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Development and Characterization of Innovative Hemp–Gypsum Composites for Application in the Building Industry

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Abstract: At present, the development of new eco-friendly building materials for the production of lightweight partitions has become a challenge in order to advance towards the industrialization of the building sector. This work aims to design, characterize, and analyze the possibilities of applying innovative ecological gypsum composites lightened with hemp. To achieve this, samples have been prepared with partial replacement of 15% and 30% in volume of the original gypsum material by adding hemp both in the form of powder and fiber. The results show how the replacement of 15% of gypsum by hemp fiber with a length between 8 and 12 mm improves the flexural strength of the composites. Likewise, all the dosages prepared for this study have met the minimum requirements for mechanical strength required by current regulations, while also improving the water resistance behavior of gypsum composites. However, the main advantage derived from the use of these hemp-lightened gypsum-based materials lies in their reduced thermal conductivity, being up to 50% lower than that obtained for traditional materials. These results suggest the possible application of these materials to produce prefabricated boards and panels for a more sustainable construction.

Keywords: lightweight gypsum composites; plant-based additions; hemp; innovative plasterboards; sustainable building

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1. Introduction

Currently, Spain ranks as the seventh largest gypsum producer worldwide, with an outcrop area of 21,700 km^2, representing approximately 4.2% of the national territory [1]. As a consequence of this abundance, gypsum is a widely used material in the building sector, and it is employed for plastering, the production of prefabricated elements, or as interior coating, among other applications [2]. Additionally, it is one of the construction binding materials with a lower environmental impact in terms of its manufacturing process [3]. This, combined with its straightforward recycling process, makes it a material with a high added value to enhance circular economy strategies in construction [4]. For this reason, in recent decades, the application of gypsum composite materials has proliferated in the prefabrication process due to their versatility, ease of assembly, and the reduced amount of waste generated during their installation [5].

However, one of the major challenges for researchers today is undoubtedly to design gypsum-based products that incorporate secondary raw materials and present an optimal relationship between the mechanical and thermal properties of the produced composites [6]. While gypsum materials are known for their excellent hygrothermal regulation capacity and cost-effectiveness [7], the inclusion of recycled raw materials in the production process of new prefabricated elements generally worsens the mechanical behavior of the original material [8]. This leads to the implementation of strategies to mitigate this effect, such as the incorporation of reinforcing fibers or the adjustment of the water-to-gypsum ratio by means of additives, allowing for the improvement of the prefabricated material's ductility and the optimal growth of dihydrate crystals, respectively [9,10].

In this work, we advocate for the use of hemp additions as a substitute for the original plaster material, aiming to develop environmentally friendly composites that are more cost-effective and meet regulatory requirements [11]. The basic components that impart properties to these natural fibers are cellulose, hemicellulose, and lignin [12]. However, it has to be taken into account that the application of surface treatments using alkaline composites, silanes, acetylenes, or peroxides has demonstrated its beneficial effects in other research works to improve the durability and moisture resistance of these composites [13–15]. Some of the studies carried out by different researchers involving gypsum composites and plant additions are schematically presented in Table 1.

Table 1. Schematic literature review on studies covering gypsum composites and plant additions.

Reference	Binder	Plant Addition	Most Relevant Results of the Study
[16]	Gypsum	Abaca fibers 1–2–3% by weight (wt.)	Three treatments were applied to the abaca additions: (a) distilled water for 24 h at 20 °C, (b) sodium hydroxide (NaOH), and (c) ethylene diamine tetraacetic acid (EDTA), without affecting the setting time of the gypsum composites. The addition of 2% wt. yielded the best results in the flexural strength test.
[17]	Gypsum	Wheat residues 0–2.5–5–7.5–10% wt.	The progressive substitution of gypsum material with wheat residues reduced the mechanical strengths of these composites. However, its use is feasible in the interior of buildings with low humidity, as it exhibits a good thermal and acoustic performance.
[18]	Plaster	Sisal fibers 0–0.52–0.78–1.04% by volume (vol.)	The best flexural strength results were obtained for fibers with a length of 120 mm and 0.78% substitution by volume, experiencing greater deformation capacity.
(a) [19] and (b) [20]	Plaster	Cork aggregates (a) 6–20% wt. (b) Cork/Plaster ratio 0.025–0.05–0.075–0.1–0.15–0.2% wt.	(a) Prefabricated gypsum and cork elements were designed, demonstrating excellent ductility with good buckling and bending resistance. They are suitable for use as partition walls. (b) Lightweight composites with thermal conductivity ranging from 0.46 to 0.168 W/m·K suitable for non-structural applications were obtained.
[21]	Plaster	Wood–Cereal Straw 0–5–10–15–20% (vol.)	The incorporation of these plant residues enables the production of lightweight gypsum composites with low thermal conductivity and low effusivity, making them competitive with traditional materials.
[22]	Plaster	Alfa fibers 0–1–2–3–4% wt.	The random fiber distribution in the composites led to a reduction in thermal conductivity, allowing the production of prefabricated elements with ductile fracture, albeit with a lower flexural strength.
[23]	Plaster	Jute fabrics 0.1–0.2% wt.	Jute fabrics embedded in the plaster matrix were used to enhance the ductility and toughness of the composites subject to bending and compression, making them suitable for the production of prefabricated elements.
[24]	Gypsum	Rice husk and coir fiber 10–20–30% wt.	The produced composites exhibited an excellent thermoacoustic performance, with good flexural strength and a lower environmental impact due to the reduction in the consumption of traditional gypsum.
[25]	Gypsum	Date palm fibers 0–5–10–15–20% wt.	A significant improvement in thermal properties was achieved by adding date palm fibers to gypsum. This allowed for a reduction in the overall energy consumption of buildings constructed with these composites, as demonstrated in the theoretical simulations that were conducted.

After analyzing Table 1, it has been observed that the incorporation of plant-based additions into the matrix of gypsum composites has a positive impact on reducing their thermal conductivity [17,20,21]. This effect contributes positively to enhancing the energy efficiency of buildings, which has boosted their application in the development of lighter, ecological, and sustainable prefabricated boards and panels [26]. On the other hand, in the case of plant-based raw materials added in the form of reinforcing fibers, several authors have achieved an improvement in the flexural strength of gypsum composites [23,24]. Additionally, due to the effective integration between the plant-based fibers and the gypsum or plaster matrix, an enhancement in the ductility of the composites appears, preventing brittle fracture [22].

Hemp fibers, on the other hand, have been employed for over 1000 years as reinforcement material in construction [27]. This plant of Asian origin has become one of the most attractive to the industry today due to its low cost, good mechanical properties, and high cellulose content [28]. Additionally, its ease of cultivation and rapid growth have enhanced its industrial exploitation, driven by its positive life cycle assessment [29]. One of the most widespread current applications of this material is in hemp–lime mortars, developed in France as a result of a mixture of hemp and an air lime binder. These are used as high-performance hygrothermal filler and coating materials [30]. Hemp has also been employed as a reinforcement material in cement mortars, where an improvement in mechanical properties has been observed when adding around 2–3% by weight of 12 mm-long hemp fiber [31]. Finally, it is worth noting hemp's application as an additive in the development of eco-friendly concretes, enhancing their thermoacoustic properties and durability and making them ideal for the production of prefabricated blocks [32].

Several authors have conducted research by using hemp additions in the development of gypsum composites for building. Boccarusso et al. conducted a research study with hemp fabrics embedded in the gypsum matrix for prefabricated design, achieving flexural strengths that doubled those of gypsum without additions [33]. Babu and Ratnam conducted a study with hemp fibers of varying lengths and proportions. They found that an addition of 12% by volume of 15 mm fibers improved the final flexural and compressive strength of the composites while enhancing their thermal properties [34]. This effect was also observed by Iucolano et al., who demonstrated in their research how hemp fibers are an economically and environmentally sustainable substitute for fiberglass in the production of gypsum boards [35]. Additionally, these authors conducted another study with hemp fibers in gypsum composites subject to high temperatures, confirming the beneficial effect of these additions in increasing the toughness of gypsum prefabricated elements and preventing brittle collapse [36]. Several studies have highlighted the advantages of adding hemp material to improve the fire behavior of prefabricated blocks [37], emphasizing the effective integration between the additions of this plant-based compound and the gypsum composite matrix [38].

The main objective of this research is to develop innovative plaster materials with two different hemp additions and subsequently carry out a physical–mechanical characterization of these composites. Hemp incorporation is considered as a partial replacement for traditional plaster material at two volume percentages, namely 15% and 30%. Additionally, the feasibility of these eco-friendly materials for the production of prefabricated panels is analyzed, exploring their potential application in the construction of partitions and interior linings in homes. To achieve this, an experimental campaign with these materials is accomplished, covering three key aspects: mechanical characterization, the study of water behavior, and prefabrication tests and discussion of their potential applications.

2. Materials and Methods

This section provides a description of the raw materials used and the manufacturing process of the developed plaster composites, as well as an overview of the experimental program conducted in this research.

2.1. Materials

The raw materials used for the completion of this work include fine gypsum, water, and hemp additions.

As the binding material, a construction-grade gypsum type B1 has been utilized, following the classification of the EN 13279-1:2009 standard [39]. This type of gypsum has been successfully employed in various recent studies [40,41], and it possesses the following properties as detailed in Table 2, according to the manufacturer Saint Gobain Placo Ibérica S.A. (Madrid, Spain) [42].

Table 2. Characteristics of the gypsum binding material.

Purity Index [%]	Fire Reaction	Flexural Strength [MPa]	Compressive Strength [MPa]	pH	Water Vapor Diffusion (μ)	Granulometry [mm]
80	A1	>1	>2	>6	6	0.0–0.2

In order to mix the designed gypsum composites, tap water from the Canal de Isabel II (Madrid, Spain) has been used, following the guidelines of Council Directive 98/83/EC [43].

The two types of hemp additions used in this research are detailed in Figure 1. The powdered fraction has a particle size ranging from 0 to 2 mm, and the fibers have a length between 8 and 12 mm. The hemp material used belongs to the subspecies *cannabis sativa* and was extracted from the stalk of this plant, whose organic composition is cellulose (57–77%), hemicellulose (14–22.4%), lignin (3.7–13%), ash (0.8%), and wax (0.8%). Prior to their use, they were cleaned with pressurized water to remove existing polluting particles and then left to dry in an oven at a temperature of 24 ± 1 °C for 48 h. The final bulk density of these composites was 110 ± 5 kg/m^3.

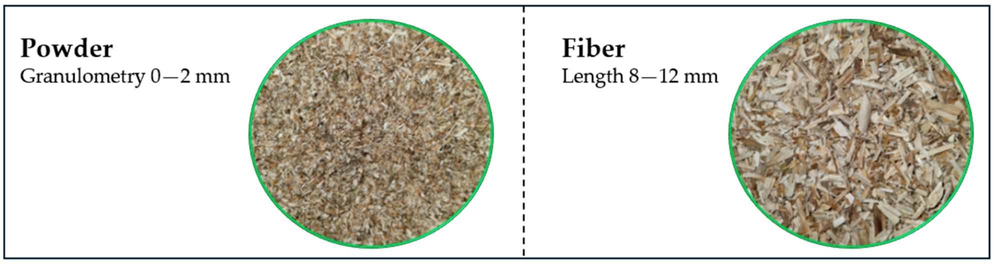


Figure 1. Hemp additions used in the production of gypsum composites.

2.2. Sample Preparation

The preparation of the different gypsum composites used in this research has been carried out following the recommendations of the EN 13279-2:2014 standard [44]. To achieve this, the steps outlined in Table 3 have been followed.

Table 3. Mixing and preparation process of gypsum composites.

Time [s]	Action
180	Manual mixing of hemp additions with gypsum powder until a homogeneous mixture is obtained.
30	Progressive dusting of gypsum powder (with or without hemp addition) onto mixing water.
60	Rest time before the mixing begins.
30	Manual mixing by means of a constant helical movement.
30	Intermediate mixture rest time.
30	Manual mixing by means of a constant helical movement.
120	Mold filling and manual compaction (approximately 20 shakes from a one-centimeter height).

Moreover, the formulations used are detailed in Table 4, where the volume ratios and weight quantities needed to prepare a mold for three specimens of 4 × 4 × 16 cm^3 are presented. All mixtures were prepared for a water-to-gypsum weight ratio of 0.65, ensuring a plastic and workable consistency with a paste diameter after the shaking table test of 165 ± 5 mm. Likewise, the two hemp percentages employed for the replacements were 15% and 30% by volume, aiming to successfully integrate them into the gypsum matrix without compromising its workability.

Table 4. Formulations used for the preparation of gypsum composites.

Series	Volume Ratios [%]				Mass Quantities [g]			
	Gypsum	Water	Powder	Fiber	Gypsum	Water	Powder	Fiber
G0.65	60.6	39.4	—	—	1000	650	—	—
G0.65–15%P	51.5	33.5	15.0	—	850	553	30	—
G0.65–30%P	42.4	27.6	30.0	—	700	455	60	—
G0.65–15%F	51.5	33.5	—	15.0	850	553	—	25
G0.65–30%F	42.4	27.6	—	30.0	700	455	—	50

As can be observed in Table 4, the progressive incorporation of hemp material has a beneficial effect by reducing the amount of gypsum binder used. The reduction in the consumption of raw materials resulting from the production of traditional building materials has been established as one of the key objectives for achieving sustainable development and responsible economic growth in various countries [45].

Once they had been prepared, the composites were cured under laboratory conditions at a temperature of 20 ± 2 °C and relative humidity of 50 ± 5% for a period of six days. Next, 24 h before conducting the tests, the samples were placed in a laboratory oven at a temperature of 40 ± 2 °C and relative humidity of 50 ± 5%, so as to ensure that all samples were tested under the same initial conditions. The composites' final state, as well as the appearance of the matrices, can be seen in Figure 2.

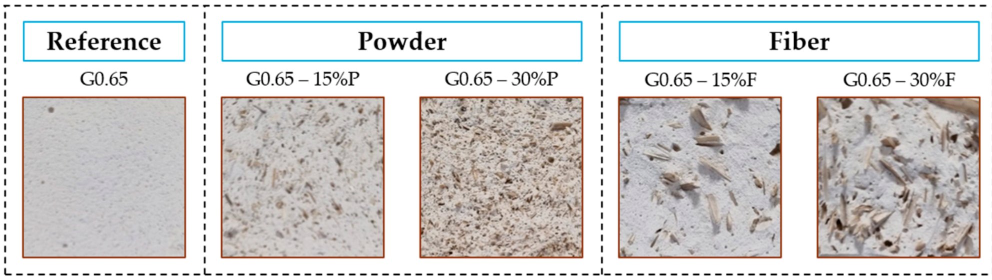


Figure 2. Matrices of the various gypsum composites that have been prepared and cured.

2.3. Experimental Program

In this section, the tests conducted to carry out the physical and mechanical characterization of the composites developed in this research are described. Figure 3 outlines the developed experimental program in a schematic manner.

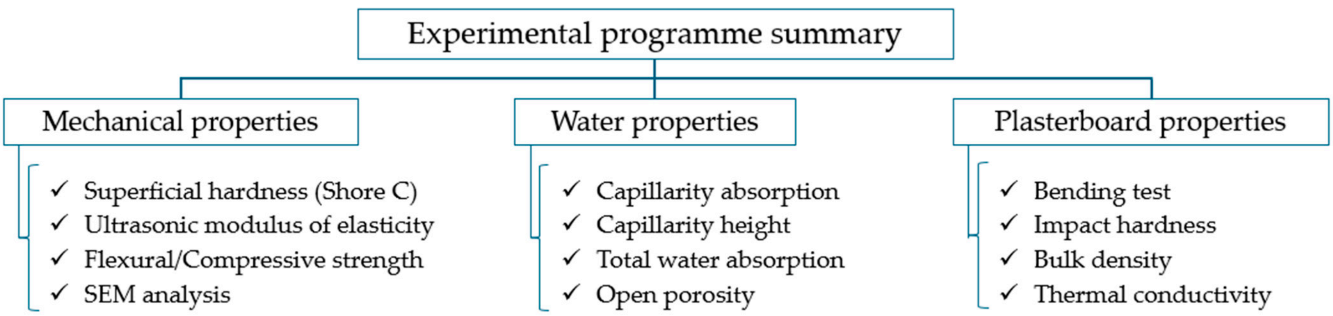


Figure 3. Outline of the developed experimental program.

As depicted in Figure 3, in the initial phase of the research, a mechanical characterization of the developed gypsum composites was conducted. Three samples of each type of gypsum, measuring 4 × 4 × 16 cm^3, were used for the following tests and methods:

- **Surface hardness:** Measured using a Shore C durometer. It reflects the resistance of gypsum composites to surface scratching. The test is conducted according to the UNE 102042:2023 standard [46], using five measurements on two plane-parallel faces separated by at least 2 cm from each other and from the ends.
- **Dynamic elastic modulus:** Employing a C368 ultrasonic emission-reception device by Matest (Treviolo, Italy), with 55 kHz contact transceiver probes measuring longitudinally along the 16 cm dimension of the specimen.
- **Flexural strength:** Utilizing a hydraulic press by Ibertest, model AUTOTEST 200–10SW (Madrid, Spain). It consists in a simple three-point bending test conducted in accordance with the EN 13279-2:2014 standard [44]. A loading speed of 10 N/s was applied, testing the samples until fracture.
- **Compressive strength:** In accordance with the EN 13279-2:2014 standard [44] and using the aforementioned equipment. The test is performed on the half specimens obtained after the flexural test, with a loading speed of 20 N/s until the final fracture of the gypsum composites.
- **SEM analysis:** Conducted on a sample extracted from the matrix of the cured gypsum composite and previously coated with a thin gold film using a Cressington 108 auto metallizer (Watford, UK). The analysis is performed using a TESCAN Vega 4 scanning electron microscope (Watford, UK), with color cathodoluminescence and two EDX Bruker detectors (30 and 60 mm^2) operating at 20 kV.

In the second phase, the behavior of the composites developed in this work against water exposure was assessed. For this purpose, the following tests were conducted on sets of three specimens measuring 4 × 4 × 16 cm^3:

- **Capillary water absorption:** Determined according to the EN 1925:1999 standard. It relates the mass of water absorbed by the gypsum composites per unit area and as a function of time [47].
- **Maximum height reached by water in the capillarity test:** Determined as the average of three values measured on each specimen, reflecting the final height reached by the water after 40 min of capillarity test. Infrared images were also taken to understand the water evolution inside the composites.
- **Total water absorption:** Performed adapting the indications in the EN 14617-1:2013 standard [48]. In order to do this, the samples were completely submerged in water for a period of 8 h, after which the percentage change in mass experienced by the gypsum composites due to water absorption was obtained.
- **Open porosity:** Defined as the ratio between the volume of accessible pores and the apparent volume of the material. It was determined using the method outlined in the EN 1936:2007 standard [49].

In the final phase, a study was conducted on prefabricated panels intended for modular construction, performing the following tests and always using three samples for each:

- **Bulk density:** Defined as the ratio between the dry state mass and the bulk volume of the different analyzed samples and determined following the indications included in the EN 13279-2 standard [44].
- **Thermal conductivity:** Using samples of size 24 × 24 × 2 cm^3, the thermal conductivity coefficient of the composites was determined with the help of a mini Hot-Box equipped with thermocouples.
- **Flexural strength in panels:** The maximum breaking load was determined on prefabricated panels measuring 40 × 30 × 1.5 cm^3. For this purpose, two types of prefabricated panels were designed, with and without Kraft paper reinforcement. Tests were conducted according to the EN 12859:2012 standard [50].

- **Impact hardness:** It represents the ability of the samples to absorb energy during the impact. The test is carried out following the indications included in the EN 12859:2012 standard [50], using a 50 mm-diameter steel ball that impacts the panel when falling freely from a height of 50 cm.

Finally, a section of discussion and potential applications has been included to showcase the potential of the developed composites, supported by the results obtained in the experimental campaign.

3. Results

In this section, the results obtained from the physical–mechanical characterization of the gypsum composites designed in this research are described.

3.1. Mechanical Characterization

Firstly, Table 5 presents the results obtained for the surface hardness and longitudinal dynamic elastic modulus of the different composite materials developed determined by ultrasound (MOEus).

Table 5. Dynamic elastic modulus measured by ultrasound (MOEus) and surface hardness of the composites.

Series	G0.65	G0.65–15%P	G0.65–30%P	G0.65–15%F	G0.65–30%F
Surface Hardness [Shore C units]	86 ± 1	78 ± 2	73 ± 1	77 ± 1	75 ± 1
MOEus [MPa]	5196 ± 89	4212 ± 102	3608 ± 34	4286 ± 28	3788 ± 91

As shown in Table 5, the use of hemp additions as a partial replacement for the original plaster material results in a decrease in the surface hardness of the composites. Thus, for the samples with a higher hemp content, G0.65–30%P and G0.65–30%F, there is a reduction of around 15.1% and 12.8%, respectively, with respect to the reference material (G0.65). As confirmed in other studies, a decrease in surface hardness is generally associated with a loss of compressive strength [8]. However, the values obtained for this property in this study are in line with those obtained by Leiva-Aguilera in her research on plaster with rice husk additions, who also observed a decrease in hardness when incorporating these plant-based additions [51]. Additionally, in all cases, the obtained values exceed the recommended minimum value for this type of gypsum-based material in this surface hardness test, which is set at 45 Shore C units [52].

On the other hand, Table 5 also shows a progressive decrease in the dynamic longitudinal elastic modulus as the added hemp content increases. Thus, composites with a 30% substitution of plaster with hemp powder showed an MOEus value 30.6% lower with respect to the G0.65 sample. A similar effect can be observed in composites with hemp fiber. This reduction in the MOEus value is a consequence of the lower density and speed of ultrasound propagation through the matrix of these hemp-containing composites. A similar effect has been observed in other previous research [53], where replacing the original plaster material with recycled raw materials, such as rubber from used tires, manages to lighten the hardened composites and results in a reduction in this property.

Figure 4 presents the results obtained for the flexural and compressive strengths of the different tested gypsum materials, including the minimum recommended value according to current regulations.

Firstly, Figure 4a presents the results from the standardized bending test. It can be observed that the gypsum composites prepared with hemp fiber exhibited higher flexural strengths compared to their counterparts with hemp powder addition (particle size less than 2 mm). Thus, in the G0.65–15%F composite, despite having replaced 15% of the gypsum material with a light addition of hemp fiber, the flexural strength was on average 2.34% higher than the traditional material (G0.65). Similarly, the type of fracture in the composites with hemp powder addition was brittle, with the two gypsum pieces completely separating after the fracture. In any case, both additions used in partial substitution of the base gypsum composite surpassed the minimum value established by the current regulations of 1 MPa, making them suitable for use in building projects.

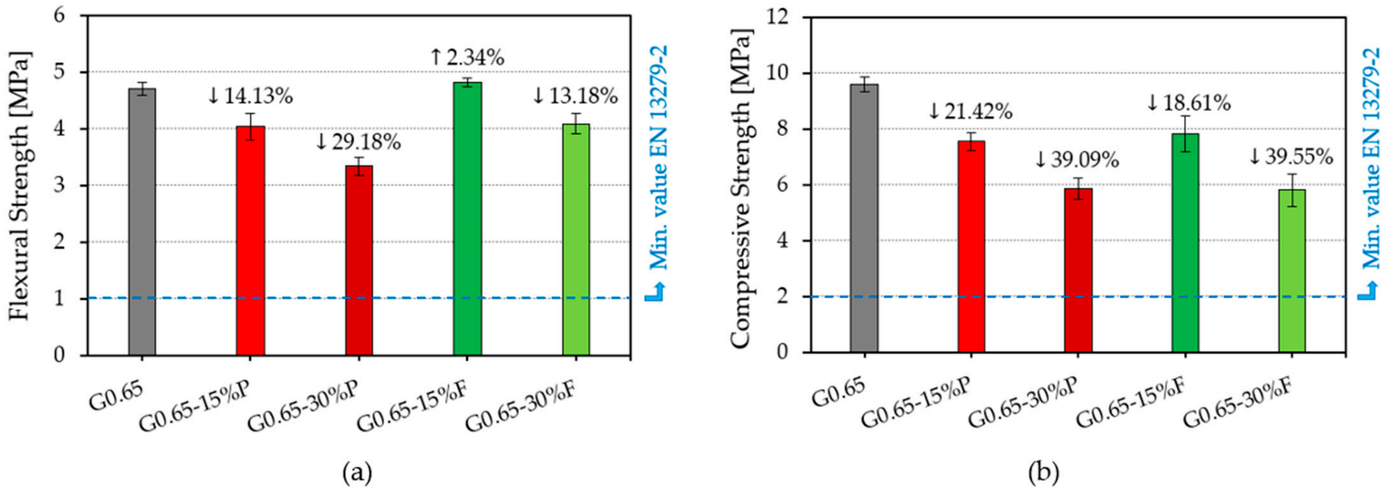


Figure 4. Mechanical test results. (**a**) Flexural strength; and (**b**) compressive strength.

Similarly, the results from the compressive strength test are presented in Figure 4b. It can be observed that, in line with the surface hardness results obtained in Table 5, all the hemp-lightened composites exhibited a compressive strength lower than the reference material. However, even in the least favorable cases, G0.65–30%P and G0.65–30%F, where the decrease in compressive strength was close to 40%, all the analyzed composites exceeded the limit of 2 MPa set by the current regulations.

The results obtained are consistent with those obtained by other researchers in previous studies. As a synthesis for the discussion, Table 6 compiles the results obtained for flexural and compressive strength in other research studies that incorporate lightweight additions in gypsum. It can be seen that the values obtained in this study are consistent with those presented.

Table 6. Critical literature review: results of flexural and compressive strength obtained in other research studies.

Reference	Binder	Addition	Flexural Strength [MPa]	Compressive Strength [MPa]
[54]	Plaster	10% wt., cork granulates (<1 cm)	2.15	4.88
[34]	Gypsum	94% gypsum, 6% hemp fiber (15 mm)	7.20	8.30
[51]	Plaster	1% wt., rice husk	3.54	7.88
[55]	Gypsum	6% wt., jute fiber	2.46	—
[24]	Gypsum	70% gypsum, 30% coir	5.23	—
[56]	Gypsum	3.5% wt., cellulose acetate fibers	2.40	7.10
[57]	Plaster	1% wt., end-of-life tire textile fibers	4.96	7.36

Finally, with the aim of understanding in detail the interface between the added hemp material and the gypsum matrix, an analysis was carried out through scanning electron microscopy. In Figure 5, the images obtained for the matrix of the G0.65–30%P composite are shown.

In Figure 5a, the good dispersion of hemp particles in the gypsum matrix and their perfect integration can be observed. While there are pores formed during the setting process, there is no apparent detachment of the hemp material due to the lack of cohesion between it and the gypsum base composite. In Figure 5b, a detailed view of the composite matrix reveals the characteristic acicular morphology of the dihydrate ($CaSO_4 \cdot 2H_2O$). Additionally, the rough surface of the hemp additions promotes their adhesion to the matrix [31], with no discontinuities observed between the addition and the gypsum matrix.

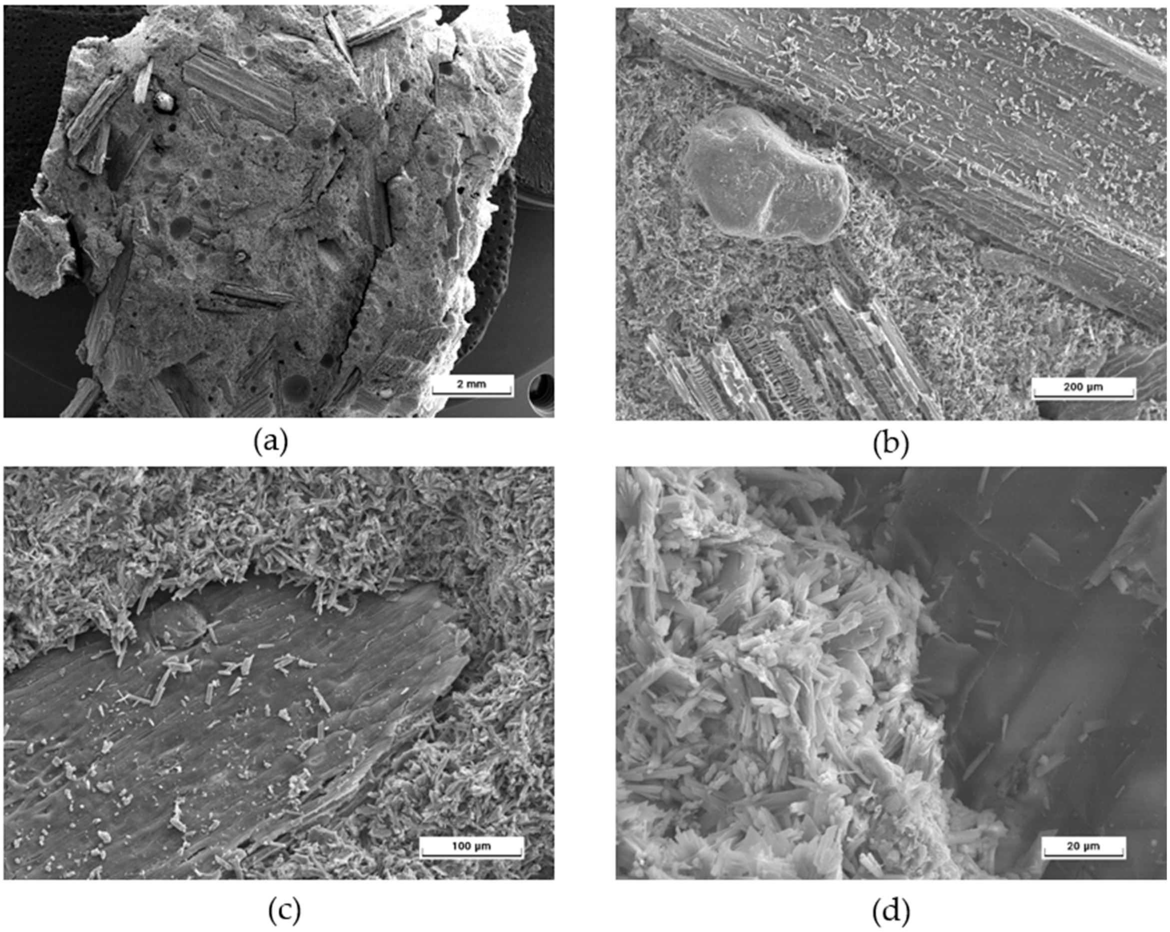


Figure 5. SEM analysis of the G0.65–30%P composite. (**a**) 20× magnification; (**b**) 250× magnification; (**c**) 500× magnification; and (**d**) 2000× magnification.

In Figure 5c, a closer look reveals the formation of gypsum crystals on the surface of the hemp compounds, a phenomenon previously observed by Iucolano et al., highlighting the effective integration of these plant-based additions compared to other synthetic additions [35]. However, at 500× magnification, some areas with a weaker bond between the addition and the matrix are noticeable, explaining the lower mechanical resistance of compounds with the addition of hemp powder. Finally, Figure 5d provides a detailed view of the hemp–gypsum interface, where the proper formation of gypsum crystals around the hemp particles can be observed.

3.2. Tests on Behavior Regarding Water Exposure

In this section, the behavior regarding the water exposure of the gypsum composites developed in this work is analyzed. To begin with, the results obtained for the total water absorption coefficient and open porosity of each formulation are shown in Table 7.

As shown in Table 7, there is a decrease in total water absorption as the content of added hemp material increases. This is attributed to the replacement of the original gypsum material with this plant-based addition, resulting in the composite retaining less water in its matrix. Similar observations have been made in prior research [11,58]. Additionally, it is observed that composites with hemp fiber addition exhibit a lower water absorption capacity compared to their counterparts with hemp powder. Similarly, the volume of pores accessible from the exterior is reduced, with the G0.65–30%F composite having the lowest open porosity.

Table 7. Total water absorption coefficient and open porosity of the gypsum composites developed.

Series	G0.65	G0.65–15%P	G0.65–30%P	G0.65–15%F	G0.65–30%F
Total Water Absorption [%]	42.5 ± 1.2	39.3 ± 0.9	37.2 ± 1.2	37.8 ± 0.8	36.7 ± 1.0
Open Porosity [%]	40.9 ± 0.6	38.1 ± 0.6	37.0 ± 0.7	37.1 ± 1.1	34.8 ± 0.9

On the other hand, Figure 6 presents the results obtained for the capillary water absorption test for the different gypsum composites.

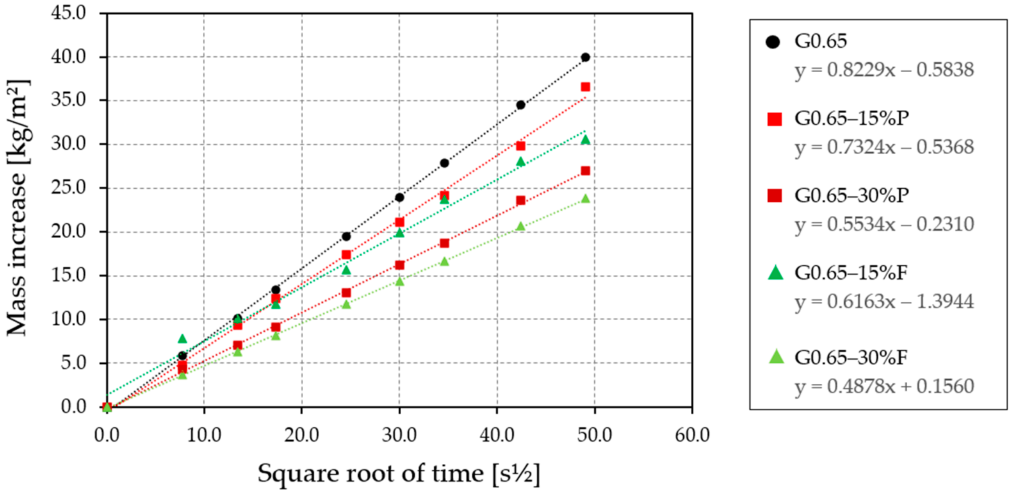
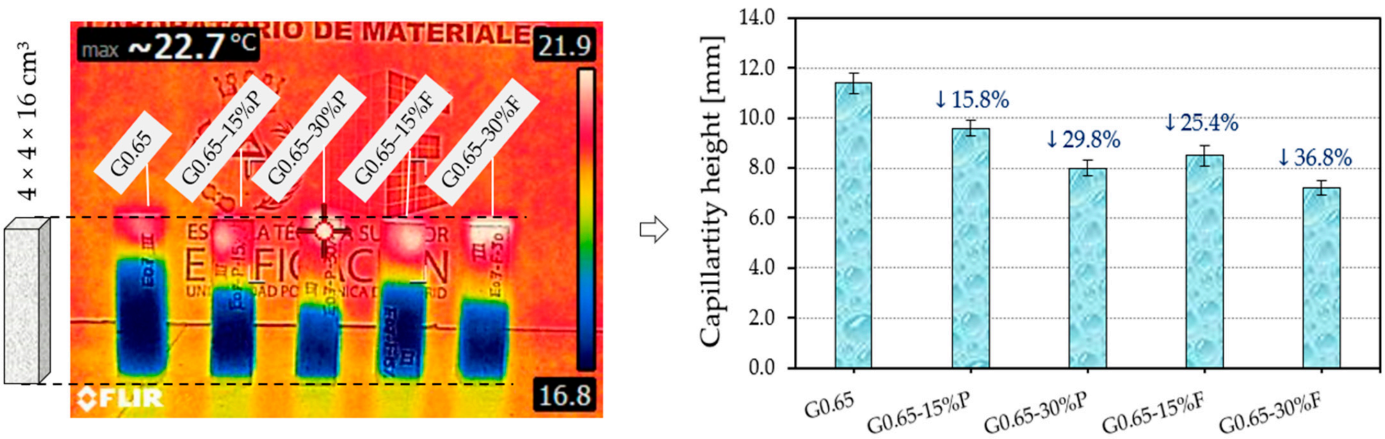


Figure 6. Capillarity test: mass variation per unit area over time.

In Figure 6, it can be observed that the mass of water absorbed per unit area over time is lower in the composites with hemp addition. Additionally, there is lower absorption in the composites with hemp fiber compared to those containing hemp powder, which is consistent with the results shown in Table 7. Thus, the material exhibiting a better performance after the capillarity test is the sample G0.65–30%F. Previous research has also confirmed the positive effect of replacing gypsum material with secondary raw materials to reduce capillary water absorption, as seen in gypsum composites made with rice husk waste [51] or cotton fiber [59].

Complementary to this, a thermographic analysis conducted after the capillarity test is presented in Figure 7a, with Figure 7b showing the maximum water height reached in the various produced composites.



(a) (b)

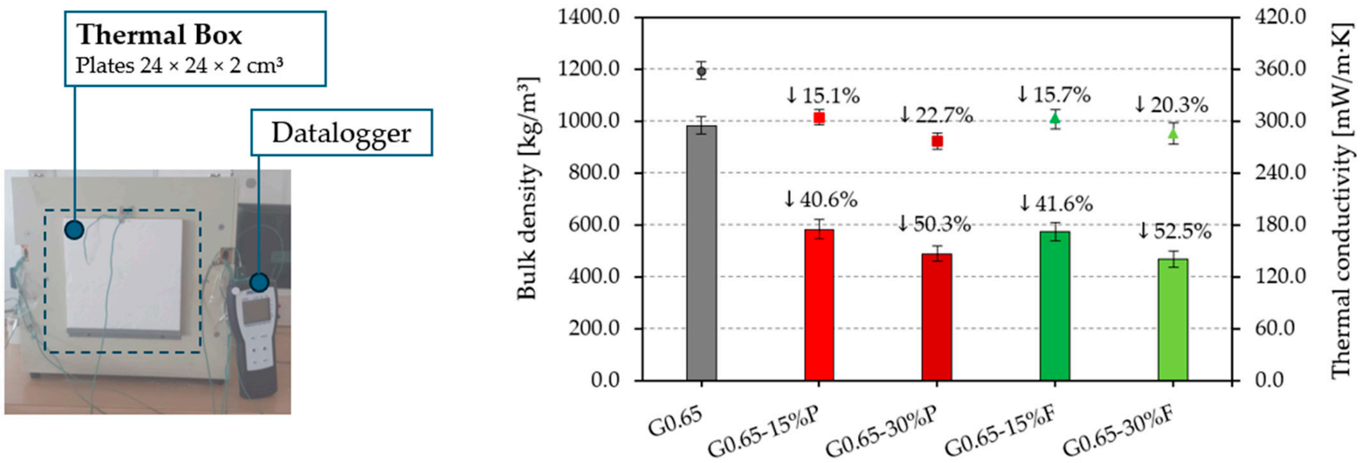
Figure 7. Capillarity test: (**a**) Thermographic image of the composites; and (**b**) the maximum height reached by water.

Thus, in Figure 7a, it can be observed that the height reached by water inside the gypsum composites with partial hemp substitution is lower than in the reference material (G0.65). With a higher percentage of substitution, there is a lower final height reached by water after the test. These differences are quantified numerically in Figure 7b, showing a decrease of up to 36.8% for the G0.65–30%F compound compared to traditional gypsum material. This positive effect resulting from the incorporation of hemp into the matrix of gypsum composites as partial substitution for the original raw material constitutes a step forward in mitigating potential pathologies caused by capillary water penetration into the matrix of the manufactured compounds. Notwithstanding, this phenomenon has been observed previously in other studies, where the use of low-density secondary raw materials decreases the capillary water absorption capacity [60].

Finally, it is important to note that this study utilized manually processed and crushed hemp material. In general, natural fibers are very heterogeneous, hydrophilic, and exhibit reduced long-term durability, leading to a decrease in the bond strength between the hemp composite and the binder matrix. Therefore, and in order to achieve a real and sustained improvement in the water resistance of the newly developed gypsum composites over time, it would be advisable to perform a surface treatment on the hemp additions. The literature suggests that the most recommended treatment consists of the use of concentrated NaOH solutions ranging from 3% to 9% [61].

3.3. Tests on Prefabricated Elements

An important feature when selecting gypsum composites for their use in lightweight partitions is the relationship existing between their bulk density and thermal conductivity. Therefore, first of all, Figure 8 presents the results obtained for these two properties.



(a) (b)

Figure 8. Determination of the thermal conductivity of the composites: (**a**) Thermal box used in the tests; and (**b**) results obtained for thermal conductivity and bulk density of the gypsum composites.

As can be observed in Figure 8, the decrease in density caused by the partial substitution of the original gypsum material with hemp additions results in an improvement in the thermal behavior of the composites. Thus, for compounds with a higher hemp powder G0.65–30%P and hemp fiber G0.65–30%F addition, the thermal conductivity was reduced by around 50% with respect to the original material without additions (G0.65). Additionally, bulk densities below 1000 kg/m^3 are obtained, which, combined with the fulfillment of the minimum mechanical resistances shown in Figure 4, suggests the potential application of these composites as a material for the manufacturing of lightweight building partitions.

The results obtained for thermal conductivity and bulk density are aligned with those observed by other researchers. Leiva, for instance, achieved a reduction in thermal conductivity in gypsum composites with crushed rice husk close to 25.5%, as well as a

45.4% reduction using rice husk ash [51]. Guna et al. also observed a decrease in the thermal conductivity of gypsum composites made with wool and coconut fibers for use in prefabricated false ceiling boards [62]. Similarly, the addition of crushed cork fibers can be employed in the manufacturing of lightweight plasterboards, with the primary advantage being a reduction in thermal conductivity by over 50% compared to the traditional material without additions [63].

On the other hand, it is advisable to analyze the mechanical strengths of gypsum composite materials by testing samples with dimensions close to those used in their final form for commercialization. In this regard, two different types of panels with dimensions of 40 × 30 × 1.5 cm^3 were designed. One of them was solely composed of the gypsum materials designed in this study, whereas the other, which was closer to reality, incorporated Kraft paper reinforcement strips on both sides of the prefabricated panels. This manufacturing process is schematically illustrated in Figure 9.

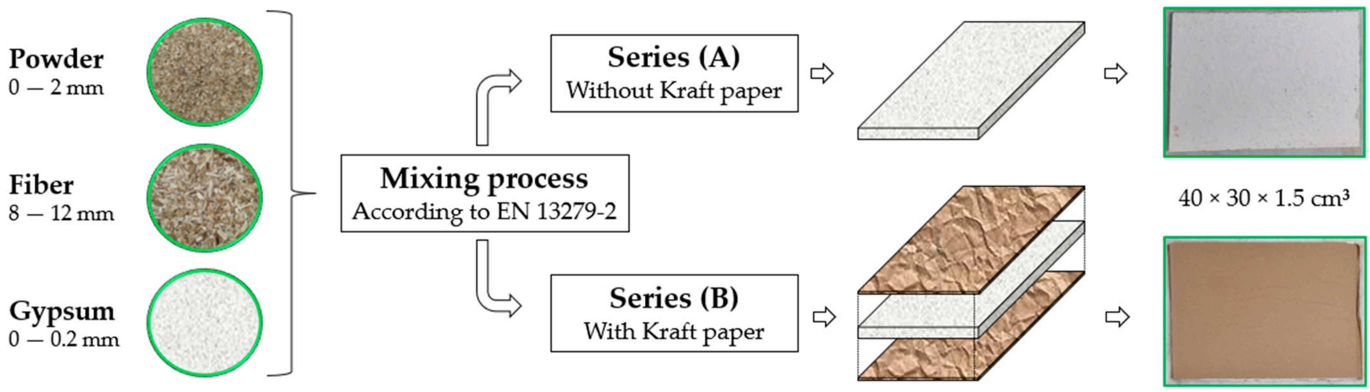


Figure 9. Preparation process of the prefabricated panels made with hemp–gypsum composites.

The results of the bending strength test on panels are shown in Figure 10. Additionally, Figure 11 shows the testing device and the final state of the panels after being tested.

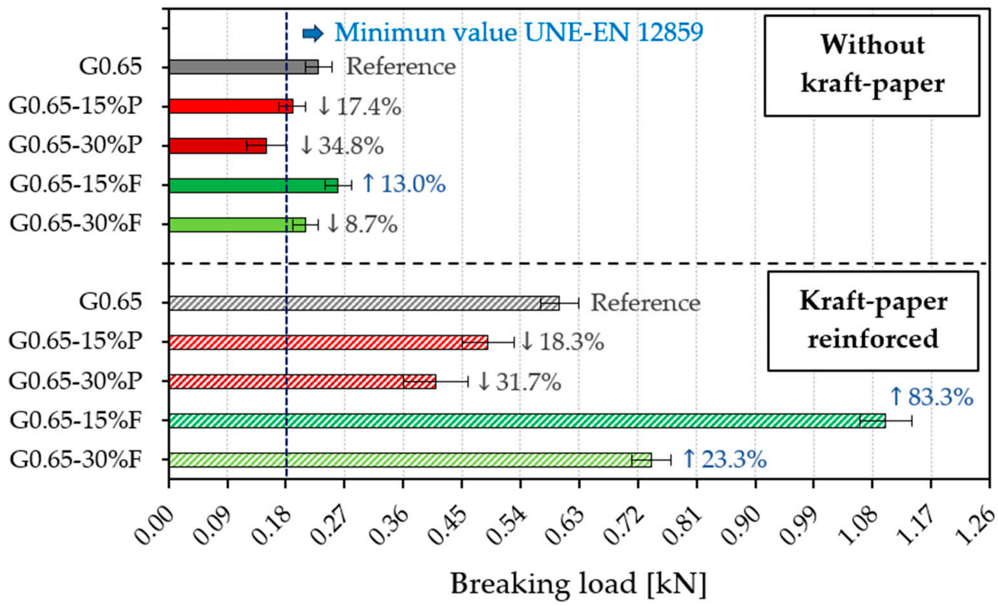


Figure 10. Bending strength test on panels: determination of the maximum breaking load.

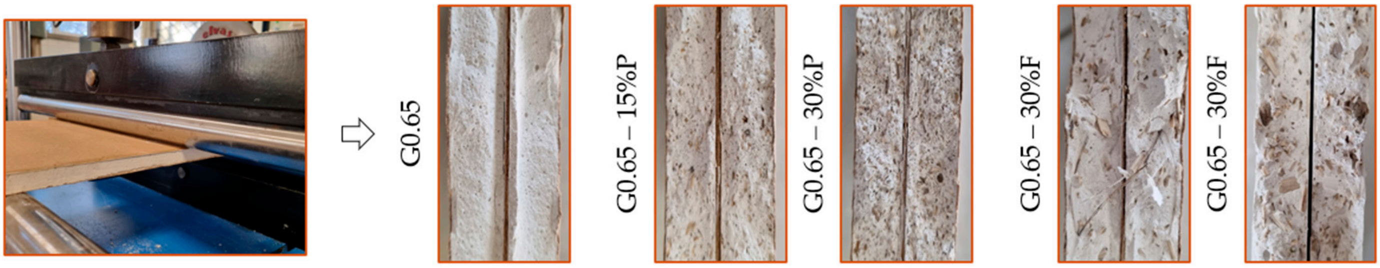


Figure 11. Arrangement of the bending test on panels and image of the plasterboards after being broken in the press.

As can be observed in Figure 10, gypsum composites containing hemp fiber yielded the best results in this bending test. In the initial phase, where the panels without Kraft paper reinforcement were tested, the sample G0.65–15%F achieved a breaking load 13.0% higher than the reference material G0.65. However, in this first phase of tests, some composites, such as G0.65–30%P, did not surpass the minimum value established by current regulations at 0.18 kN. For this reason, a study closer to reality was conducted, using Kraft paper reinforcement to enhance the flexural strength in panels, as is performed in commercial products. This is the case where the best results were obtained, especially in fiber-reinforced composites, showing that all gypsum materials designed in this work can be used to produce lightweight plasterboards.

When examining Figure 11, it is noteworthy to highlight the correct integration of hemp addition into the matrix, as well as its uniform distribution in all the composites and substitution percentages analyzed. A similar effect was observed by Iucolano et al., who demonstrated in their research how hemp fibers could replace conventional glass fibers as a reinforcement material in gypsum composites, resulting in an increased ductility and deformation capacity under external loads [35]. On the other hand, previous studies have emphasized the importance of recovering the fine fraction (<2 mm) generated as a byproduct in the industry [53], advocating for the integration of these materials in the development of prefabricated building components as an alternative to their accumulation in landfills.

Finally, the impact hardness of the materials developed in this research was studied. The results and images obtained from these tests are presented in Figure 12.

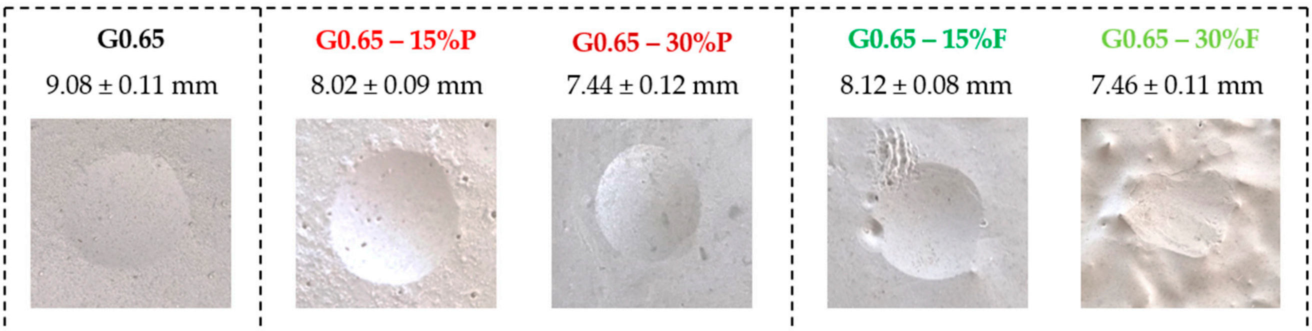


Figure 12. Impact hardness test results and final image of the composites.

Firstly, it is worth noting that none of the tested panels broke during the impact test, making all impacts valid. Additionally, it can be observed that all samples made with hemp as a partial replacement for the original gypsum material had a smaller indentation diameter than the G0.65 reference. There are hardly any differences between using hemp in powder or fiber form to mitigate the impact on the surface, which aligns with the results obtained for surface hardness presented in Table 5. In other research where recycled materials were used to make lightweight panels for false ceilings, similar results were obtained when using waste from end-of-life tires (ELT), such as recycled rubber or textile fiber [64].

3.4. Critical Discussion and Potential Applications

In this section, a synthesis of potential applications for the innovative materials developed in this research is provided based on the results obtained in the experimental campaign. In Figure 13a, a possible construction detail is shown for the application of these lightweight panels with hemp addition in the construction of lightweight partitions. Additionally, in Figure 13b, a comparative visual analysis is presented between the reference material G0.65 and the various composites developed, displaying the percentage variation in each analyzed property for each dosage with respect to this traditional composite.

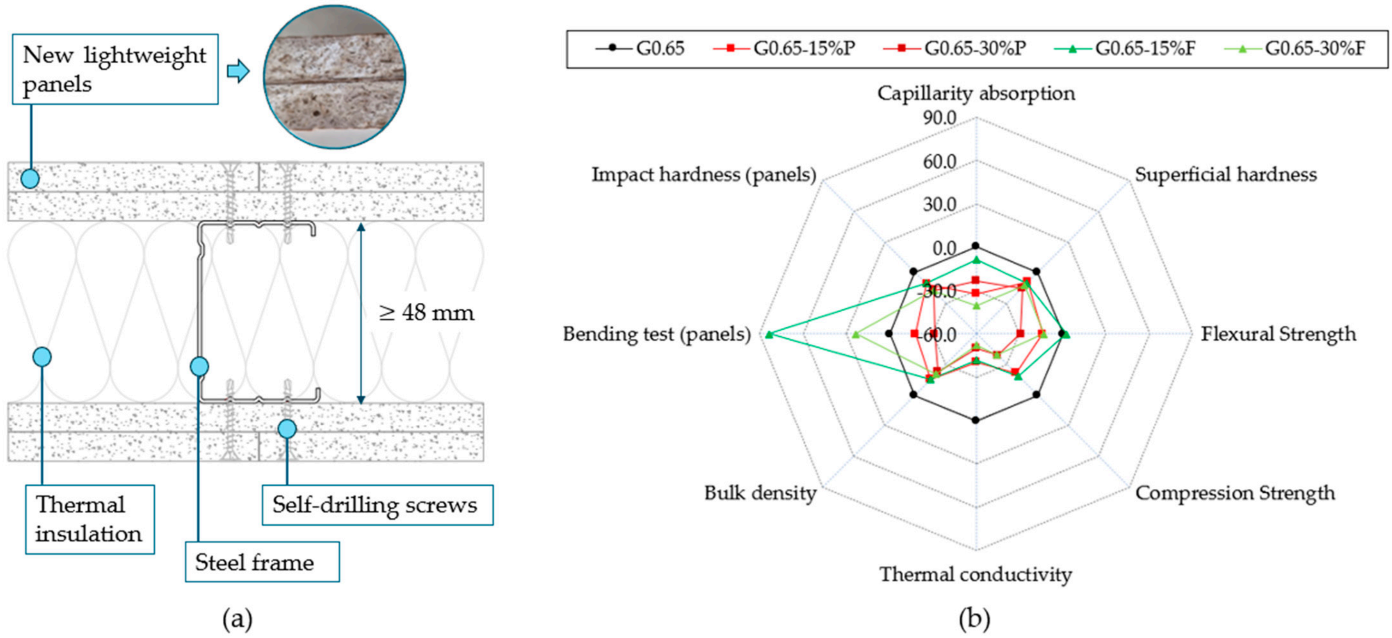


Figure 13. (**a**) Example of application of the panels developed in the research; and (**b**) visual comparative analysis of the physical–mechanical properties.

In general terms, the materials developed in this research align with European objectives aimed at reducing energy consumption in buildings. Currently, the building sector accounts for approximately 40% of the total energy consumed in the European Union [65]. Therefore, the development of new lightweight partitions with a good thermal performance would contribute to mitigating this effect [66]. Lightweight partitions, as shown in Figure 13a, based on light steel framing (LSF partitions), offer significant advantages over traditional construction, including easier handling and reduced execution times, shorter transportation times and lower emissions from the logistic process, higher quality in the execution of building systems, lower volumes of waste generated during construction, increased recyclability, and the possibility of producing standardized and more reliable pieces [67,68]. However, as demonstrated in other previous research, it is advisable to use thermal break strips to mitigate the effect of cold spots caused by the load-bearing steel structure [69].

On the other hand, in the visual comparison shown in Figure 13b, it can be observed that the G0.65–15%F composite exhibits good behavior for its use in lightweight partitions due to its favorable combination of flexural strength, density, and thermal conductivity. In this regard, with an appropriate treatment of the hemp additions to enhance their durability, the composites developed in this study present themselves as a viable alternative to conventional lightweight plasterboards. This offers an environmental benefit by reducing gypsum consumption and the use of synthetic fibers [35,70].

4. Conclusions

In this section, the most relevant conclusions obtained from the research conducted on gypsum materials lightened with hemp in powder and fiber form are presented:

- The partial replacement of gypsum with hemp in powder and fiber has been observed to decrease the surface hardness of the cured composites while reducing the compressive strength with respect to traditional gypsum material. Nevertheless, even with a decrease in strength of around 40% with a 30% substitution of gypsum with hemp in the most unfavorable case, the obtained strength still exceeded the minimum value set by regulations by more than 3 MPa.
- The G0.65–15%F compound exhibited the best results in flexural strength tests, achieving higher strength values than the reference material G0.65. Notably, in the study with prefabricated elements, all panels made with Kraft paper reinforcement exceeded the minimum value set by regulations at 0.18 kN.
- The composites with hemp incorporation showed a good performance against water action, reducing the water absorption through capillarity and the final height reached by the liquid inside the composite.
- All samples that used hemp as a partial substitution for gypsum obtained lower values of bulk density and thermal conductivity than the original composite G0.65, achieving a reduction in thermal conductivity close to 50% in some cases. Furthermore, SEM images demonstrated the effective integration of hemp material into the gypsum matrix, resulting in a homogeneous and cohesive distribution.

Finally, it is worth noting that this research opens up new lines of work related to the design of sustainable building prefabricated. Future studies, for both powder and fiber composites, could complement this research by conducting acoustic tests and economic feasibility studies, and, most importantly, by comparing different surface treatments on hemp additions to assess their durability. In any case, the presented research has rigorously collected the results obtained in a designed experimental campaign, achieving the goal of demonstrating to professionals and specialists in the building sector the potential applications of hemp material as a partial substitution in lightweight gypsum composites.

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References

1. Bel-Anzué, P.; Elert, K. Changes in traditional building materials: The case of gypsum in Northern Spain. *Archaeol. Anthropol. Sci.* **2021**, *13*, 177. [CrossRef]
2. Pedreño-Rojas, M.A.; Fořt, J.; Černý, R.; Rubio-de-Hita, P. Life cycle assessment of natural and recycled gypsum production in the Spanish context. *J. Clean. Prod.* **2020**, *253*, 120056. [CrossRef]
3. Doleželová, M.; Scheinherrová, M.; Krejsová, J.; Keppert, M.; Černý, R.; Vimmrová, A. Investigation of gypsum composites with different lightweight fillers. *Constr. Build. Mater.* **2021**, *297*, 123791. [CrossRef]

4. Pedreño-Rojas, M.A.; Flores-Colen, I.; de Brito, J.; Rodríguez-Liñán, C. Influence of the heating process on the use of gypsum wastes in plasters: Mechanical, thermal and environmental analysis. *J. Clean. Prod.* **2019**, *215*, 444–457. [CrossRef]
5. Vidales-Barriguete, A.; Santa-Cruz-Astorqui, J.; Piña-Ramírez, C.; Kosior-Kazberuk, M.; Kalinowska-Wichrowska, K.; Atanes-Sánchez, E. Study of the Mechanical and Physical Behavior of Gypsum Boards with Plastic Cable Waste Aggregates and Their Application to Construction Panels. *Materials* **2021**, *14*, 2255. [CrossRef]
6. Balti, S.; Boudenne, A.; Dammark, L.; Hamdi, N. Mechanical and thermophysical characterization of gypsum composites reinforced by different wastes for green building applications. *Constr. Build. Mater.* **2023**, *372*, 130840. [CrossRef]
7. Guijarro-Miragaya, P.; Ferrández, D.; Atanes-Sánchez, E.; Zaragoza-Benzal, A. Characterization of a New Lightweight Plaster Material with Superabsorbent Polymers and Perlite for Building Applications. *Buildings* **2023**, *13*, 1641. [CrossRef]
8. del Río, M.; Vidales, A.; Piña, C.; Vitiello, V.; Santa Cruz-Astorqui, J.; Castelluccio, R. A review of the research about gypsum mortars with waste aggregates. *J. Build. Eng.* **2022**, *45*, 103338. [CrossRef]
9. Li, Z.; Wang, X.; Yan, W.; Ding, L.; Liu, J.; Wu, Z.; Huang, H. Physical and mechanical properties of gypsum-based composites reinforced with basalt, glass, and PVA fibers. *J. Build. Eng.* **2023**, *64*, 105640. [CrossRef]
10. Elaiwi, E.H.; Ibrahim, A.K.; Al-Chalabi, S.F.; Abbood, A.A.; Hussein, F.M.; Hussein, H.H.; Al-Ridha, A.S.D. The influence of water-gypsum ratio on the properties of national gypsum (Joss) for various additives. *Mater. Today Proc.* **2023**, *80*, 1327–1333. [CrossRef]
11. Ferrández, D.; Álvarez Dorado, M.; Zaragoza-Benzal, A.; Leal Matilla, A. Feasibility of Ecofriendly Mortars with Different Hemp Additions for Use in Building Sector. *Heritage* **2023**, *6*, 4901–4918. [CrossRef]
12. Bollino, F.; Giannella, V.; Armentani, E.; Sepe, R. Mechanical behavior of chemically-treated hemp fibers reinforced composites subjected to moisture absorption. *J. Mater. Res. Technol.* **2023**, *22*, 762–775. [CrossRef]
13. Ferreira, S.R.; Pepe, M.; Matrinelli, E.; Andrade Silva, F.; Toledo Filho, R.D. Influence of natural fibers characteristics on the interface mechanics with cement based matrices. *Compos. Part B Eng.* **2018**, *140*, 183–196. [CrossRef]
14. Keener, T.J.; Stuart, R.K.; Brown, T.K. Maleated coupling agents for natural fibre composites. *Compos. Part A Appl. Sci. Manuf.* **2004**, *35*, 357–362. [CrossRef]
15. Stocchi, A.; Lauke, B.; Vázquez, A.; Bernal, C. A novel fiber treatment applied to woven jute fabric/vinylester laminates. *Compos. Part A Appl. Sci. Manuf.* **2007**, *38*, 1337–1343. [CrossRef]
16. Iucolano, F.; Caputo, D.; Leboffe, F.; Liguori, B. Mechanical behavior of plaster reinforced with abaca fibers. *Constr. Build. Mater.* **2015**, *99*, 184–191. [CrossRef]
17. Correa Gomes, D.A.; de Novais Miranda, E.H.; Resende, F.C.; Vega Villaruel, D.C.; Marin Mendes, L.; Guimaraes Júnior, J.B. Analysis of the influence of wheat residues on gypsum composites. *Innov. Infrastruct. Soluntions* **2023**, *8*, 31. [CrossRef]
18. Miraoui, I.; Jaballi, S.; Rabeh, S. Analysis of long unidirectional sisal fibers reinforced plaster: An experimental investigation. *Mater. Today Proc.* **2022**, *52*, 152–157. [CrossRef]
19. Medjmadj, S.; Si Salem, A.; Ait Taleb, S. Experimental behavior of plaster/cork functionally graded core sandwich panels with polymer skins. *Constr. Build. Mater.* **2022**, *344*, 128257. [CrossRef]
20. Svetlana, P.; Toussaint, B.; Paul-Antoine, S.; Yann, Q. Valorization of virgin cork by the design of cork-plaster composites. *Inorg. Chem. Commun.* **2024**, *161*, 111782. [CrossRef]
21. Mehrez, I.; Hachem, H.; Jemni, A. Thermal insulation potential of wood-cereal straws/plaster composite. *Case Stud. Constr. Mater.* **2022**, *17*, e01353. [CrossRef]
22. Touil, M.; Lachheb, A.; Saadani, R.; Rachid Kabiri, M.; Rahmoune, M. A new experimental strategy assessing the optimal thermo-mechanical properties of plaster composites containing Alfa fibers. *Energy Build.* **2022**, *262*, 111984. [CrossRef]
23. Segura Alcaraz, J.; Montava, I.; Juliá Sanchis, E.; Gadea Borrel, J.M. Mechanical properties of plaster reinforced with yute fabrics. *Compos. Part B Eng.* **2019**, *178*, 107390. [CrossRef]
24. Aramwit, P.; Vui Sheng, D.D.C.; Krishna Moorthy, G.; 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]
25. Braiek, A.; Karkri, M.; Adili, A.; Ibos, L.; Nasrallah, S.B. Estimation of the thermophysical properties of date palm fibers/gypsum composite for use as insulating materials in building. *Energy Build.* **2017**, *140*, 268–279. [CrossRef]
26. Jia, R.; Wang, Q.; Feng, P. A comprehensive overview of fibre-reinforced gypsum-based composites (FRGCs) in the construction field. *Compos. Part B Eng.* **2021**, *205*, 108540. [CrossRef]
27. Rashid, B.; Leman, Z.; Jawaid, M.; Ishak, M.R.; Al-Oqla, F.M. Eco-Friendly Composites for Brake Pads from Agro Waste: A Review. *Encycl. Mater. Compos.* **2017**, *3*, 209–228. [CrossRef]
28. Hussain, A.; Calabria-Holley, J.; Lawrence, M.; Ansell, M.P.; Jiang, Y.; Schorr, D.; Blanchet, P. Development of novel building composites based on hemp and multi-functional silica matrix. *Compos. Part B Eng.* **2019**, *156*, 266–273. [CrossRef]
29. Prade, T.; Svensson, S.E.; Andersson, A.; Mattsson, J.E. Biomass and energy yield of industrial hemp grown for biogas and solid fuel. *Biomass Bioenergy* **2011**, *35*, 3040–3049. [CrossRef]
30. Shea, A.; Lawrence, M.; Walker, P. Hygrothermal performance of an experimental hemp–lime building. *Constr. Build. Mater.* **2012**, *36*, 270–275. [CrossRef]
31. Çomak, B.; Bideci, A.; Salli bideci, Ö. Effects of hemp fibers on characteristics of cement based mortar. *Constr. Build. Mater.* **2018**, *169*, 794–799. [CrossRef]

32. Jami, T.; Karade, S.R.; Singh, L.P. A review of the properties of hemp concrete for green building applications. *J. Clean. Prod.* **2019**, *239*, 117852. [CrossRef]
33. Boccarusso, L.; Durante, M.; Iucolano, F.; Mocerino, D.; Langella, A. Production of hemp-gypsum composites with enhanced flexural and impact resistance. *Constr. Build. Mater.* **2020**, *260*, 120476. [CrossRef]
34. Babu, K.S.; Ratnam, C. Mechanical and thermophysical behavior of hemp fiber reinforced gypsum composites. *Mater. Today Proc.* **2021**, *44*, 2245–2249. [CrossRef]
35. Iucolano, F.; Boccarusso, L.; Langella, A. Hemp as eco-friendly substitute of glass fibres for gypsum reinforcement: Impact and flexural behaviour. *Compos. Part B Eng.* **2019**, *175*, 107073. [CrossRef]
36. Iucolano, F.; Liguori, B.; Aprea, P.; Caputo, D. Thermo-mechanical behaviour of hemp fibers-reinforced gypsum plasters. *Constr. Build. Mater.* **2018**, *185*, 256–263. [CrossRef]
37. Shewalul, Y.W.; Flores, N.; Streicher, D.; Walls, R. Fire behavior of hemp blocks: A biomass-based construction material. *J. Bulding Eng.* **2023**, *80*, 108147. [CrossRef]
38. 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]
39. *EN 13279-1:2009*; Gypsum Binders and Gypsum Plasters—Part 1: Definitions and Requirements. British Standards Institution (BSI): London, UK, 2009.
40. Romero-Gómez, M.I.; Costa-Pereira, M.F.; Soares Dias, A.P.; Flores-Colen, I. Influence of high-temperature exposure on the properties of gypsum-plastic waste composites: Thermophysical and microstructural analysis. *J. Build. Eng.* **2023**, *79*, 107862. [CrossRef]
41. Pedreño-Rojas, M.A.; Morales-Conde, M.J.; Pérez-Gálvez, F.; Rubio de Hita, P. Influence of polycarbonate waste on gypsum composites: Mechanical and environmental study. *J. Clean. Prod.* **2019**, *218*, 21–37. [CrossRef]
42. Placo Saint Gobain. Available online: https://www.placo.es/Producto/iberfinor#marketing-description (accessed on 21 January 2024).
43. European Union. Council Directive (EU) 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. *Off. J. Eur. Communities* **1998**, *330*, 32–54.
44. *EN 13279-2:2014*; Gypsum Binders and Gypsum Plasters—Part 2: Test Methods. European Committee for Standardisation: Brussels, Belgium, 2014.
45. Lederer, J.; Gassner, A.; Fellner, J.; Mollay, U.; Schremmer, C. Raw materials consumption and demolition waste generation of the urban building sector 2016–2050: A scenario-based material flow analysis of Vienna. *J. Clean. Prod.* **2021**, *288*, 125566. [CrossRef]
46. *UNE 102042:2023*; Gypsum Plasters. Other Test Methods. AENOR: Madrid, Spain, 2023.
47. *EN 1925:1999*; Natural Stone Test Methods—Determination of Water Absorption Coefficient by Capillarity. European Committee for Standardisation: Brussels, Belgium, 1999.
48. *EN 14617-1:2013*; Agglomerated Stone—Test Methods—Part 1: Determination of Apparent Density and Water Absorption. European Committee for Standardisation: Brussels, Belgium, 2013.
49. *EN 1936:2007*; Natural Stone Test Methods—Determination of Real Density and Apparent Density, and of Total and Open Porosity. European Committee for Standardisation: Brussels, Belgium, 2007.
50. *EN 12859:2012*; Gypsum Blocks—Definitions, Requirements and Test Methods. European Committee for Standardisation: Brussels, Belgium, 2012.
51. Leiva-Aguilera, M.J. Escayola aditivada con residuos de cáscara de arroz. Doctoral Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2017. [CrossRef]
52. Jimenez Rivero, A.; Guzmán Báez, A.; García Navarro, J. New composite gypsum plaster—Ground waste rubber coming from pipe foam insulation. *Constr. Build. Mater.* **2014**, *55*, 145–152. [CrossRef]
53. Ferrández, D.; Álvarez, M.; Zaragoza-Benzal, A.; Santos, P. Eco-Design and Characterization of Sustainable Lightweight Gypsum Composites for Panel Manufacturing including End-of-Life Tyre Wastes. *Materials* **2024**, *17*, 635. [CrossRef]
54. Hernández-Olivares, F.; Bollati, M.R.; del Río, M.; Parga-Landa, B. Development of cork–gypsum composites for building applications. *Constr. Build. Mater.* **1999**, *13*, 179–186. [CrossRef]
55. Abir, N.; Bakr Siddique, A.; Ara Begum, H.; Abdul, M.; Nabi, A.; Arif Mahmud, M. Effect of fibre loading on mechanical properties of jute fibre bundle reinforced gypsum composites. *Heliyon* **2023**, *9*, e18147. [CrossRef]
56. Romero-Gómez, M.I.; Silva, R.V.; Costa-Pereira, M.F.; Flores-Colen, I. Thermal and mechanical performance of gypsum composites with waste cellulose acetate fibres. *Constr. Build. Mater.* **2022**, *356*, 129308. [CrossRef]
57. Zaragoza-Benzal, A.; Ferrández, D.; Atanes-Sánchez, E.; Morón, C. New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry. *Case Stud. Constr. Mater.* **2023**, *18*, e02178. [CrossRef]
58. Collet, F.; Bart, M.; Serres, L.; Miriel, J. Porous structure and water vapour sorption of hemp-based materials. *Constr. Build. Mater.* **2008**, *22*, 1271–1280. [CrossRef]
59. Castillo Rodríguez, A.P.; García Navarro, J. Gypsum compounds with the addition of post-consumer textile fibres of cotton. *Inf. Construcción* **2023**, *75*, 571. [CrossRef]
60. Vidales-Barriguete, A.; Atanes-Sánchez, E.; Rio-Merino, M.; Piña-Ramírez, C. Analysis of the improved water-resistant properties of plaster compounds with the addition of plastic waste. *Constr. Build. Mater.* **2020**, *230*, 116956. [CrossRef]

61. Poletanovic, B.; Janotka, I.; Janek, M.; Bacuvcik, M.; Merta, I. Influence of the NaOH-treated hemp fibres on the properties of fly-ash based alkali-activated mortars prior and after wet/dry cycles. *Constr. Build. Mater.* **2021**, *309*, 125072. [CrossRef]
62. Guna, V.; Yadav, C.; Maithri, B.R.; Ilangovan, M.; Touchaleaume, F.; Saulnier, B.; Grohens, Y.; Reddy, N. Wool and coir fiber reinforced gypsum ceiling tiles with enhanced stability and acoustic and thermal resistance. *J. Build. Eng.* **2021**, *41*, 102433. [CrossRef]
63. Sair, S.; Mandili, B.; Taqi, M.; El Bouari, A. Development of a new eco-friendly composite material based on gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation. *Compos. Comun.* **2019**, *16*, 20–24. [CrossRef]
64. Álvarez, M.; Santos, P.; Lopes, P.; Abrantes, D.; Ferrández, D. Performance Characterisation of a New Plaster Composite Lightened with End-of-Life Tyres' Recycled Materials for False Ceiling Plates. *Materials* **2022**, *15*, 5660. [CrossRef]
65. Santos, P.; Lopes, P.; Abrantes, D. Thermal Performance of Load-Bearing, Lightweight, Steel-Framed Partition Walls Using Thermal Break Strips: A Parametric Study. *Energies* **2022**, *15*, 9271. [CrossRef]
66. Santos, P.; Ribeiro, T. Thermal Performance Improvement of Double-Pane Lightweight Steel Framed Walls Using Thermal Break Strips and Reflective Foils. *Energies* **2021**, *14*, 6927. [CrossRef]
67. Santos, P.; Lemes, G.; Mateus, D. Thermal Transmittance of Internal Partition and External Facade LSF Walls: A Parametric Study. *Energies* **2019**, *12*, 2671. [CrossRef]
68. Zaragoza-Benzal, A.; Ferrández, D.; Diaz-Velilla, J.P.; Zúñiga-Vicente, J.A. Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria. *Case Stud. Constr. Mater.* **2023**, *19*, e02380. [CrossRef]
69. Moga, L.; Petran, I.; Santos, P.; Ungureanu, V. Thermo-Energy Performance of Lightweight Steel Framed Constructions: A Case Study. *Buildings* **2022**, *12*, 321. [CrossRef]
70. Pedreño-Rojas, M.A.; Morales-Conde, M.J.; Pérez-Galvez, F.; Rodríguez-Liñán, C. Eco-efficient acoustic and thermal conditioning using false ceiling plates made from plaster and wood waste. *J. Clean. Prod.* **2017**, *166*, 690–705. [CrossRef]