

Article

Experimental Study on the Hygrothermal Effect of Incorporating Phase-Change Materials in Cob Construction

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Abstract: Faced with the current challenges of the energy transition and the quest for sustainable materials, biobased materials are attracting growing interest for their environmental and thermal properties. Cob is well known for regulating humidity and improving thermal comfort in buildings. A building's thermal inertia can be increased by integrating phase-change materials (PCMs), enabling energy storage. This study explores the integration of microencapsulated PCMs into biobased materials considering realistic environmental conditions during experimental tests. The results show a homogeneous thermal distribution with low temperature variation at different locations. The relative humidity results confirm a one-dimensional thermal and hygroscopic distribution. The material with PCMs exhibits better thermal regulation. It retains more heat on the outside and reduces indoor temperature variations, improving thermal insulation. Measurements show that PCM integration contributes to reducing wall thermal conductivity and increases its thermal capacity, reaching 2.6 times during phase transition. The simulation is conducted with real 96 h Normandy climate data (January and August) for conventional and biobased walls incorporating PCMs. The results show that winter heat losses are highest for conventional walls (-44.08 kWh/m^2), low for cob walls (-24.17 kWh/m^2), and lowest for cob walls with PCMs (-13.17 kWh/m^2). In summer, all walls exhibit the lowest heat gain, while adding PCMs stabilizes heat flux, reducing peak summer heat flux from 150 W/m^2 to 50 W/m^2 . The results show that the addition of PCMs significantly improves thermal and hygroscopic performance.

Keywords: cob; hygrothermal transfer; phase-change material; biobased materials; thermal insulation; thermal storage; passive thermal systems



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1. Introduction

In an era where global energy demand is on an upward trajectory, largely propelled by the rapid economic development seen in emerging economies [1], buildings stand out as major energy consumers, accounting for up to 45% of the total energy consumption [2,3]. Among the significant energy expenditures lie heating, ventilation, and air conditioning (HVAC), which devour nearly 40% of the energy used within buildings [4]. This situation highlights the urgent need to design and implement strategies to reduce the energy consumption of buildings while maintaining an adequate level of comfort for occupants. Two complementary approaches are emerging in this quest for energy efficiency: the active approach, which is based on optimizing existing technical systems such as heating, ventilation, and air-conditioning equipment by integrating intelligent technologies and

advanced energy management solutions; and the passive approach, which favors the use of architectural concepts, material innovations, and design techniques aimed at minimizing the intrinsic energy demand of buildings. This includes improving the thermal and hygric performance of the building envelope [5,6].

The building envelope, which is constantly subject to temperature and humidity gradients, plays a fundamental role in thermal and hygric exchanges between the interior and exterior. These dynamic processes have a direct impact on the building's energy requirements, as well as on the thermal and hygrometric comfort of its occupants. Understanding and controlling the hygrothermal behavior of the building envelope is therefore becoming a priority in the context of the energy transition. In this context, increasing attention is being paid to biobased buildings. A recent study [7] examined the use of biologically sourced construction materials, highlighting their properties, recommended applications, and performance expectations. Biobased materials, derived from animal or plant biomass, have garnered increasing interest in recent decades [8]. These materials not only offer multiphysical performances comparable to, or even superior to, those of traditional materials [9] but they also have the advantage of carbon storage, thus contributing to the reduction in greenhouse gas emissions [10]. Röhlen et al. [11] demonstrated that the soil's absorption and evaporation capacity help harmonize temperatures by regulating atmospheric humidity and moderating temperature fluctuations. Moreover, this capacity aids in air filtration by trapping particles and removing pollutants, thus improving the surrounding air quality. From a hygrothermal standpoint, raw earth behaves as a thermal and hygrometric regulator, slowing and attenuating heat waves and stabilizing indoor relative humidity more quickly than other building materials [8]. Extensive studies have shown that compressed earth blocks outperform adobe materials in terms of durability [12,13], while offering equivalent or superior thermal performance to concrete in hot climates [12,14–16]. Neyra et al. [17] examined the impact of insulation and wall thickness on the thermal performance of compressed earth buildings located in hot and dry regions. They constructed a test cell using cement-stabilized compressed earth blocks and modeled its thermal performance using EnergyPlus software. The results showed that adding thermal insulation reduced heat transmission, while wall thickness influenced thermal lag and occupant comfort. This research underscores the importance of striking a balance between insulation, wall thickness, and durability to design buildings suited to hot and dry climatic conditions. Desogus et al. [18] examined monitoring and simulation comparisons for an earthen residential building in Sardinia (Italy) during summertime. Their research confirmed the high thermal inertia of an adobe wall and demonstrated internal temperature values within the comfort range. The authors concluded that roofs are the limiting factor, causing local discomfort due to radiant asymmetry. Additionally, they emphasized that these findings underscore the need for careful attention to roof design to ensure optimal thermal comfort in earthen buildings. Martín et al. [19] conducted a field monitoring study in Navapalos, Spain, comparing the thermal performance of traditional and non-traditional houses. Their findings revealed significant disparities in thermal behavior. During summer, when temperatures averaged 23 °C with peaks reaching 35.7 °C, the indoor temperature of a traditional adobe house with 40 cm thick walls remained within the comfort zone. Palme et al. [20] presented monitoring and simulation studies on four houses constructed with various materials in a desert climate during winter in San Pedro de Atacama, Chile. The study examined adobe, rammed earth, wood, and concrete as building materials. Their results indicated that earthen constructions outperformed wood and concrete in terms of thermal decrement, thermal lag, insulation properties, and solar radiation gain. Another interesting study for earthen constructions was performed by Miño et al. [21], who selected two residences to assess the impact of key envelope parameters

on indoor thermal performance in a rural region of the Ecuadorian Andes. One residence comprised compressed stabilized earth blocks (CSEBs) and concrete tiles, while the other was a typical, uninsulated lightweight structure utilizing hollow concrete blocks and zinc sheet roofing. Their findings from monitoring and simulation revealed that the roof, floor, and airtightness significantly influenced indoor thermal conditions. Notably, the traditional dwelling exhibited greater thermal stability, with a 4.7 °C reduction in total temperature fluctuation compared to the alternative structure.

Phase-change materials (PCMs) are another innovative solution for reducing energy consumption in buildings [22]. These materials have the ability to absorb or release large quantities of thermal energy as they transition between solid and liquid states, thus stabilizing indoor temperature fluctuations and reducing the sensitive load imposed on air-conditioning systems [23,24]. They fall into three main categories—organic, inorganic, and eutectic—and cover a wide range of melting points and are used in both passive and active thermal storage systems. Their efficiency is particularly marked when their melting point is within the range of human thermal comfort, between 15 °C and 30 °C. This enables them to efficiently store and release heat or coolness, providing better thermal regulation for occupants. PCMs can be integrated into various elements of building envelopes, such as walls, floors, suspended ceilings, roofs, and windows [25–28]. By increasing the thermal mass of structures, they promote passive heating and cooling while limiting the dependence on mechanical ventilation systems. Their high latent heat of fusion also contributes to more efficient heat and moisture transfer management within buildings.

While extensive research has been conducted on the thermal performance of biobased walls, the scientific literature remains limited regarding an in-depth analysis of the integration of phase-change materials (PCMs) into these construction systems. Indeed, most existing studies have focused on the thermophysical properties of materials individually, without systematically exploring the potential synergies between biobased walls and PCMs. The combination of technological innovations such as phase-change materials (PCMs) and solutions based on biobased materials represent a promising response to today's energy challenges. These approaches combine the modernity of advanced materials with the sustainability of natural resources, fully in line with the objectives of sustainable development. In buildings using traditional materials such as cob, the integration of PCMs can significantly improve thermal performance while maintaining the authenticity and low ecological footprint of these structures. Two main integration methods have been explored. The first, direct immersion, involves impregnating the building material with PCMs. Although this approach enables immediate and effective thermal interaction, it can lead to leakage risks when the PCMs enter a liquid state, thus limiting their practical application. The second technique, micro-encapsulation, represents a more reliable and durable alternative. This method involves encapsulating the PCMs in small protective structures, thus avoiding problems associated with changes in state and guaranteeing greater stability within the material. By integrating PCMs in a micro-encapsulated form, cob constructions can benefit from optimized thermal regulation while retaining the material's natural hygroscopic properties. In this work, the impact of incorporating PCM into biobased materials, particularly in enhancing both the energy and hygrothermal performances of buildings, was investigated. The heat storage process within the biobased material and their influence on moisture transfer were analyzed.

In light of the previous analyses, the present study investigates the hygrothermal properties via an experimental study for biobased materials based on soil and plant fibers. French soil is used for the preparation of the tested material as it contains a strong composition of soil and a low fiber content, provides structural performance, and can withstand significant loads. Our testing of moisture buffering values was inspired by the Nordtest

project [29], which represents their ability to dampen variations in indoor relative humidity due to their moisture buffering capacity. The objective of this article is to examine the effect of integrating PCMs into cob material on its thermal and hygroscopic behavior by studying two materials: cob and cob with 20% microencapsulated PCMs. The experimental results shed light on the thermal and hygroscopic variations induced by the incorporation of PCMs into this traditional building material. A simulation was carried out to study the impact of wall materials on the building's thermal performance using the transient heat equation. The numerical model, developed in MATLAB, employs the alternating direction implicit (ADI) finite difference method, solving the transient heat equation. Real outdoor temperature data, extracted for summer and winter conditions, serve as boundary conditions, with an internal temperature fixed at 20 °C. This study compares three wall configurations: a cob wall, a cob wall incorporating PCM, and a conventional multi-layer wall. The model considers homogeneous material properties, effective thermal conductivity, and latent heat storage effects for PCM integration. The simulation tracks heat conduction, convection, and phase transition dynamics, evaluating energy efficiency, heat flux regulation, and indoor temperature stability under seasonal variations. Heat losses and gains are quantified through an integral formulation of the global heat flux, assessing each wall's capacity to mitigate temperature fluctuations and improve indoor comfort.

2. Materials and Methods

2.1. Materials

The material studied is soil excavated in Normandy (Manche and Calvados) and mixed with fibers. It is a local material chosen to reduce the carbon footprint compared to conventional materials. The materials under study consist of soil (Figure 1a) with a density of 1284 kg/m³, containing a significant proportion of silt. They are mixed with 2.5% of flax straw fibers (Figure 1b) and 28.5% of water by mass relative to the dry soil. The density of the fibers is 1266 kg/m³ and the water absorption capacity is 350% [30]. The overall performance of soil depends on a balanced granulometric composition: clay (<2 µm) provides cohesion through its binding properties (though an excess may lead to cracking), silt (2 to 63 µm) improves workability, and sand (63 µm to 2 mm) contributes to mechanical strength and reduces shrinkage. Additionally, the methylene blue value is used to assess the adsorption capacity of the clay minerals, indicating their effectiveness in promoting cohesion within the mixture. The tested soil's characteristics are summarized in Table 1.

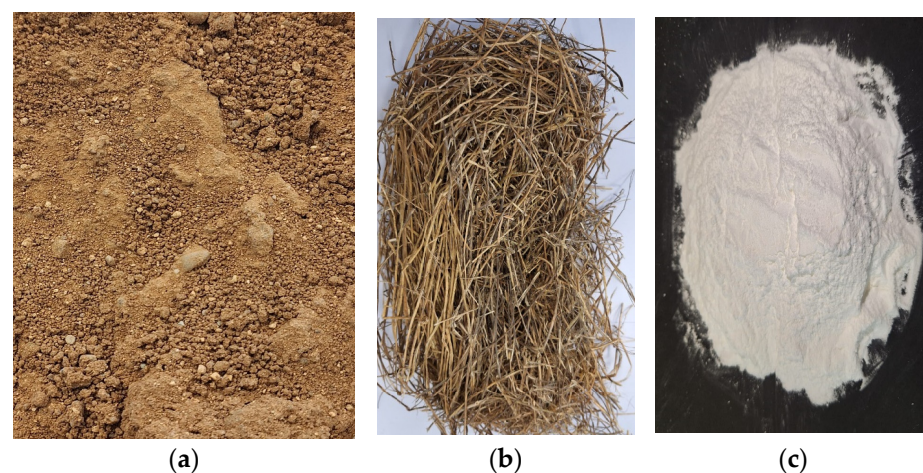


Figure 1. Cob wall components: (a) soil, (b) flax straw fibers, (c) PCM.

For the samples without PCMs, the soil was manually mixed with the required fiber content (2.5%) in a dry state to ensure a homogeneous distribution; afterward, the necessary

amount of water (28.5%) was added. For the cob with PCMs, 20% of microencapsulated PCM was incorporated into the mixture following the same preparation process. The mixture was then placed in molds for four days to obtain samples sized 20 cm × 20 cm × 7 cm for cyclic tests and 10 cm × 10 cm × 7 cm for the moisture buffer value investigation (MBV). The test was performed according to the Nordtest standards. After drying at the laboratory's ambient air temperature, the samples (Figure 2) were removed from the mold and stored in an oven under 40 °C for more than five days to standardize the initial moisture conditions. The PCM used in this study was INERTEK microcapsules (Figure 1c), exclusively made from plant waxes. The melting process occurred at 18 °C, with a latent heat of approximately 180 J/g. Table 2 summarizes the composition of the two materials studied.



Figure 2. Cob sample photography.

Table 1. Soil characteristics [31].

Property	Value
Methylene blue value (g/100 g)	0.55
Clay fraction (% < 2 µm)	7.64
Silt fraction (2 < % < 63 µm)	54.38
Sand fraction (63 µm < % < 2 mm)	10.70

Table 2. Composition of cob materials with and without PCMs.

Formulation	Cob	Cob with PCM
Soil	100%	100%
Fiber	2.5% (by mass of dry soil)	2.5% (by mass of dry soil)
Water	28.5% (by mass of dry soil)	28.5% (by mass of dry soil)
PCM-INERTEK	-	20% (by mass of dry soil)

2.2. Experimental Protocols

The hygrothermal behavior of a building significantly affects its energy performance. For accurate energy analysis, it is essential to consider the transport and storage of moisture in porous construction materials. Previous studies have shown that up to 90% of issues related to construction materials and building durability are caused by moisture. Furthermore, recent research indicated that neglecting the absorption and desorption of moisture in materials during the design and construction phases can lead to an overestimation of peak thermal loads by up to 210% and an underestimation of 59% of thermal flux due to latent heat and moisture effects [32]. In this context, moisture buffering is recognized as an effective passive strategy for humidity regulation. This process involves the gradual absorption and desorption of water vapor, measured by the mass changes induced by discrete increases and decreases in relative humidity over different time intervals. This method not only helps maintain optimal indoor comfort but also prevents premature

material degradation. The moisture buffering value of the studied material is measured, providing crucial insights into its effectiveness.

Another goal of this study is to explore the effect of integrating microencapsulated phase-change materials (PCMs) into cob materials. The aim is to evaluate their impact on both the hygroscopic and thermal properties of materials, as well as their contribution to the overall energy efficiency of the building. A climate chamber (Kambic KK-190 CHLT model) is then used to impose precise boundary conditions during the experiments. This equipment ensures high accuracy in controlling thermal and hygrometric parameters, with a temperature range of $-40\text{ }^{\circ}\text{C}$ to $180\text{ }^{\circ}\text{C}$ and a relative humidity range of 10% to 98%. The temperature regulation accuracy varies between $\pm 0.08\text{ }^{\circ}\text{C}$ and $\pm 0.5\text{ }^{\circ}\text{C}$, while the relative humidity accuracy ranges from $\pm 0.5\%$ to $\pm 2\%$, depending on the set parameters. Once the conditions are configured, the processes of humidification, dehumidification, heating, and cooling are fully automated, ensuring consistent stability of the parameters throughout the experiments.

2.2.1. MVB Investigation

The tests were conducted using the NORDTEST standard method [29] to characterize the hygroscopic behavior of the cob without PCMs through humidity and mass variation measurements. This procedure defines the moisture buffer value (MVB) of building materials, characterizing its potential to improve indoor thermal comfort, material longevity, and building energy efficiency. Samples tested using the NORDTEST method must be a minimum of 100 cm^2 with rectangular geometry according to the protocol recommendations. Before starting the tests, the materials were dried in an oven at $40\text{ }^{\circ}\text{C}$ to obtain the samples' dry masses. The samples were sealed with aluminum tape all over the side surfaces, except for the top one, to ensure unidirectional heat and moisture transfer during the tests. They were placed on a balance with a resolution of 0.01 g and inserted into a climatic chamber, as shown in Figure 3.



Figure 3. Cob samples inside the climatic chamber.

The tested sample was preconditioned at $23\text{ }^{\circ}\text{C}$ and 50% RH until hygroscopic equilibrium was achieved as sample mass variation remained lower than 0.1% over 24 h. The climatic cycles of the Nordtest protocol consist of exposing the samples to a constant temperature of $23\text{ }^{\circ}\text{C}$, with cyclic variation of relative humidity. During the 24 h cycle, humidity is set to 33% for 16 h and then 75% for 8 h. Cycles are reconducted over several days, and the instantaneous mass of each sample is monitored and recorded during the test. The

equilibrium condition is defined by sample mass variation of less than 5% during the last three cycles.

The moisture buffering value [$\text{kg m}^{-2} \cdot \%RH^{-1}$] of each material is obtained from the mass variation measured at the end of the adsorption and desorption cycle during the last five stabilized cycles. MBV is calculated using the following equation:

$$MBV = \frac{\Delta m}{A (RH_{High} - RH_{Low})} \quad (1)$$

In this equation, Δm [kg] is the average between the absorbed and released water content during the last cycles, A is the exposed surface area [m^2], and RH_{High} and RH_{Low} are the high and low relative humidity values [%] occurring during the cycles.

2.2.2. Dynamic Hygrothermal Analysis and Energy Performance of Cob Envelopes Incorporating Phase-Change Materials (PCMs)

To study the effect of integrating microencapsulated phase-change materials (PCMs) within cob materials, an experimental setup is designed to replicate various environmental conditions. One side of the sample is connected to a climatic chamber to simulate external environmental conditions, while the other side is exposed to the laboratory's interior environment, where the hygrothermal conditions remain relatively stable, representing the typical indoor conditions of a real building. This experimental configuration allows for a realistic simulation of thermal and moisture dynamics both inside and outside buildings.

The setup, illustrated in Figure 4, is designed to investigate the interaction between heat and moisture under controlled conditions, in order to assess the effectiveness of phase-change materials in managing these fluxes. Figure 4a presents the acquisition system, while Figure 4b shows the test bench and the surface of the material on the laboratory side. To ensure optimal thermal insulation and limit moisture transfer in the perpendicular direction to the thickness of the sample, a layer of polystyrene foam is wrapped around the lateral sides of the sample. Additionally, a polyethylene film is applied to form an airtight barrier, preventing undesired exchanges and ensuring a rigorous experimental configuration for testing the performance of the materials.



Figure 4. Experimental setup for controlled heat and humidity transfer through materials: (a) acquisition system, (b) the test bench.

Four combinations of temperature and relative humidity variations were applied: two with similar trends and two with opposite trends. Each cycle lasted 24 h to evaluate the influence of climatic fluctuations on the hygrothermal behavior of the material. These

dynamic conditions were designed to simulate the external environment to which a building envelope is exposed throughout the seasons. For instance, outdoor temperatures can range between 10 °C and 45 °C, while relative humidity fluctuates between 45% and 70%, directly affecting heat and moisture transfers within the walls. Figure 5 provides a detailed illustration of these variation profiles. The selection of 40 °C with 45% relative humidity and 10 °C with 70% relative humidity reflects the typical climatic conditions observed in specific regions. The former simulates a hot and dry summer day, characteristic of continental or Mediterranean climates where high temperatures are often accompanied by drier air. The latter represents a cold and humid night, typical of winter or transitional seasons in temperate regions, where lower temperatures result in higher relative humidity.

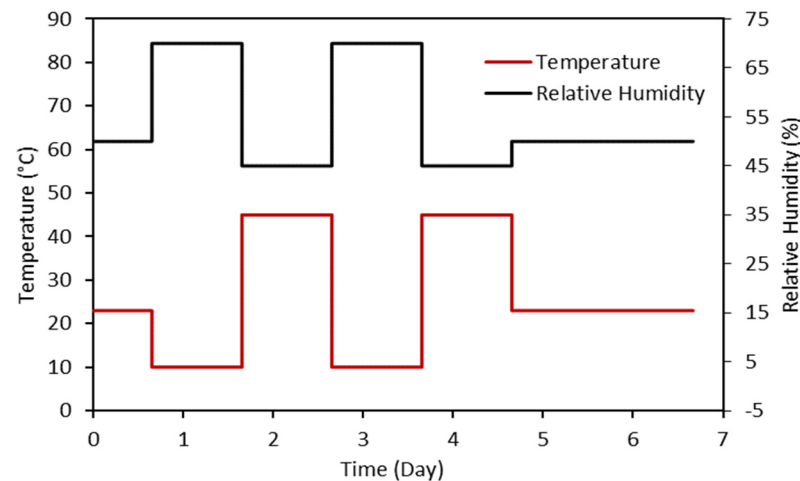


Figure 5. Temperature and relative humidity boundary conditions provided by the climatic chamber.

2.2.3. Instrumentation and Calibration

The experimental protocol is designed to ensure accurate and reliable measurements using strategically positioned temperature and relative humidity sensors. To enhance data reliability, multiple sensors were placed at the same depth, allowing the verification of the homogeneity and one-dimensional nature of heat and moisture distribution while minimizing errors in case of sensor failure. The sensors were installed at specific locations: inside the climate chamber, in the ambient air of the laboratory, and at two predefined depths in the materials (3 cm and 5 cm from the surface exposed to the climate chamber). Temperature measurements were carried out using K-type thermocouples (0.5 mm in diameter), positioned on the main surfaces (internal and external) and at each depth within the materials. For relative humidity, HMP110 sensors were placed in the ambient air, while smaller HIH-400-003 sensors were embedded into the materials at different depths for precise local measurements. Additionally, two HFP01 heat flux meters were installed on the main surfaces to measure thermal flux. Figure 6 shows a detailed diagram of the test rig, with sensor positioning at the material level (Figure 6a). Figure 6b provides an in-depth view, illustrating the distribution of temperature and relative humidity sensors at different depths in the sample. In contrast, the surface view (Figure 6c) shows the arrangement of the sensors and their dimensions on the exposed face of the sample.

All sensors were connected to data acquisition boards linked to a central computer, where a program developed in LabVIEW automatically recorded measurements every 30 s for humidity, temperature, and flux during the cycles. Despite minor fluctuations in temperature and humidity in the laboratory, the conditions remained generally stable, with an average temperature of 21 °C and relative humidity of approximately 40%. Table 3 provides the measurement ranges and accuracy of each sensor.

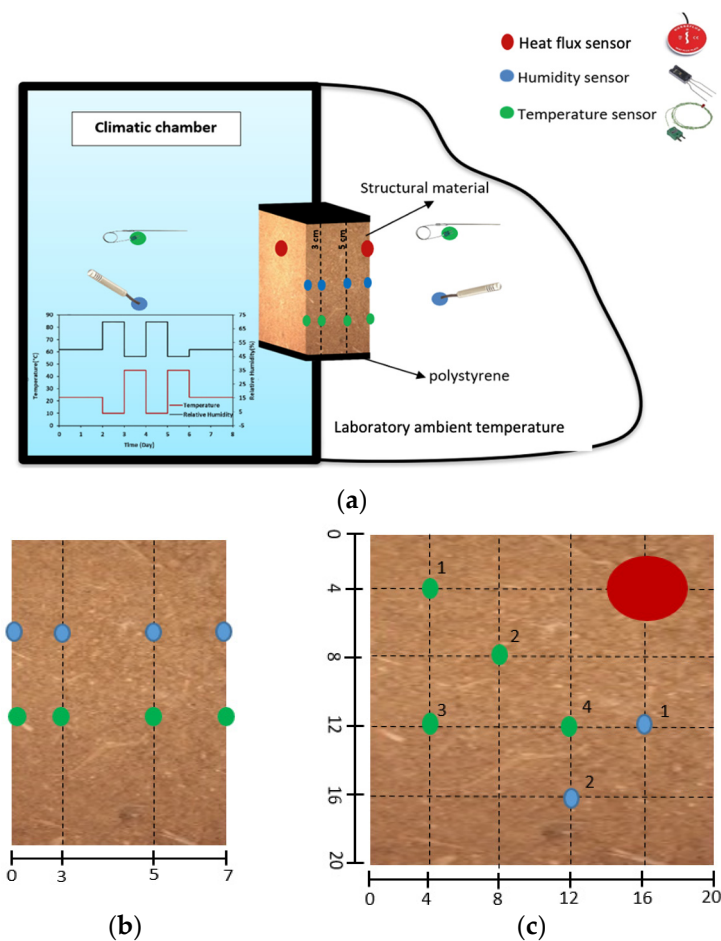


Figure 6. Sample instrumentation: (a) sensor positions in the sample, (b) depth view within the sample, and (c) surface view.

Table 3. Accuracy of the sensors and their measurement range.

Sensor	Accuracy	Measurement Range
Temperature (K-type)	$\pm 0.5\text{ }^{\circ}\text{C}$	$[-50\text{ }^{\circ}\text{C}, 250\text{ }^{\circ}\text{C}]$
Relative humidity (HIH-400-003)	$\pm 3.5\%$	$[0, 100\%]$
Relative humidity HMP110	$\pm 1.5\%$	$[0, 100\%]$
Heat flux (HFP01)	$\pm 3\%$ of reading	$\pm 2000\text{ W}\cdot\text{m}^{-2}$

3. Experimental Results and Discussions

3.1. Moisture Buffer Value Measurements

The experimental tests consist of 8 cycles of a 24 h cyclic RH stepwise variation between 33% RH for 16 h and 75% RH for 8 h using a climatic chamber. The time variation of the cob sample mass during the tests is shown in Figure 7. A significant increase in mass during the first three cycles is observed. After the fourth cycle, a slight increase in mass is obtained during the adsorption and desorption cycles, which may indicate stable moisture storage of the sample. The required stationary state is obtained for cycles 4–8, as the mass variation is less than 5% and the difference between weight gain and weight loss in each cycle is less than 5%.

The Nordtest protocol provides a scale that interprets the results by classifying the values into five levels, as shown in Figure 8.

The MBV has been calculated for the tested cob sample and reported in Figure 9. MBV values for different conventional materials [33] are also reported for comparison.

According to the Nordtest classification, as MBV is close to 2.3 [g/m² %RH], the cob material can be considered an “excellent moisture regulator”. Other common materials such as concrete and bricks have an MBV of less than 0.5 [g/m² %RH]. They are considered weak moisture regulators. Spruce wood is a good moisture regulator because the MBV is higher than 1 [g/m² %RH]. This result confirms that using earth as a material provides good hygroscopic properties.

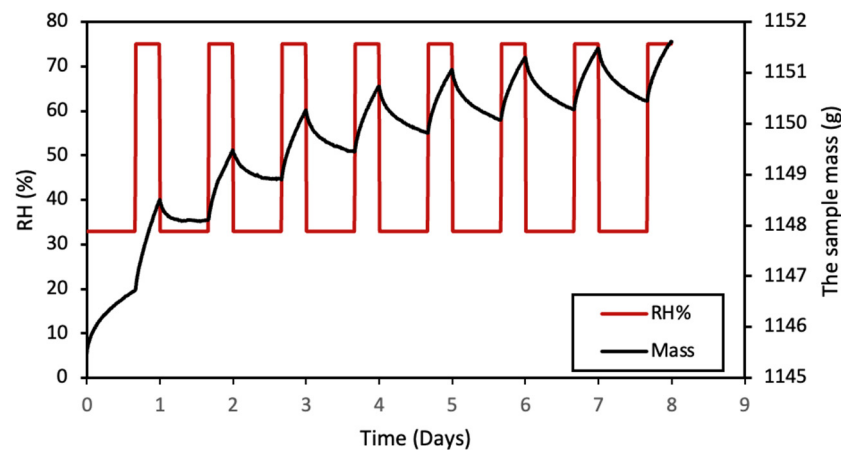


Figure 7. The sample mass variation during the first eight adsorption cycles.

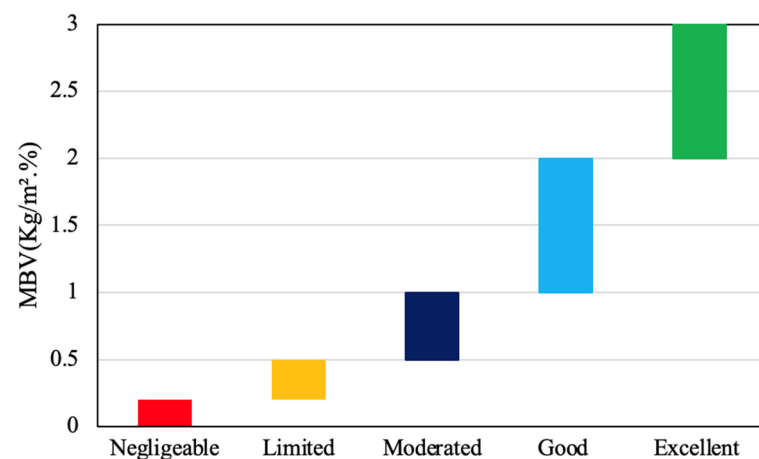


Figure 8. The Nordtest method classification of materials versus moisture buffer value.

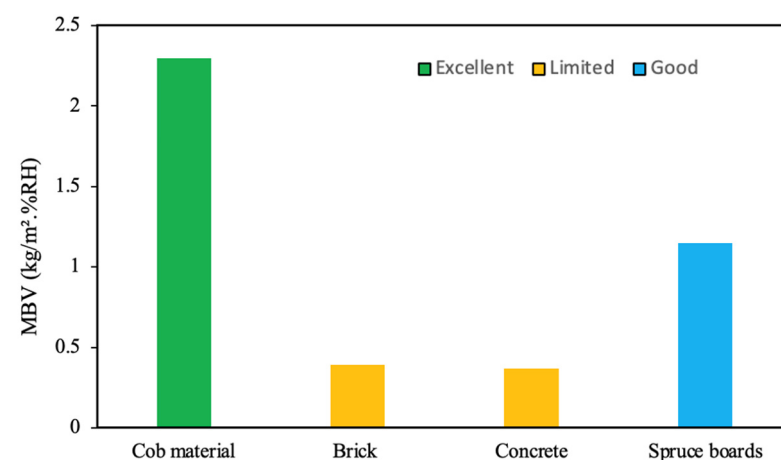


Figure 9. Moisture buffer values of our materials and other building materials [33].

3.2. Hygrothermal Performance of Cob Material with and Without PCM

Before starting the tests, a thermal and hygrometric stabilization phase was implemented to standardize the initial state of the tested samples. The temperature and relative humidity were maintained at 23 °C and 50%, respectively, for seven days, ensuring a stable equilibrium of heat and moisture exchanges within the studied cob material. The studied climatic profile (Figure 6) also aligns with the natural correlation between temperature and relative humidity in the atmosphere: higher temperatures allow the air to hold more water vapor, reducing relative humidity, while cooler temperatures decrease this capacity, increasing ambient humidity.

3.2.1. Monodimensionality of Temperature and Humidity Distribution in Materials

Figure 10 shows the temperature distribution on the surface facing the climatic chamber (depth 0 cm) using several temperature sensors placed at different locations for the two materials studied: the cob without MCPs and the cob with 20% MCPs. The results demonstrate that for both materials, the four thermocouples placed at different locations record very similar values, with a slight difference of about 0.02 °C. This small variation of 0.02 °C, even with the varied positions of the thermocouples on the surface facing the climatic chamber, indicates a relatively homogeneous thermal distribution. This uniformity suggests that the thermal effects are well spread within the materials, which is crucial for ensuring the stable and predictable operation of the system. In conclusion, the materials exhibit thermal homogeneity and the temperature distribution follows a one-dimensional profile.

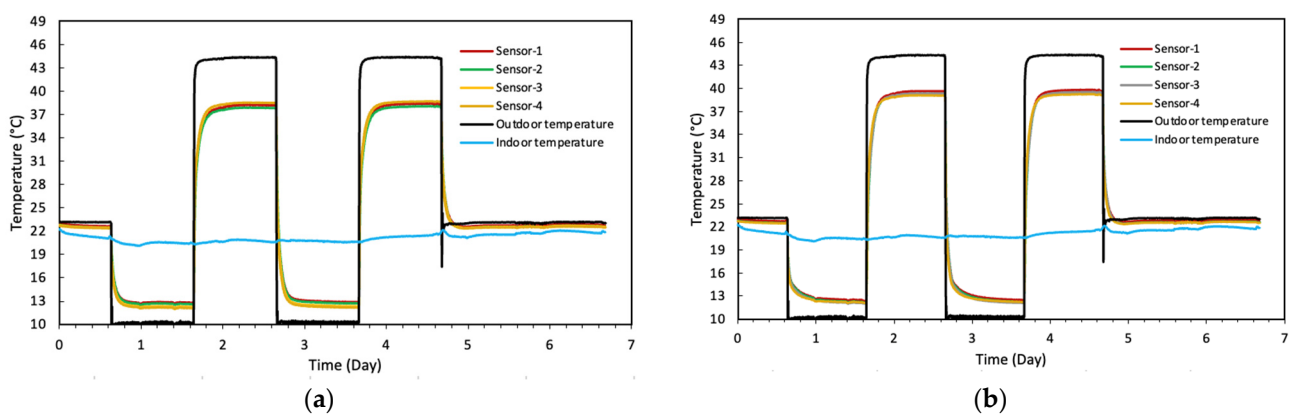


Figure 10. Temperature distribution on the surface of the climatic chamber side (depth 0 cm): (a) cob material without PCMs and (b) cob material with PCM (20%).

Figure 11a shows the distribution of relative humidity measured by two sensors inserted into the material without MCPs at a depth of 3 cm, placed at different positions in terms of width and length. Similarly, Figure 11b presents the distribution of relative humidity in the material with MCPs at the same depth, with sensors positioned at different widths and lengths. The experimental results indicate that in both configurations (with and without MCPs), the relative humidity values measured by the sensors, despite their different positions, are remarkably similar. This homogeneity in the measurements suggests a uniform distribution of relative humidity. This consistency can be interpreted as evidence that the humidity distribution in these materials follows a homogeneous profile. Furthermore, the small variation between the measured values strengthens the idea that humidity is distributed stably and evenly throughout the material, which is crucial for validating the hypothesis of a one-dimensional distribution of humidity.

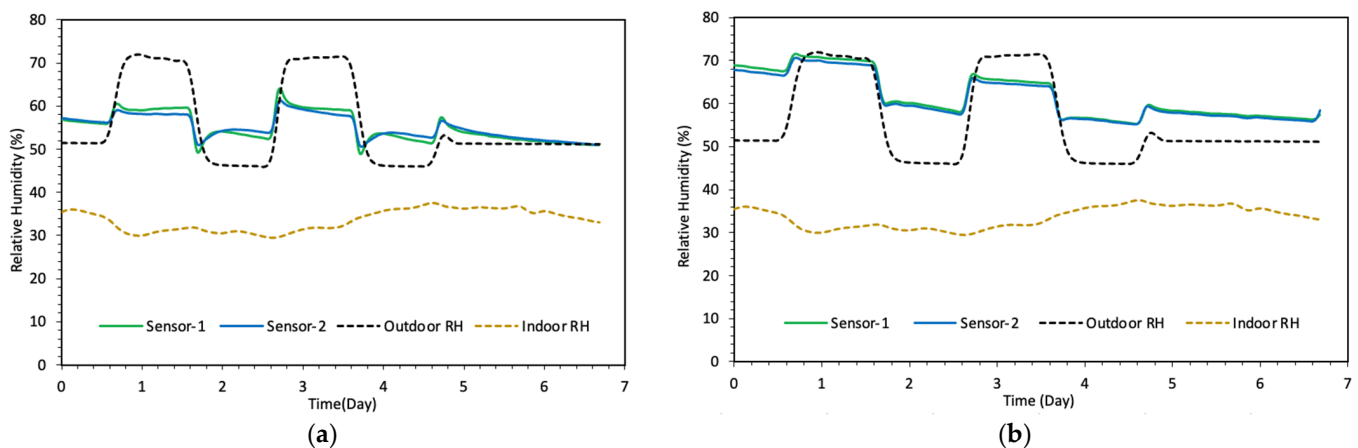


Figure 11. Relative humidity distribution at 3 cm depth: (a) cob material without PCMs and (b) cob material with PCM (20%).

3.2.2. Heat Transfer Inside the Tested Samples

Figure 12 illustrates the temperature distribution of the material outdoor side, the adjacent surface of the climatic chamber ($y = 0$ cm), and the material indoor side, surface ($y = 7$ cm) in contact with the laboratory ambiance. Two types of cob materials with and without phase-change materials were examined. Figure 12 also shows the ambient temperature inside the climatic chamber and in the laboratory environment, measured using temperature and RH sensors installed inside the climatic chamber. A maximum relative error of 0.3°C for temperature and 0.8% for humidity were obtained. At $y = 0$ cm from the climatic chamber, the cob material with PCMs shows a higher temperature than the cob material without PCMs, suggesting an increased heat absorption capacity by integrating the PCM. Part of the thermal energy is retained in the phase transition zone, delaying the heat transfer to the interior of the material. Conversely, at $y = 7$ cm, the cob material without PCMs shows a higher temperature, particularly when the climate chamber temperature reaches 45°C . This difference can be explained by the fact that part of the absorbed energy is used to melt the PCM when the temperature exceeds its phase-change point (18°C). In contrast, when the external temperature drops to 10°C , the PCM begins to solidify, gradually releasing the stored latent heat. This process prevents a rapid decrease in the interior temperature and contributes to a more stable thermal regulation compared to the cob material without PCMs. In the latter case, the absorbed heat is rapidly transferred to the interior, leading to greater thermal fluctuations.

In a more detailed manner, Figure 13 illustrates the temperature distribution within the tested materials, both with and without PCM, at two different depths, namely 3 and 5 cm. At a depth of 3 cm, the temperature within the cob material with PCM is observed to be higher than that of the cob material without PCM, thus highlighting the PCM's ability to efficiently absorb heat near the thermal source. Conversely, at a depth of 5 cm, the temperature inside the cob material without PCM is higher, indicating that the PCM has stored some of the heat and dissipated it more effectively at this depth. These temperature variations at different depths underscore the PCM's effect on the thermal regulation of the cob materials. It is also observed that, for both studied materials, the temperature variation trends inside the material are repetitive for each imposed condition in the climatic chamber. This indicates a stable and characteristic behavior of the material in response to the applied thermal cycles. This consistency confirms that the observed phenomenon is typical of the studied materials and validates their ability to store and release heat consistently over successive cycles.

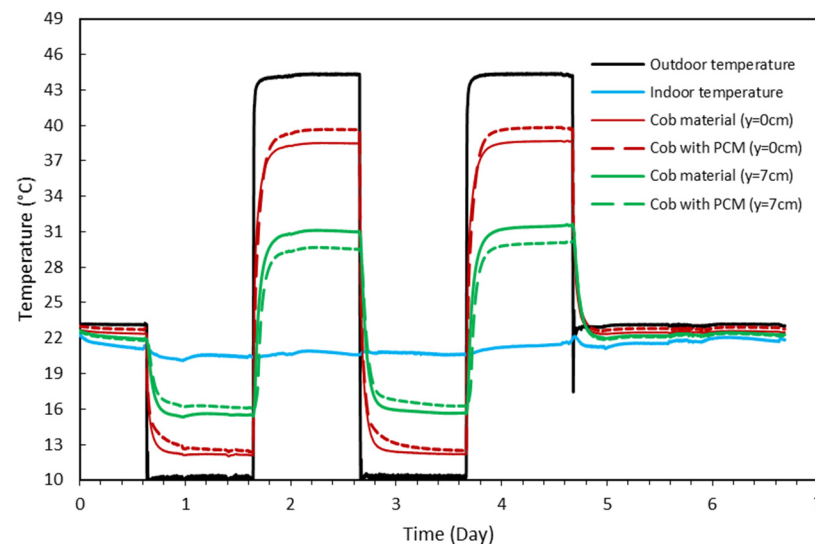


Figure 12. Comparative analysis of temperatures on surfaces of cob materials with and without PCM.

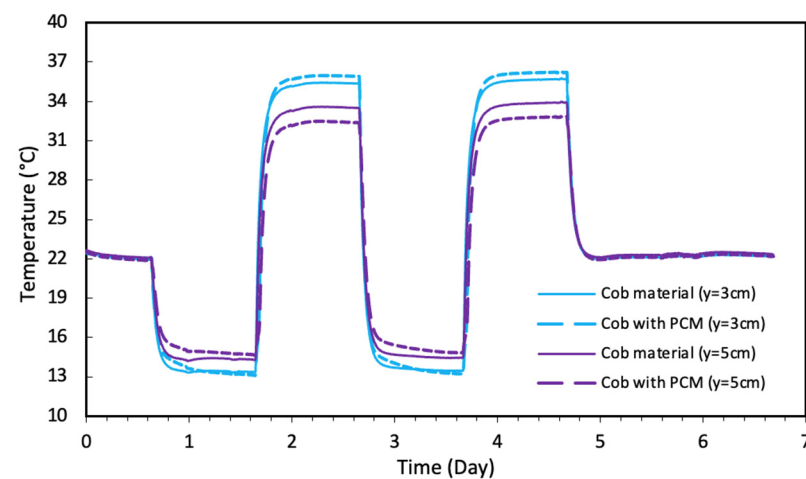


Figure 13. Analysis of temperature distribution at different depths in cob material with and without PCM.

Figure 14 illustrates the variations in heat flux measured on the outer and inner surfaces of the two materials studied. On the outer surface, the wadding, devoid of phase-change material (PCM), stores a limited amount of heat. This behavior is characteristic of materials that cannot efficiently manage temperature variations as they store heat linearly as a function of temperature increase. When the temperature rises sharply, the material without PCM stores a large amount of heat at that very moment. The cob with PCM, on the other hand, records the highest density of stored heat flux. The phase-change material absorbs excess heat when temperatures rise and releases it when they fall, thus maintaining a more stable temperature at the surface of the material. This ability to absorb and release latent heat contributes to better heat flux management. PCM thus enables more fluid and controlled management of stored heat, making it a more effective solution for damping thermal variations. Both materials end up releasing a similar amount of heat over time. This suggests that, although PCM improves thermal regulation during temperature peaks, in the long term, heat release is comparable between the two materials.

On the inner surface, the cob without PCM registers the highest thermal fluxes, reflecting higher inward heat transmission and lower thermal insulation performance. This observation reveals the poor ability of PCM-free material to handle thermal fluctuations, which can lead to uncomfortable temperature peaks indoors. In contrast, the cob with

PCM has significantly lower internal heat fluxes, demonstrating a better ability to limit the heat transmitted. This is mainly because PCM absorbs excess heat in the form of latent heat during temperature peaks, thus reducing the thermal load transmitted to the interior. During the heat release phase, it was also observed that the cob without PCM released a greater amount of heat than the cob with PCM. This indicates that the PCM, by gradually regulating heat flux, not only improves thermal management but also reduces sudden variations in interior heat.

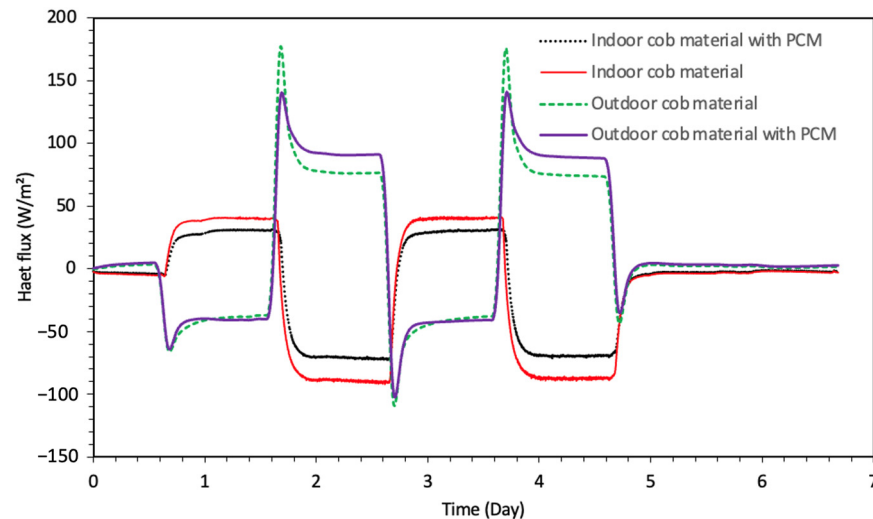


Figure 14. Indoor/outdoor heat flux distribution at surfaces of cob material with and without PCM.

3.2.3. Moisture Distribution Inside the Tested Samples

The physical analysis of the measurements presented in Figure 15 reveals complex mechanisms governing the interactions between phase-change materials and relative humidity on both surfaces. Figure 15 also shows profiles of relative humidity imposed inside the climatic chamber equivalent to the outdoor climatic conditions and the indoor relative humidity measured in the laboratory. The results indicate significant trends: near the climatic chamber, the cob material with PCM displays a higher relative humidity than the material without PCM. This can be attributed to the absorbent nature of the PCM, which acts as a moisture reservoir, accumulating excess moisture from the surrounding environment. This moisture absorption capability of the PCM can be attributed to its microencapsulated structure, which allows it to retain moisture more effectively than the material without PCM. Furthermore, on the interior surface, both materials absorb a similar amount of moisture, but the material with PCM releases more moisture than the one without PCM. This highlights the moisture release process of the PCM when its melting temperature is reached.

Figure 16 shows measurements of relative humidity at two different depths, namely at $y = 3$ cm and $y = 5$ cm, for the two types of materials analyzed. Upon examining these curves, it is noteworthy that the relative humidity absorbed or released by the material containing PCM is higher than that of the material without PCM. This observation can be interpreted by considering the specific thermal properties of PCM. Indeed, PCMs have the remarkable ability to store and release large amounts of thermal energy as they transition from a solid to a liquid state and vice versa. This thermal regulation capacity not only influences the temperature of the environment but also the relative humidity. When the temperature increases, PCM absorbs heat and can simultaneously absorb more moisture from the surrounding air, thereby increasing the relative humidity of the material. Similarly, when it gets colder, PCM releases stored heat, also influencing the amount of moisture present in the material and thus promoting an increase in relative humidity. In previous works,

numerous studies have demonstrated that integrating PCM into building materials not only enhances thermal comfort but also improves hygroscopic regulation. PCM influences the material's thermal inertia by absorbing and releasing heat in response to temperature fluctuations. It plays an important role in moisture management by capturing and releasing water depending on ambient conditions. These mechanisms explain the trends observed in the present work, confirming that the addition of PCM can alter the interactions between heat and moisture within the material and impact the indoor climate [34–37].

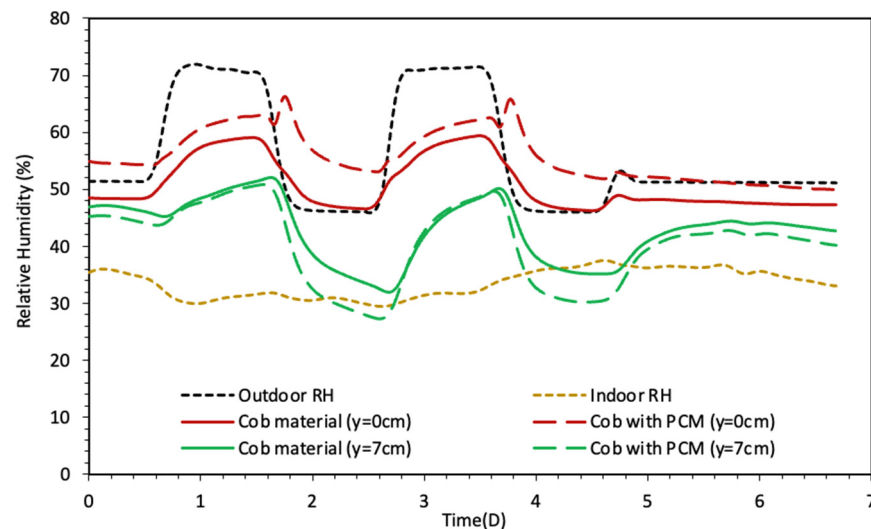


Figure 15. Comparison of surface relative humidity between materials with and without PCM.

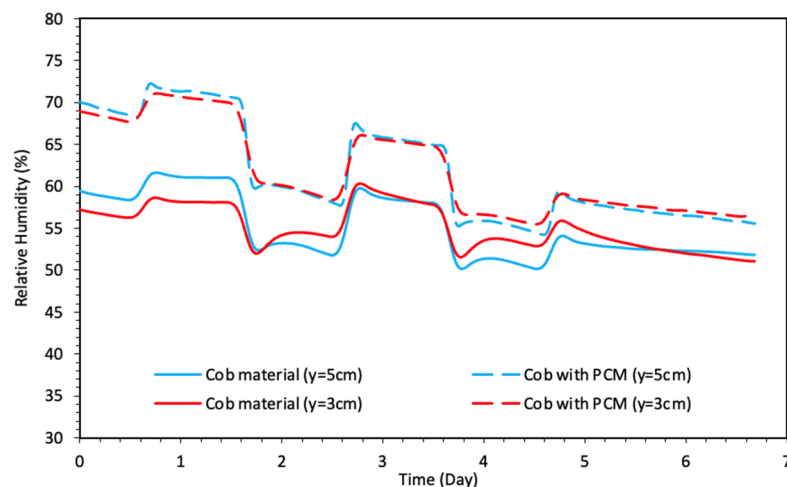


Figure 16. Comparison of relative humidity between cob materials with and without PCM at different depths.

4. Impact of Microencapsulated PCM on the Thermal Behavior of the Cob Material

As part of this study, the thermal conductivity and specific heat capacity of the two materials studied (cob without and with PCM) were determined using the HFM 436 Lambda. The thermal conductivity of the cob, as well as that of the cob incorporating PCM, was measured at three distinct temperatures: 11 °C, 18 °C, and 28 °C. These temperatures were carefully selected to assess thermal conductivity within the phase transition range of PCM (18 °C) and outside this range (11 °C and 28 °C). At 11 °C, PCM is entirely in the solid state, while at 28 °C, it is completely in the liquid state, enabling us to study the impact of different physical states on thermal properties.

Figure 17a illustrates the evolution of thermal conductivity as a function of temperature for cob with and without PCM. In the case of cob material without PCM, thermal conductivity increases with temperature, following a classic thermal behavior, with an average value of $0.34 \text{ W/(m}\cdot\text{K)}$, in line with data reported in the literature [38]. On the other hand, for cob containing 20% PCM, an overall decrease in thermal conductivity is observed, attributed to the low intrinsic thermal conductivity of PCM (around $0.12 \text{ W/(m}\cdot\text{K)}$). This reduction is particularly pronounced around the phase-transition temperature (18°C), where PCM absorbs latent thermal energy, slowing heat transfer. This behavior underscores the positive effect of integrating PCM on thermal regulation, in comparison with cribbing without PCM.

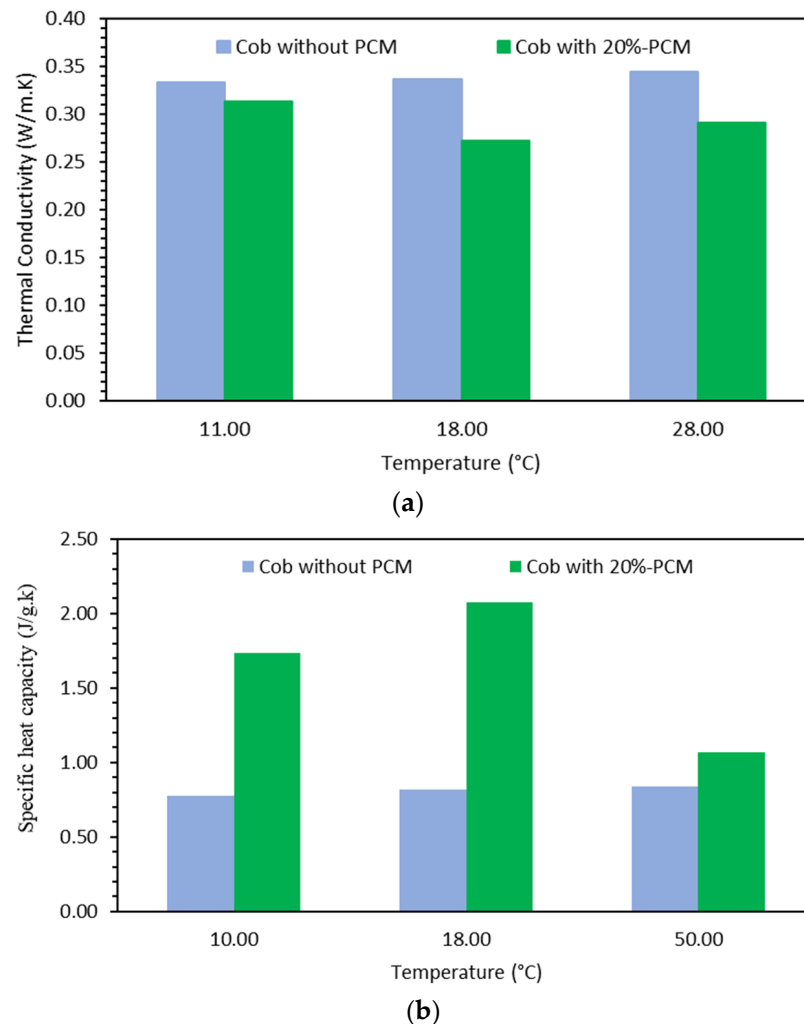


Figure 17. Thermal properties: (a) thermal conductivity; (b) specific heat capacity.

The evolution of the mass heat capacity of the two cob mixes, with and without PCM, as a function of temperature is shown in Figure 17b. Measurements were carried out at three specific temperatures corresponding to the different physical states of INERTEK 18 PCM: at 10°C , when the PCM is entirely in the solid state; at 18°C , during the solid–liquid phase transition; and at 50°C , when the PCM is entirely in the liquid state. These measurement points enable us to assess the impact of phase change on the thermal mass capacity of the composite material.

INERTEK 18 PCM has a significantly higher thermal capacity by mass than the cob material. This characteristic enables its incorporation to significantly improve the thermal properties of the mixture. Indeed, analysis of the results reveals an overall increase in

thermal mass capacity thanks to the presence of PCM. Before the phase transition, at 10 °C, the heat capacity of the mixture containing MCP is around 2.2 times greater than that of the cob sample. This effect is explained by the specific properties of MCP in the solid state, which contribute to better heat storage. During the phase transition, at 18 °C, an even more significant increase is observed. The heat capacity reaches a value some 2.6 times higher than that of the cob without PCM. This sharp rise is due to the latent energy absorbed by the PCM during its solid–liquid phase change. This phenomenon considerably increases the energy storage capacity of the composite material at this key temperature. After the phase transition, at 50 °C, although the effect is more moderate, the heat capacity by mass of the mixture containing PCM remains higher than that of the cob sample without PCM. An increase of around 1.3% is recorded, reflecting the thermal properties of PCM in the liquid state. Although this contribution is less pronounced, it nevertheless maintains an advantage over the unmodified material.

A simulation is conducted to study the impact of wall materials on thermal performance, considering the transient heat equation using real outdoor temperature data for two scenarios—summer (first four days of August 2023) and winter (first four days of January 2024). The data were extracted from Wunderground for the Normandy region in France. The study initially examines a 70 cm thick wall made entirely of structural biobased material. Secondly, it analyzes a 70 cm wall made of structural biobased material with 20% of its mass replaced by PCM. Lastly, a conventional multi-layer wall following a 35 cm standard is studied, consisting of 25 cm of concrete mortar, 8 cm of polystyrene, and 2 cm of plaster, Figure 18. This conventional wall, studied by Ferroukhi et al. [39], considers coupled heat and moisture transfer, with the thermal transfer coefficients extracted from the book *Moisture Analysis and Condensation Control in Building Envelopes* [40], complying with EN 12939 and ISO 6946 standards, which outline the measurement of thermal properties and the calculation method for the thermal performance of multilayer walls. The thermal properties of the conventional materials composing the studied wall are summarized in Table 4.

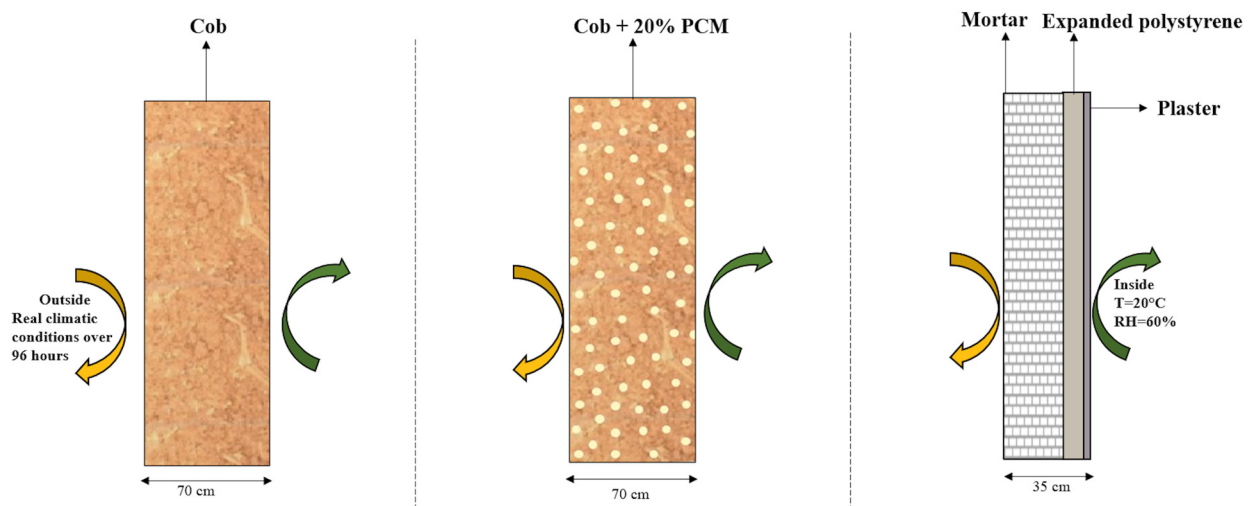


Figure 18. Schematic diagram of the three walls studied.

A fairer comparison of wall performance considers both thermal transmittance (U-value) and specific heat capacity rather than thickness alone. The 35 cm conventional multi-layer wall, designed for strength, thermal efficiency, and cost-effectiveness, has a U-value of 0.36 W/m²K, with internal insulation often used in retrofitting to prevent moisture condensation. In contrast, the 70 cm cob wall, selected in the CobBauge project to enhance thermal inertia and structural stability, shares the same U-value of 0.36 W/m²K,

while the addition of PCM lowers it to 0.31 W/m²K, improving insulation. The higher thermal inertia of cob construction, linked to its greater specific heat capacity, contributes to better temperature regulation and energy efficiency.

Table 4. Materials thermal properties forming the simulated conventional wall layers.

Propriety	Mortar	Expanded Polystyrene	Plaster
Thermal conductivity, W/m·K	0.85	0.033	0.6
Specific heat, J/kg·K	840	1470	840
Density, kg/m ³	1800	22.3	1380

The modeled transient heat equation represents the energy conservation principle in a mortar wall containing 20% phase-change material (PCM), capturing the combined effects of heat conduction and latent heat exchange during phase transitions:

$$\rho_{eff} C_{eff} \frac{\partial T}{\partial t} = \nabla (\lambda_{eff} \nabla T) + \rho_{PCM} L_f \frac{\partial f(T)}{\partial t} \quad (2)$$

where ρ_{eff} and C_{eff} represent the effective density and specific heat capacity, with λ_{eff} as the effective thermal conductivity. The term $\rho_{PCM} L_f \frac{\partial f(T)}{\partial t}$ incorporates the latent heat of fusion of the 20% presented PCM's density in the material, which varies with the melting fraction $f(T)$. The melting fraction is described by a linear model

$$f(T) = \begin{cases} 0 & T < T_{solid} \\ \frac{T - T_{solid}}{T_{liquid} - T_{solid}} & T_{solid} \leq T \leq T_{liquid} \\ 1 & T > T_{liquid} \end{cases} \quad (3)$$

The model includes convection as boundary conditions. The convective heat transfer at the surface of the mortar wall is expressed as:

$$-\lambda_{eff} \frac{\partial T}{\partial n} = h_{ext,int} (T_{ext,int} - T_{surf}) \quad (4)$$

where T_{surf} represents the surface temperature of the wall, T_{ext} is the external air temperature, which depends on real climatic conditions, T_{int} is the internal air temperature fixed at 20 °C, h_{ext} (17 W/m²K) is the convective heat transfer coefficient at the exterior surface, and h_{int} (8 W/m²K) is the convective heat transfer coefficient at the internal surface. The model allows us to simulate the PCM's ability to store heat during melting and release it during solidification, stabilizing the wall temperature. The model considers several hypotheses. simplifying the physical system to make the model computationally manageable:

- (1) The PCM distribution within the mortar is homogeneous, ensuring uniform thermal properties.
- (2) The effective thermal conductivity λ_{eff} , density ρ_{eff} , and specific heat capacity C_{eff} are constant and averaged over the composite.
- (3) The phase-change process occurs over a specific temperature range with a linear dependence of the melting fraction.
- (4) Heat transfer is modeled exclusively via conduction and convection, neglecting radiative effects within the wall.
- (5) Thermal equilibrium is assumed between the PCM and the structural material matrix at all times.

The numerical resolution of the heat transfer equation, programmed in version 9.0 of MATLAB using the ADI finite difference method, was performed with a time step of 1 s and a spatial step of 1 cm. The model incorporates real climatic data from the Normandy region as external boundary conditions, representing the temperature variations and environmen-

tal interactions accurately. The time-dependent global heat flux equation simplifies to an integral along the length of the domain in terms of heat conduction. It can be expressed as:

$$Q(t) = \int_0^L \lambda_{eff} \frac{\partial T(x,t)}{\partial x} dx \quad (5)$$

Figure 19 provides a numerical validation of cob material with and without PCM under boundary conditions imposed by the climatic chamber in the experimental of the present study. The model considers 7 cm of thickness, and the initial state corresponds to the mean of all initial measurements. Figure 19a (cob without PCM) shows a rapid temperature rise and decline, with the model capturing conductive heat transfer with minor deviations due to material inhomogeneities. In Figure 19b (cob with PCM), the simulation shows a rapid temperature drop at the transition phase (9 h) due to asymmetric heat absorption, as the 3 cm PCM layer reaches its melting temperature of 18 °C first, creating a localized heat sink and causing a sudden thermal gradient. The effect is less pronounced in thicker PCM layers.

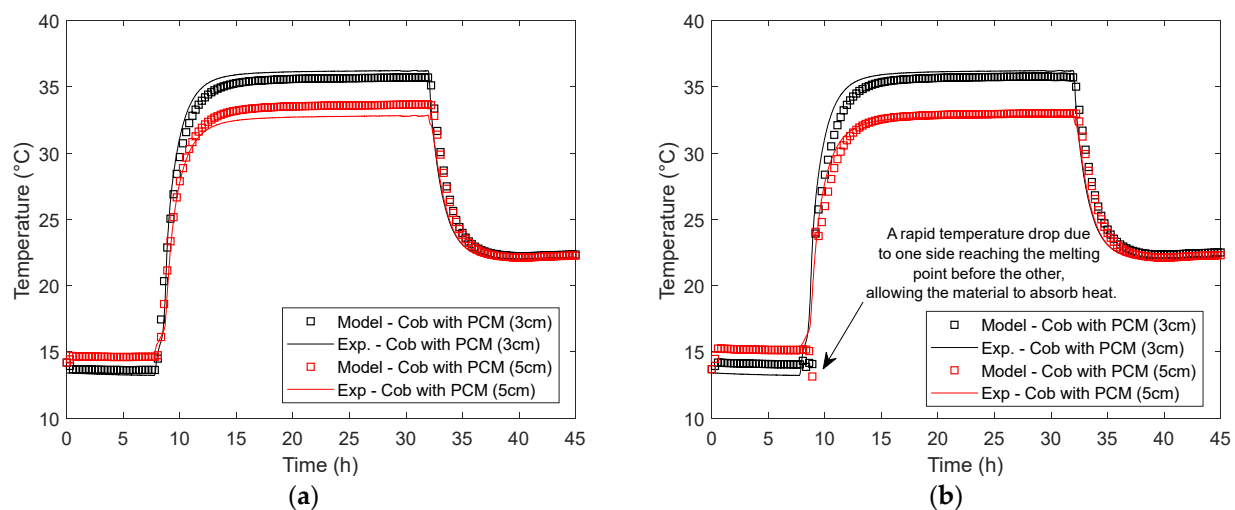


Figure 19. Numerical validation of thermal behavior in cob: (a) without PCM and (b) with PCM based on experimental results in the present study.

Figure 20 compares the thermal performance of walls made from different materials under fluctuating outside temperatures in January, ranging from approximately 6 °C to 15 °C, with an indoor temperature maintained at 20 °C. Walls built with conventional multi-layer materials exhibit significant heat losses, reaching up to -600 W/m^2 during colder periods. Walls constructed with biobased structural materials reduce these losses to approximately -200 W/m^2 . Incorporating 20% PCM into the biobased structural material further enhances thermal stability, limiting heat losses to around -100 W/m^2 . The walls made with biobased materials, with or without PCM, outperform walls made with conventional materials. This improvement is due to the lower thermal conductivity and optimized thickness of biobased walls, which enhance their insulating capacity. Adding PCM to biobased walls significantly improves the thermal performance by considering the latent heat storage capacity. When the outside temperature drops sharply, the PCM within the wall releases heat during its phase change, effectively stabilizing the wall's interior temperature, compared to biobased walls alone. PCM-enhanced walls act as thermal reservoirs.

Figure 21 shows the thermal performances under fluctuating outside temperatures in August (15 °C to 28 °C), heat flux is positive when the exterior temperature exceeds 20 °C, indicating inward heat flux (thermal gain), and negative when below 20 °C, showing outward heat flux (thermal loss). PCM-biobased walls significantly outperform conven-

tional and biobased walls in reducing heat flux. The conventional multi-layer wall exhibits the highest heat flux peaks, exceeding $+200 \text{ W/m}^2$ during thermal gain and -200 W/m^2 during thermal loss, indicating rapid heat transfer. Biobased walls reduce heat flux to below -120 W/m^2 and 150 W/m^2 , leveraging higher thermal inertia. However, PCM-biobased walls show the best performance, with heat flux dampened to around -35 W/m^2 and 50 W/m^2 . This is due to the PCM storing thermal energy (enthalpy) during high external temperatures, preventing heat from entering the interior and releasing it during cooling periods. This highlights the PCM's ability to regulate heat transfer, improve energy efficiency, and maintain stable indoor conditions. Oscillations and noise in the PCM-biobased curve arise from the dynamic phase-change process, as the material absorbs and releases heat intermittently, causing small fluctuations in heat flux due to localized thermal gradients.

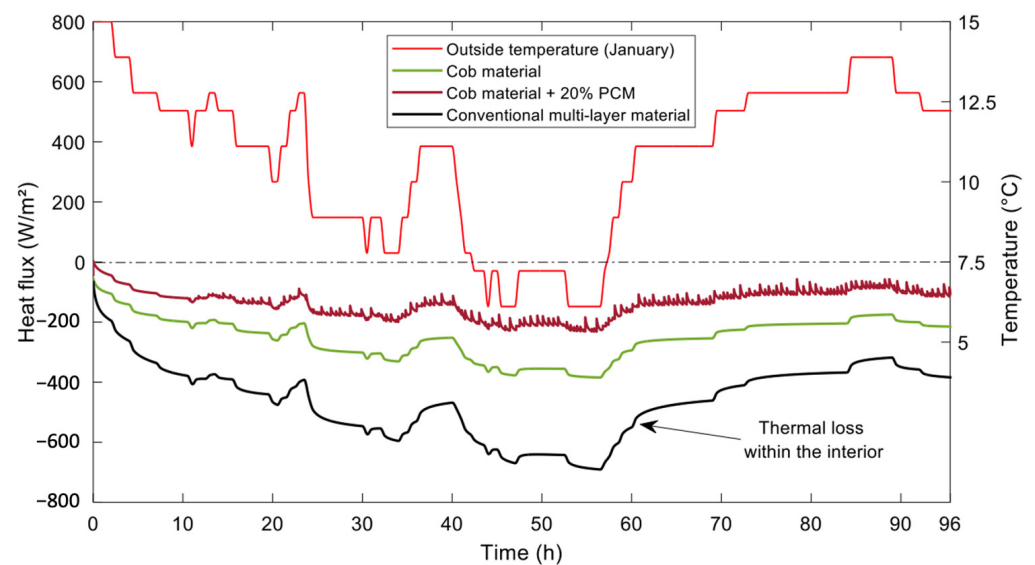


Figure 20. Thermal performance of wall materials in winter (January): Temperature variations and thermal losses.

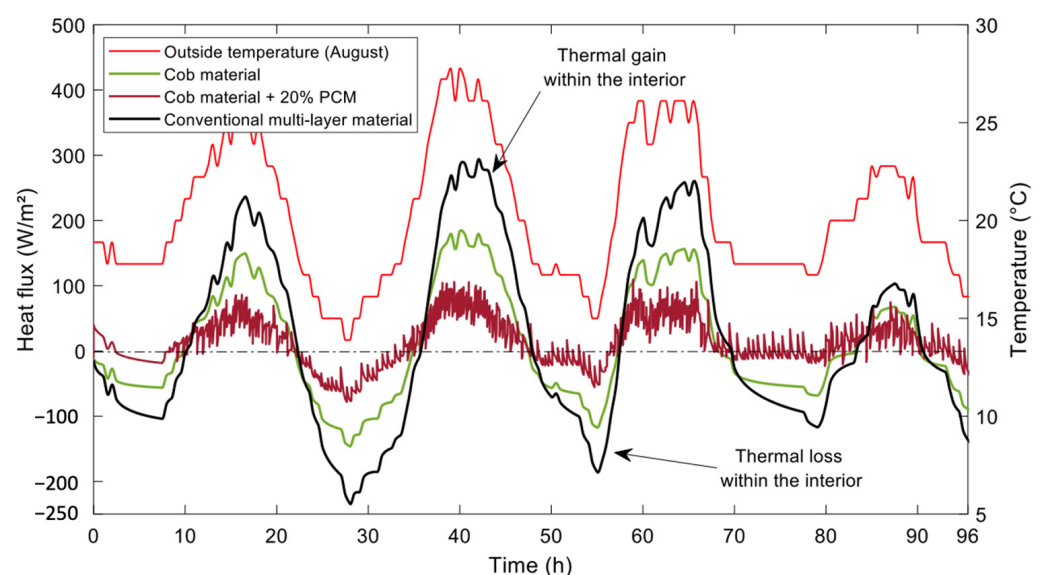


Figure 21. Thermal performance of wall materials in summer (August): temperature variations, thermal gains and losses.

Figure 22 illustrates heat energy within walls over 96 h in winter and summer, comparing three wall materials. In winter, the conventional multi-layer wall loses the most energy at -44.078 kWh/m^2 , highlighting poor insulation, while the biobased wall reduces losses

to -24.169 kWh/m^2 due to better thermal properties. The biobased wall with 20% PCM performs best, limiting losses to -13.169 kWh/m^2 by storing heat as latent energy and reducing thermal flux. In summer, all walls show net heat gain, as exterior temperatures consistently exceed the interior's 20°C . Gains are low due to averaging between variations of thermal gain and loss, with the conventional wall gaining 1.7525 kWh/m^2 , the biobased wall gaining 1.6634 kWh/m^2 , and the PCM wall gaining only 1.2168 kWh/m^2 . PCM effectively buffers temperature fluctuations and outperforms the other materials in both seasons.

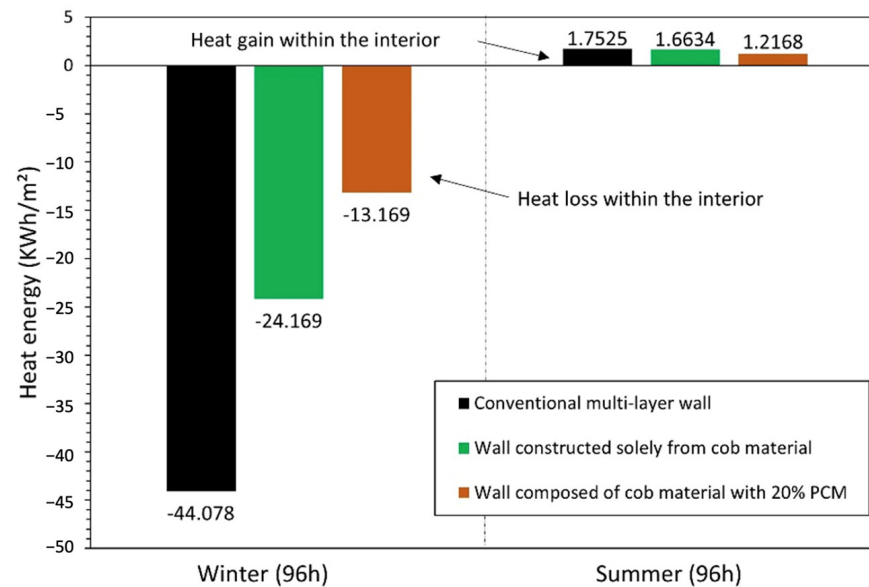


Figure 22. Heat energy of wall materials in summer and winter seasons.

5. Conclusions

This paper explores the effects of integrating microencapsulated phase-change materials into cob materials to improve their thermal and hygroscopic performance. An experimental setup simulated realistic environmental conditions, with one side exposed to a climate chamber and the other maintained under stable indoor conditions. The results show a homogeneous thermal and hygroscopic distribution, with minimal temperature variations ($\approx 0.02^\circ\text{C}$) and a uniform distribution of relative humidity, confirming the one-dimensional profiles essential for stable performance.

Samples containing PCM demonstrated improved thermal and hygroscopic regulation. These materials absorb and release heat in a controlled manner, providing improved thermal insulation and attenuating temperature variations. In terms of humidity, PCM enables better management by absorbing and releasing moisture according to ambient conditions.

In addition, the integration of PCM reduces the thermal conductivity of the cob and increases its thermal capacity by up to 2.6 times that of conventional cob at phase transition, improving energy storage and thermal regulation. These results highlight the potential of PCM to optimize building materials from a sustainable bioclimatic perspective.

Finally, a simulation was carried out to study the impact of wall materials on thermal performance, taking into account the transient thermal equation. This study compared three scenarios: a 70 cm wall made entirely of cob, a 70 cm wall with 20% phase-change material (PCM), and a conventional 30 cm multi-layer wall made of concrete, polystyrene, and gypsum. The results show that cob walls, with or without PCM, reduce heat flux more than conventional walls. The integration of PCMs improves thermal regulation and energy efficiency, offering a sustainable solution for bioclimatic construction while notably reducing the ecological footprint and contributing to comfort.

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