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Phase Change Materials Integrated Into the Building Envelope to Improve Energy Efficiency and Thermal Comfort

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ABSTRACT

The approach of space cooling to achieve indoor thermal comfort is one of the main energy-consuming aspects of buildings. To reduce the amount of energy used in buildings ultimately, it is essential to design building envelopes that are energy-efficient. The primary strategies used in this research are analysed in order to determine innovative and successful approaches, with an emphasis on phase change materials (PCMs), for improving the building envelope performance. The technique of incorporating PCMs into building envelope is becoming more prevalent because of its enhanced energy capacity to store and release heat during phase conversion, which is one of the sustainable methods used for regulating space temperature. The application of PCM as a construction material for thermal energy storage is the main focus of this study, it emphasises the Phase Change Materials main concept. The most common PCM types for usage in building envelopes, together with their material composition and diverse qualities. This research also illustrate the different techniques for incorporating PCM into building envelope components. As a case study, an energy consumption analysis is conducted on a building located in Alexandria, Egypt. Subsequently it is suggested to integrate PCM in the construction materials, the impact of this suggestion is then simulated using Design Builder software. Using this software the current state of the building had been simulated and its condition after modifications using the PCMs had been simulated, and the results demonstrate a significant improvement in the thermal performance of the building.

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1. INTRODUCTION

An estimated one-third of the energy used in the building sector is for space heating and cooling. By 2050, cooling will require 150% more energy. By 2050, building cooling energy demand in developing nations will rise by 300% to 600%. (Rathore et al., 2022). Therefore, the greatest chance to maximise building energy consumption patterns is through space cooling. The thermo-physical characteristics of the building envelope are a major determinant of the space cooling demand. The structure that protects a building's interior spaces from its exterior surroundings is called the building envelope. The building envelope consists of various components, such as the walls, roof, floor, windows, doors, and external shading. Optimising thermal efficiency in building components eliminates the energy needed for space cooling while also enhancing indoor thermal comfort (Ürge-Vorsatz et al., 2015).

Studies and researchers used a variety of techniques to enhance the building components' thermal performance in order to reduce the energy needed for space cooling. Optimising the amount of energy needed for space cooling has been demonstrated through enhancing the building envelope's thermal energy storage capacity and adding Phase Change Material (PCM) to the building materials. Usually, thermal energy is stored in a tangible form in construction materials including bricks, concrete, cement, and wood. The disadvantage of sensible thermal energy storage is its poor energy density (Al-Yasiri & Szabó, 2021). Furthermore, a large temperature range is covered by the thermal energy storage technique. In order to eliminate the negative aspects of sensible thermal energy storage, PCM is incorporated in the building components. Thermal energy is latently stored in PCM. By going through a phase change at a nearly constant temperature, the material in latent heat storage is able to store thermal energy. Thus, adding PCM to a building element can control the indoor thermal comfort and increase the element's capacity for heat storage (Rathore et al., 2022).

Several approaches are presently being researched to enhance the building envelope's thermal performance and boost its thermal storage capacity. These methods, which can be applied passively or actively, have demonstrated improvements in lowering the building's energy consumption and regulating the loads for heating and cooling. By using such affordable technology, it is technically conceivable to save building energy by up to 20% by 2030 (Al-Yasiri & Szabó, 2021).

Effective thermal resistance is one of the building envelope's main functions in preventing heat waves via the outside from getting into the building. As a result, it improves to maintain of indoor thermal comfort appropriate. Unfortunately, the conventional building envelopes are not able to keep up with the increase in world temperature due to the acceleration of global warming. Heat waves enter buildings more readily as a result of the rising external temperature, which reduces indoor thermal comfort. Consequently, the building's cooling load will rise, placing greater pressure on the electrical equipment that powers the HVAC system (heating, ventilation, and air conditioning). As a result, increasing building exterior energy efficiency is essential (Rathore et al., 2022).

The HVAC systems (heating, ventilation, and air conditioning) account for 60% of all energy use in the building sector. In general, solutions for active, passive, and hybrid cooling promote thermal comfort within buildings. Indoor thermal comfort has a major impact on building residents' productivity and well-being (Sharma et al., 2022). The utilization of renewable energy sources in passive cooling results in an environmentally friendly method for meeting the current thermal demands (Taleb, 2014). Thus, depending entirely on conventionally powered cooling systems has contributed to a rise in the need for fossil fuel-based energy in the future, impeding the development of thermal energy storage systems based on renewable energy sources globally. In order to make building envelopes sustainable, a number of recently created perfect renewable energy passive cooling technologies have been developed and generically categorized into heat protection, heat modulation, and heat loss techniques (Bhamare et al., 2019).

The following section provides a quick overview of the widely utilised methods for enhancing a building's thermal mass and performance. These methods include the detailed of inclusion of PCM, which is part of Passive cooling technique Heat Modulation.

2. PHASE CHANGE MATERIALS

During circumstances involving relatively constant temperature, PCMs can absorb and release heat during phase transition (mostly from the solid to liquid form and vice versa) as shown in (Figure 1). In recognition of a given relatively small unit volume, these materials have the capacity to store and release significant amounts of heat. In its initial stages, the PCM melts at its melting point without going through a phase shift that would store heat. The PCM absorbs energy as a result of the chemical bonds breaking in parallel with the endothermic process when the temperature approaches its melting point. The PCM experiences a solid-liquid phase shift at nearly constant temperature during this stage of operation (Tyagi et al., 2016). sensible heating will cause the PCM temperature to rise further with additional temperature increases. Chemical bonds rebuild through an exothermic mechanism that releases energy when the PCM's temperature drops to the freezing point. As a result, PCM experiences a phase change from liquid to solid. It is possible to repeat the charging (heat gain) and discharging (heat loss) processes multiple times. Thus, it is possible to refer to PCM as a thermal storage. Additionally, PCMs are used to move peak demand to off-peak hours, which improves building efficiency (Al-Absi et al., 2019).

Providing an example, when a solid substance's temperature is raised to its melting point, it melts by absorbing a significant amount of heat and changes from a solid to a liquid phase. Within a specific temperature range, the phase states of the PCMs can change (Bayraktar & Kose, 2022).

2.1. PCMS CATEGORIZATION AND PROPERTIES

PCM is preferable to alternative thermal energy storage materials and technologies in a variety of ways, including high heat of fusion, wide range of availability, chemical stability, non-toxicity, affordability, and low impact on the environment. PCMs are primarily categorized as organic, inorganic, and eutectic materials based on their chemical properties (Figure 2) (Sharma et al., 2009). Considering that each category has a range of thermophysical characteristics and operating temperatures, some are more suited for particular applications than others. (Table 1) lists the shared attributes of the three groups, along with their primary positive and negative aspects. Along with the other desired qualities, the operating temperature range of the application and the melting temperature of the chosen PCM play a significant role in the proper selection of PCM (Abbas et al., 2021).

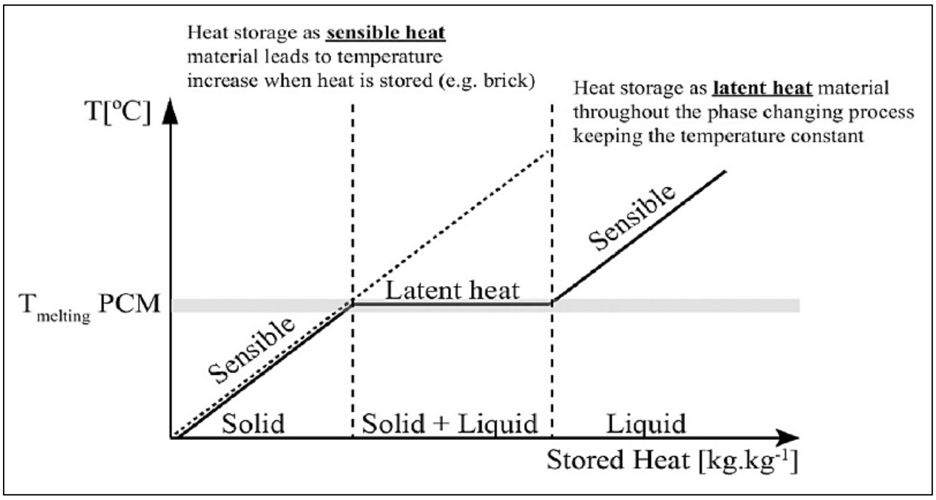

Figure 1 Sensible heat and Latent heat storage for the case solid–liquid (Bhamare et al., 2017).

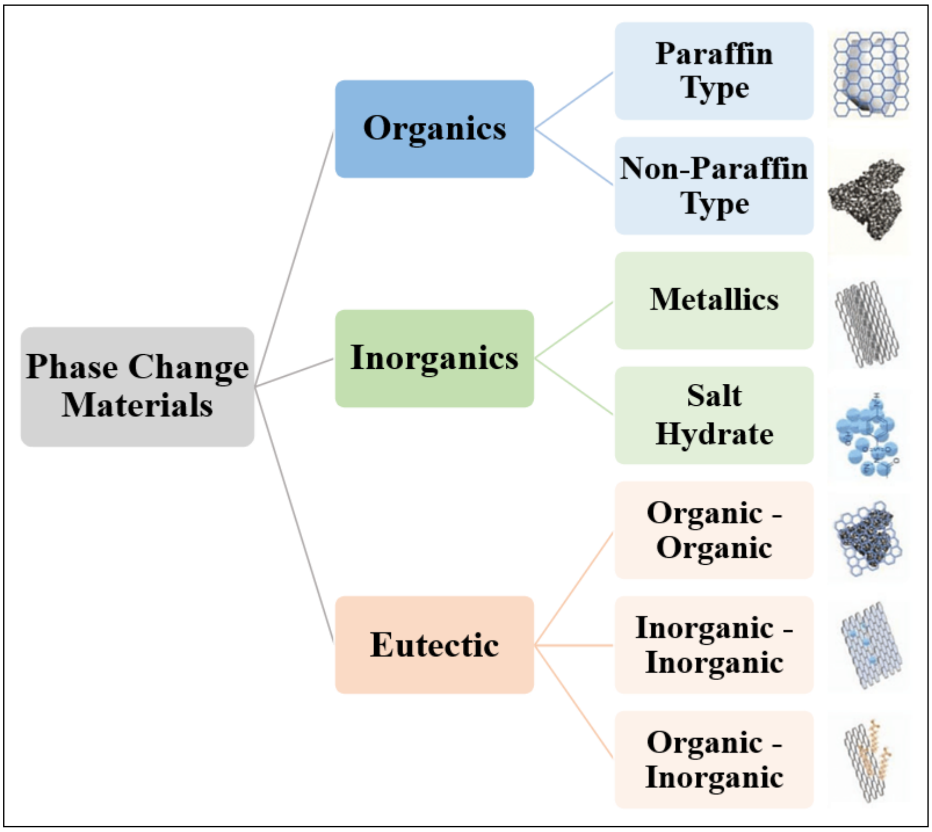

Figure 2 Classification of Phase change Materials (PCMs) (Paul et al., 2022) – Edited by the researcher.

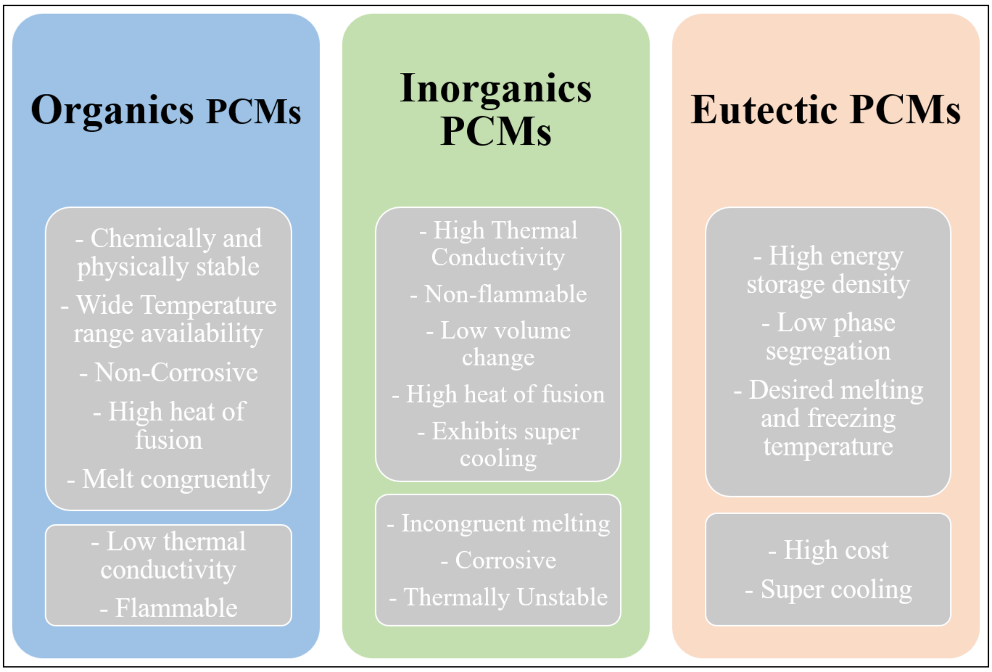

Table 1 Advantages and disadvantages of PCMs (Paul et al., 2022) – Edited by the researcher.

2.2. THE IMPLEMENTATIONS OF PCMS

It has been demonstrated that PCMs provide great potential for a variety of heat transfer and energy storage applications. Recent research on PCMs has focused on their application in a range of solar applications because to their high heat transfer system performance. The potential of PCMs as a thermal storage medium in heat storage tanks, solar distillers, solar cookers, and refrigeration and air conditioning systems has been the subject of several investigations. They are also utilised in solar modules and electronic equipment as heat sink material. In addition, PCMs are effectively integrated into building envelopes as suppliers or heat barriers, and they are utilised as insulation materials in shipping containers and electrical distribution transformers for heat dissipation (Abbas et al., 2021).

2.3. THE PCM PARAMETERS THAT IMPACT THE ENVELOPE PERFORMANCE

By incorporating PCM into the building envelope, the building's peak temperature can be lowered by up to 4°C, maintaining consistent thermal comfort conditions during the summer months. Several factors influence PCM's activity, which consequently affects its thermal performance, which can occasionally perform poorly. It is recommended to take these factors into consideration in order to assure PCM's optimal functioning and fully utilise its potential (Rathore et al., 2022). The optimal thermal performance and the ideal location for the PCM application were achieved by completing a full daily melting/freezing cycle, even though several optimum placements were found in the experiments that were carried out. As a result, the most suitable position for the PCMs to be applied in a wall is one that allows for sufficient warmth during the day to completely melt the PCMs and sufficient cold during the night to totally freeze them (Al-Absi et al., 2020).

A variety of factors could impact this procedure; thus, they can be divided into two categories: external parameters and internal parameters (Table 2).

Whether the PCM is being implemented for the goal of reducing heating or cooling loads, or both, will determine the positioning of the PCM layer in the building under consideration. In buildings, PCM integration has typically demonstrated better performance for reducing cooling demand as opposed to heating load. Furthermore, the PCM is capable of active operation at temperatures above its melting point (Plytaria et al., 2019). The PCM layer should be positioned closer to the heat energy source, according to several studies (Yua et al., 2019). Additional research revealed that a mid-element location improves the building's annual performance. The PCM layer needs to be put on the outside of the building element in order to provide cooling. In contrast, for heating purposes, it should be located closer to the interior (Vukadinović et al., 2020).

2.4. PCM INCORPORATION TECHNIQUES IN BUILDING

Researchers have identified many strategies for embedding PCM into the building envelope, these methods are gathered and classified as shown in (Table 3) (Rathore et al., 2022). The different methods are classified into direct integration or indirect integration methods which can be used to incorporate the PCM into the building envelope.

The easiest and most affordable approach of the following mentioned techniques is the direct incorporation technique, in which PCM is generated by mixing it directly with building materials including cement, concrete,

PARAMETERS INFLUENCING THE OPTIMUM POSITION OF PCMS APPLICATION		
EXTERNAL PARAMETERS		**INTERNAL PARAMETERS**
1. Climate and weather	**1.** Indoor Environment	**1.** PCMs thermal Properties
2. Application target	**2.** Wall Orientation	**2.** PCMs quantity and layers thickness
	3. Wall Material	

Table 2 The main factors that affect the PCM application's optimal position in building walls (Al-Absi et al., 2020) – Edited by the researcher.

METHODS OF PCM INTEGRATION IN BUILDING ENVELOPE	
DIRECT INCORPORATION	**INDIRECT INCORPORATION**
1. Wet Mixing Technique	**1.** Micro-encapsulated PCM
2. Immersion Technique	**2.** Macro-encapsulated PCM
	3. Shape-stabilized PCM

Table 3 Incorporation Techniques of PCM in building envelope (Rathore et al., 2022) – Edited by the researcher.

and wallboards (Lu et al., 2017). PCM can be directly included using two different techniques: Wet Mixing and Immersion techniques. In the wet mixing procedure, at the production site, PCM is mixed directly with building materials including concrete, mortar, and cement. The building material's ability to store thermal energy can be enhanced by directly mixing PCM. The PCM must not interfere with the hydration process and must not react with any mix component in order for this approach to be applied successfully (Frigione et al., 2019).

The porous building materials (concrete blocks, gypsum wallboard, porous aggregate, etc.) are submerged in a container of liquid PCM when using the immersion approach. By capillary action, the building element absorbs the PCM. The concrete's absorption capacity, the temperature, and the kind of PCM used determine how well the porous construction element works and how long it takes to fully soak into it (Whiffen & Riffat, 2013).

Indirect incorporation is a further technique for integrating the PCM into the building envelope. This method involved encapsulating the PCM before integrating it into the structural component (Al-Yasiri & Szabó, 2021).

The Encapsulation method contains the liquid phase by first encapsulating the PCM before incorporating it into the building components. For the encapsulating material to be compatible with the building materials, it must satisfy specific requirements: (1) the creation of a shell around the PCM known as the core; (2) preventing the leakage of molten PCM; (3) incorporating impurities into the core/shell system; and (4) resistance to thermal and mechanical stressors (Sawadogo et al., 2021). The synthesis technique and the type of shell material employed determine the size and shape of the capsules, which are then classed. When the diameter of the capsule is less than 1 mm or 1 cm, they are called micro-capsules; when the diameter of the capsule is greater than 1 mm or 1 cm, they are called macro-capsules. They are also referred to as nano-capsules or nano-spheres (Sivanathan et al., 2020).

Enhancing the PCM's thermal performance is mostly dependent on the material of the shell. The PCM and the surrounding environment must get along with the shell material. Both natural and synthetic polymers can be used as suitable shell materials for microencapsulation preparation. In addition to being poisonous and combustible, polymers typically have low heat conductivity. Therefore, some research has proposed using non-polymers—such as silica, calcium carbonate, and melamine-formaldehyde resin—as a shell material to encase PCM since they are environmentally safe and have a high heat conductivity. Aluminium is the most often utilised shell material for microencapsulation due to its excellent heat transfer properties. Stainless steel and copper are also utilised in the encapsulation of PCM (Sawadogo et al., 2021).

Each method of both the direct and indirect techniques of incorporating PCM into construction materials presents different advantages and disadvantages. These aspects will be illustrated in (Table 4).

PCMs that are shape-stabilized are manufactured by impregnating PCMs in porous construction materials. Because of capillary force, surface tension, hydrogen bonding connection, and other interactions between the porous matrix and the PCMs contained in the building materials' nanopores, this technology stabilises the PCMs and prevents leakage problems throughout the phase transition process (Sawadogo et al., 2021).

3. USE OF PCM IN BUILDING MATERIALS

The potential benefit of PCM for enhancing the building envelope's indoor thermal performance is discussed in this section. The use of PCM in common building materials such as bricks, concrete, wallboard, and glazing were thoroughly reviewed (Rathore et al., 2022).

3.1. PCM INCORPORATED BRICKS

In many different countries, bricks are the most widely used building material. They have many benefits, including strength, low cost, excellent durability, and ease of manufacture. However, typical bricks perform poorly in terms of heat due to environmental factors. This results in an uncomfortable temperature environment indoors. As a result, the burned clay bricks' thermal performance needs to be improved. Increasing the heat storage capacity of bricks by adding PCM is one efficient way to improve their thermal performance (Gupta et al., 2023). A numerical

METHOD OF INCORPORATION	ADVANTAGES	DISADVANTAGES
Direct incorporation	Simple and cheap	Possible leakage of PCM in the melting state; flammability of the impregnated elements is possible, as well as incompatibility between the materials.
Direct impregnation	Simple, practical and cheap	Leakage and incompatibility can occur affecting the mechanical properties and durability of the construction elements.
Micro-encapsulated PCM	Reduced leakage of PCM during phase transition; higher heat transfer rate; improved chemical stability and thermal reliability.	The capsules are expensive; their rigidity may prevent natural convection and reduce the heat transfer rate; the mechanical properties of the construction materials may be affected.
Macro-encapsulated PCM	A significant quantity of PCM is Macro-encapsulated PCM packed in the container; easiness and suitability for any specific application.	Poor thermal conductivity and tendency to solidification at the edges; introduction in the structure must be carried out.
Shape-stabilized PCM	Large apparent specific heat; suitable thermal conductivity; ability to maintain the shape of PCM during the phase-change; thermal reliability over a long period of time; reduced leakage phenomena.	Complex equipment is needed for their preparation; need to use additives to improve the thermal conductivity.

Table 4 The advantages and disadvantages of multiple PCM integration techniques in construction materials (Frigione et al., 2019).

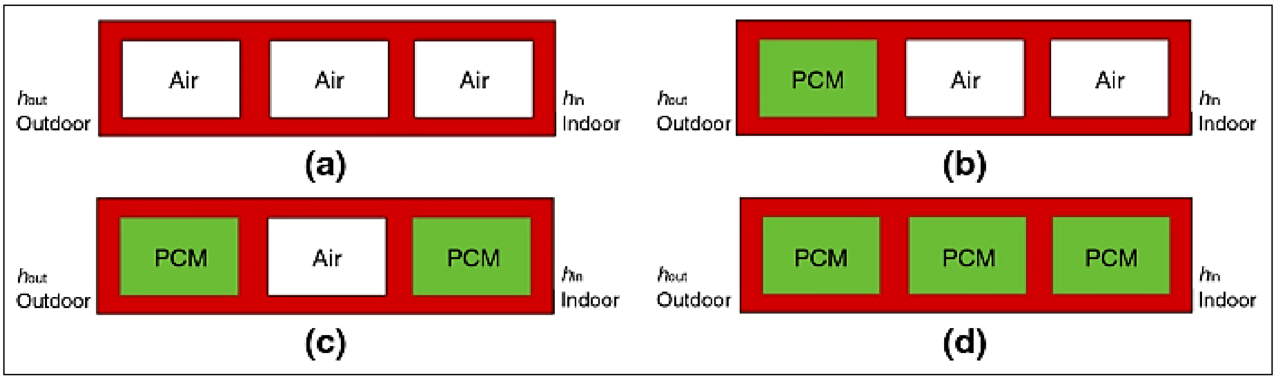

Figure 3 Bricks with PCM integration models (Tunçbilek et al., 2020).

investigation of the heat transmission of hollow bricks containing PCM has been conducted. Simulation research was conducted to examine the thermal performance of traditional brick that has been combined with PCM (Gao et al., 2020), as shown in (Figure 3). The brick is 240 × 240 × 135 mm and contains three identical 30 × 30 mm square cavities that are filled with air. According to the findings, when only one gap is filled with PCM, the highest energy savings occur when the gap near the indoor side is filled with the material. By adding PCM to the brick, annual energy consumption was reduced by 17.6%. Additionally, during the heating season, the impact of implementing PCM integrated bricks on energy conservation was higher (Al-Yasiri & Szabó, 2021).

3.2. PCM INCORPORATED CONCRETE

Due to its exceptional qualities, including its great compressive strength, fire resistance, durability, and moldability, concrete is one of the thermal mass materials used in structures the most frequently. Cement, water, and fine and coarse particles combine to form concrete. The thermophysical behaviour of the concrete is determined by the age of the material, its qualities, the ratio of these ingredients in the mixture, and how they are treated during preparation at the construction site. The two most crucial thermal characteristics of concrete that have a big impact on its thermal behaviour are its heat capacity and thermal conductivity (Berardi & Gallardo, 2019).

Enhancing the latent heat storage capacity of concrete through PCM embedding improves indoor thermal behaviour by reducing thermal loads and temperature fluctuations, which has a positive effect on energy efficiency. Every year, the researchers analyse how the building envelope's integrated macro-encapsulated PCM performs indoors. As illustrated in (Figure 4), two comparable building constructions measuring 1.12 m 1.2 m 1.2 m were created using concrete. PCM was integrated in one of the building structures, but PCM wasn't incorporated in the other building structure (Carlucci et al., 2021). According to the results, the building structure with PCM demonstrates a reduction in indoor temperature variation from –2.43% to 51.3% throughout the year, as well as a reduction in peak temperature ranging from 0.2°C to 4.3°C (Rathore et al., 2020).

3.3. PCM INCORPORATED WALLS

The performance of PCM walls is significantly impacted by the PCM position. Therefore, improving the PCM position can enhance the building walls' thermal performance. The most suitable location may vary depending on the PCM characteristics (such as melting point, heat of fusion, and thermal conductivity) weather condition and wall structure (Cuia et al., 2015). According to the research, using PCM might lower CO2 emissions in warm-climate buildings by 1% and save 6% on energy use for constructing walls. Additionally, the study found that the PCM layer's location within the wall is sensitive; as a result, inserting the PCM layer inside the insulation of the wall can save 1%–7% more energy than placing it outside. Furthermore, in severe and hot temperature zones, an increase in PCM thickness can result in 2%–6% more energy savings (Al-Yasiri & Szabó, 2021).

The ideal location of a thin PCM layer integrated with a frame wall to lower the heat transfer that travels through it was investigated both mathematically and physically. As illustrated in (Figure 5) the layer was positioned differently in relation to the interior and outside wall layers. The simulation findings showed that the ideal PCM layer location was influenced by both the PCM layer's thermal characteristics and the surrounding environment. Two locations were found to be effective: the layer closer to the outside wall surface (case d) when the PCM layer thickness, the heat of fusion, and the melting temperature of PCM increased, and the layer closer to the interior wall surface (case a) when the interior temperature increased (Al-Yasiri & Szabó, 2021).

3.4. PCM INCORPORATED GLAZING

One distinctive way to increase the thermal inertia of glazing units and lower building energy consumption is to add phase transition materials to the enclosure between two or more glass panes. To conduct a thorough assessment and comparison between the performance of a water flowing double glazing window and a conventional double-glazing system (i.e., a double-glazing system with an air cavity), the researchers investigated the system's energy performance, economic viability, and carbon footprint behaviour. They determined the monthly and annual energy

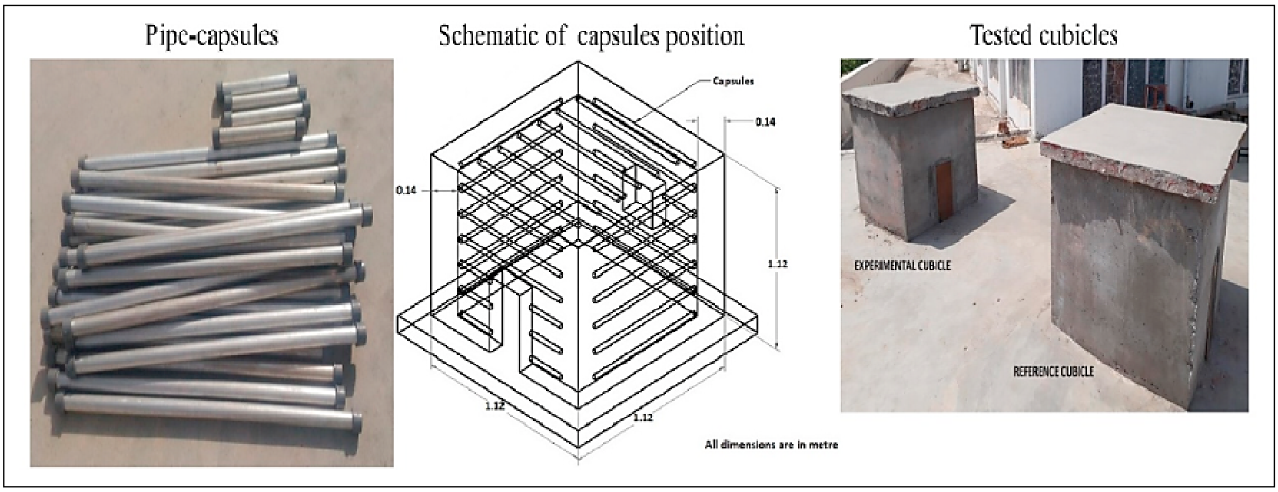

Figure 4 The indicated installation procedures for pipe macro-encapsulated PCM (Al-Yasiri & Szabó, 2021).

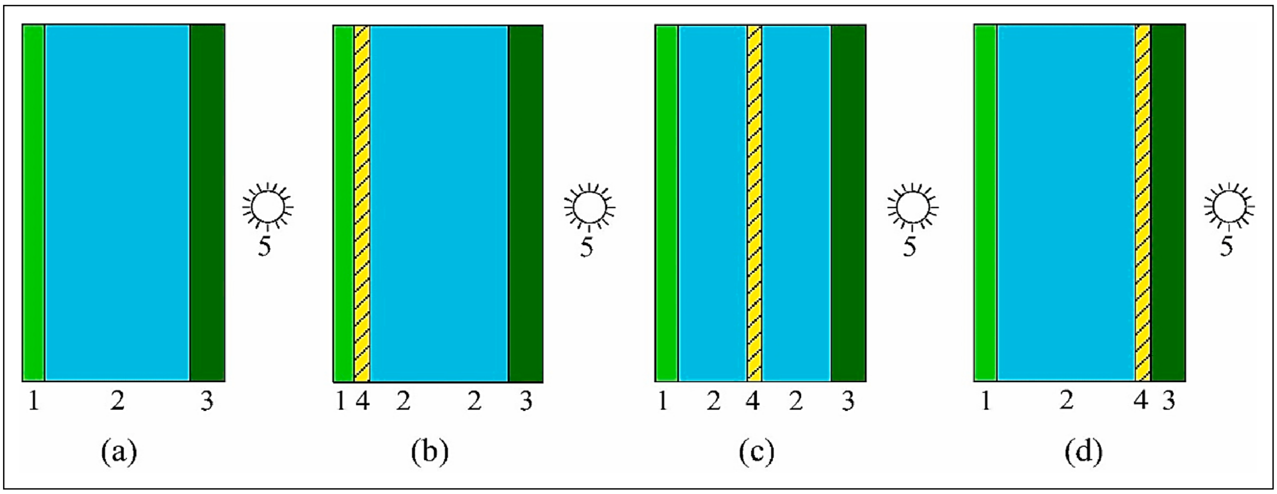

Figure 5 Diagram illustrating the placements of the PCM layers that were studied: **(a)** ordinary wall; **(b)** PCM layer placed near the interior; **(c)** PCM layer positioned in the centre; and **(d)** PCM layer placed near the exterior.

1. gypsum board, 2. insulating layer, 3. oriented strand board, 4. PCM layer and 5. outdoor (Al-Yasiri & Szabó, 2021).

demands of various glazing types based on the energy balance analysis aspect (Li et al., 2022). The researchers computed the amount of energy used and CO2 released. It is apparent that by switching from a standard glazing system to a double-glazing unit with a flowing water chamber in the façade, CO2 emissions are decreased by roughly 18% (Li et al., 2022).

4. CASE STUDY

4.1. SITE LOCATION

The house of this case study is located in Moharram Bek at the south edge of Alexandria, Egypt, on Qanat El-Sweis Main Road. It is part of a small-scale residential compound consisting of 100 houses of different types. It is located in a central location in the compound (Figure 6).

4.1.1. Weather conditions

Alexandria, Egypt has a Mediterranean climate, where it is relatively hot in the summer with temperatures up to 33 degrees Celsius, and cool in the winter where the temperature drops to 9 degrees Celsius. Buildings in Alexandria require air conditioning in almost half of the days of the year and rarely require heating only in the very cool winter days, so the buildings are thus cooling dominated meaning that most of the energy consumed goes to cooling. Egypt also lies in the southern hemisphere which means that the elevations most subjected to direct sunlight in the summer are the east and west elevations, followed by the south and the north elevation is hardly ever subjected to direct sunlight making it the most suitable elevation for large openings. The prevailing wind in Alexandria comes from the North West.

4.1.2. Building Description

The building is a two-story detached house with a footprint of 255 m^2 and a total buildup area of 500 m^2. The height of the ground floor is 3 m and the height of the first floor is 2.7 m with a total building height of 6.6 m. The ground floor consists of the reception, living areas and services while the first floor consists of mostly bedrooms and the staircase lies in the center of the dwelling (Figure 7).

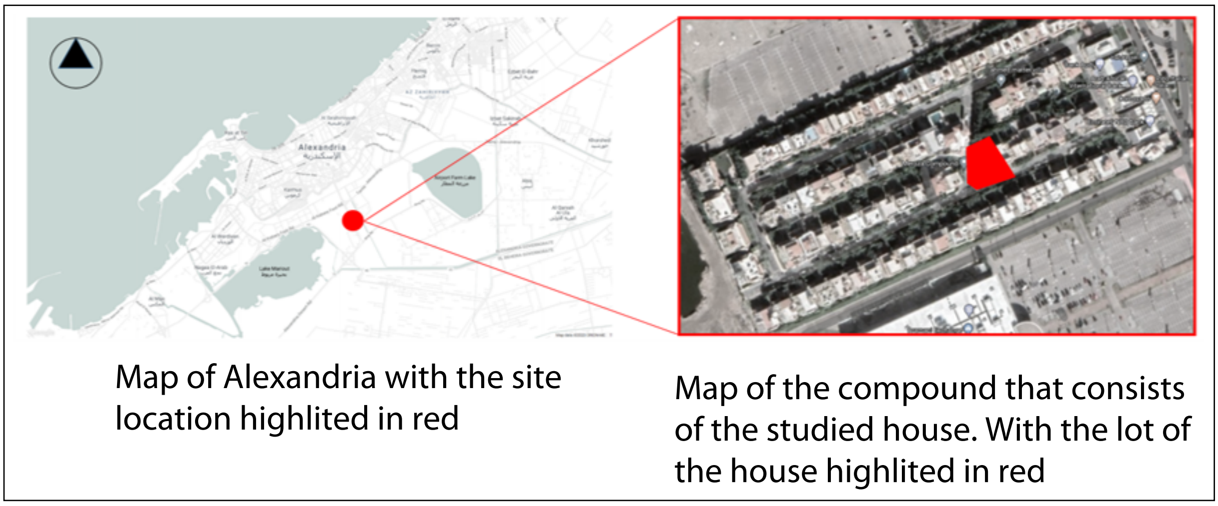

Figure 6 Site location, Alexandria – EGYPT.

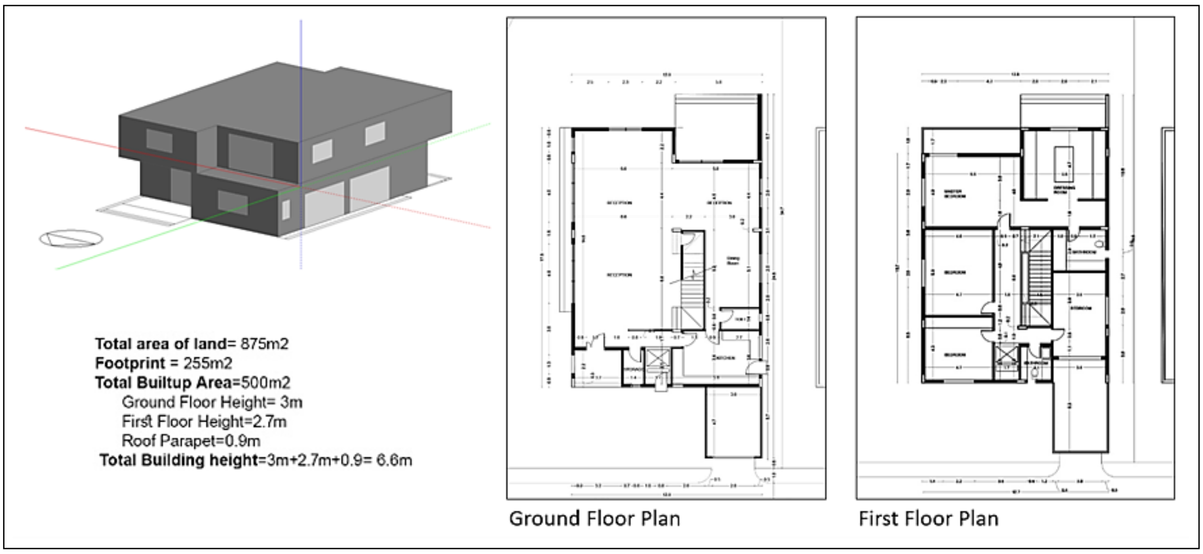

Figure 7 Aarchitectural plans and Design Builder model of studied building.

4.2. DATA ENTRY

Design Builder is the programme used to simulate energy in this case study. This software is capable of precisely simulating the building's year-round environmental parameters, such as humidity, lighting, thermal balance, and energy usage. To achieve an accurate simulation, each element of building data needs to be entered with high accuracy.

4.2.1. Activity

The activity of each space must be specified accurately as well as the number of users (Figure 8).

4.2.2. Construction

One of the most important data that must be entered in order to achieve an accurate simulation is the construction data, the material of the walls and slabs or roof to be accurate. Since the wall and roof conduct the majority of the heat from the surrounding environment, its composition, U-value, and level of insulation have a significant impact on energy usage.

1- Wall materials: External walls are 200 mm thick brick walls with 2.5 cm external plaster and 1.5 cm internal plaster. Internal walls are 12 mm thick brick walls with 1.5 cm plaster on both sides
2- Roof: the roof slab is a 15 cm thick reinforced concrete slab with 5 cm thermal insulation and an8 cm plain concrete with tile finish.

4.2.3. Opening

Openings, especially windows in particular, have a significant impact on heat gains and losses, which in turn has a significant impact on energy use. The majority of heat gain in warm areas and buildings with cooling systems originates from solar heat gains transmitted through windows. For this reason, the kind of glazing and shading of the windows is an essential information that needs to be provided precisely for a simulation to be accurate.

Windows: single transparent glazing in aluminum frame with no shading
Doors: wooden doors 5 cm thick

4.2.4. Microclimate

It is important to model surrounding buildings as component blocks because they will have a strong effect on the microclimate: shading daylight and ventilation (Figure 9a).

4.2.5. Cooling

It is important to enter which spaces in the building are cooled and the type of cooling system used in the building for an accurate simulation. The spaces in (Figure 9b) that are colored blue are the cooled spaces and the red spaces are not cooled.

4.3. SIMULATION- CURRENT STATE

4.3.1. Heat Transfer

Considering walls make up the majority of the building envelope and are not insulated, they allow a significant quantity of heat into the building. As a result, the walls responsible for the majority of heat gains and losses throughout the year. (Note that this does not include the heat gains by solar radiation.) The heat gains and losses through ambient heat transfer through glazing follow the walls (Figure 10). Ultimately, there is very little heat loss via the roof and flooring.

4.3.2. Cooling

The cooling design is simulated based on one of the hottest days of the year which is July 15th. The heat balance diagram (Figure 11) shows that the amount of heat that enters the building appears to be mostly from the solar heat gains of the glazing. Thus, the windows are responsible

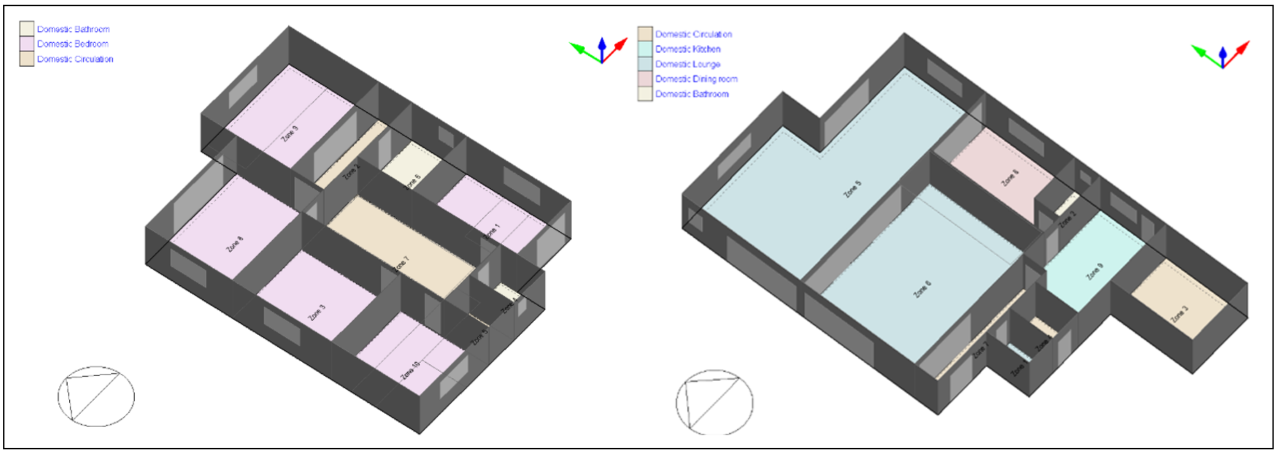

Figure 8 Illustrated the Ground and first floor functions.

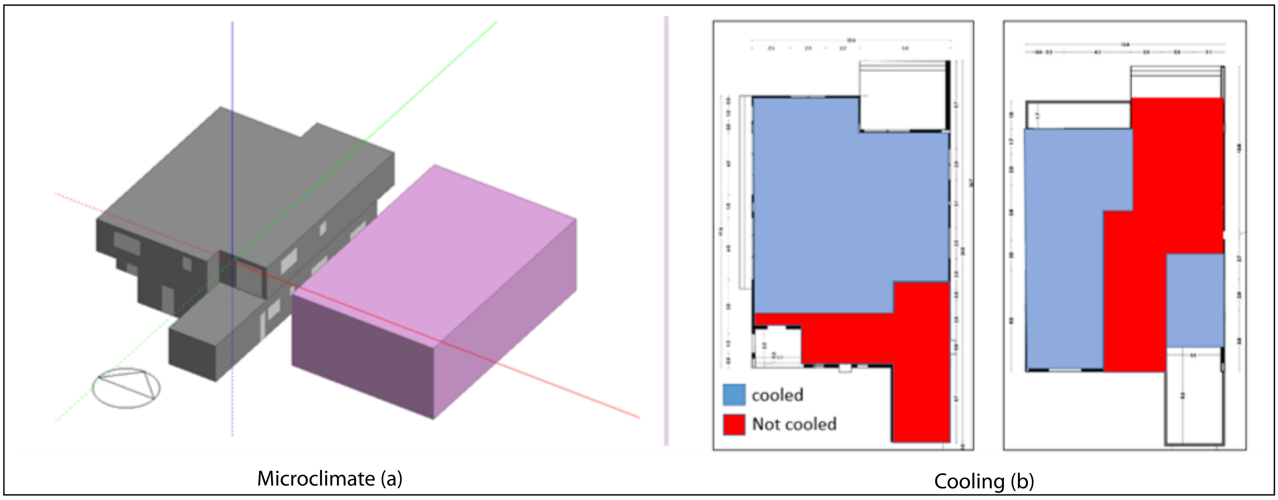

Figure 9 The Diagram illustrates the Microclimate and cooling requirements of building. Microclimate **(a)**. Cooling **(b)**.

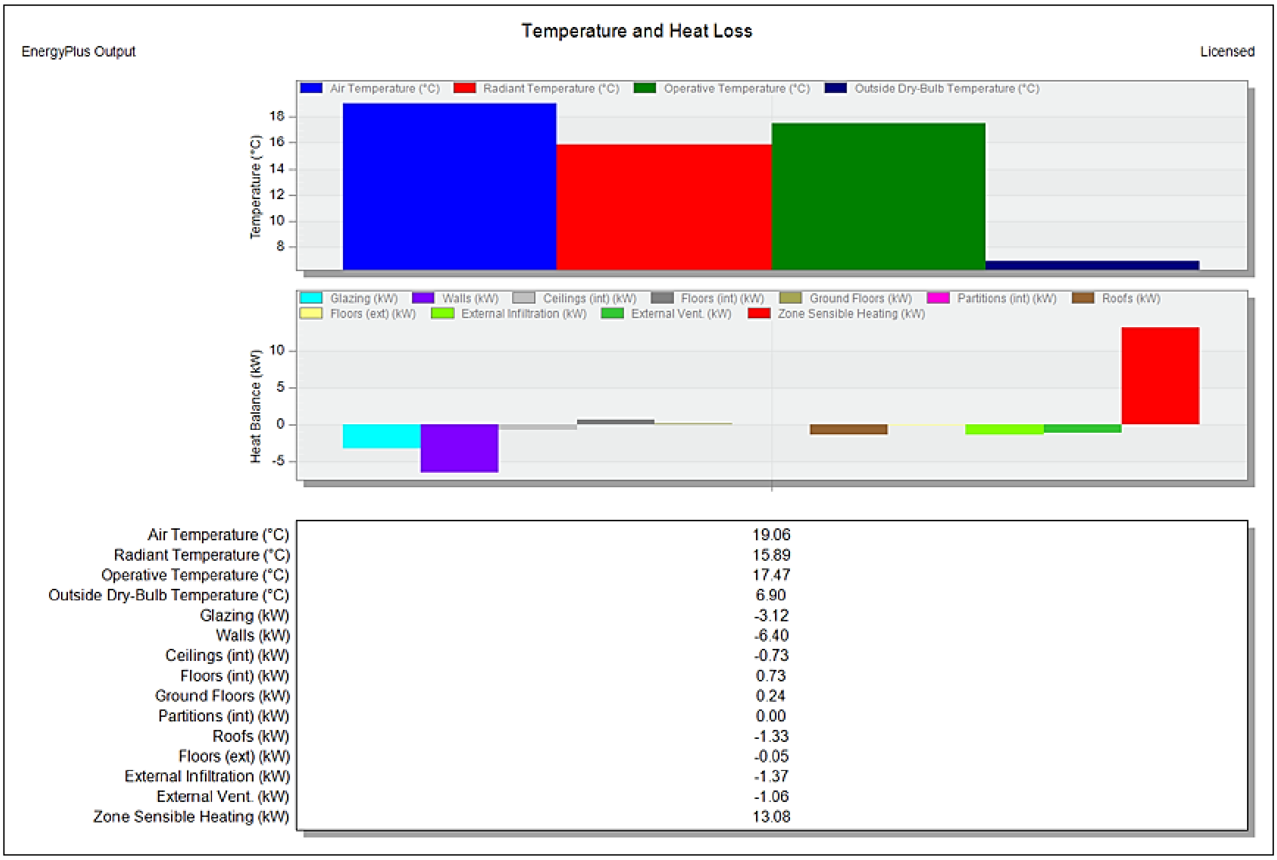

Figure 10 Temperature and heat loss.

for most of the heat gain in the building and are hence responsible for most of the energy consumed for cooling.

4.3.3. Annual Simulation

The first chart in (Figure 12) represents the total energy consumption throughout the year. The amount of energy consumed for cooling is very clearly a large amount and more than the energy used for lighting and other utilities. This highlights that the main problem and the aspect that consumes most of the energy is cooling, which is also why it is very clear that energy consumption in the summer is over twice as much as the energy consumed in the winter. Energy consumed for heating is a very small amount and almost negligible in most cases. Furthermore, the heat balance diagram in (Figure 12) shows that, as stated before, most of the heat gains in the building throughout the entire year is from the glazing of the windows. In the winter this heat gains are desirable as it provides warmth on the cold winter days. However, in the summer this large heat gains are responsible for the large amount of electricity consumed for cooling.

PCM would be beneficial because Alexandria's buildings are cooling-dominated, as they have been demonstrated to be more effective in this regard than

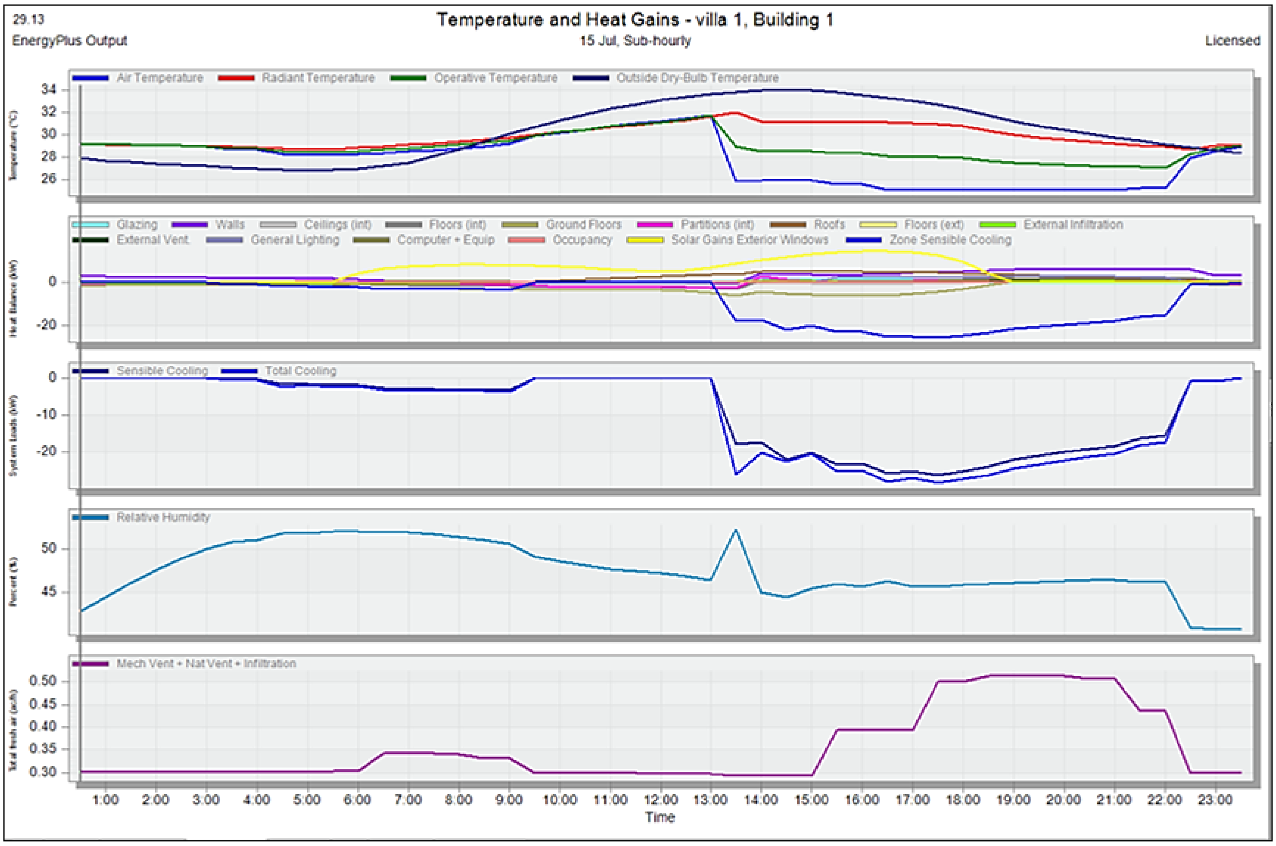

Figure 11 Temperature and heat gains on the 15th of July.

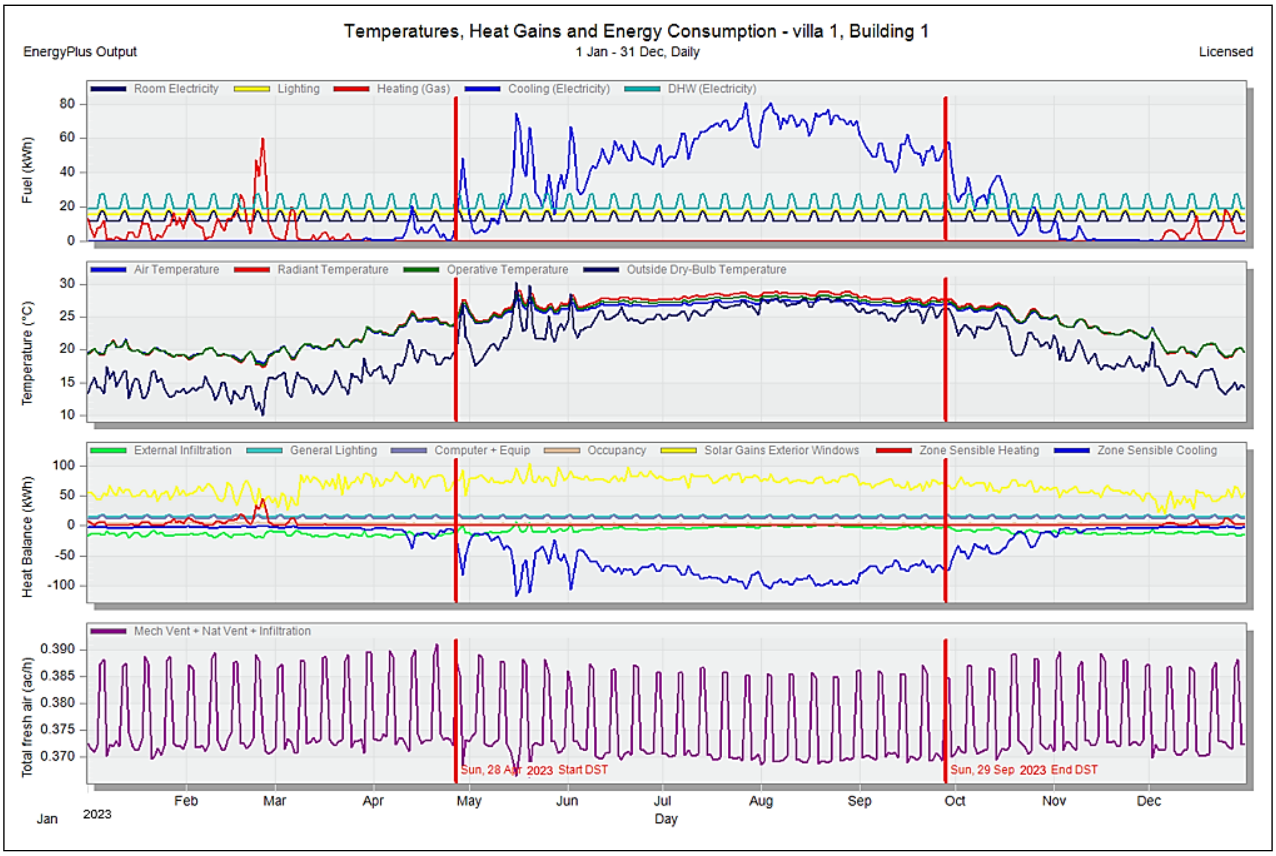

Figure 12 Temperature, Heat Gains and Energy Consumption from 1 Jan–30Dec.

heated-dominated structures. Brick walls make up the building's outside walls. That means that brick walls make up the majority of the building envelope. Consequently, using PCM-incorporated bricks in place of conventional brick walls would be an efficient solution. Consequently, adding PCM to the roof's concrete would similarly effectively enhance its thermal performance. Lastly, PCM integrated glass panels should be used in place of the big glazing surfaces.

4.4. SIMULATION- AFTER MODIFICATIONS

4.4.1. Heat Transfer

The amount of heat loss through windows is about 3 KW in the building original state (Figure 10). After changing the window glazing and the heat transfer sinks to about 1.2 KW which shows that by using PCM glazing the amount of ambient heat transfer through windows can be decreased by over 50% (Figure 13). The amount of heat entering through the walls has decreased from 6 KW to 4 KW after using PCM bricks in the walls.

4.4.2. Annual simulation

In the case of the building with PCM glazing the amount of solar heat gains through the window has decreased dramatically. This is one of the most noticeable effects of PCM glazing. It lets in almost no solar heat gains. Thus, it is also noticeable that the total energy used for cooling in the summer has decreased as a result of the low thermal heat gains, which means that less energy is required to provide thermal comfort for the users (Figure 14).

CONCLUSION

The annual simulation of heat gains in the building shows that after substituting the walls with PCM incorporated bricks and the single glazing with PCM glazing the heat gains through the walls and glazing decreases very noticeably (Figure 15A).

The Annual simulation shows the large decrease in the amount of energy required for cooling in the building and the very large decrease in the amount of solar heat gains in the building after incorporation of PCM in the window glazing (Figure 15B). Thus, the thermal comfort of the users can be achieved with the consumption of a much smaller amount of energy.

DISCUSSION

PCM has demonstrated its suitability for various applications involving efficient thermal energy storage. The purpose of this study is to evaluate PCM's performance as a thermal energy storage material

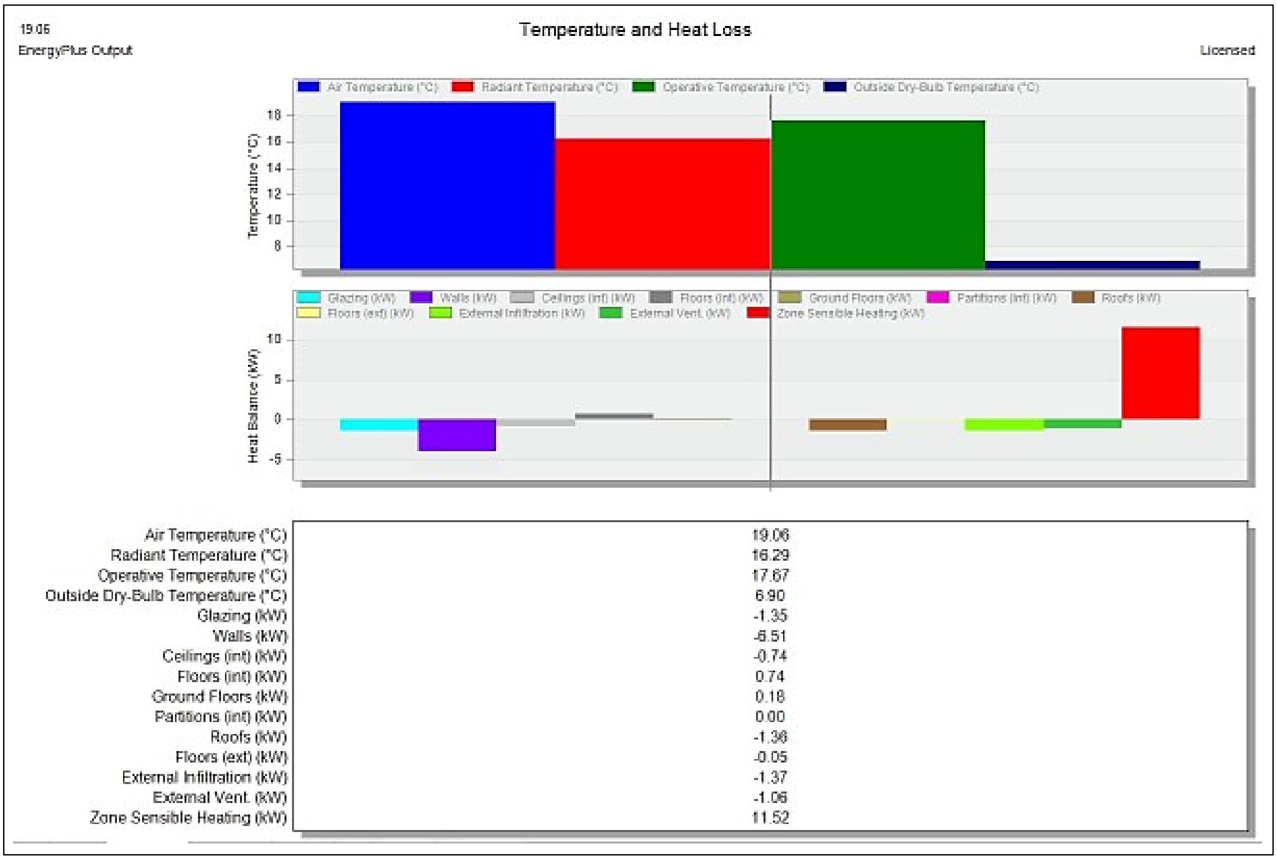

Figure 13 Temperature and heat loss.

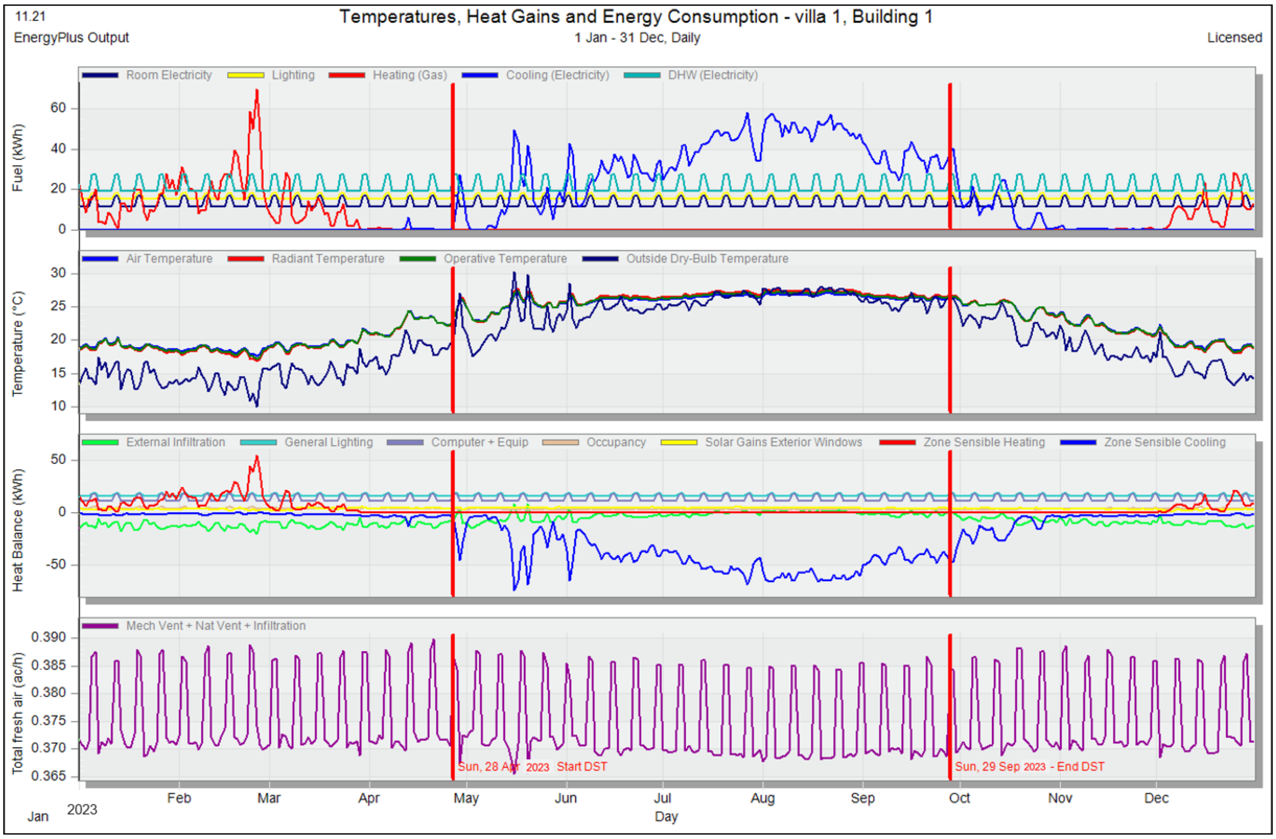

Figure 14 Temperature, Heat Gains and Energy Consumption from 1 Jan–30Dec.

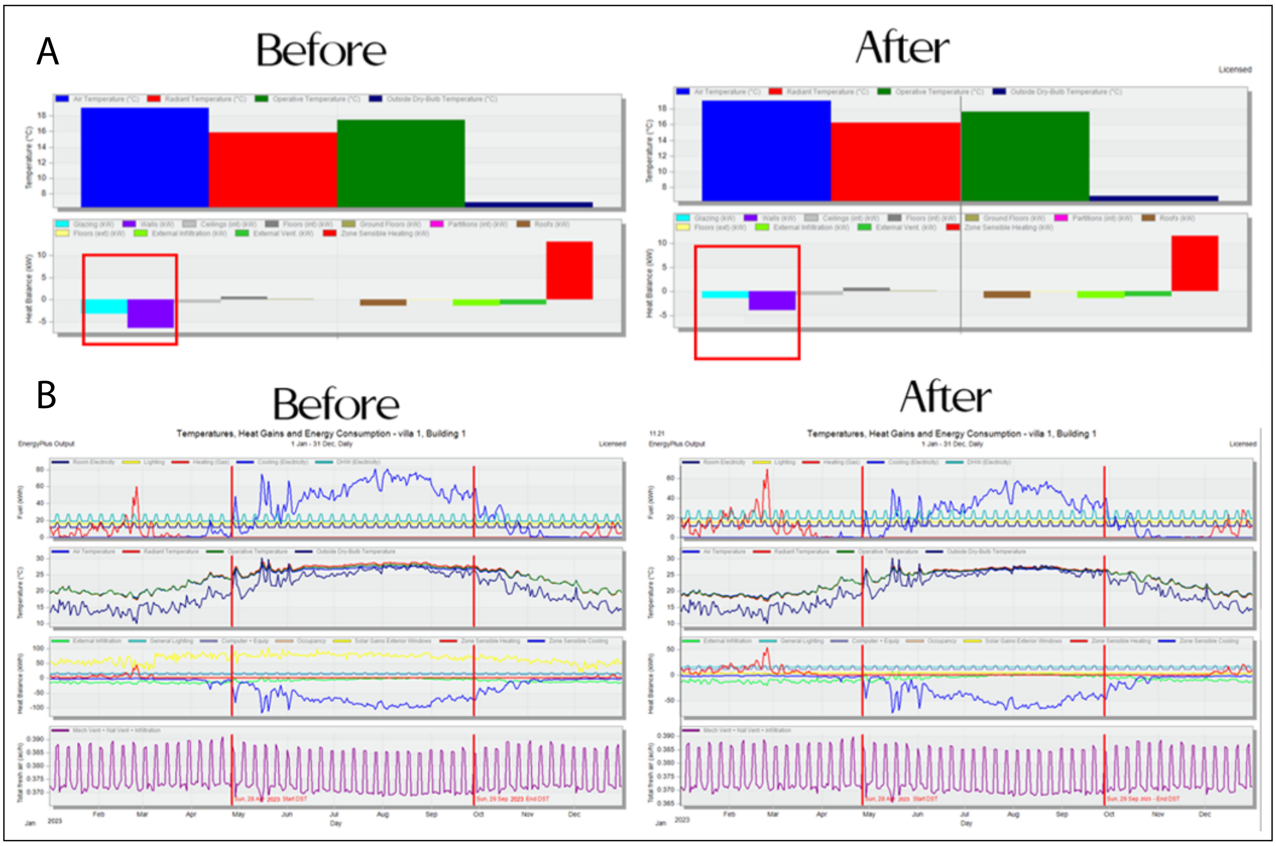

Figure 15 (A): The diagrams illustrate the building before and after simulations of Temperature and heat loss. **(B):** The diagrams illustrate the building before and after simulations of Temperature, Heat Gains and Energy Consumption from 1 Jan–30Dec.

incorporated in a building envelope to improve indoor thermal performance. The following observations can be applied to further research.

- Compared to traditional building materials including concrete, bricks, tiles and cement plaster, PCM has a double energy storage capacity.
- Because PCM are available in a broad temperature range, they can be used in a variety of climate scenarios and seasons.
- There are three different ways that PCM can be incorporated into a construction element: shape-stabilized PCM, Macro-encapsulation, and Micro-encapsulation. Among these three methods, Micro-encapsulation and Macro-encapsulation are frequently used because they reduce leakage and provide easier integration into the building envelope.
- The latent heat storage capacity of the building material is enhanced when PCM is incorporated into it. Increasing the amount of PCM incorporated will improve the heat storage further. However, it has a detrimental effect on the construction element's strength. Thus, suitable optimisation between mechanical and thermal properties must be studied.
- The majority of the research presented involve testing on a lab size or actual outdoor analysis of small-scale prototypes. But in order to adequately investigate the impact of adding PCM to the building envelope, full-scale buildings in real settings must be assessed. This will assist in maximising the PCM system's design by taking the building's internal heat gains into account.
- The roof is the main source of heat gain for all building orientations. There isn't many research that look into how PCM affects a roof's temperature response. Investigations of PCM's suitability for flooring applications are also necessary.

COMPETING INTERESTS

The authors have no competing interests to declare.

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