANSYS Fluent, there are two methods often used for the heat transfer problem: the enthalpic method and the apparent Cp method. It has been claimed that the methods taking into account phase change effects have similar performance [76].

4.3 EnergyPlus

EnergyPlus is an open-source program, widely used in the context of numerical simulation focused on building energy performance by researchers, engineers and architects. Its algorithm is mainly based on conduction transfer functions (CTF). This type of solution allows to solve the heat transfer without taking into account the stored and diffused moisture in the building domain. It allows to model globally the energy consumption of the building while integrating all the heating/cooling systems and other types of systems. With this software, the user has the possibility to add the phase change module allowing the integration of PCMs. Several researches have used this free software, showing a good performance in the energy analysis of the building integrating phase change materials [77-80]. It was also stated in one study that the energy analysis performed on EnergyPlus had good accuracy [77].

4.4 Comsol Multiphysics

COMSOL Multiphysics is a computational fluid dynamics software for modeling and numerical simulation of many types of physical phenomena and engineering applications. Its code is based on the finite element method with a fixed mesh.

In the field of building, this software is used to evaluate the heat transfer and the thermal behavior of the walls constituting the building.

Several researches have used this software to study the integration of phase change materials in buildings [81-83]. To solve the heat transfer problem with a phase change, the software proposes two different methods: the apparent Cp method and the enthalpic method [84].

Moreover, the models studied with these tools must necessarily be validated beforehand with other studies in the literature for a more meaningful and reliable analysis.

V. ANALYSIS AND DISCUSSION

The results presented in this review allow to affirm that the influence of the phase change material integrated in the vertical wall of the building has multiple advantages, especially on the thermal comfort as well as the energy consumption of the architecture. Today, composite panels represent a new passive building system and their use has reached the highest level of interest. Several researches have thought about the incorporation of organic PCMs due to their various advantages, widening the thickness of this layer, or taking into consideration other parameters such as shading and orientation of the wall in relation to solar radiation. On the other hand, the low thermal conductivity can sometimes limit their application. For this reason, some research has focused on the choice of matrix to increase the thermal conductivity of the material. To solve this problem, a new method has been developed: wrapping the PCM with a poly dopamine layer [85]. In order to have better energy savings, the placement of the layer is very important within the wall. Indeed, it should be placed on the inner side of the test room [64].

To answer the question raised above, a double layer system with phase change materials is proposed to have a better energy consumption in winter and summer periods [86]: one layer for the hot period and another one for the cold period (Figure 16). However, there is a problem with the leakage of phase change materials. Li and Chen [87] were able to solve this problem by incorporating hydrophobic fumed silica or precipitated silica for their effectiveness in preventing leakage of PX25, a PCM, produced by Rubitherm GmbH, [27]. In addition, some studies have emphasized the importance of natural night ventilation coupled with the addition of PCMs, considered as an excellent passive method to increase the cooling performance of buildings [88]. Despite all the advantages listed in this review related to the use of PCMs, there are various complications for which this material is not exploited in the building sector such as the leakage of the material during its integration in the building material, considered as a major problem reported in several scientific studies, and the often-higher cost of the material, which must be evaluated according to its contribution on the reduction of the energy consumption and the electricity bill.

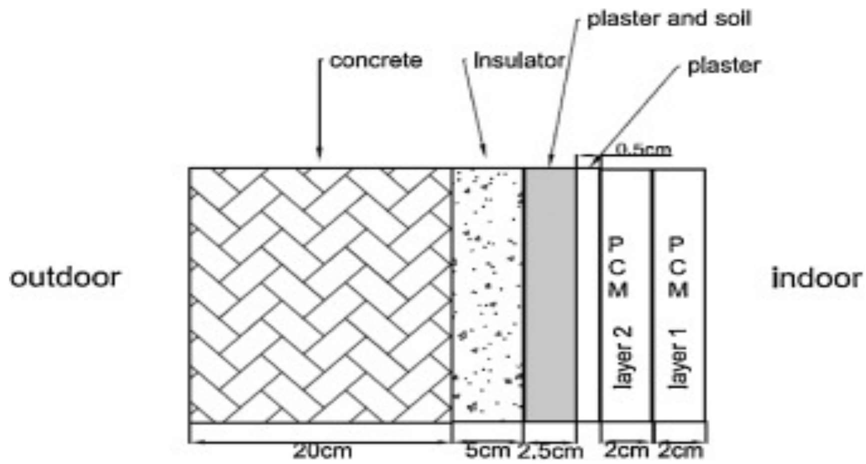


Figure16: Location of the two layers of the PCM [86].

VI. CONCLUSION AND PERSPECTIVES

In sum, the addition of phase change materials currently offers an alternative for passive cooling in the residential and tertiary building sector. In this paper, several experimental and numerical studies on the integration of PCMs into the architectural wall, dating from 1996 to 2019, have been synthesized and analyzed.

The use of wall panels with PCMs is increasingly studied due to its ability to mitigate ambient temperature fluctuations, reduce energy consumption and carbon footprint, improve thermal comfort and performance of the building envelope.
In conclusion, some conclusive recommendations for future work are listed below:

- The literature is now focused, especially on the application of solid/liquid transition phase change materials. Thus, it would be preferable to focus on PCMs with solid/solid transition that can facilitate the incorporation of the material in its matrix and thus, avoid the "encapsulation" phase. It allows more particularly a considerable saving of time.
- Construction materials must meet certain strict safety requirements. Fire safety is one of them, an essential point for all materials, especially organic PCMs because of their high flammability.
- To limit the pollution of our environment and to preserve natural resources, PCMs must be reused: The recycling of PCMs is not sufficiently studied to date.
- Numerous studies have highlighted the problem of leakage linked to the integration of phase change material. It would therefore be desirable that this point be studied further for all types of PCM.
- The economic aspect plays a considerable role on the exploitation of these materials. Indeed, the cost of the application of PCMs within the building should not be neglected and is mainly aimed at attracting and involving the major manufacturers of the market. This approach generally consists in evaluating the investment cost and the economic profitability.

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