

Article

Analysis of the Physical and Thermal Characteristics of Gypsum Panels with Hemp Hurds for Building Insulation

Chatpon Chaimongkol ¹, Sukunya Ross ² , Dachaphon Kealkaew ¹ and Atthakorn Thongtha ^{1,*} 

¹ Department of Physics, Faculty of Science, Naresuan University, Phitsanulok 65000, Thailand; chatpon12123@gmail.com (C.C.)

² Department of Chemistry, Faculty of Science, Naresuan University, Phitsanulok 65000, Thailand

* Correspondence: atthakornt@nu.ac.th; Tel.: +66-5-596-3550

Abstract

The study investigates the potential of enhancing gypsum board properties through the integration of hemp hurds and glass fibers. The investigation focuses on evaluating the composite material's density, water absorption, flexural strength, compressive strength, and thermal performance. Experimental results demonstrate a reduction in gypsum composite density and improved thermal insulating properties with the introduction of hemp hurds. Water absorption, a significant drawback of gypsum boards, is mitigated with hemp hurds, indicating potential benefits for insulation efficiency. For mechanical tests, the gypsum ceiling board at approximately 5% by weight exhibits a flexural strength value exceeding the minimum average threshold of 1 MPa and the highest average compressive strength at 2.94 MPa. Thermal testing reveals lower temperatures and longer time lags in gypsum boards with 5% hemp hurds, suggesting enhanced heat resistance and reduced energy consumption for cooling. The study contributes valuable insights into the potential use of hemp hurds in gypsum-based building materials, presenting a sustainable and energy-efficient alternative for the construction industry.

Keywords: gypsum; hemp hurds; glass fibers; density; water absorption; thermal performance



Academic Editor: José Ignacio Alvarez

Received: 20 May 2025

Revised: 20 June 2025

Accepted: 24 July 2025

Published: 26 July 2025

Citation: Chaimongkol, C.; Ross, S.; Kealkaew, D.; Thongtha, A. Analysis of the Physical and Thermal Characteristics of Gypsum Panels with Hemp Hurds for Building Insulation. *Sustainability* **2025**, *17*, 6801. <https://doi.org/10.3390/su17156801>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Electricity consumption in the worldwide building section has continually grown from 26% in 1980 to 54% in 2010 and is forecasted to be 84% in 2050 [1,2]. The main electricity consumption in buildings is from air conditioning systems and mechanical ventilation for obtaining indoor thermal comfort, accounting for up to approximately 64% of electricity consumption in South Asia because of its hot climate regions with year-round summer conditions [1,2]. The building cooling demand in high-solar-radiation-intensity areas corresponds to the ability of the building envelope to decrease solar thermal accumulation in buildings [3–6]. A decrease in the heat gain of buildings is one of the keys to reducing the amount of energy consumption and is now required for the improvement of new and sophisticated building designs. One of the approaches to reducing energy consumption in buildings is the use of ceilings [7]. Ceilings, as a key component of the building envelope, offer potential for reducing heat gain and maintaining indoor comfort [3]. Gypsum (calcium sulfate dihydrate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is a widely used material in ceiling panel construction due to its favorable properties including fire resistance, rapid setting, and cost-effectiveness [8]. However, limitations such as brittleness, low water resistance, and inadequate mechanical strength have necessitated research into reinforcing options [9,10].

Previous studies have focused on improving gypsum-based tiles by incorporating various reinforcements such as natural fibers, synthetic fibers, and mineral particles. For instance, Aramwit et al. (2023) [11] investigated the effects of coir and rice husk fibers as individual and hybrid reinforcements in gypsum composites. They reported significant improvements, including up to a 187% increase in flexural strength, reduced moisture absorption, and enhanced thermal resistance. A blend containing 30% coir achieved the highest flexural strength (5.6 MPa), while a 50:50 mix of coir and rice husk provided optimal properties in hybrid composites. Benchouia et al. (2024) [12] investigated the use of date palm petiole fibers (DPPs) and expanded polystyrene (EPS) waste in gypsum plaster composites. Although the inclusion of DPPs and EPS reduced mechanical properties, the composites exhibited improved thermal performance, with thermal conductivity ranging from 0.265 to 0.414 W/(m·K) and bulk density between 852 and 925 kg/m³, compared to 0.425 W/(m·K) and 977 kg/m³ for neat gypsum plaster. Kehli et al. (2023) [13] developed a lightweight gypsum composite by incorporating barley straws treated with hot water (BS.HW) and further modified with a bio-based phase change material, palm oil (PO). The optimized formulation with a PO:BS.HW.3% ratio of 2.6:1 achieved a 12.1% reduction in thermal diffusivity compared to the control. Microstructural analysis also confirmed good chemical stability, indicating the material's potential for regenerative and thermally efficient wall insulation. Trociński et al. (2024) [14] examined the effect of incorporating hemp fibers of varying lengths and concentrations into a gypsum matrix. They found that adding 4 wt% of 50 mm long hemp fibers significantly enhanced static flexural strength, reaching a peak of 4.19 N/mm², and also improved longitudinal tensile strength. However, fiber contents above 4 wt% were detrimental to mechanical performance, and fibers longer than 50 mm posed processing challenges due to difficulties in uniform dispersion. Additionally, increasing fiber content reduced composite density, while extending setting time due to moisture absorption by the fibers. Hemp, derived from the industrial form of the *Cannabis Sativa L.* plant, emerges as a prevalent additive in cutting-edge building materials and research and development construction projects [15]. Renowned for its high cellulose content [16], hygrothermal efficiency [17], and carbon storage capacity [18], hemp has garnered widespread attention. This surge has led to the proliferation of hemp industry companies worldwide, covering both cultivation and processing. Extensive research supports hemp's role as an alternative material for low-carbon building applications [19]. Various tests involving treated and untreated hemp compounds, including fibers representing the outer part of the stem and shives or hurds constituting the inner woody part [20], have been conducted to develop environmentally friendly hemp-based building materials with optimal properties.

This research explores the potential of hemp hurds as a sustainable reinforcement for gypsum-based building materials. Despite limited prior investigations into the integration of hemp hurds into gypsum boards, this study delves deeply into its capacity to enhance both physical and thermal properties. The thermal performance and mechanical characteristics of hemp hurd–gypsum composites were systematically examined to uncover new insights that could lead to more energy-efficient building solutions. The study focuses on the material's ability to provide passive cooling, which could significantly reduce the energy consumption of buildings. This comprehensive analysis aims to contribute to the broader field of sustainable construction materials and promote the adoption of environmentally friendly practices in the industry.

2. Materials and Methods

2.1. Raw Materials and Preparation of Gypsum Board

In this study, multi-purpose gypsum plaster (Rhinolite) obtained from a commercial source was used in accordance with the Thai Industrial Standards Institute standard (TIS 219-2009) [21]. The plaster had a particle size range of approximately 5–850 μm , a bulk density of 0.8–1.2 g/cm^3 , and a pH value of 10.5–12.5 when wet. The primary chemical component was calcium sulfate dihydrate [22–25]. All of the gypsum plaster used was mixed well and then packed in plastic bags to protect from moisture and weighed before mixing. The hemp hurds used for this study were collected from an agricultural field factory in the Tak region of Thailand, where hemp is a major commercial crop and abundant quantities of hemp are produced every year. Hemp hurds from this factory are relatively large and dry, suitable for use as raw materials for testing and development into ceiling panels. Hemp hurds obtained from the factory undergo a preparation process to transform them into suitable raw materials for ceiling panels. This process involves manual hand grinding to reduce the hemp hurds into smaller sizes, making them suitable for further processing in a large herb grinder. Then, they are further refined with a fine powder grinder. This refinement process utilizes the centrifugal impact mechanism, breaking the hemp hurds into smaller pieces. In this study, a 2 mm screen was placed at the lower part of the machine frame. This screen is crucial in determining the fineness of the raw materials during the grinding process. The machine will continue grinding until the hemp hurds reach a size smaller than the sieve holes. After being ground using a fine powder grinder, the hemp hurds had a relative humidity of approximately 60%. They were then dried in an oven at 40 °C for 24 h [21]. After drying, the hemp hurds were removed from the oven, and their relative humidity was measured again, which was found to be approximately 50%. This material was then used as a filler component in the gypsum board samples. Glass fibers (CEM-FIL 54) were used as a comparative reinforcement material alongside hemp hurds. The fibers were chopped into lengths of 2.5 cm and 4 cm, which were approximately one-fourth the average length of the hemp hurd specimens. The selected glass fibers possessed an average diameter of approximately 14 μm and a density of 2.68 g/cm^3 . The tensile strength ranged from 1000 to 1700 MPa, and the modulus of elasticity was 72 GPa [26–28]. These mechanical properties were used to evaluate the differences in performance between specimens reinforced with natural particulate material and those reinforced with synthetic fibers.

In this investigation, the specimens were meticulously prepared by incorporating varying weight percentages of hemp hurds (ranging from 1% to 5% by weight) and glass fibers (at 1% and 2% by weight), in conjunction with a water-to-gypsum weight ratio of 0.6, as detailed in Table 1. This specific ratio was selected based on the study by Trociński et al. (2024), which demonstrated that a water-to-gypsum ratio of 0.6 provides a balanced formulation yielding specimens with high mechanical strength, reduced brittleness, and moderate mass [14]. The selection of hemp hurd content up to 5% by weight was guided by the findings of Ejaz et al., indicating optimal mechanical performance in gypsum agricultural waste composites when the filler content does not exceed this threshold [29]. Furthermore, the incorporation of glass fibers at 1–2% by weight follows the principle reported by Iucolano et al., stating that these are the most commonly used fiber proportions in gypsum composites due to the significant volumetric disparity between gypsum and fibers. Excessive fiber addition can adversely affect matrix integrity and overall composite performance, reinforcing the decision to adopt these modest yet effective reinforcement levels [30].

Table 1. Material composition of test specimens.

Conditions	Composite Mix Ratios							
	RS	H1	G1	H2	G2	H3	H4	H5
Water/gypsum weight ratio [g/g]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Hemp hurds [wt.%]	-	1	-	2	-	3	4	5
Glass fiber [wt.%]	-	-	1	-	2	-	-	-

The mixing process began by thoroughly combining gypsum plaster with water at the specified water-to-gypsum ratio. Hemp hurds (ranging from 1 to 5% by weight) were incorporated during the mixing of gypsum plaster with water, blended thoroughly until a uniform mixture was obtained, and then poured into molds. In mixtures incorporating glass fibers, the designated amount of fiber (ranging from 1% to 2% by weight) was positioned as a middle reinforcement layer during the casting process. Air bubbles were removed by gently vibrating or compacting the molds. All specimens were cured in a controlled room environment at an ambient temperature for 24 h.

For all the developed mixtures, physical and mechanical characterizations, including density, water absorption, flexural strength, compressive strength, and thermal properties, were evaluated, as summarized in Table 2. The sample preparation process is illustrated in Figure 1.

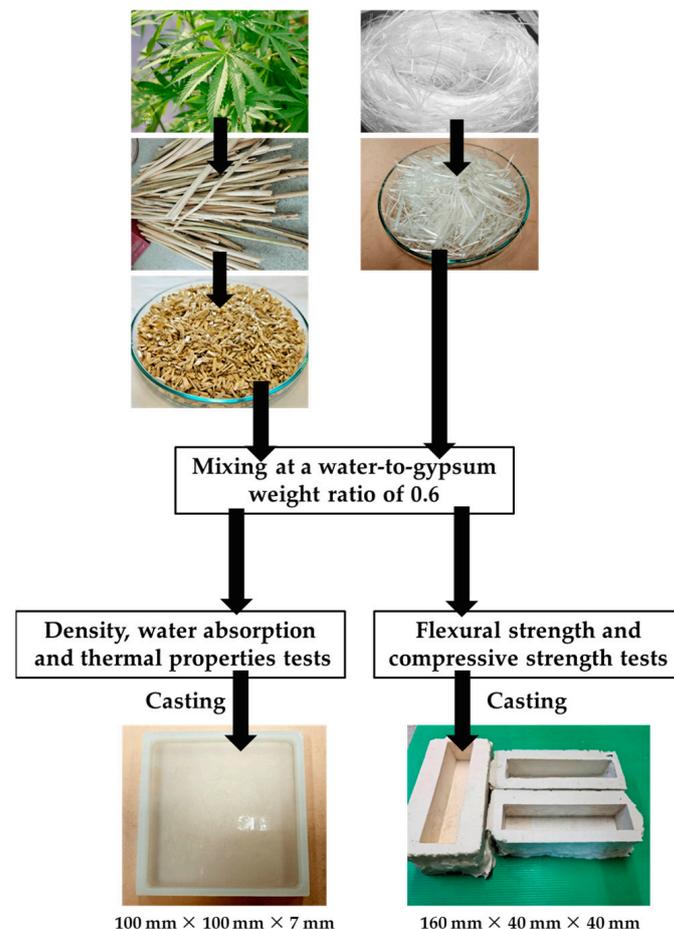
**Figure 1.** Specimen preparation process for gypsum board incorporating hemp hurds and glass fiber.

Table 2. Details of test samples.

Test	Dimensions of Test Specimen
Density, water absorption	100 mm × 100 mm × 7 mm
Flexural strength	160 mm × 40 mm × 40 mm
Thermal properties	100 mm × 100 mm × 7 mm

2.2. Measurement of Gypsum Board: Assessing Physical and Thermal Characteristics

Following the casting process in a 10 cm × 10 cm × 0.7 cm mold, the specimens underwent a curing period at room temperature for one day, followed by subsequent 24 h exposure to a 40 °C oven. After this process, some of these samples were next tested for density and water absorption. The water absorption test was conducted in accordance with the Thai Industrial Standards Institute standard (TIS 219-2009) [21]. The specimens were immersed in a water bath maintained at a constant temperature of approximately 23 °C. During immersion, the specimens were positioned horizontally without contact with the bottom surface of the container. After a soaking period of 2 h, the specimens were removed from the bath, and excess water on the surface and along the edges was carefully wiped off. The specimens were then weighed using a precision balance.

The thermal testing phase involved the creation of a test chamber (25 cm × 25 cm × 25 cm), which was constructed with PE insulation walls and black EPDM rubber insulation, having a thermal conductivity coefficient (K-value) of 0.038 W/m·K. The insulation was used to prevent heat loss and to direct heat flow vertically from the bottom to the top of the chamber. Fixed Type K thermocouple cables were connected to a data logger (HIOKI LR8431-20) to record the temperature inside the chamber. Controlled temperature conditions (40 °C, 50 °C, and 60 °C) were established using a precision heater. The results were systematically recorded through tests conducted at 1 min intervals, giving a 240 min test cycle. The variables monitored included temperatures under the heat source (T_{BH}), on the heat source (T_{UH}), in the air gap between the heat source and specimen (T_{AH}), under the specimen (T_B), on the specimen (T_U), in the middle of the room (T_R), on the upper side of the room (T_{UR}), and the controlled temperature outside the test chamber (T_{AM}), as shown in Figures 2 and 3.

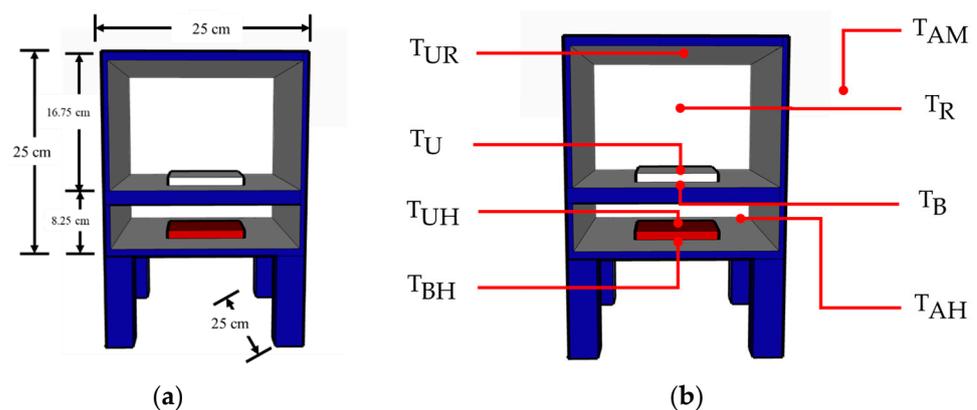


Figure 2. (a) Dimensions of the experimental testing models and (b) schematic diagram depicting the placement of fixed thermocouples for the experiment.

For the flexural and compressive strength tests, specimens measuring 160 mm × 40 mm × 40 mm were fabricated according to the specifications outlined in Figure 4 by following EN 13279-2:2014 [31]. Three samples were prepared for each mix. Subsequent to demolding, the samples were stored for 7 days under controlled environmental conditions of 23 ± 2 °C temperature and $50 \pm 5\%$ relative humidity. Afterwards, the samples were subjected to

an oven at 40 °C for 24 h and then placed in room temperature. The three-point bending test was used to determine the flexural strength of composites according to standard UNE-EN 13279-2:2014 [31], using a HUNGTA universal testing machine (HT-2402) with a load capacity of 50 kN. The test was conducted at a loading rate of 50 N/min. The samples were placed on the platform with their horizontal axis perpendicular to the supports of the test press machine. To obtain the bending strength of the plasters, three measurements were conducted for each mixture, obtaining the flexural strength of the materials as the mean value of those three samples. The measured values of the maximum applied load of the individual test samples were recorded. According to Equation (1), the values of flexural strength (σ_t) were calculated. Subsequently, the average flexural strength values (f_t) for each series were calculated.

$$\sigma_t = 0.00234 \times f_t \quad (1)$$

where σ_t is the flexural strength ($\text{N}\cdot\text{mm}^{-2}$) and f_t is the maximum applied load (N).

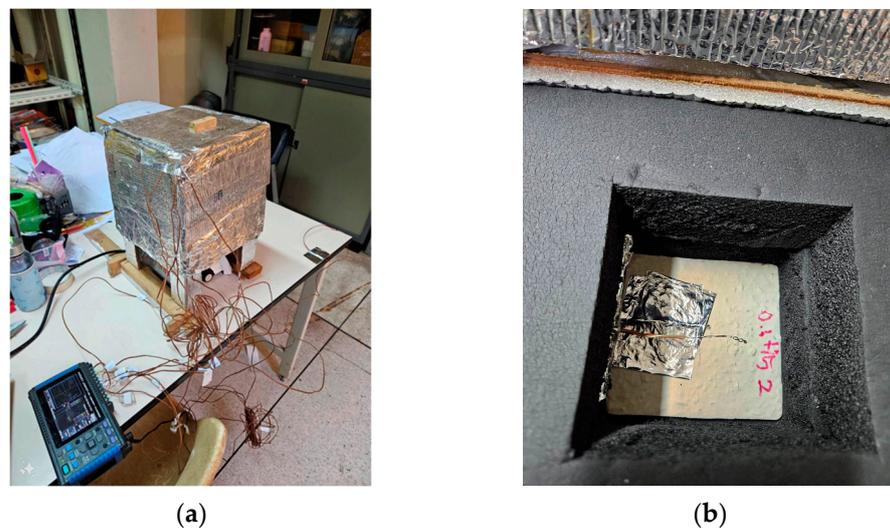


Figure 3. Test chamber used in the thermal testing phase (a) exterior and (b) interior view with Type K thermocouple cables connected to the data logger.

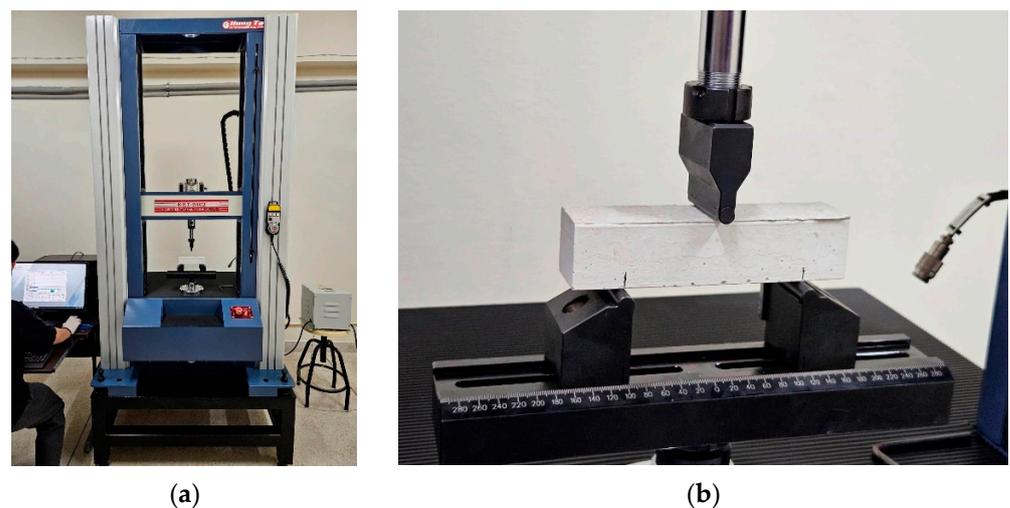


Figure 4. (a) HUNGTA universal testing machine (HT-2402) and (b) flexural strength measurement.

Following the UNE-EN 13279-2:2014 standard [31], three of the six half-pieces obtained from the flexural strength test were utilized to determine the compressive strength of the new samples, as shown in Figure 5. During this testing procedure, a specimen was placed

on a platen with a central progressive load, perpendicular to the specimen. The entirety of the specimen's surface made contact with the loading platen. The loading speed was set to 50 N/s to determine the compressive strength (σ_c) of each sample, as outlined in Equation (2).

$$\sigma_c = \frac{f_c}{A} \quad (2)$$

where σ_c is the compressive strength ($\text{N}\cdot\text{mm}^{-2}$), f_c is the maximum applied load (N), and A is the area of load boards (mm^2).

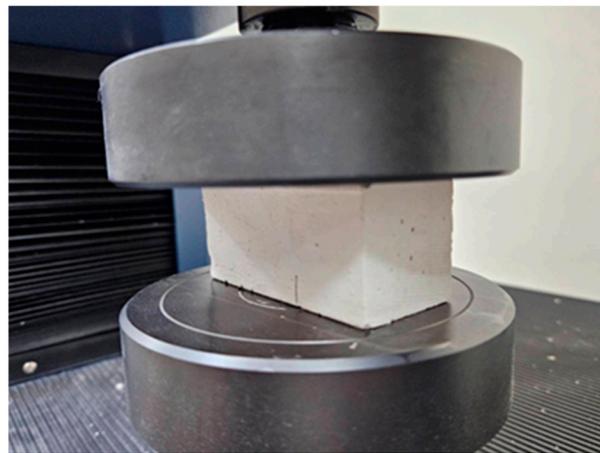


Figure 5. The compressive strength measurement.

2.3. Economic Evaluation

A comprehensive analysis of the cost efficiency and economic performance of the specimens was conducted, with a specific focus on calculating the unit cost per square meter. These values were then compared with those of commercially available gypsum ceiling boards to assess their relative economic viability.

3. Results

3.1. Density

Figure 6 demonstrates a notable reduction in the density of gypsum composites when glass fibers and hemp core are incorporated, compared to the control sample. The addition of these lightweight materials effectively increases the porosity of the gypsum matrix. Specifically, the inclusion of 5% hemp core results in a 4.8% decrease in density. This increase in porosity is significant because it enhances the material's thermal insulation properties. By creating more void spaces within the composite structure, the rate of heat transfer is reduced, thereby improving the overall thermal performance of the material. This finding highlights the potential of using glass fibers and a hemp core as viable additives in gypsum composites to achieve not only a lighter material but also one with superior insulating capabilities, contributing to energy efficiency in building applications.

3.2. Water Absorption

The pure gypsum samples display a significant propensity for water absorption, with measurements indicating that they absorb approximately 25% of their weight in water for 2 h. This high level of water uptake is problematic as it can lead to increased thermal conductivity, thereby compromising the insulation properties of gypsum boards. However, the study found that the introduction of glass fibers and hemp hurds into the gypsum matrix markedly enhances water resistance. Specifically, incorporating 5% hemp hurd content resulted in a substantial reduction in water absorption, bringing it down by 20.6%.

This improvement is critically important for maintaining the thermal insulating efficiency of gypsum panels. By reducing water absorption, the composite material retains its low thermal conductivity, ensuring that it continues to provide effective insulation. Regarding the correlation between water absorption and the density of gypsum boards incorporating hemp hurds and glass fibers at various mixture ratios, as shown in Figure 7, a decrease in density tends to result in a corresponding decrease in the water absorption percentage. This trend results from changes in porosity and internal structure caused by the material composition. The correlation between water absorption and the density of gypsum boards incorporating glass fibers at different mixture ratios exhibits a weak relationship, with an R^2 value of 0.1749, indicating that density has little influence on water absorption when glass fibers are added. In contrast, the correlation between water absorption and the density of gypsum boards incorporating hemp hurds at different mixture ratios shows a much stronger linear relationship, with an R^2 value of 0.7833, suggesting that hemp hurds significantly influence the internal structure and porosity of the gypsum matrix, leading to more predictable variations in water absorption as density changes. These findings underscore the potential benefits of integrating natural fibers and reinforcements into gypsum-based materials, offering a sustainable solution that enhances thermal performance in construction applications.

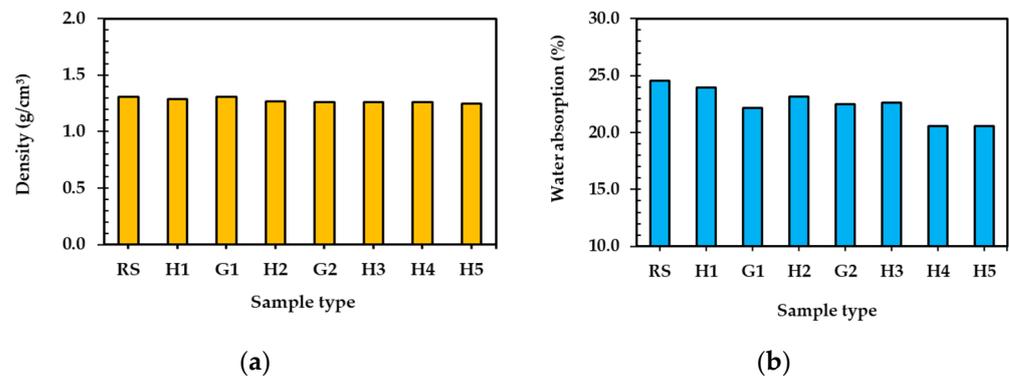


Figure 6. (a) The density and (b) water absorption characteristics of gypsum board incorporating hemp hurds and glass fiber at different mixtures.

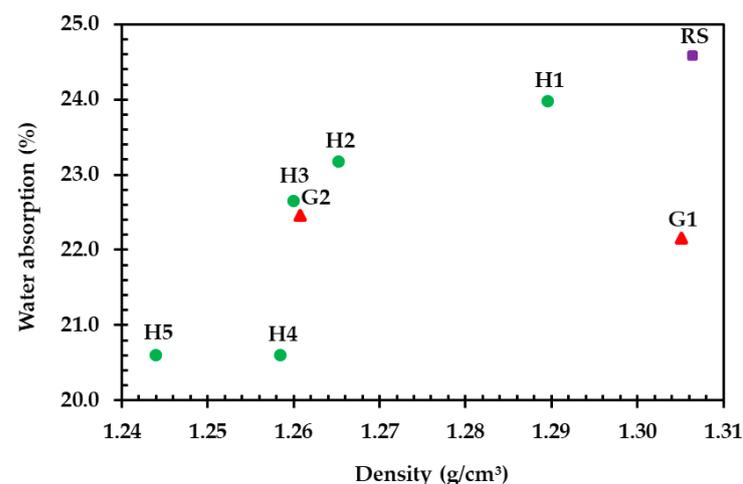


Figure 7. The correlation between water absorption and density of gypsum boards incorporating hemp hurds and glass fibers at different mixture ratios.

3.3. Flexural Strength Tests

The incorporation of hemp hurds and glass fibers significantly impacted the mechanical behavior of gypsum composites. Detailed flexural tests, as summarized in Table 3

and illustrated in Figure 8, demonstrated a marked difference between the reinforced and control samples. Specifically, the reference gypsum exhibited brittle failure, characterized by a low flexural strength of merely 0.58 MPa. This contrast highlights the potential of incorporating hemp hurds and glass fibers to enhance the structural integrity and flexibility of gypsum composites, thereby addressing the inherent brittleness and improving overall performance as shown in Figure 9.

Table 3. Flexural strength of the test samples.

Specification Samples	Percentage Proportions			Flexural Loading Limit f_t [N]	Flexural Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]	Average Value of Flexural Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]	Standard Deviation of Flexural Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]
	Plaster [%]	Hemp Hurds [%]	Glass Fiber [%]				
RS ₁	100	0	0	329.99	0.77	0.58	0.17
RS ₂				218.78	0.51		
RS ₃				198.18	0.46		
H1 ₁	99	1	0	205.87	0.48	0.50	0.02
H1 ₂				218.03	0.51		
H1 ₃				220.00	0.51		
G1 ₁	99	0	1	1077.38	2.52	2.31	0.44
G1 ₂				772.17	1.81		
G1 ₃				1115.29	2.61		
H2 ₁	98	2	0	409.65	0.96	0.83	0.12
H2 ₂				307.08	0.72		
H2 ₃				341.76	0.80		
G2 ₁	98	0	2	1238.80	2.90	3.16	0.27
G2 ₂				1470.46	3.44		
G2 ₃				1338.98	3.13		
H3 ₁	97	3	0	394.16	0.92	0.88	0.06
H3 ₂				346.80	0.81		
H3 ₃				386.23	0.90		
H4 ₁	96	4	0	430.17	1.01	1.05	0.05
H4 ₂				470.55	1.10		
H4 ₃				448.13	1.05		
H5 ₁	95	5	0	664.13	1.55	1.53	0.02
H5 ₂				645.36	1.51		
H5 ₃				655.84	1.53		

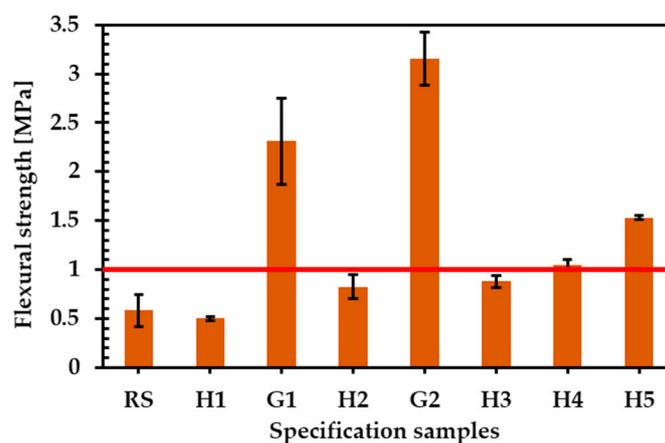


Figure 8. Comparison of flexural strength of each component.

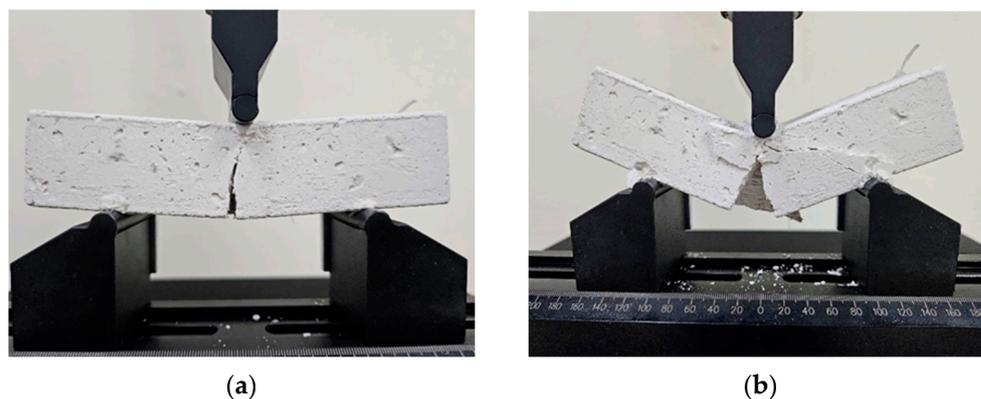


Figure 9. Comparison of failure modes for gypsum composites reinforced with (a) hemp hurds and (b) glass fibers.

The incorporation of hemp hurds and glass fibers markedly enhanced the flexural strength and overall mechanical performance of gypsum composites in comparison to the control samples. The structural modifications introduced by these reinforcements were evident in the distinct fracture patterns observed during testing. Specifically, the hemp hurd-reinforced samples typically exhibited central fractures, whereas the glass fiber composites displayed cracks at the support and loading points, indicating varied stress distribution characteristics. Flexural strength results, presented in Table 3, reveal significant enhancements in composite performance. Notably, the inclusion of 2% glass fibers yielded the highest flexural strength of 3.16 MPa, emphasizing the reinforcing efficacy of glass fibers within the gypsum matrix. Both hemp hurds and glass fibers contributed to the improved load distribution, thereby increasing overall flexural capacity. Composite formulations incorporating 4% and 5% hemp hurds, as well as 1% and 2% glass fibers, successfully met the minimum flexural strength standard of 1 MPa [21]. Comparative analysis with the existing literature indicates a dearth of studies focusing on hemp hurds in gypsum ceiling boards. While the maximum flexural strength of 1.53 MPa achieved with 5% hemp hurds is comparable to the 1.50 MPa reported by Aramwit et al. for rice husk-reinforced composites [11], the current study's results surpass those of Kuqo et al. for wood fiber (WF-C) and *Posidonia oceanica* fiber (POF-C) composites [32]. Similarly, the flexural strength aligns with findings by Benchouia et al. using date palm petiole fibers [12]. These comparisons underscore the potential of hemp hurds and glass fibers to elevate the mechanical performance of gypsum-based materials, contributing to the development of more robust and sustainable building solutions. These findings highlight the potential of natural and synthetic fibers to enhance the mechanical properties of gypsum-based materials, suggesting a pathway towards more robust and resilient construction materials. The integration of hemp hurds and glass fibers not only augments the mechanical strength but also promotes the development of sustainable and efficient building solutions.

3.4. Compressive Strength Tests

Compressive strength values, as detailed in Table 4 and illustrated in Figure 10, reveal significant improvements in samples reinforced with glass fibers compared to the control. Notably, the inclusion of glass fibers resulted in a clear trend: higher fiber content correlated with increased compressive strength. Among the tested composites, the 5% hemp hurd variant achieved the highest compressive strength, reaching 2.94 MPa. Furthermore, composites containing both 4% and 5% hemp hurds met the established minimum compressive strength standards for gypsum plaster at 2 MPa [21]. Comparative analysis with the existing literature reveals that the compressive strength values obtained

in this study surpass those reported by Kuqo et al. for wood and *Posidonia oceanica* fiber composites [32] and Benchouia et al. for date palm petiole fiber composites [12], while demonstrating comparable performance to Kehli et al. for barley straw composites [13]. These findings underscore the efficacy of incorporating hemp hurds and glass fibers to enhance the mechanical properties of gypsum composites. The improvements in compressive strength suggest that such reinforcement can contribute to the development of more robust and reliable construction materials, offering a promising approach to addressing the limitations of traditional gypsum plaster in building applications.

Table 4. Compressive strength of the test samples.

Specification Samples	Percentage Proportions			Compressive Loading Limit f_t [N]	Compressive Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]	Average Value of Compressive Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]	Standard Deviation of Compressive Strength σ_t [$\text{N}\cdot\text{mm}^{-2}$]
	Plaster [%]	Hemp Hurds [%]	Glass Fiber [%]				
RS ₁	100	0	0	4773.41	1.49	1.47	0.020
RS ₂				4666.91	1.46		
RS ₃				4662.99	1.46		
H1 ₁	99	1	0	4016.86	1.26	1.32	0.086
H1 ₂				4527.96	1.41		
H1 ₃				4088.85	1.28		
G1 ₁	99	0	1	5244.71	1.64	1.63	0.092
G1 ₂				4916.06	1.54		
G1 ₃				5504.32	1.72		
H2 ₁	98	2	0	5759.37	1.80	1.77	0.04
H2 ₂				5517.83	1.72		
H2 ₃				5761.54	1.80		
G2 ₁	98	0	2	6868.22	2.15	1.93	0.23
G2 ₂				6289.13	1.97		
G2 ₃				5405.01	1.69		
H3 ₁	97	3	0	6304.60	1.97	1.95	0.07
H3 ₂				6406.78	2.00		
H3 ₃				5975.86	1.87		
H4 ₁	96	4	0	7367.39	2.30	2.13	0.16
H4 ₂				6318.11	1.97		
H4 ₃				6750.35	2.11		
H5 ₁	95	5	0	10,606.73	3.31	2.94	0.33
H5 ₂				8735.46	2.73		
H5 ₃				8881.43	2.78		

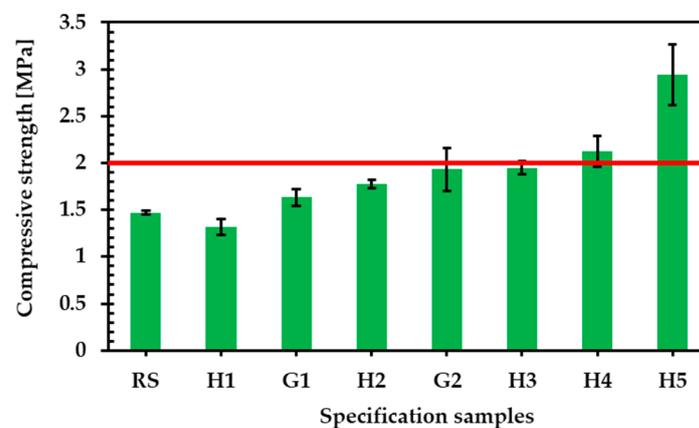


Figure 10. Comparison of compressive strength of each component.

3.5. Thermal Performance of Gypsum Board

When maintaining a temperature of 40 °C, 50 °C, and 60 °C, the temperatures at various positions exhibited fluctuations, as depicted in Figure 11. The temperatures included temperatures under the heat source (T_{BH}), on the heat source (T_{UH}), in the air gap between the heat source and specimen (T_{AH}), under the specimen (T_B), on the specimen (T_U), in the middle of the room (T_{AR}), on the upper side of the room (T_{UR}), and the controlled temperature outside the test chamber (T_{AM}), observed throughout a 240 min temperature evolution in each condition. Beyond 150 min of testing time, the wall temperatures at each location demonstrated a stable trend. Average temperatures for each gypsum board mixture were determined based on readings collected over a 150 min period. Notably, the composite containing 5% hemp hurds exhibited the lowest temperature values, indicating superior thermal performance. Although there were variations among the other samples, their overall temperatures remained comparable to the 5% hemp hurd composite. These findings, detailed in Table 5, highlight the potential of hemp hurds to enhance the thermal insulation properties of gypsum boards, suggesting a viable strategy for improving energy efficiency in building materials.

Table 5. Average temperatures at various locations in all testing models under controlled temperatures of (a) 40 °C, (b) 50 °C, and (c) 60 °C.

Controlled Temperature (°C)	Specification Samples	Temperatures at Different Positions (°C)							
		T_{BH}	T_{UH}	T_{AH}	T_B	T_U	T_R	T_{UR}	T_{AM}
40	RS	53.2	51.1	43.4	41.8	40.9	35.6	34.7	24.6
	H1	52.3	51.3	43.0	41.3	40.9	35.5	34.1	25.2
	G1	52.7	52.1	42.1	40.2	39.2	34.5	32.7	24.8
	H2	50.9	50.2	41.3	40.2	39.0	34.1	32.8	24.6
	G2	52.9	50.9	42.9	41.8	40.5	35.7	34.5	25.1
	H3	55.3	54.2	44.8	42.6	40.4	35.7	33.4	24.5
	H4	48.2	47.8	40.0	41.0	37.8	33.7	32.0	24.3
	H5	47.7	47.2	40.1	40.5	37.3	33.2	31.4	24.4
50	RS	67.0	65.7	53.3	50.1	48.9	42.0	40.4	25.1
	H1	64.9	63.8	52.7	50.1	49.3	41.5	40.2	25.9
	G1	68.8	67.6	53.2	50.1	48.1	40.8	38.4	25.0
	H2	67.1	65.6	51.1	50.6	47.8	40.1	38.3	25.7
	G2	67.7	66.2	53.6	50.6	48.1	40.6	39.2	24.8
	H3	67.0	65.9	52.0	50.1	45.8	39.6	36.5	25.6
	H4	64.6	63.4	50.2	50.3	45.0	39.1	36.7	24.7
	H5	64.0	62.8	49.9	50.5	44.6	38.4	35.9	25.1
60	RS	81.0	79.3	65.0	59.9	58.1	48.4	46.4	25.8
	H1	78.9	77.6	63.1	59.8	58.4	48.2	46.2	26.0
	G1	82.1	80.4	63.2	58.7	55.4	45.8	42.5	25.5
	H2	84.2	82.3	63.1	59.8	56.1	45.6	42.4	24.9
	G2	81.1	80.2	64.9	60.7	56.8	47.4	45.0	25.2
	H3	81.3	79.8	62.9	61.1	54.6	46.0	44.4	25.2
	H4	82.0	80.3	61.5	61.1	54.1	45.6	42.8	25.3
	H5	79.2	77.0	61.1	60.4	51.3	43.3	39.9	24.8

In evaluating the thermal behavior of gypsum board composites, temperature gradient measurements were conducted under controlled conditions at 40 °C, 50 °C, and 60 °C. The results are illustrated in Figure 12, which shows the temperature gradients (°C/m) across specimens incorporating varying proportions of hemp hurds and glass fiber. Specifically, samples H1 through H5 contained 1% to 5% hemp hurds by weight, respectively, while samples G1 and G2 contained 1% and 2% glass fiber, respectively. A general trend was

observed wherein the temperature gradient increased with rising external temperature across all sample types. Among these, the H5 specimen exhibited the highest temperature gradient at each temperature level, reaching approximately 448 °C/m at 60 °C. This indicates that the H5 composite allows heat to transfer more rapidly across the board, reflecting lower thermal resistance. Such a property may lead to reduced heat retention within the material, potentially contributing to more efficient thermal management in building applications. These findings support the material's suitability for energy-conscious and sustainable construction practices.

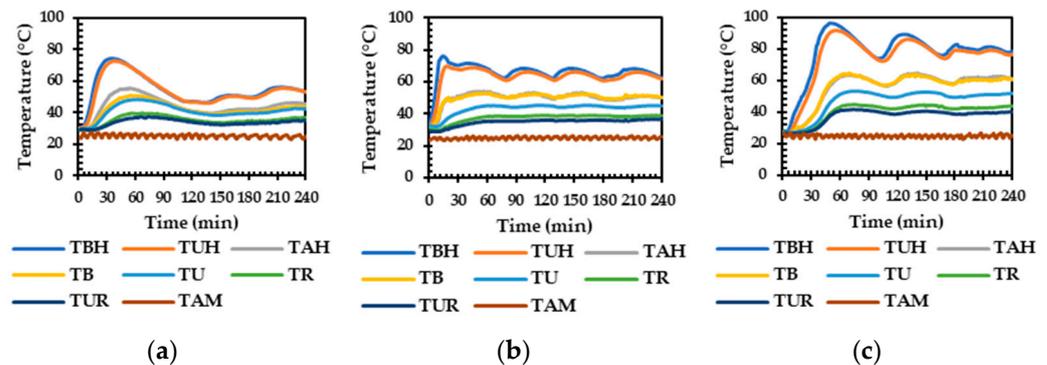


Figure 11. Temperature evolution of gypsum board incorporating 5% by weight of hemp hurds at a controlled temperature of (a) 40 °C, (b) 50 °C, and (c) 60 °C.

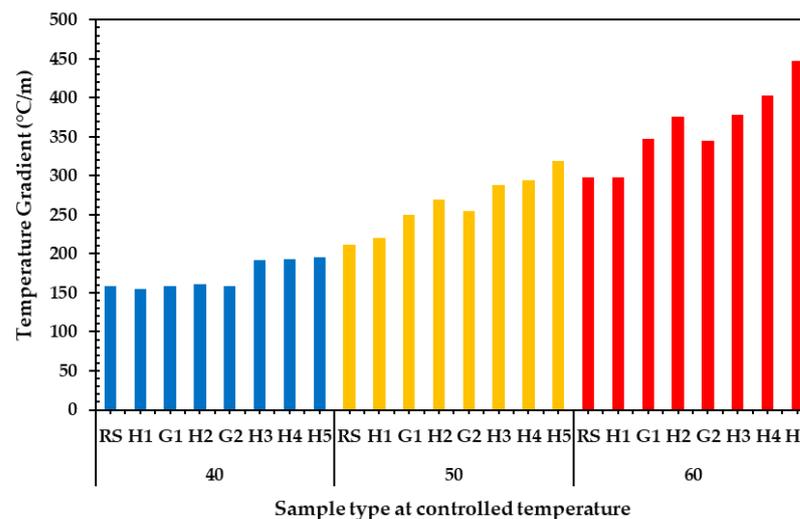


Figure 12. Comparison of the temperature gradients of each component.

The time lag (ϕ) [33] is determined by the following Equation (3):

$$\phi = \tau_{qi,max} - \tau_{qe,max} \quad (3)$$

where $\tau_{qi,max}$ is the time at the maximum interior sample surface heat flux, and $\tau_{qe,max}$ is the time at the maximum exterior sample surface heat flux, respectively. In controlled temperature tests at 40 °C, 50 °C, and 60 °C, the gypsum board mixture incorporating approximately 5% by weight of hemp hurds exhibited the longest time lag at 16 min, 16 min, and 7 min, respectively. Additionally, this type of composite showed the lowest average room temperatures of 33.2 °C, 38.4 °C, and 43.3 °C at the respective controlled temperatures, as detailed in Table 5. This extension modestly prolongs the duration required for heat transfer from the outside to the inside wall surface, significantly mitigating the magnitude of heat oscillations.

Among the various compositions tested at controlled temperatures of 40 °C, 50 °C, and 60 °C, the gypsum ceiling board with approximately 5% by weight of hemp hurds exhibited the lengthiest time lag, as shown in Table 6. This effect is particularly notable in the behavior of the gypsum ceiling board with around 5% by weight of hemp hurds, which modestly prolongs the time required for heat transfer from the outside to the inside wall surface and significantly diminishes the magnitude of heat oscillations. Consequently, the gypsum board with approximately 5% by weight of hemp hurds maintains a comparatively lower room temperature, showing a difference of approximately 7 °C compared to conventional gypsum. This observed temperature difference directly correlates with the impact of the extended time lag, as depicted in Figure 13. Moreover, the experimental findings suggest that the inclusion of hemp hurds in gypsum board production enhances both physical and thermal properties compared to conventional gypsum board. This research contributes to the broader goal of developing more energy-efficient and environmentally responsible buildings for a sustainable future.

Table 6. Comparison of the time lag at different sample types.

Controlled Temperature (°C)	Time Lag at Different Sample Type (min)							
	RS	H1	G1	H2	G2	H3	H4	H5
40	6	8	7	9	10	10	16	16
50	4	8	7	9	7	9	16	16
60	2	6	5	6	6	6	6	7

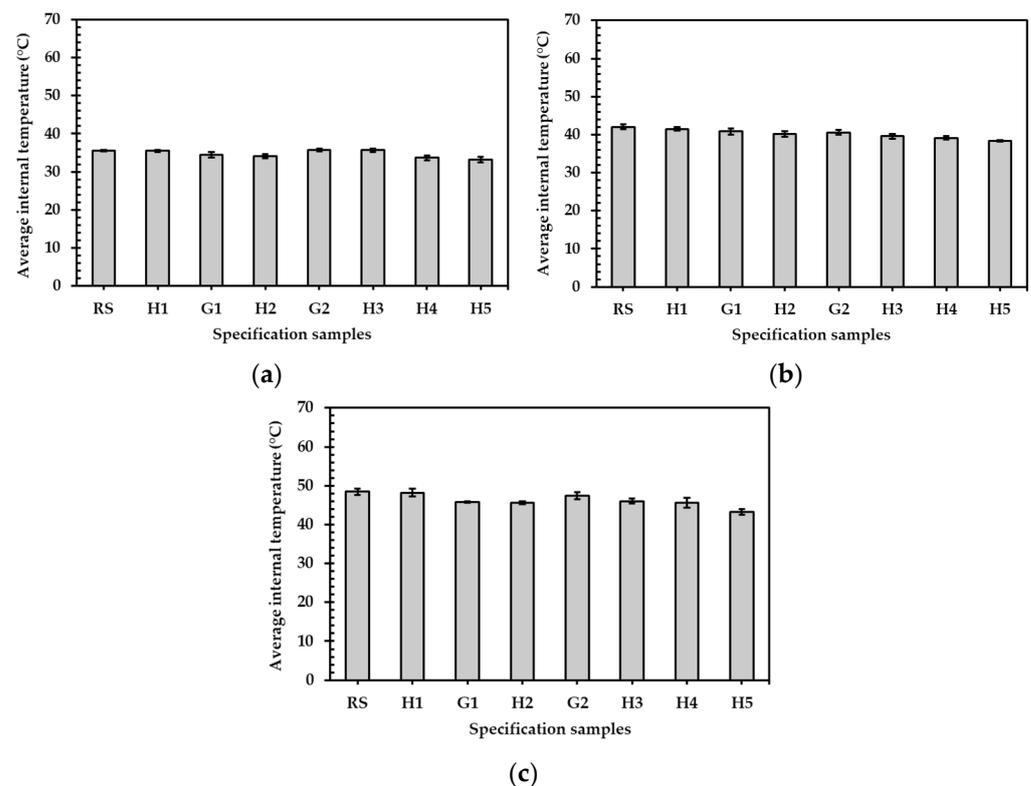


Figure 13. Comparison of average internal temperatures at a controlled temperature of (a) 40 °C, (b) 50 °C, and (c) 60 °C.

3.6. Economic and Holistic Sustainability Assessment

The cost analysis from Table 7 highlights the economic implications of incorporating alternative fibers into gypsum board production. The commercial ceiling board presents the lowest material cost at 1.32 USD/m² and requires no additional investment. However,

the use of glass fibers at 1–2% (G1 and G2) results in a substantial increase in total cost, with additional investments exceeding 2.00 USD. In contrast, gypsum boards with hemp hurds (H1–H5) demonstrate more balanced economic potential. Although the initial material costs are slightly higher than the commercial option, ranging from 3.36 to 3.79 USD/m², the additional investment decreases as the hemp hurd content increases. Notably, H5 (5% by weight of hemp hurds) shows the lowest additional investment among all modified samples at only 2.04 USD, suggesting better scalability and cost efficiency in mass production. When gypsum is partially replaced with hemp hurds, it not only reduces the overall cost related to gypsum content but also minimizes the environmental impact associated with gypsum manufacturing processes. From an industrial perspective, this indicates that hemp hurd-based gypsum boards offer a more economically and environmentally sustainable alternative, particularly suitable for construction sectors seeking to reduce raw material dependency and support environmentally responsible manufacturing.

Table 7. Total cost of each type of gypsum board samples.

Type of Samples	Material Cost (USD/m ²)	Additional Investment (USD)
Commercial ceiling	1.32	0.00
0.6 G1	3.66	2.35
0.6 H1	3.49	2.18
0.6 G2	3.79	2.48
0.6 H2	3.47	2.15
0.6 H3	3.47	2.15
0.6 H4	3.40	2.08
0.6 H5	3.36	2.04

The construction sector has traditionally relied on a range of conventional ceiling board materials such as gypsum boards [34], autoclaved aerated concrete (AAC) [35,36], and sand-lime bricks [37]. These materials have maintained their dominance due to their well-documented performance characteristics, ease of installation, and broad market availability. However, increasing global attention to environmental sustainability has prompted a critical reassessment of such materials, particularly in relation to their embodied energy, greenhouse gas emissions, and waste management challenges at end of life [38–40]. This shift in perspective has led to a growing interest in biocomposite alternatives, with hemp-based systems, including hempcrete and hemp–gypsum composites, emerging as promising solutions that better align with contemporary sustainability objectives in green construction [34,39–41]. Among these, the H5 hemp–gypsum composite offers a notable advancement in sustainable building technology. This material integrates 5% hemp hurds and 2% glass fibers into a modified gypsum matrix, resulting in performance enhancements across several critical parameters. When compared with traditional gypsum boards, the H5 composite demonstrates improved thermal insulation, structural stability, and economic efficiency. Notably, its thermal time lag reaches up to 16 min, while the maximum reduction in indoor surface temperature is 5.1 °C. These properties contribute significantly to passive cooling, offering a practical solution to energy reduction challenges in tropical and subtropical regions, where thermal load management is essential to achieving energy-efficient building performance.

Comparative evaluation between the H5 composite and hempcrete underscores the strengths and limitations of each material system. Hempcrete offers impressive thermal conductivity values between 0.051 and 0.22 W/m·K, making it an excellent insulator [42,43]. Nonetheless, its compressive strength remains low, typically under 1 MPa [44,45] unless supplemented with structural additives such as calcium oxide cement or aluminum sul-

fate [46,47]. Despite this mechanical limitation, hempcrete delivers outstanding lifecycle environmental benefits, acting as a carbon sink through a combination of carbon absorption during hemp cultivation and lime carbonation during curing [39,40]. This results in net negative carbon emissions of $-36.08 \text{ kg CO}_2/\text{m}^2$, surpassing traditional construction systems such as AAC and conventional concrete, which are associated with high embodied carbon and limited recyclability [39,48,49]. From a circular economy perspective, both the H5 composite and hempcrete exhibit strong sustainability attributes. The H5 composite reduces gypsum usage and incorporates biodegradable agricultural residues, contributing to waste minimization and offering potential for end-of-life repurposing. Hempcrete also aligns with circular economy principles through its recyclability and potential for reuse as lightweight aggregate or soil amendment. However, further research is needed to understand its degradation behavior under landfill or long-term disposal conditions. Economically, the H5 composite offers a production cost advantage of 7.2–11.8% over standard gypsum boards, mainly due to the partial replacement of gypsum with lower-cost hemp hurds. While hempcrete involves higher initial costs (EUR 190/m² compared to EUR 145/m² for AAC), it delivers lower lifecycle environmental costs (EUR 514 vs. EUR 1060 for AAC), indicating its potential economic viability in long-term sustainable construction [37]. In terms of application, the H5 composite is well-suited for ceiling boards and interior wall systems, especially in buildings designed for energy efficiency. Hempcrete is more appropriate for non-load-bearing walls [48], insulation [42], and eco-retrofitting projects [50]. Real-world implementations such as the Hemp Hotel in South Africa [51] and the Adnams Distribution Centre in the UK [52] further validate the functional and environmental benefits of these hemp-based systems. Overall, while traditional materials retain popularity for their regulatory acceptance and consistent performance, hemp-based composites, particularly the H5 formulation, offer a well-rounded alternative, combining structural reliability, thermal efficiency, and environmental benefits, thereby advancing the shift toward more sustainable, low-carbon practices in the modern construction industry.

4. Conclusions

Incorporating approximately 5% by weight of hemp hurds into gypsum board significantly improves both its mechanical and thermal properties. In the density test, the inclusion of hemp hurds and glass fiber resulted in a decrease in the overall density of the gypsum composites compared to the control gypsum mix. The specimen containing 5 wt.% hemp hurds exhibited the lowest density, with a measured density of 1.24 g/cm^3 , showing a 4.8% reduction compared to the control gypsum board.

Regarding the water absorption test, increasing the proportion of hemp hurds and glass fiber contributed to a reduction in water absorption capacity. The specimen with 5 wt.% hemp hurds demonstrated the lowest water absorption, showing a 16.2% reduction compared to the control gypsum board.

In the flexural and compressive strength tests, the specimens without any additional components exhibited relatively low resistance to bending and compression. Therefore, the inclusion of hemp hurds and glass fiber was necessary to enhance the mechanical performance to meet the required standard levels. The specimen containing 5 wt.% hemp hurds achieved an average flexural strength of 1.53 MPa and an average compressive strength of 2.94 MPa. Both results satisfy the minimum requirements specified in EN 13279-2:2014.

Under controlled temperature conditions, the specimen with 5 wt.% hemp hurds exhibited the lowest average internal temperature across all tested ambient temperatures. When compared to the control gypsum board, the temperature reductions were 6.74%, 8.57%, and 10.53%, respectively. Furthermore, this specimen showed the highest temperature gradient

and time lag values among all specimens, with the incorporation of hemp hurds yielding a 160% increase in thermal time lag, highlighting its superior thermal insulation properties.

The cost comparison indicates that gypsum boards reinforced with hemp hurds offer better economic viability than those with glass fibers. While glass fiber samples (G1 and G2) required additional costs exceeding 2.00 USD, an increase of over 50% compared to the commercial sample (1.32 USD/m²), hemp hurd samples (H1–H5) showed more favorable results. Notably, the H5 sample, containing 5% by weight of hemp hurds, had an additional cost of only 2.04 USD, representing a cost reduction of approximately 25% compared to G1, while also reducing gypsum usage. This demonstrates that hemp hurds can serve as a cost-effective and more sustainable alternative in gypsum board production.

These enhancements contribute to lower indoor temperatures and reduce cooling energy consumption, highlighting the composite's efficiency in managing heat. The observed benefits suggest that gypsum boards reinforced with hemp hurds present a promising and sustainable alternative for building materials. By improving energy efficiency and potentially lessening the environmental impact associated with construction, these advanced composites could play a significant role in promoting more eco-friendly building practices and reducing the overall carbon footprint of the construction industry.

Author Contributions: Conceptualization, A.T. and C.C.; methodology, A.T., D.K., and C.C.; formal analysis, A.T., D.K. and C.C.; investigation, A.T., D.K., and C.C.; resources, S.R.; data curation, A.T. and C.C.; writing—original draft preparation, A.T. and C.C.; writing—review and editing, A.T.; visualization, A.T.; supervision, A.T.; project administration, A.T.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded the Thailand Science Research and Innovation (TSRI) through the Fundamental Fund (2024), with support under grant number R2567B083.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article.

Acknowledgments: The authors would like to thank the Development and Promotion of Science and Technology Talents Project (DPST), Faculty of Science, Naresuan University, and our research center for its valuable contributions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ürge-Vorsatz, D.; Cabeza, L.F.; Serrano, S.; Barreneche, C.; Petrichenko, K. Heating and Cooling Energy Trends and Drivers in Buildings. *Renew. Sustain. Energy Rev.* **2015**, *41*, 85–98. [[CrossRef](#)]
2. Ürge-Vorsatz, D.; Petrichenko, K.; Staniec, M.; Eom, J. Energy Use in Buildings in a Long-Term Perspective. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 141–151. [[CrossRef](#)]
3. Chan, A.L.S.; Chow, T.T. Evaluation of Overall Thermal Transfer Value (OTTV) for Commercial Buildings Constructed with Green Roof. *Appl. Energy* **2013**, *107*, 10–24. [[CrossRef](#)]
4. Yang, L.J.; Yang, E.H. Energy Performance of Building Envelopes Integrated with Phase Change Materials for Cooling Load Reduction in Tropical Singapore. *Appl. Energy* **2016**, *162*, 207–217. [[CrossRef](#)]
5. Levinson, R.; Berdahl, P.; Akbari, H.; Miller, W.; Joedicke, I.; Reilly, J.; Suzuki, Y.; Vondran, M. Methods of Creating Solar-Reflective Nonwhite Surfaces and Their Application to Residential Roofing Materials. *Sol. Energy Mater. Sol. Cells* **2007**, *91*, 304–314. [[CrossRef](#)]
6. Nahar, N.M.; Sharma, P.; Purohit, M.M. Performance of Different Passive Techniques for Cooling of Buildings in Arid Regions. *Build. Environ.* **2003**, *38*, 109–116. [[CrossRef](#)]
7. Chen, Y.; Xia, B. Building as Major Energy Consumer. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Amsterdam, The Netherlands, 2017.

8. Khalil, A.A.; Tawfik, A.; Hegazy, A.A. Plaster Composites Modified Morphology with Enhanced Compressive Strength and Water Resistance Characteristics. *Constr. Build. Mater.* **2018**, *167*, 55–64. [[CrossRef](#)]
9. Kondratieva, N.; Barre, M.; Goutenoire, F.; Sanytsky, M. Study of Modified Gypsum Binder. *Constr. Build. Mater.* **2017**, *149*, 535–542. [[CrossRef](#)]
10. Shim, H.; Choi, G.J. Study of Construction Convergence Technology for Performance Improvement in Functional Building Materials. *J. Build. Eng.* **2017**, *11*, 108–114. [[CrossRef](#)]
11. Aramwit, P.; Sheng, D.D.C.V.; Moorthy, G.K.; Guna, V.; Reddy, N. Rice Husk and Coir Fibers as Sustainable and Green Reinforcements for High Performance Gypsum Composites. *Constr. Build. Mater.* **2023**, *393*, 132065. [[CrossRef](#)]
12. Benchouia, H.E.; Boussehel, H.; Guerira, B.; Sedira, L.; Tedeschi, C.; Becha, H.E.; Cucchi, M. An Experimental Evaluation of a Hybrid Bio-Composite Based on Date Palm Petiole Fibers, Expanded Polystyrene Waste, and Gypsum Plaster as a Sustainable Insulating Building Material. *Constr. Build. Mater.* **2024**, *422*, 135735. [[CrossRef](#)]
13. Kehli, K.; Belhadj, B.; Ferhat, A. Development of a New Lightweight Gypsum Composite: Effect of Mixed Treatment of Barley Straws with Hot Water and Bio-Based Phase Change Material on the Thermo-Mechanical Properties. *Constr. Build. Mater.* **2023**, *389*, 131597. [[CrossRef](#)]
14. Trociński, A.; Wieruszewski, M.; Bartkowiak, M.; Mirski, R. The Influence of Hemp Fibers (*Cannabis sativa* L.) on the Mechanical Properties of Fiber–Gypsum Boards Reinforcing the Gypsum Matrix. *Polymers* **2024**, *16*, 2644. [[CrossRef](#)]
15. Abu-Jdayil, B.; Mourad, A.-H.; Hittini, W.; Hassan, M.; Hameedi, S. Traditional, State-of-the-Art and Renewable Thermal Building Insulation Materials: An Overview. *Constr. Build. Mater.* **2019**, *214*, 709–735. [[CrossRef](#)]
16. Jones, D.; Brischke, C. *Performance of Bio-Based Building Materials*; Woodhead: Cambridge, UK, 2017.
17. Ait Oumeziane, Y.; Collet, F.; Lanos, C.; Moujalled, B. *Modelling the Hygrothermal Behaviour of Hemp Concrete: From Material to Building*; Springer: Cham, Switzerland, 2020.
18. Pervaiz, M.; Sain, M.M. Carbon Storage Potential in Natural Fiber Composites. *Resour. Conserv. Recycl.* **2003**, *39*, 325–340. [[CrossRef](#)]
19. Ingrao, C.; Giudice, A.L.; Bacenetti, J.; Tricase, C.; Dotelli, G.; Fiala, M.; Siracusa, V.; Mbohwa, C. Energy and Environmental Assessment of Industrial Hemp for Building Applications: A Review. *Renew. Sustain. Energy Rev.* **2015**, *51*, 29–42. [[CrossRef](#)]
20. Gregoire, M.; De Luycker, E.; Bar, M.; Musio, S.; Amaducci, S.; Ouagne, P. Study of Solutions to Optimize the Extraction of Hemp Fibers for Composite Materials. *SN Appl. Sci.* **2019**, *1*, 1293. [[CrossRef](#)]
21. TIS 219-2552; Industrial Standards Institute (TISI). Hot-Rolled Structural Steel Sections. Ministry of Industry: Bangkok, Thailand, 2009.
22. Saint-Gobain Gyproc. *Gyproc Multi-Purpose Plaster: Product Data Sheet*; Saint-Gobain Gyproc: Bangkok, Thailand, 2022.
23. Saint-Gobain Gyproc. *Gyproc Rhinolite Natural Plus: Product Technical Guide*; Saint-Gobain Gyproc: Johannesburg, South Africa, 2021.
24. British Gypsum. *Gypsum-Based Plasters: Safety and Technical Properties*; British Gypsum: Loughborough, UK, 2020.
25. Gyproc Thailand. *Material Safety Data Sheet: Gypsum Plaster Products*; Gyproc Thailand (Saint-Gobain): Bangkok, Thailand, 2021.
26. Owens Corning. *Cem-FIL® 54 AR-Glass Fibre for GRC: Product Data Sheet*; Owens Corning: Toledo, OH, USA, 2021.
27. Owens Corning. *Cem-FIL® 54: Declaration of Performance According to Regulation (EU) No. 305/2011*; Owens Corning: Chambéry, France, 2020.
28. Vetrotex Saint-Gobain. *Technical Data Sheet: Cem-FIL® Alkali Resistant Glass Fibres*; Vetrotex International: Chambéry, France, 2010.
29. Ejaz, M.F.; Riaz, M.R.; Azam, R.; Hameed, R.; Fatima, A.; Deifalla, A.F.; Mohamed, A.M. Physico-Mechanical Characterization of Gypsum-Agricultural Waste Composites for Developing Eco-Friendly False Ceiling Tiles. *Sustainability* **2022**, *14*, 9797. [[CrossRef](#)]
30. Iucolano, F.; Liguori, B.; Aprea, P.; Caputo, D. Evaluation of Bio-Degummed Hemp Fibers as Reinforcement in Gypsum Plaster. *Compos. Part B Eng.* **2018**, *138*, 149–156. [[CrossRef](#)]
31. UNE-EN 13279-2; Gypsum Binders and Gypsum Plasters: Part 1: Definitions and Requirements. European Committee for Standardization: Brussels, Belgium, 2006.
32. Kuqo, A.; Mai, C. Mechanical Properties of Lightweight Gypsum Composites Comprised of Seagrass *Posidonia oceanica* and Pine (*Pinus sylvestris*) Wood Fibers. *Constr. Build. Mater.* **2021**, *282*, 122714. [[CrossRef](#)]
33. Asan, H. Effects of Wall's Insulation Thickness and Position on Time Lag and Decrement Factor. *Energy Build.* **1998**, *28*, 299–305. [[CrossRef](#)]
34. Sonnier, R.; Belkhane, O.; Ferry, L.; Aprin, L.; Delot, P.; Garcia, C.; de Menibus, A.H.; Lenormand, H.; Potin, M. Fire behaviour of hemp, clay and gypsum-based light biobased concretes and renders. *Constr. Build. Mater.* **2022**, *331*, 127230. [[CrossRef](#)]
35. Thongtha, A.; Maneewan, S.; Fazlizan, A. Enhancing thermal performance of autoclaved aerated concrete (AAC) incorporating sugar sediment waste and recycled AAC with phase change material-coated applications for sustainable energy conservation in building. *Sustainability* **2023**, *15*, 14226. [[CrossRef](#)]
36. Mano, C.; Thongtha, A.; Maneewan, S.; Punlek, C. Improvement of the thermal efficiency of autoclaved aerated concrete by black powder. *ScienceAsia* **2021**, *47*, 76–82. [[CrossRef](#)]

37. Vontetsianou, A. The Effectiveness of Hempcrete in the Reduction of the Environmental and Financial Costs of Residences (A Case Study in The Netherlands). Master's Thesis, School of Civil Engineering and Geo-sciences, Delft, Netherlands, 2023.
38. Sutton, A.; Black, D.; Pete, W. Hemp lime: An introduction to low-impact building materials. In *BRE Information Papers*; HIS BRE Press: Bath, England, 2011.
39. Ip, K.; Miller, A. Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK. *Resour. Conserv. Recycl.* **2012**, *69*, 1–9. [[CrossRef](#)]
40. Pretot, S.; Collet, F.; Garnier, C. Life cycle assessment of a hemp concrete wall: Impact of thickness and coating. *Build. Environ.* **2014**, *72*, 223–231. [[CrossRef](#)]
41. Barbhuiya, S.; Das, B.B. A comprehensive review on the use of hemp in concrete. *Constr. Build. Mater.* **2022**, *341*, 127857. [[CrossRef](#)]
42. Hussain, A.; Calabria-Holley, J.; Lawrence, M.; Jiang, Y. Hygrothermal and mechanical characterisation of novel hemp shiv-based thermal insulation composites. *Constr. Build. Mater.* **2019**, *212*, 561–568. [[CrossRef](#)]
43. Al-Tamimi, A.S.; Qasem, N.A.A.; Bindiganavile, V. Thermal performance evaluation of hempcrete masonry walls for energy storage in cold weather. *Appl. Therm. Eng.* **2024**, *248*, 123304. [[CrossRef](#)]
44. Abdellatef, Y.; Khan, M.A.; Khan, A.; Alam, M.I.; Kavic, M. Mechanical, thermal, and moisture buffering properties of novel insulating hemp-lime composite building materials. *Materials* **2020**, *13*, 5000. [[CrossRef](#)]
45. Brzyski, P.; Gładcki, M.; Rumińska, M.; Pietrak, K.; Kubiś, M.; Łapka, P. Influence of hemp shives size on hygro-thermal and mechanical properties of a hemp-lime composite. *Materials* **2020**, *13*, 5383. [[CrossRef](#)]
46. Pantawee, S.; Sinsiri, T.; Jaturapitakkul, C.; Chindapasirt, P. Utilization of hemp concrete using hemp shiv as coarse aggregate with aluminium sulfate $[Al_2(SO_4)_3]$ and hydrated lime $[Ca(OH)_2]$ treatment. *Constr. Build. Mater.* **2017**, *156*, 435–442. [[CrossRef](#)]
47. Arehart, J.H.; Nelson, W.S.; Srubar, W.V. On the theoretical carbon storage and carbon sequestration potential of hempcrete. *J. Clean. Prod.* **2020**, *266*, 121846. [[CrossRef](#)]
48. Arrigoni, A.; Pelosato, R.; Melia, P.; Ruggieri, G.; Sabbadini, S.; Dotelli, G. Life cycle assessment of natural building materials: The role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. *J. Clean. Prod.* **2017**, *149*, 1051–1061. [[CrossRef](#)]
49. Sinka, M.; Van den Heede, P.; De Belie, N.; Bajare, D.; Sahmenko, G.; Korjakins, A. Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete. *Resour. Conserv. Recycl.* **2018**, *133*, 288–299. [[CrossRef](#)]
50. Tronet, P.; Lecompte, T.; Picandet, V.; Baley, C. Study of lime hemp concrete (LHC)—Mix design, casting process and mechanical behaviour. *Cem. Concr. Compos.* **2016**, *67*, 60–72. [[CrossRef](#)]
51. AfricaNews. World's tallest hemp hotel set to open in June in South Africa. *AfricaNews*, 3 May 2023.
52. Aukett, S. Adnams Distribution Centre. 2023. Available online: <https://www.aukettswanke.com/projects/adnams-distribution-centre/> (accessed on 21 October 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.