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Article

Analysis of Mechanical and Thermal Performance and Environmental Impact of Flax-Fiber-Reinforced Gypsum Boards

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Abstract: Gypsum board is a building material known for its various qualities and functional characteristics, including its low density, fire resistance, thermal insulation, moisture regulation, and decorative appeal. However, it is important to consider the environmental aspects, as the production of one ton of gypsum board releases approximately 355 kg of CO₂ into the atmosphere. This research aims to reduce the carbon footprint while improving the mechanical and thermal properties of gypsum boards. To achieve this objective, flax fibers of three different lengths (12 mm, 24 mm, and 36 mm) were used to replace gypsum at a certain volume fraction. Incorporating up to 10% flax fiber effectively offsets the carbon footprint of gypsum boards. However, practical constraints related to the processing conditions and mechanical strength limited the addition of flax fiber to levels of 1%, 2%, and 3%. A 3% fiber incorporation gave us a more homogeneous mix with good workability, ensuring good mechanical performance and a 29% reduction in the carbon footprint. This study showed an improvement in flexural strength for flax-fiber-reinforced composites regardless of their length. In particular, the addition of 3% flax fiber (36 mm in length) showed the most significant increase in flexural strength, exceeding 438%. In addition, the mechanical behavior, including toughness, showed improvements over unreinforced gypsum. Flax fibers were found to be effective in bridging microcracks and limiting their propagation. Notably, all reinforced composites showed a decrease in thermal conductivity, resulting in a 47% improvement in thermal insulation with the addition of flax fibers.



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Keywords: gypsum board; carbon footprint; flax fibers; mechanical behavior; thermal conductivity

1. Introduction

Gypsum board is a material long used in the field of construction due to its multiple qualities and functional properties, such as its low density, fire resistance, thermal and sound insulation, hygrometry regulation of enclosures, and low production cost. However, gypsum board has high brittleness and low mechanical strength, which can limit its use in certain applications.

To address these performance deficiencies, some authors [1–9] have proposed reinforcing the gypsum matrix with synthetic fibers (glass, carbon, polyamide, polypropylene, etc.). This approach has the potential to increase the mechanical strength and toughness of a material. In general, the incorporation of fibers, whether natural or synthetic, into a mineral matrix can help improve post-crack behavior by limiting the formation and propagation of cracks in the material. This increases the durability and load-bearing capacity of the material [10–13]. However, the use of synthetic fibers in the gypsum matrix has several limitations. On the one hand, it is hampered by the high cost and significant environmental impact of synthetic fibers. On the other hand, synthetic fibers can sometimes exhibit limited adhesion due to chemical compatibility issues with the gypsum matrix. In addition, their high stiffness limits their ability to dissipate energy, which can reduce their effectiveness in reinforcing the material [1,3,4]. Furthermore, a life cycle analysis of gypsum board

shows a significant environmental impact, with 355 kg of carbon dioxide emitted into the atmosphere for every ton of gypsum board produced [14–16]. In the current context of climate change and environmental concerns, the use of plant fibers (flax, hemp, jute, etc.) in gypsum board production seems to be a promising solution to reduce carbon dioxide emissions into the atmosphere. Plant fibers come from a variety of sources, giving them different characteristics, especially in terms of density, mechanical strength, etc. [17].

Several experimental campaigns [18–30] have been carried out to study the mechanical behavior, especially the flexural behavior, of gypsum reinforced with plant fibers. The results show that the incorporation of plant fibers strengthens the gypsum, resulting in increases in flexural strength and load-bearing capacity. In addition, a post-cracking phase is observed, whereas it is absent in the case of unreinforced gypsum, which exhibits a sudden failure. For example, a study by Hamza et al. [23] investigated the mechanical behavior of a fiber/gypsum composite using fibers from alfa, rush stalks, and palm leaves. The results showed an increase in flexural strength from 4.8 to 5.6 MPa, representing a 17% improvement in the load-bearing capacity of the fiber-reinforced composites at a 5% fiber content. However, beyond a 5% fiber content (7% total), no further improvement was observed, and instead, a decrease in strength relative to the maximum value obtained at a 5% fiber content was observed. Similarly, Iucolano et al. [28] obtained a similar increase of about 14% in the flexural strength of gypsum reinforced with 2% abaca fibers. The reinforced composites exhibited ductile material behavior, confirming the effectiveness of plant fibers in bridging, and reducing the propagation of microcracks. The limit for fiber content was 3%, beyond which no further increase in strength or improvement in toughness was observed. In another study by Iucolano et al. [25], the addition of 2% short hemp fibers to the gypsum matrix resulted in a significant increase in flexural strength of 80%. When comparing these results to those mentioned above [23,28], it is important to note that the influence of fiber addition depends on key parameters such as the physical properties (length, fiber diameter, etc.) and mechanical properties of the fibers (tensile strength). Hernández-Olivares et al. [22] conducted an experimental study on the mechanical properties of gypsum reinforced with randomly blended sisal fibers. The results showed that unreinforced gypsum had the lowest flexural strength, measured at 4.8 MPa, while the reinforced composites showed flexural strengths ranging from 6.84 to 8.12 MPa, an increase of more than 50% with the addition of 3% fibers. Wool and coconut fibers of smaller dimensions (3 to 12 mm in diameter) were also used by Guna et al. [20] to reinforce gypsum boards. They reported that a 30% reinforcement with coconut and wool fibers resulted in a significant improvement in flexural strength, up to 90% higher than that of fibreless gypsum board. However, a progressive decrease in strength was observed beyond the 30% addition.

In studies involving the use of plant fibers in the gypsum matrix, most authors have used short fibers. However, Boccarusso et al. [26] recently presented an alternative approach to short fibers to improve the mechanical properties of gypsum boards by using hemp fabrics. Their results showed that the addition of 2% of fibers resulted in an increase of more than 90% in flexural strength compared to the reference gypsum boards.

There are a limited number of studies in the literature that have investigated the effect of incorporating plant fibers on the mechanical strength of gypsum board under high-temperature conditions. A recent study by Iucolano et al. [19] focused on the thermo-mechanical behavior of hemp-fiber-reinforced gypsum board. Gypsum board is commonly used in fire protection systems due to its fire-resistant properties. However, these materials are often exposed to high temperatures during fires, resulting in gypsum dehydration and cracking due to thermal shrinkage caused by the release of bound water molecules. The objective of this research was to investigate the effect of hemp fibers on the thermo-mechanical behavior of gypsum boards. The results showed that even at high temperatures, hemp fibers maintained their “crack bridging” effect between fractured surfaces, increasing the toughness of the gypsum and preventing brittle failure. For example, after 20 min of heating at 150 °C, the flexural strength of reference panels without fibers decreased

from 2.21 MPa to 0.79 MPa, a reduction of approximately 64%. In contrast, the flexural strength of the fiber-reinforced panels decreased from 2.26 MPa to 1.4 MPa, a decrease of 36%. Furthermore, with longer heating times (40 min) and exposure to higher temperatures (250 °C), all panels showed a convergence toward flexural strengths of 0.5 to 0.6 MPa. Hemp fibers, which primarily affect the crack phase, significantly improved flexural strength at high temperatures, indicating the improved fire resistance of the hemp-fiber-reinforced composite. Wang et al. [31] also investigated the fire behavior of gypsum boards reinforced with palygorskite (a natural fibrous clay), and glass fibers. The results showed that the addition of up to 30% by weight of palygorskite and 0.5% by weight of glass fibers to the gypsum resulted in an approximate 70% reduction in the flexural strength of the composite. However, fire resistance tests were promising, as the unreinforced gypsum boards exhibited the greatest cracking after 90 min of fire exposure. The presence of palygorskite and glass fibers effectively limited crack propagation in the reinforced gypsum boards.

Plant fibers are also known for their ability to regulate temperature due to their micro-porous structure and low thermal conductivity. They offer a sustainable and promising approach to reducing energy consumption and carbon footprints in the construction sector. Several studies have shown that the incorporation of natural fibers into a material improves the thermal insulation quality and reduces heat transfer. A study conducted by Charai et al. [32] focused on improving the thermal properties of gypsum board by adding short alfa fibers at varying rates of 2%, 4%, 6%, and 8%. The results showed that the addition of alfa fibers improved the thermal insulation quality by 34% and reduced the heat transfer by 26.9%, especially with an 8% addition of plant fibers to the gypsum matrix, compared to the reference board without fibers. The reduction in thermal conductivity was attributed to the increased porosity resulting from the substitution of gypsum with alfa fibers. Further increasing the fiber incorporation rate would further reduce the thermal conductivity, but there is an optimal rate due to constraints related to the workability and mechanical strength of the composite. In another study by Charai et al. [33], hemp fibers were used, and a 6% incorporation rate was found to be optimal, resulting in a 32% reduction in thermal conductivity from 0.53 to 0.36 W/m.K. Similarly, Pinto et al. [34] recently obtained similar results by incorporating 1% sisal fibers into gypsum, reducing the thermal conductivity by 21%, from 0.75 to 0.59 W/m.K.

Based on this brief overview of plant-fiber-reinforced gypsum, it is important to note that most studies have focused primarily on improving the mechanical and thermal properties without addressing the carbon footprint of the fiber-reinforced composite. The objective of this study is to evaluate the carbon footprint as well as the mechanical and thermal properties of flax-fiber-reinforced gypsum. Special emphasis will be placed on the effect of fiber length and incorporation rate on the mechanical and thermal performance of the fiber-reinforced gypsum composite.

2. Materials and Methods

2.1. Gypsum and Short Flax Fibers

The gypsum used in this study consists of semi-hydrated calcium sulfate type β , the chemical formula of which is $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$, obtained via high temperature grinding of gypsum without additives, which was supplied by Siniat (Avignon, France) of the Etex Building Performance Group.

Different lengths of flax fibers (Figure 1) were used in this research. These flax fibers were supplied by Teillage Vandecandelaere of the Depestele Group (Bourguebus, France). It is worth noting that the fibers remained unaltered, neither chemically nor biologically, throughout the course of this study, in accordance with environmental considerations.

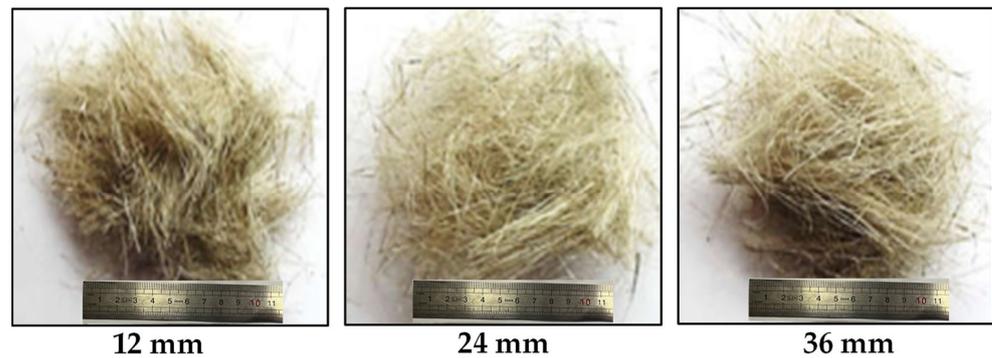


Figure 1. Flax fibers used in various lengths.

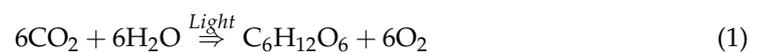
These flax fibers were used in a study by Page et al. [35], and their mechanical properties are reported in Table 1.

Table 1. Mean values of mechanical properties of flax fibers [35].

| | Mean | Standard Deviation |
|----------------------------|-------|--------------------|
| Diameter (μm) | 14.66 | ± 2.95 |
| Elasticity modulus (GPa) | 65.50 | ± 14.80 |
| Ultimate strain (%) | 1.86 | ± 0.60 |
| Tensile strength (MPa) | 1254 | ± 456 |

2.2. Environmental Impact: Assessment of the Carbon Footprint of Gypsum Board

As a first approach to this study, it was important to understand how plant fibers could reduce the carbon footprint of gypsum boards. Some data from the BA 13 Life Cycle Assessment (LCA) [14–16] were collected and used to quantify the mass of carbon dioxide that could be released into the atmosphere by fiber composites. This calculation is based on the establishment of mathematical equations derived from the equilibrium between the phenomenon of photosynthesis and the mass of carbon sequestered in a plant species. Photosynthesis is described using Equation (1):



It should also be remembered that the mass of carbon dioxide (Equation (2)) in a plant fiber depends on its carbon content (Table 2). Equation (2) can, therefore, be used to predict the mass of CO_2 that could be sequestered in a gypsum board.

$$m_{\text{CO}_2} = m_{\text{dry}} \times \frac{\%C}{100} \times \frac{M_{\text{CO}_2}}{M_C} \quad (2)$$

where:

M: molar mass;

%C: carbon content (%);

m_{dry} : dry mass of plant fibers;

m_{CO_2} : mass of sequestered carbon dioxide.

Table 2. Carbon content of selected plant fibers.

| Plant Fibers | Cellulose (%) | Hemicellulose (%) | Pectin (%) | Lignin (%) | Carbon Content (%) |
|--------------|---------------|-------------------|------------|------------|--------------------|
| Hemp | 77.7 | 10 | 2.9 | 6.8 | 43.749 |
| Flax | 92 | 2 | - | 4 | 43.92 |

Figure 2 shows the variation in the carbon footprint of gypsum boards as a function of the amount of flax fiber incorporated into the gypsum matrix. It is important to note that the carbon footprint of gypsum board with a 10% flax fiber incorporation is almost zero. It is, therefore, necessary to verify the experimental feasibility of producing gypsum boards with 10% flax fibers. This approach to reducing CO₂ by adding plant fibers is a form of compensation, i.e., it does not reduce the amount of CO₂ released in the production of the gypsum board, but by promoting the use of plants, the amount of CO₂ in the atmosphere is reduced. A series of preliminary tests have identified the limits of production under the conditions of improved workability. The incorporation rate, dimensions, and microscopic nature of the plant fibers into the gypsum matrix have an unfavorable effect on the workability of the reinforced gypsum composite. In fact, the higher the incorporation rate and the longer the fibers, the lower the workability [35]. This reduction in workability leads to heterogeneity in the composite, with an uneven distribution of fibers. In addition, the performance (mechanical or thermal) of composites depends on the quality and distribution of the fibers in the matrix. As a result, a limit of 3% of fiber incorporation allowed us to obtain a more homogeneous mix with good workability, ensuring good mechanical performance and a 29% reduction in carbon footprint.

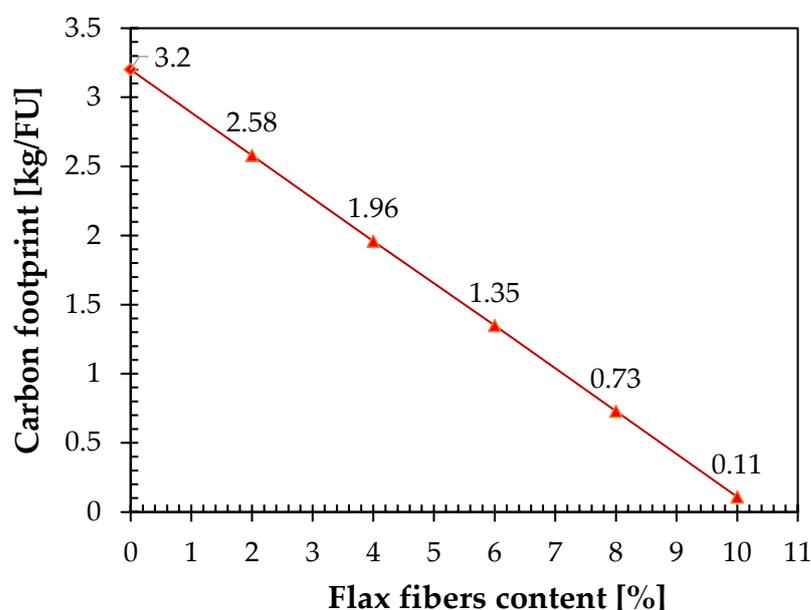


Figure 2. Evaluation of the carbon footprint of flax-fiber-reinforced gypsum board.

2.3. Production of Fiber-Reinforced Gypsum Composites

The mixture is mainly based on the water/gypsum ratio (w/g). The density of the flax fiber particles used is 1302 kg/m³. The flax fibers were used as a volume fraction of the gypsum matrix. Considering the high absorbency of plant fibers, the addition of flax fibers has a great influence on the homogeneity and workability of the mixture. As mentioned in the previous paragraph, fiber entanglements have been observed in some preliminary production processes. For this reason, the fiber incorporation rate was set at 1, 2, and 3%. To produce the different specimens, the mixing is performed manually, as follows:

1. Add the gypsum to the mixing water (water to gypsum weight ratio = 0.8), and allow it to soak for a few seconds (approximately 30 s);
2. Mix the mixture by hand using a whisk or spatula for 30 s;
3. Gradually introduce the plant fibers manually while continuing to mix for an additional 60 s.

The mixture was cast into prismatic molds of $40 \times 40 \times 160 \text{ mm}^3$ (Figure 3) and compacted with a conventional vibration table for about 30 s, according to the guidelines of BS EN 13279-2 [36]. These samples were demolded after 24 h and stored in a climatic chamber at a temperature of $20 \text{ }^\circ\text{C}$ (RH = 50%). Finally, the samples were dried for 48 h, at $50 \text{ }^\circ\text{C}$ (RH = 50%) before being tested. All compositions of the gypsum composites are reported in Table 3.



Figure 3. Sample preparation.

Table 3. Sample type composition.

| Samples | | | Volume Fraction of Fibers (%) | Gypsum (g) | Fibers (g) | Water (g) | W/C (C = Gypsum + Fibers) |
|--------------|----------|----------|-------------------------------|------------|------------|-----------|---------------------------|
| Fiber Length | | | | | | | |
| 12 mm | 24 mm | 36 mm | | | | | |
| GRF_12_1 | GRF_24_1 | GRF_36_1 | 1 | 228.1 | 3.33 | 185.14 | 0.8 |
| GRF_12_2 | GRF_24_2 | GRF_36_2 | 2 | 225.79 | 6.66 | 185.97 | 0.8 |
| GRF_12_3 | GRF_24_3 | GRF_36_3 | 3 | 223.49 | 10 | 186.79 | 0.8 |
| | GB_REF | | 0 | 230.4 | 0 | 184.32 | 0.8 |

2.4. Mechanical Characterization

Studies have demonstrated the excellent tensile strength of plant fibers. However, due to the brittleness of the mineral matrix, it is difficult to evaluate the improved strength of fiber-reinforced composites using pure tensile tests. Therefore, three- or four-point flexural tests are more practical to characterize their mechanical properties. According to BS EN 13279-2 [36], a three-point flexural test is required for gypsum. However, this test only provides maximum stress at mid-span, which can sometimes overestimate the flexural strength of the reinforced composites and only partially reflect the behavior of the composite. For this reason, a four-point flexural test, which maintains a constant moment between the two upper support points, was used to study the mechanical behavior of different samples.

The four-point flexural test was carried out over 7 days on three prismatic samples ($40 \times 40 \times 160 \text{ mm}^3$) in accordance with standard BS EN 12390-5 [37], using a Zwick/Roell electromechanical press (Figure 4) equipped with a 50 kN calibre load cell, the displacement of which was controlled at a load speed of 1 mm/min.



Figure 4. Flexural test setup.

To measure the flexural modulus according to UNE EN ISO 14125 [38], it is necessary to calculate the deflections s' and s'' (expressed in millimeters) of the specimen at its center corresponding to the given values of flexural deformation $\varepsilon_{f'}$ = 0.0005 and $\varepsilon_{f''}$ = 0.0025 using Equation (3):

$$s' = \frac{\varepsilon_{f'} L^2}{4.7h} \text{ and } s'' = \frac{\varepsilon_{f''} L^2}{4.7h} \quad (3)$$

where:

L is the length, in mm, of sample;

h is the thickness, in mm, of sample;

s' and s'' are the deflections in mm of the center sample;

$\varepsilon_{f'}$ and $\varepsilon_{f''}$ are the flexural strains, the values of which are given above.

The flexural modulus (E_{elast}) is given by Equation (4):

$$E_{\text{elast}} = \frac{0.21L^2}{bh^3} \left(\frac{\Delta F}{\Delta s} \right) \quad (4)$$

where:

E_{elast} in MPa;

L is the length, in mm, of sample;

b is the width, in mm, of sample;

h is the thickness, in mm, of sample;

Δs is the change in deflection between s' and s'' ;

ΔF is the change (in N) in force between F'' for deflection s'' and F' for deflection s' .

For a more detailed analysis of the mechanical behavior of reinforcing gypsum, the ductility factor (Equation (5)) is calculated as the ratio of the ultimate displacement to the elastic displacement.

$$\mu = \frac{d_{\text{max}}}{d_{\text{elast}}} \quad (5)$$

where:

μ is the ductility factor;

d_{elast} is the elastic zone displacement (mm);

d_{max} is the maximum displacement (mm).

2.5. Thermal Conductivity Characterization

Thermal conductivity is the ability of a material to conduct or dissipate heat in a given environment. In the context of this study, the thermal conductivity of various samples was experimentally determined using the hot-wire method. This method is carried out using an FP2C device, manufactured by NEOTIM, and adheres to the ASTM D5930-97 standard [39]. In this method, a resistive wire, typically composed of platinum, is employed as both a heating element and a temperature sensor. This wire is subjected to a constant power supply, and an analysis of the resulting thermogram provides the means to calculate the thermal conductivity of the material being examined. The process of measurement unfolds as follows:

1. Positioning of the hot-wire sensor: The hot-wire sensor, also referred to as the conductivity meter, is carefully placed between two identical samples, as visually depicted in Figure 5.
2. Thermal stabilization: Following this placement, a period of thermal stabilization ensues, typically lasting 2 to 3 min. This phase allows the system to reach an equilibrium temperature.
3. Heating through electric current: Once stabilization is achieved, a direct electric current is applied to heat the samples through the hot-wire sensor.
4. Data acquisition: Subsequently, the integrated data acquisition software within the FP2C device records the value of the thermal conductivity of the material.

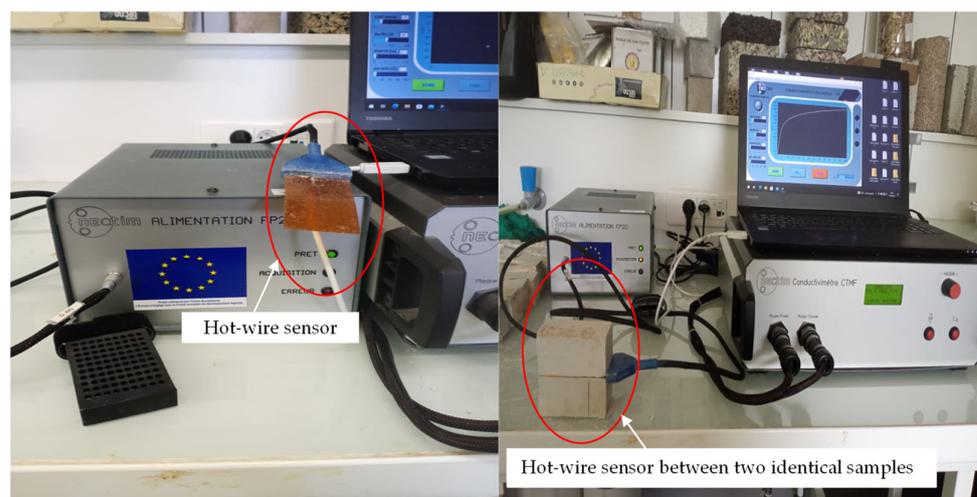


Figure 5. Experimental setup of hot-wire method.

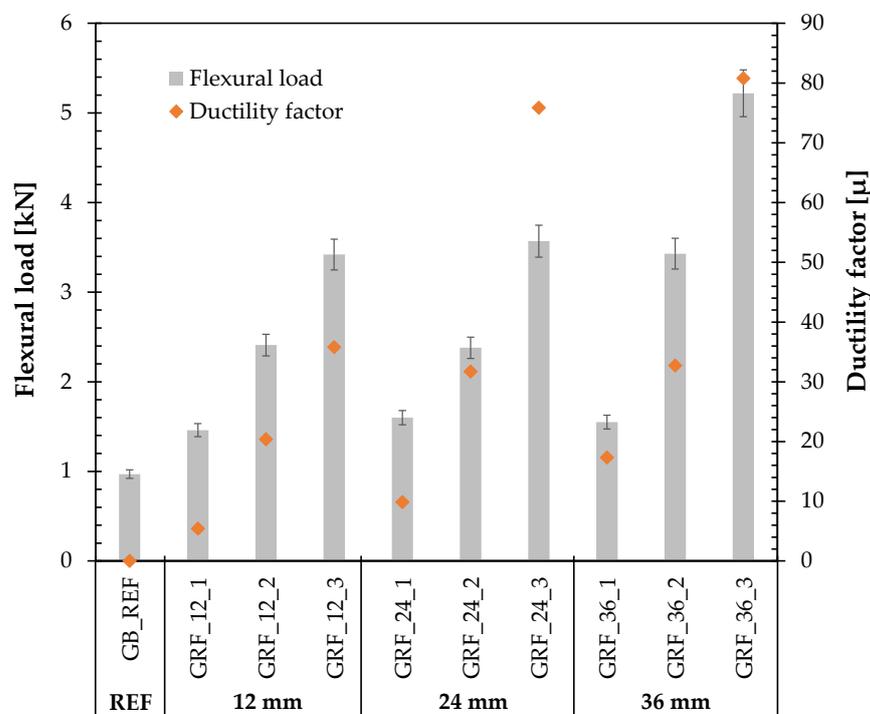
3. Results and Discussion

3.1. Flexural Strength Response

Studies of composites containing plant fibers show a change in the mechanical behavior of the composite. The different compositions and mechanical parameters studied in the development of flax-fiber-reinforced gypsum composites are summarized in Table 4. Figure 6 shows the flexural load data for the flax-fiber-reinforced gypsum composites. The reference gypsum shows the lowest load with a value of 0.97 kN compared to the flax-fiber-reinforced gypsum composites. It is important to note that the incorporation of flax fibers significantly improved the mechanical properties of the gypsum composites. For example, the addition of 2% 12 mm flax fibers resulted in an increase in load capacity of approximately 148% compared to the reference gypsum.

Table 4. Mean values of mechanical properties.

| Fiber Length | Sample | Fiber Rate (%) | F_{max} (kN) | E_{elast} (GPa) | Ductility Factor (μ) |
|--------------|----------|----------------|-----------------|-------------------|----------------------------|
| Reference | GB_REF | 0 | 0.97 ± 0.81 | 1.48 ± 0.70 | - |
| 12 mm | GRF_12_1 | 1 | 1.46 ± 0.45 | 1.16 ± 0.21 | 5.45 ± 1.10 |
| | GRF_12_2 | 2 | 2.41 ± 1.03 | 0.90 ± 0.40 | 20.40 ± 2.50 |
| | GRF_12_3 | 3 | 3.42 ± 1.50 | 0.63 ± 0.34 | 35.80 ± 3.21 |
| 24 mm | GRF_24_1 | 1 | 1.6 ± 0.90 | 1.02 ± 1.10 | 9.86 ± 0.89 |
| | GRF_24_2 | 2 | 2.38 ± 1.10 | 0.96 ± 0.53 | 31.72 ± 5.30 |
| | GRF_24_3 | 3 | 3.57 ± 0.78 | 0.70 ± 0.29 | 75.89 ± 12.40 |
| 36 mm | GRF_36_1 | 1 | 1.55 ± 0.64 | 1.25 ± 1.00 | 17.32 ± 4.17 |
| | GRF_36_2 | 2 | 3.43 ± 1.10 | 0.91 ± 0.60 | 32.74 ± 6.20 |
| | GRF_36_3 | 3 | 5.22 ± 1.6 | 0.61 ± 0.30 | 80.8 ± 20.45 |

**Figure 6.** Mean values of the flexural strength and ductility factor for each sample type.

Furthermore, it is important to note that the mechanical performance of these composites depends on both the fiber length and the content of flax fiber incorporation. On the one hand, for the same content of flax fiber incorporation, the greater the fiber length, the greater the improvement in flexural load [27,35,40]. For example, at a 3% flax fiber incorporation, the flexural load increases are 250%, 270%, and 430% for fibers 12, 24, and 36 mm in length, respectively, compared to the reference gypsum. On the other hand, for the same fiber length, an increase in fiber incorporation results in a significant improvement in flexural load. For example, with 36 mm long fibers, the increase in flexural strength is 86%, 254%, and 438%, respectively, compared to the reference gypsum for incorporation contents of 1%, 2%, and 3% flax fiber. The increase in flexural load with the increasing length and rate of fiber incorporation can be explained in several ways. First, as the length and rate of fiber incorporation increase, the flax fibers have a greater ability to effectively distribute loads over a larger surface area, thereby increasing the flexural load of the composite. This increase in fiber length provides a larger contact surface area with the matrix, allowing for

better interaction between the fibers and the matrix. This increased interaction between the fibers and the matrix improves cohesion, allowing for more efficient load transfer and increased resistance. Second, longer plant fibers can have superior intrinsic mechanical properties, such as greater strength and stiffness. These intrinsic fiber properties help to increase the flexural load of the composite in which they are incorporated. In addition, longer fibers can be more efficiently oriented and arranged in the direction of principal stresses (horizontal in this study), thereby optimizing the utilization of their tensile capacity. This fiber arrangement improves the ability of the composite to withstand flexural load. The results of this study are consistent with the findings of other researchers. For example, Iucolano et al. [25] obtained similar results by adding 2% hemp fiber to a gypsum composite, resulting in an increase of approximately 80% in the flexural strength of the gypsum material. Similarly, Boccarusso et al. [26] observed an increase of approximately 90% compared to the reference gypsum by adding 2% hemp fabrics.

In addition to the observed improvement in flexural load, the presence of flax fibers also affected the stiffness of the various gypsum composites. An analysis of the flexural modulus (Figure 7) of the composites showed a significant reduction in this parameter. It is important to note that the flexural modulus decreases with increasing fiber content and fiber length, contrary to what was observed for flexural load. This reduction in stiffness can be explained by the increased porosity of the reinforcing composite induced by the addition of the flax fibers. As a result, the reference gypsum is stiffer than the reinforced gypsum. Other researchers [28–30,40] have also shown that the presence of plant fibers in a mineral matrix leads to a reduction in the elastic modulus of the material.

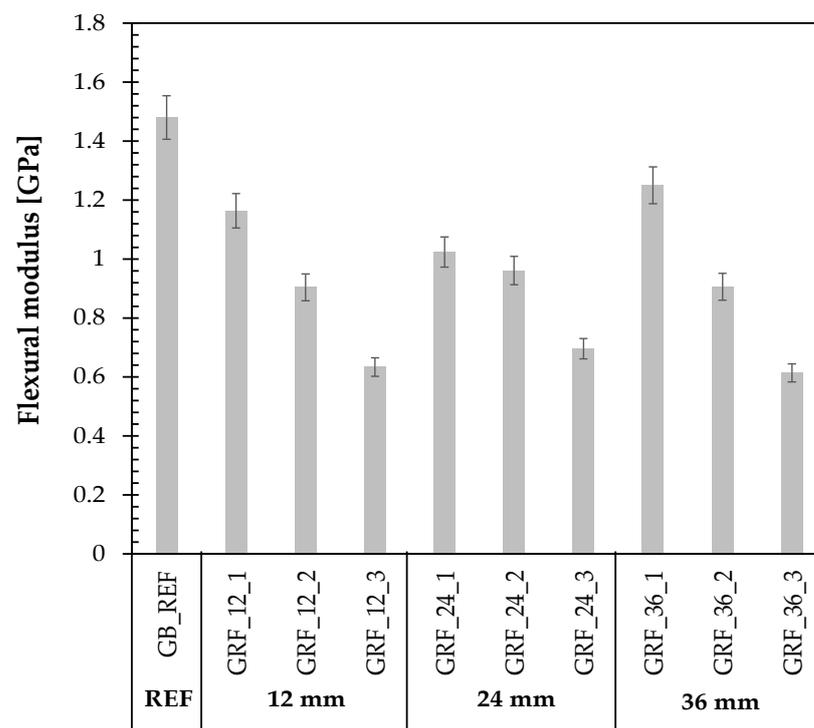


Figure 7. Mean values of the flexural modulus for each sample type.

3.2. Flexural Behavior of Each Sample Type

The representative curves of the flexural behavior of the various specimens produced are shown in Figure 8. The reference specimen exhibited brittle elastic behavior (Figure 8a), followed by sudden failure. This brittle failure (Figure 9a) is due to the instantaneous propagation of cracks, resulting in a net failure of the material, which is characteristic of a brittle, non-ductile material. In contrast, the flax-fiber-reinforced composites exhibited plastic material behavior with a post-cracking phase. It is important to note that the post-

cracking behavior is strongly influenced by the presence of flax fibers. The appearance of this phase can be explained by the fibers absorbing forces greater than the ultimate load of the reference gypsum matrix (i.e., the appearance of the first crack).

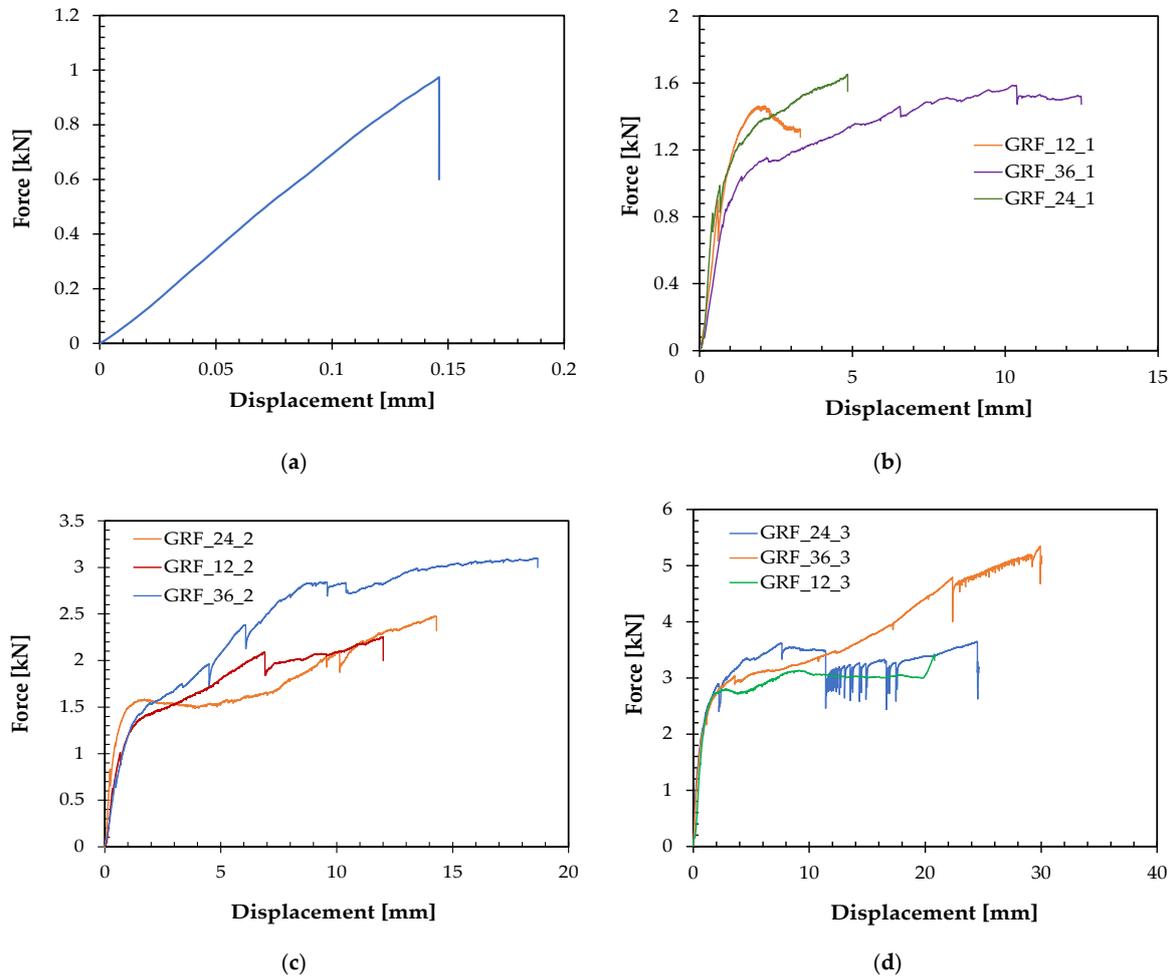


Figure 8. Mechanical behavior for each sample type as a function of flax fiber content: (a) 0% (reference gypsum; (b) 1%; (c) 2%; (d) 3%.

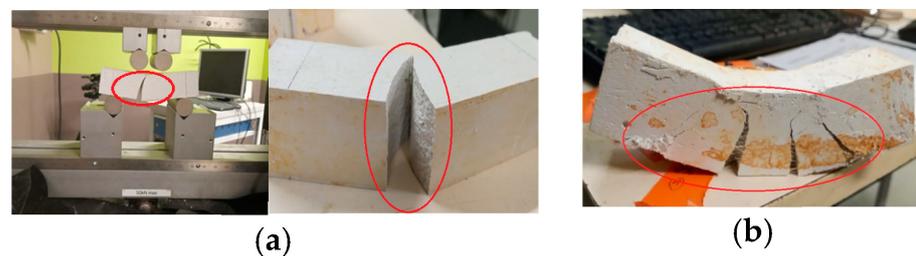


Figure 9. Failure mode. (a) Reference gypsum, (b) reinforced gypsum.

In fact, three distinct phases can be identified in the behavior of the reinforced composites, as is generally the case with fibrous mineral matrices. A typical response describing the flexural behavior of a fibrous mineral matrix is shown in Figure 10, where I, II, and III represent the extent of the three phases. Phase I, which has no cracks, is characterized by a linear elastic behavior similar to that of the reference gypsum. This phase defines the mechanical properties of the matrix. It should be noted that in Phase I, the stiffness of the reinforced composite is lower than that of the reference gypsum, as mentioned above. It is also important to note that the strength of the reinforced composite at the appearance of

the first crack is lower than that of the reference gypsum. This decrease can be explained by the amount of water used in the preparation of the reinforced composite, which is higher than that of the reference gypsum. An increase in water content can increase the porosity of a mineral matrix. This increased porosity reduces the compactness of the composite, thereby compromising the ability of the mineral matrix to withstand loads. The increase in the amount of water is due to the fact that, in the ratio $W/C = 0.8$, the variable C represents the total weight of the gypsum, including the weight of the fibers added. The increase in the weight of C has led to an increase in the amount of water used in the preparation of the reinforced composite, which has modified the mechanical properties of the reinforced composite matrix compared to those of the reference matrix.

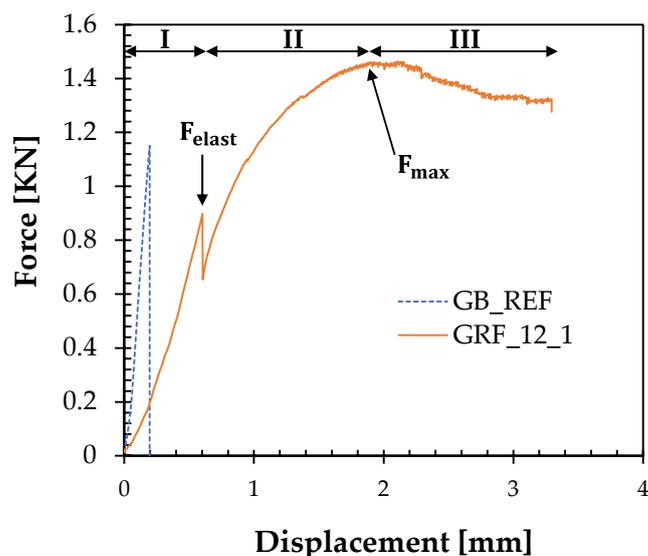


Figure 10. Different zones of flexural behavior in reinforced gypsum composites.

The appearance of the first crack in the matrix, starting at F_{elast} (Figure 10), marks the beginning of Phase II, followed by the formation of multiple cracks (Figure 9b). Stress transfer occurs from the matrix to the fibers. The bond between the gypsum matrix and the plant fibers, as well as the reinforcement ratio, determine the extent of Phase II. The cracks generated are hindered by the presence of the fibers, thus limiting their propagation. This result can be explained by the effectiveness of the flax fibers in bridging microcracks, inducing a controlled failure of the composite, in contrast to the sudden failure observed in the reference gypsum. The decrease in load from F_{max} (Figure 10) marks the start of Phase III, followed by the progressive failure of the reinforced composite associated with interfacial failure between the fibers and the matrix [28]. The incorporation of flax fibers into the gypsum matrix has allowed the transition from a brittle matrix to a ductile fiber-reinforced composite with controlled post-cracking behavior. This transition is due to the effect of the flax fibers in limiting crack propagation and contributing to the overall ductility of the material.

The crack width, number, and spacing depend mainly on the length and incorporation rate of the flax fibers. The failure mode of the 24 and 36 mm fiber-reinforced composites is controlled by fiber failure, while the failure mode of the 12 mm fiber-reinforced composites is characterized by fiber delamination [40,41]. This difference in failure mode can be explained by micromechanical phenomena that create variations in load distribution along the fiber–matrix interface. In addition, side effects may be negligible for long fibers but can be significant for short fibers. It is important to note that the longer the fiber and the higher the incorporation rate, the more ductile (Figure 6) and stable the failure. For example, at a 3% flax fiber incorporation rate, the ductility factors of the reinforced composites are 35, 76, and 81 for fibers 12, 24, and 36 mm in length, respectively. Similarly, at a 36 mm fiber length, the ductility factors of the reinforced composites are 17, 32, and 81 for incorporation rates of 1%, 2%, and 3% flax fiber, respectively.

In analyzing the influence of the incorporation rate and length, it is pertinent to discuss energy dissipation, which reveals a material's ability to resist large loads beyond its elastic limit. This energy dissipation is determined by calculating the area under the vertical load–displacement curve in the post-peak phase. Unreinforced gypsum shows almost zero energy dissipation, which is characterized by the absence of the post-peak phase (Figure 8a). In contrast, flax-fiber-reinforced gypsum shows an increasing capacity for energy dissipation with increasing incorporation rates and fiber lengths (Figure 8a–d).

In the case of gypsum boards, it is more appropriate to talk about toughness rather than energy dissipation. Increased toughness is a positive and beneficial aspect of gypsum board fastening resistance. This means that composites reinforced with flax fibers have a greater capacity to resist high loads beyond their elastic limit, which can improve their performance in applications such as gypsum board fastening.

3.3. Thermal Conductivity Values

Figure 11 shows the values obtained in the thermal conductivity test for the different flax-fiber-reinforced composites, including the reference gypsum. An analysis of these results showed that the reference gypsum had the highest thermal conductivity. The incorporation of flax fibers into the gypsum matrix was critical in reducing the thermal conductivity of the reinforced composites. For example, the addition of 3% flax fiber reduced the thermal conductivity from 0.256 to 0.174 W/m.K, representing a 50% reduction in the heat transfer index and a 47% improvement in thermal insulation. The reduction in thermal conductivity is due to the microporous structure of the plant fibers and their low thermal conductivity. In addition, the homogeneous distribution of flax fibers in reinforced gypsum helps distribute heat more evenly throughout the material, thus reducing thermal conductivity. This combination reduces heat transfer through the material, helps create zones of higher thermal resistance, and improves thermal insulation. This absence of an effect of fiber length on thermal conductivity can be explained by the fact that the flax fibers used have identical physicochemical properties. However, the thermal performance depends on the fiber incorporation rate, such that the higher the fiber incorporation rate, the lower the thermal conductivity of the composite [32–34]. It is also worth remembering that the addition of plant fibers reduces heat diffusion, which can be very effective for the thermal regulation of buildings.

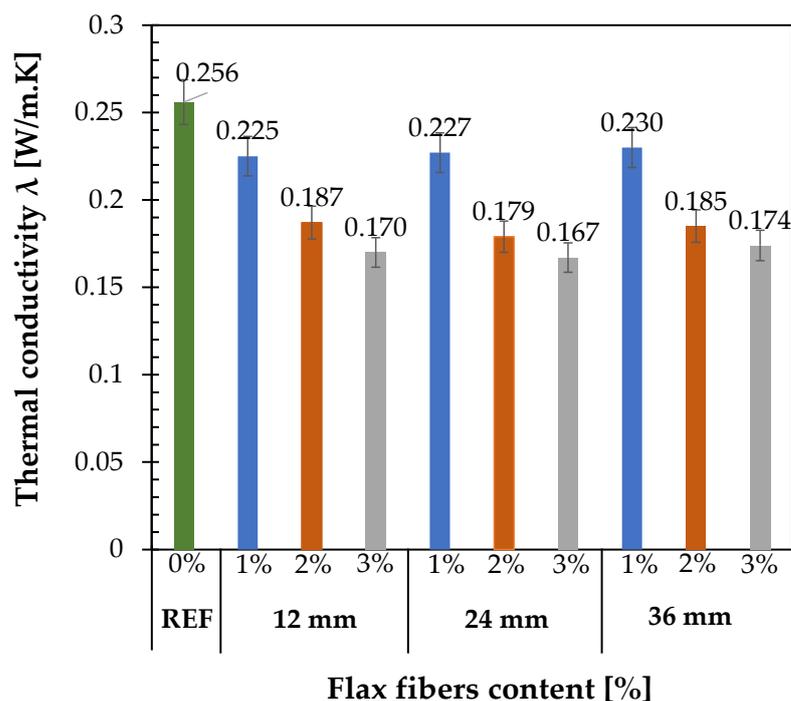


Figure 11. Mean values of the thermal conductivity for each sample type.

4. Conclusions

In this study, the environmental impact and the thermal and mechanical properties of flax-fiber-reinforced gypsum composites were evaluated. The results indicate that the addition of flax fibers to the gypsum matrix provides a means of improving the thermal and mechanical performance of gypsum boards while preserving the environment. It also expands the possible applications of these composites in the construction sector.

Based on the results obtained for the various key parameters evaluated, the following conclusions can be drawn:

- Flax fibers are renewable and biodegradable resources that can help reduce the overall environmental impact of gypsum composites. This is particularly important in the context of sustainability. For example, incorporating 3% flax fiber into the gypsum matrix can reduce the carbon footprint of gypsum boards by 29%, thus offsetting some of the carbon emissions generated during its life cycle.
- The addition of flax fiber changes the composition of the gypsum, which may require adjustments to the manufacturing process. This can result in additional costs and technical challenges. The incorporation of flax fibers into gypsum significantly reduces the workability of fresh composites. This loss of workability in the composite mix is attributed to the high water absorption capacity of plant fibers due to their high specific surface area. In addition, as the incorporation rate of flax fibers increases and the fibers become longer, the workability is further compromised. It is important to note that, the performance of the composite depends on the quality and uniform distribution of the fibers in the matrix. Inhomogeneous fiber distribution can lead to variations in material properties, particularly mechanical properties. However, improvements in the manufacturing process can increase the rate of incorporation of plant fibers into the gypsum matrix.
- Flax fibers significantly improved the mechanical properties of the gypsum, resulting in increased flexural strength and load-bearing capacity. Flexural tests demonstrated the effectiveness of the flax fibers in bridging microcracks, as well as their ability to reduce their propagation, thus avoiding sudden failure, as observed in the reference gypsum. In fact, the reinforced gypsum exhibited ductile behavior with progressive, controlled failure, resulting in increased toughness. Flax-fiber-reinforced composites have a greater ability to withstand high loads beyond their elastic limit, which can improve their performance in certain applications, such as gypsum board fasteners.
- The mechanical performance of the reinforcing gypsum depends on the length and incorporation rate of the flax fibers. Thus, the longer the fibers, the better the flexural properties (flexural strength, toughness, crack propagation, etc.) of the composite. Therefore, the addition of 3% flax fiber with a length of 36 mm resulted in the best mechanical performance, with a ductility factor of 81 and an increase in flexural strength of 438%.
- Gypsum composites reinforced with flax fibers have a lower thermal conductivity than the reference gypsum, which translates into better thermal insulation. It is important to note that the variation in thermal conductivity is not influenced by the length of the fibers, but rather by the incorporation rate of these fibers. In other words, the higher the fiber content, the lower the thermal conductivity of the composite. For example, the addition of 3% flax fiber resulted in an approximate 47% reduction in thermal conductivity. This improvement in thermal insulation can help reduce heat loss in building applications.

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