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Thermal Characterization of a New Bio-Composite Building Material based on Gypsum and Date Palm Fiber

Youssef KHRISSI[1,a,*], Amine TILIOUA[1,b,*], Najma LAAROUSSI[2,c]

[1]Research Team in Thermal and Applied Thermodynamics (2.T.A.), Mechanics, Energy Efficiency and Renewable Energies Laboratory (L.M.3.E.R.). Department of Physics, Faculty of Sciences and Techniques Errachidia. Moulay Ismael University of Meknès, B.P. 509, Boutalamine, Errachidia, Morocco

[2] Mohammed V University in Rabat, Material, Energy and Acoustics Team (MEAT), EST Sale, Morocco

[a]youssefkhrissi@gmail.com,[b]a.tilioua@umi.ac.ma,[c] lnajma@outlook.fr

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Abstract. In Morocco, the prevalent use of building materials with low thermal resistance has translated into substantial energy consumption. This has underscored the pressing need to promote the development and adoption of sustainable construction and insulation materials. The primary objective of our study is to enhance the thermal properties of plaster by incorporating date palm fibers (DPF) to create an exterior wall coating. To evaluate the thermal properties of the resulting Gypsum-DPF bio-composite material, we conducted several experimental measurements of thermophysical properties. These measurements encompassed the determination of bulk density and thermal conductivity, which were assessed using the steady-state hot plate method. Our findings reveal that the inclusion of date palm fiber in the material led to a noteworthy reduction in bulk density, amounting to approximately 17.16%. Furthermore, thermal conductivity decreased by approximately 26.24%. These outcomes underscore the potential and value of utilizing this bio-composite material in building construction to enhance thermal comfort and, critically, contribute to a reduction in greenhouse gas emissions, particularly CO2 emissions.

1. Introduction

The construction industry plays a substantial role in global energy consumption, primarily driven by the escalating need for infrastructure. Following the transportation sector, it stands as the second-largest consumer of energy, representing 28% of the total energy usage. Notably, in Morocco, this sector contributes to 25% of the nation's overall energy consumption. In light of these statistics, Morocco has introduced a comprehensive energy efficiency plan specifically tailored to the construction sector. This strategic initiative sets out to conserve approximately 1.2 million tons of oil equivalent (MTep) in energy and simultaneously slash greenhouse gas emissions by approximately 4.5 million metric tons of CO2 equivalent (MTeqco2) by the year 2020 [1]. Numerous endeavors have been undertaken to enhance energy efficiency within the construction industry. One key avenue for such improvement involves the enhancement of thermal properties in building materials. Morocco, endowed with abundant natural resources, presents a unique opportunity for this endeavor, particularly with its substantial reserves of gypsum. Although gypsum has a historical legacy as a construction material, its prevalent usage has historically been limited to decorative applications, primarily due to its fragility and subpar mechanical attributes. On another front, Morocco's bountiful date palm cultivation offers a valuable source of natural fibers boasting promising physical and mechanical characteristics. The central objective of this investigation is to explore the potential for elevating the worth of these eco-friendly materials by pioneering a novel composite material, which combines gypsum with reinforced date palm fibers.

It is worth noting that previous studies have already contributed to the characterization of diverse properties in gypsum composites strengthened with natural fibers, and these findings will be succinctly encapsulated below: Maaloufa et al [2] to enhance thermal insulation and mechanical characteristics, it is crucial to identify the ideal composition of cork and alpha fibers within a gypsum matrix. Notably, optimizing the thermal conductivity can be achieved, while also bolstering flexural strength through the incorporation of alpha fibers. However, it should be noted that the addition of cork may render the composite more susceptible to brittleness. F. Hernandez-Olivares and al [3] to enhance the strength of a gypsum composite, incorporating sisal fibers as reinforcement within the matrix is a viable approach. The introduction of randomly dispersed sisal fibers leads to a notable improvement in the overall mechanical properties of the composite. Mazhoud and al [4,5]. It has been observed that the utilization of hemp can effectively enhance the thermal and hydric properties of gypsum walls. Researchers have noted that hemp plasters exhibit significantly lower thermal conductivity in comparison to gypsum. Moreover, these hemp-based plasters demonstrate only a minor susceptibility to variations in temperature, highlighting their potential to contribute to reduced energy consumption in buildings [6]. Research efforts have extended to the exploration of composite materials incorporating date palm fibers, as exemplified by studies conducted by Benmansour and al [7]. They conducted experiments to evaluate the thermal and mechanical attributes of an innovative insulating material constructed using natural mortar reinforced with date palm fibers. Additionally, Kriker and al [8] investigated the mechanical characteristics of date palm fibers and their application in reinforcing concrete within hot and arid environmental conditions. In the study conducted by Gallala and al [9], they developed a gypsum composite incorporating date palm fibers (DPFW). Through a series of tests, it was determined that the inclusion of 17% DPFW, with a length of 20 mm, resulted in a composite exhibiting favorable thermal properties (λ=0, 52 w/m.k). Additionally, the mechanical characteristics of this composite outperformed those of non-fiber-reinforced samples. As a result of these findings, the authors advocate for the application of this biocomposite as an eco-friendly insulation material. In the experimental work by Boulaoued and al [10], an investigation into the thermal diffusivity and conductivity of palm fiber-reinforced plaster was conducted. The aim was to evaluate the feasibility of employing this innovative material for insulation, with the potential to decrease energy consumption in building structures. The outcomes of the study revealed a significant enhancement in the thermal characteristics of palm fiber-reinforced plaster. Additionally, it's worth noting that Almusawi et al. [11] highlighted the pivotal role of palm fiber reinforcement in enhancing the mechanical properties of plaster. In a study conducted by Naiiri et al. [12], an evaluation was carried out to determine the impact of doum palm fibers on gypsum mortar properties. Their research confirmed significant improvements in both mechanical and thermal attributes, as well as a reduction in damage, when doum palm fibers were integrated into plaster mortar. Djoudi et al. [13] also explored the influence of doum palm fibers on the thermal properties of plaster-gravel mixtures, revealing noteworthy enhancements in thermal conductivity, specific heat, and thermal diffusion.In a separate investigation, N. Fatma et al. [14] proposed the utilization of palm fibers in gypsum mortar to enhance density and thermal conductivity. Building on this body of research, the present study focuses on the development of a novel gypsum-based bio-composite material. This material incorporates varying mass fractions of date palm fiber (0%, 1%, 2%, 3%, 4%, and 5%) and it is designed for use in applications such as roof and interior wall cladding. The primary objectives of this innovative material are to meet thermal comfort standards, reduce energy consumption, and contribute to environmental sustainability through the utilization of waste resources.To gain insights into the critical factors influencing the performance of this material, an experimental characterization of its thermophysical properties was conducted. The key properties examined in this research encompass bulk density and thermal conductivity, and

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their evaluation was executed using the steady-state hot plate method. The resulting experimental findings are presented and comprehensively discussed in this paper.

2. Experimental materials and methods

2.1 Materials

2.1.1 Gypsum

Gypsum-based plaster is a construction material that finds common use in the building industry. A calcium sulfate material begins to harden and solidify when mixed with water. It releases heat when combined with water, unlike cement mortar, which is obtained by calcining natural gypsum (dehydrated calcium sulfate, CaSO4 2H2O) at a temperature of 120-150°C to obtain semi-hydrate with a certain amount of gypsum anhydride.

The chemical reaction in the solidification and hydration of hemihydrated calcium sulfate is:

$$2CaSO_4 . {}^{1}/_{2}\ H_2O + 3H_2O \rightarrow 2CaSO_4 . 2H_2O \qquad \text{Eq.1}$$

In this work, the gypsum used is hemi-hydrated gypsum extracted from the town of Safi in Morocco. The X-ray fluorescence spectrometer (XRF) was used to determine the chemical composition of the gypsum. Data from this analysis are presented in Table 1.

Table 1 Chemical compositions of the plaster used.

Component	Percentage
SO_3	54.93
CaO	33.34
P.a.F	9.512
SiO_2	1.047
MgO	0.5414
Al_2O_3	0.3438
Fe_2O_3	0.1201
SrO	0.09384
K_2O	0.06964
Rb_2O	0.001740

2.1.2 Date palm fiber

Recently, there has been a noticeable worldwide trend towards the use of materials derived from renewable natural resources. An excellent example of this trend is the use of palm waste fibers, which are an important and valuable source of natural fibers. These fibers are extracted from various waste products derived from palm trees, a collection process that is an integral part of seasonal delimbing, a vital agricultural procedure. The potential applications for these residues are remarkably diverse and extensive. From a socio-economic point of view, particularly in the Middle East and North Africa, date palms are of significant importance. Date palm waste has found its way into the construction industry, where it is used for tasks such as acoustic improvement and thermal insulation [15]. In our specific case, we chose to incorporate these palm fibers into plaster, thus creating an innovative eco-material that exploits local resources. The palm fibers used in this project come from the male palms of the Draa Tafilalt oases in southeastern of Morocco.

A scanning electron microscope (SEM) image, as shown in Figure 1, reveals the microporous structure of a date palm fiber particle. This structural feature suggests the possibility of trapping air, which could improve the material's thermal insulation properties.

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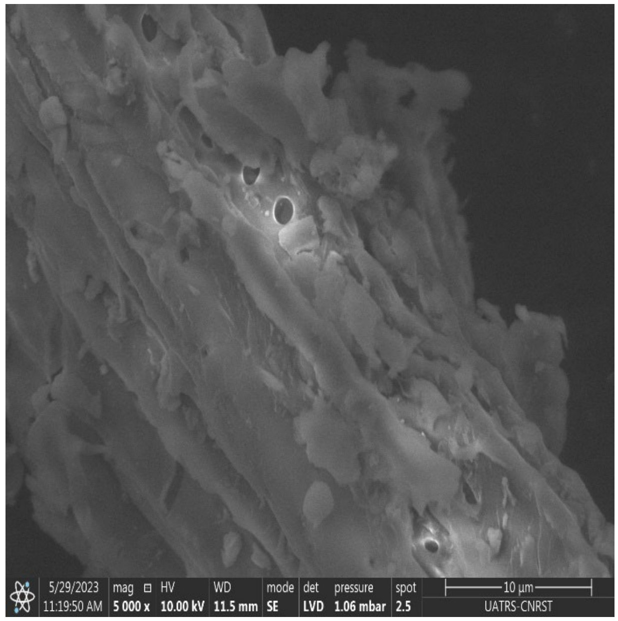

Fig.1 SEM image of a date palm fiber particle (CNRST-UATRS).

2.2 Sample preparation

The palm fibers gathered underwent a rigorous cleaning procedure, starting with a thorough washing using tap water to remove any dust or impurities. Subsequently, these fibers were manually separated into bundles. Afterward, the fibers were allowed to sit in the laboratory for a 24-hour period before being cut to the desired lengths, as depicted in Figure 2a, and then carefully stored in bags for future utilization.To enhance the compatibility of the palm fibers with the alkaline environment of the plaster, as illustrated in Figure 2b, and to eliminate weaker components such as lignin and hemicellulose that may not withstand it, a chemical treatment was implemented. This treatment not only reinforced the mechanical properties of the fibers but also optimized their bonding strength with the fiber-matrix interface. The specific treatment conditions were established based on insights from recent studies [16,17]. In this process, initially cleaned fibers were immersed in a 1% NaOH solution at 100°C for a duration of one hour. Following this, a thorough rinse was carried out to eliminate any residual NaOH on the fiber surface, and the fibers subsequently underwent a sodium chloride bleaching process. Subsequently, the fibers were meticulously washed once more and left to air dry at room temperature for a 24-hour period before deployment.The composite materials, identified as DPF, were prepared in steel parallelepiped molds measuring 150×150×30 mm^3. To achieve the desired compositions, plaster was mixed with varying mass fractions of DPF (ranging from 1% to 5%). A water ratio of W/P = 0.6 was gradually introduced, with manual stirring to ensure the proper homogenization of the components, as illustrated in Figure 2c. The resulting mixture was then poured into the molds. In order to assess the impact of fiber addition on the thermophysical properties of the composite samples, a reference sample was generated using pure gypsum. All six samples underwent air-drying at room temperature for a 24-hour duration, with their outer surfaces smoothed to ensure consistent contact for subsequent experimental measurements.Following this; the samples underwent an oven-drying process at 60°C for two days to eliminate any remaining moisture. The drying process was intermittently paused until the sample mass remained constant, fluctuating by no more than ±2 grams. Finally, the samples were sealed in plastic to preserve their dry state, as illustrated in Figure 2d.

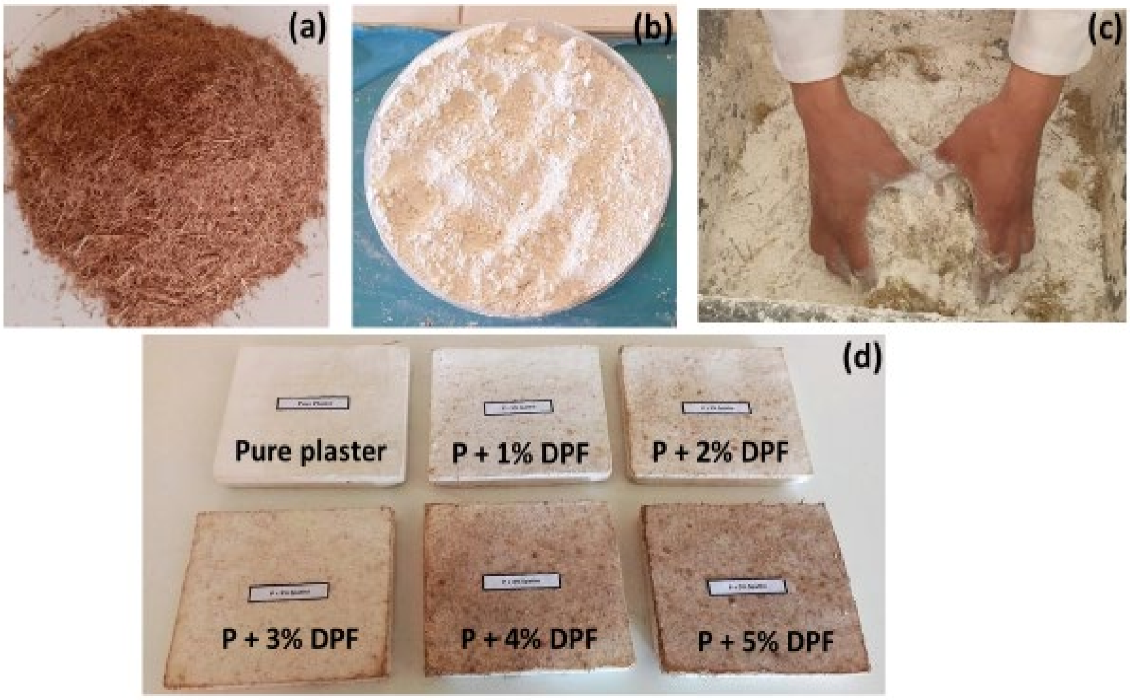

Fig. 2 Different stages in sample preparation.

2.3 Experimental description of thermal properties measurement

2.3.1 Steady-state hot-plate method

Thermal conductivity of the composite materials under examination was determined using a steady-state hot-plate apparatus, as depicted in Figure 2. This experimental arrangement involves the controlled transmission of a constant heat flux, represented as ϕ, through a heating element positioned beneath the sample. The primary objective is to monitor temperature variations on the two upper surfaces of the sample as it interacts with the heat source [18]. The heating element itself assumes a parallelepiped shape, with dimensions measuring 150×150×0.2 mm^3 and an electrical resistance of Re = 37.89 V. To ensure uniform temperature distribution on the unheated sides of the sample, the three heating elements are carefully situated between two aluminum blocks. Additionally, three K-type thermocouples, each with an uncertainty value of approximately +/- 0.6°C, are strategically positioned at the center of the sample faces.In this configuration, we are particularly interested in monitoring the temperature denoted T_0 at the center of the bottom face of the heating element,

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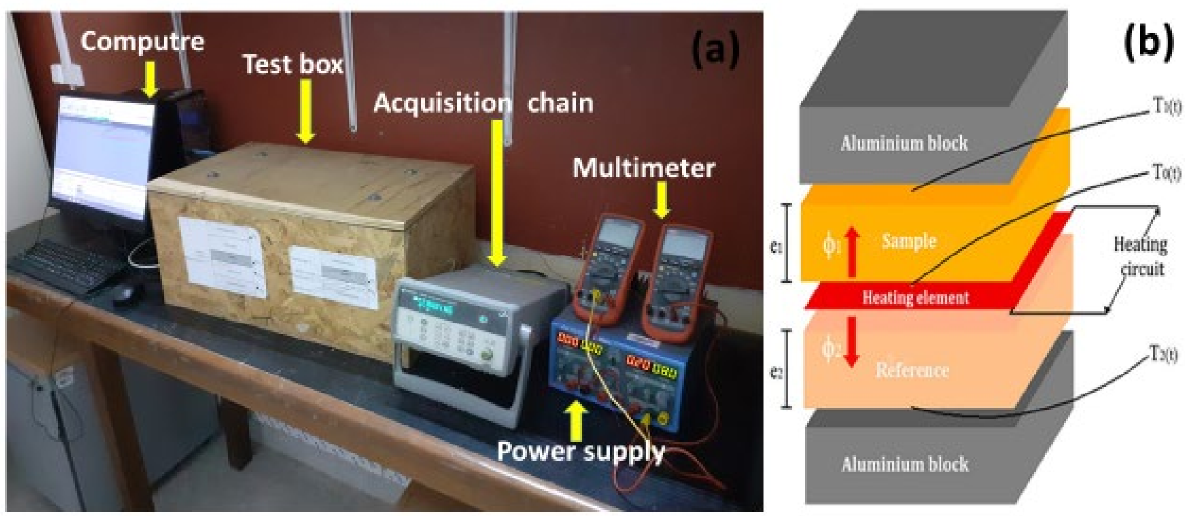

Fig. 3 Steady-state asymmetric hot-plate method: a) Experimental set-up, b) Principle of the method.

The temperatures we aim to track include T_1, positioned at the center of the unheated side of the sample, and T_2, situated at the center of the polyethylene foam, as delineated in Figure 3. It's important to highlight that the heat fluxes traveling through the sample, designated as ϕ_1 , and the polyethylene foam, denoted as ϕ_2 , are considered to be unidirectional, as outlined in equations (3) and (4). When the system reaches a steady state,

$$\phi = \frac{U^2}{RS} = \phi_1 + \phi_2 \qquad \text{Eq.2}$$

$$\phi_1 = \frac{\lambda}{e}(T_0 - T_1) \qquad \text{Eq.3}$$

$$\phi_2 = \frac{\lambda_i}{e_i}(T_0 - T_2) \qquad \text{Eq.4}$$

Where:

ϕ Represents the overall joule flux released by the heating element. In this context, $\lambda_i = 0{,}04$ W.m^{-1}.K^{-1} and $e_i = 10mm$ are successively the thermal conductivity and the thickness of the insulating foam. Furthermore, **e** denotes the thickness of the sample, **R** and **S** denote the electrical resistance and surface area, respectively, of the heating element, through which an electrical current **I** flows under the influence of a voltage **U** applied to its terminals.

The thermal conductivity of the sample is calculated by the following equation:

$$\lambda = \frac{e}{(T0 - T1)}\left[\frac{U^2}{RS} - \frac{\lambda_i}{e_i}(T_0 - T_2)\right] \qquad \text{Eq.5}$$

4. Results and discussion

In this section, we will provide an overview of the outcomes derived from the thermophysical assessment of gypsum material with varying proportions of date palm fiber, specifically examining bulk density ρ_{app} (kg/m^3) and thermal conductivity λ (W/m.K). Each sample was rigorously examined to ensure the quality of the thermograms and verify compliance with experimental specifications. The process involved the systematic removal and replacement of samples between measurements to maintain the accuracy of the experimental set-up.

4.1 Bulk density

In the construction sector, the emphasis is on lightweight materials, which underlines the importance of bulk density assessment. This process involves measuring the weight and dimensions of a sample. Samples, in their dry state, the specimens were carefully weighed using an electric precision balance, and their dimensions were meticulously assessed with a high-precision caliper. Subsequently, the bulk density was determined using the following formula:

$$\rho_{app} = \frac{m_{app}}{v_{app}} \quad \text{Eq.6}$$

Figure 4 illustrates the fluctuations in bulk density observed in gypsum composites with varying proportions of (DPF; 0% to 5%). In particular, the introduction of (DPF) into the gypsum matrix results in a significant decrease in bulk density, from 1386.13 Kg/m³ to 1148.25 Kg/m³. This is equivalent to a weight reduction of around 17.16%, particularly for the sample containing 5% fibers. The main factor in this reduction is the increase in material porosity resulting from the incorporation of date palm fibers. This result underlines the effectiveness of these materials for potential applications in interior wall and roof cladding, highlighting their value as bio-composite building materials characterized by a robust adhesive structure.

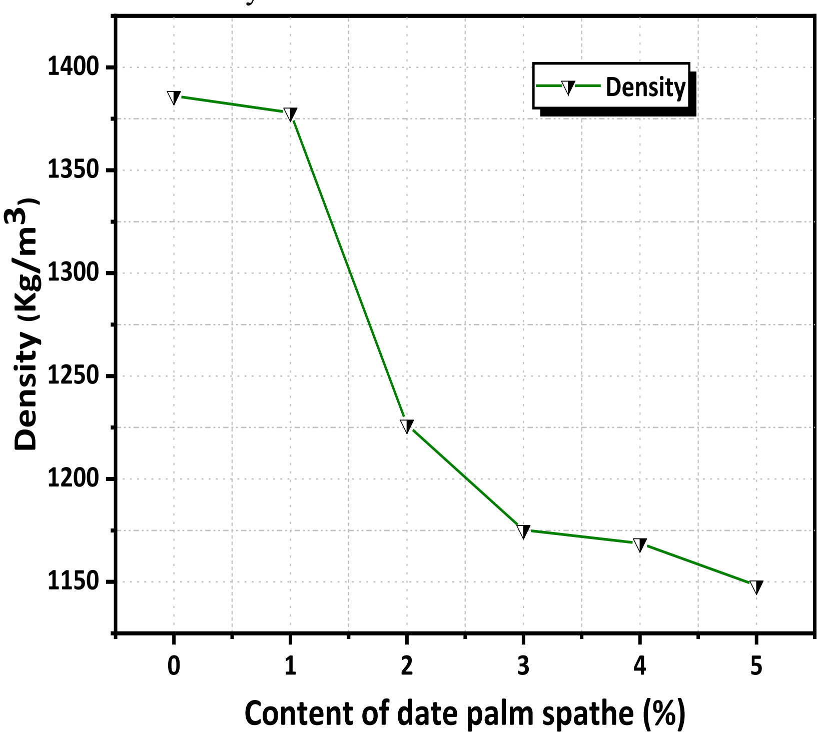

Fig. 4 Bulk density of different samples.

4.2 Thermal conductivity

The thermal conductivity of the samples tested was evaluated using the steady-state hot-plate method. The main input parameters, including sample thickness, voltage, electrical resistance and recorded temperatures (T_0, T_1 and T_2), as well as the resulting thermal conductivity measurements for the various samples, are presented concisely in Table 2. Notably, the maximum deviation observed in these measurements is around 4.1%, validating the reliability of the chosen method.An important observation in the data shows a steady decline in thermal conductivity as the proportion of date palm fiber (DPF) increases. Specifically, thermal conductivity decreases from 0.522 W/m.K, the value for pure gypsum, to 0.385 W/m.K for the composite that includes 5% DPF (P+5% DPF). This reduction in thermal conductivity can be attributed to two main factors. Firstly, it is linked to the intrinsically low thermal conductivity of the date palm fibers themselves. Secondly, it results from the formation of air-filled voids within the composite material due to the inclusion of these fibers. In particular, the air has an extremely low thermal conductivity of 0.026 W/m.K, making a significant contribution to the overall reduction in the thermal conductivity of the composite material.

Table 2 Measurement input data and experimental results for thermal conductivity of various samples.

	e(m)	U (V)	R (Ω)	S (m^2)	T_0 (°C)	T_1 (°C)	T_2 (°C)	λ (W/m.K)
Pure plaster	0,0246	15,15	37,89	0,02250	40,96	31,271	26,718	**0,522**
P+1% DPF	0,0220	15,15	37,89	0,02250	39,479	30,409	24,499	**0,490**
P+2% DPF	0,0235	15,15	37,89	0,02250	42,727	33,41	25,587	**0,485**
P+3% DPF	0,0233	15,15	37,89	0,02250	38,558	27,941	22,179	**0,430**
P+4% DPF	0,0210	15,15	37,89	0,02250	45,704	35,663	28,348	**0,400**
P+5% DPF	0,0204	15,15	37,89	0,02250	38,562	27,974	23,062	**0,385**

Conclusion

The main objective of this study is to investigate the thermal characteristics of an innovative bio-composite material that combines gypsum and date palm fibers. We used experimental methods to evaluate the bulk density and thermal conductivity of gypsum samples with different mass fractions of date palm fibers (0%, 1%, 2%, 3%, 4% and 5%). The results of this study are as follows:

- The incorporation of 5% date palm fiber (DPF) into the composite material results in a substantial reduction of around 26.24% in thermal conductivity. In addition, the addition of DPF contributes to an overall reduction in the density of the building material, with a notable decrease of 17.16%.
- The adoption of innovative composite materials in construction makes it possible to improve thermal comfort without the need for heating or cooling systems, thus reducing greenhouse gas emissions. Lower energy consumption plays a crucial role in reducing CO2 emissions.

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