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EXPERIMENTAL STUDY ON THE PRODUCTION AND CHARACTERIZATION OF HEMP–BASED INSULATING MATERIALS

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Abstract: The increasing demand for reducing the environmental footprint of the construction sector has led to the development and investigation of alternative bio–based materials. In this context, industrial hemp represents a renewable lignocellulosic resource with significant potential for application in insulating composites. This study investigates the preparation and experimental characterization of hemp–lime composites, with particular emphasis on the influence of mixture composition and particle size distribution on the resulting material properties. Ten experimental formulations were produced using manually processed hemp fibers, followed by microstructural analysis, compressive strength testing, and fire performance evaluation. The results indicate a strong correlation between mixture composition and mechanical performance, as well as favorable behavior under flame exposure. Although the composites exhibit relatively low compressive strength, their performance is adequate for non–structural applications, supporting their suitability as sustainable insulating materials in construction.
Keywords: hemp–lime composites; bio–based materials; thermal insulation

1. INTRODUCTION

The construction sector is one of the major contributors to environmental degradation, due to its intensive consumption of natural resources and the significant amounts of waste and greenhouse gas emissions associated with material production, transportation, and building operation [1]. In recent years, increasing regulatory pressure and global sustainability targets have driven the need for low-impact construction solutions, emphasizing the reduction of carbon emissions, the efficient use of resources, and the integration of circular economy principles [2]. In this context, the transition toward sustainable materials and low-carbon technologies has become a key direction in the development of modern construction systems.

Bio-based materials, derived from renewable resources, have attracted growing interest due to their potential to reduce environmental impact while maintaining or even enhancing functional performance [3]. These materials are characterized by low embodied energy, carbon sequestration capacity, and the possibility of reintegration into natural cycles at the end of their service life [4]. In addition, their use can contribute to improved indoor environmental quality and energy efficiency in buildings, particularly when applied as thermal insulation materials [5].

Among bio-based resources, industrial hemp has emerged as a particularly promising material for construction applications. Hemp is a fast-growing lignocellulosic crop that requires minimal chemical inputs and exhibits a high capacity for CO_2 absorption during its growth cycle, resulting in a potentially negative carbon footprint when incorporated into building materials [6]. From a technical perspective, hemp-based materials exhibit favorable thermal insulation properties, good moisture regulation capacity due to their hygroscopic nature, and resistance to biological degradation, making them suitable for use in building envelopes [7].

In construction practice, hemp is most commonly used in combination with mineral binders, particularly lime, to produce lightweight composite materials known as hemp-lime composites [8]. These materials are characterized by high porosity, low density, and adequate thermal performance, along with a beneficial interaction with moisture, which contributes to the durability and hygrothermal stability of building components [9]. However, the performance of hemp-lime composites is strongly influenced by several factors, including the mixture composition, the binder-to-fiber ratio, the particle size distribution of the hemp shiv, and the processing and curing conditions [10]. These parameters directly affect the internal structure, porosity, and interfacial bonding within the composite, ultimately determining its mechanical, thermal, and fire-related properties.

This paper aims to experimentally investigate the influence of mixture composition and particle size on the properties of a hemp-lime composite material, by developing and testing a series of experimental formulations, in order to assess its potential for use as a sustainable insulating material in construction applications.

2. EXPERIMENTAL METHODOLOGY

Hemp-based insulation material is a composite consisting of the woody core of the hemp stem (shiv) combined with a lime-based binder. The mixture of hemp particles and the lime binder is homogenized in the presence of water, resulting in a material with thermal insulation properties, widely used in the construction sector (Figure 1).

For the laboratory experiments, the woody core of the hemp plant was used, a component that was, until recently, considered a plant residue.

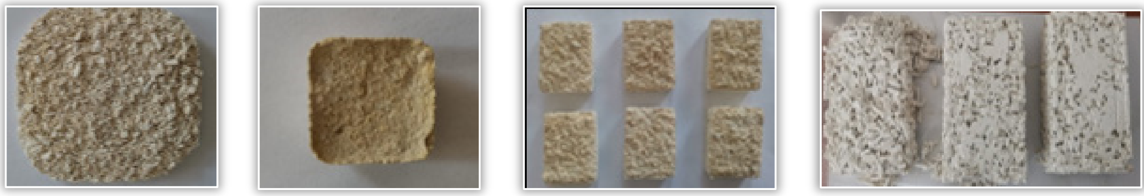

Figure 1. Hemp test specimens

For the laboratory experiments, hemp stems were procured and processed to obtain the fibers manually. Fiber extraction was performed by scoring the stems with a knife and carefully removing the fibers. After the fibers were removed, the remaining hemp stems were shredded using scissors, and the particle size was further reduced using an ultra-centrifugal mill and a ball mill (Figure 2). This procedure resulted in three distinct particle size fractions of the experimental material, which are illustrated in Figure 3.

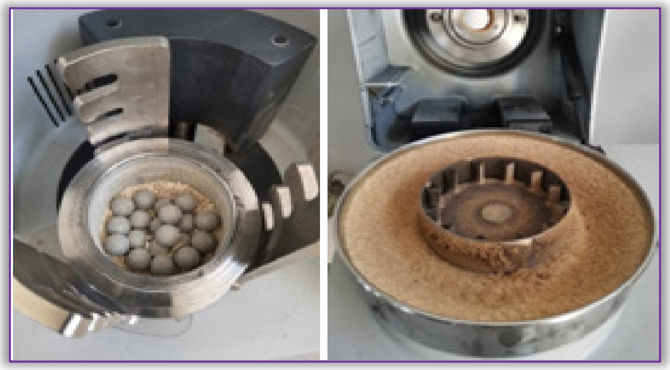

Figure 2. Size reduction of the material using a ball mill and an ultracentrifugal mill

Figure 3. Experimental material

Ten experimental formulations were prepared. To obtain the insulating material, the ground hemp was homogenized with water and lime in varying proportions. The details of the experimental formulations are presented in Table 1.

Table 1. Experimental recipes

Components/Recipe number	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
Hemp	28	25	20	20	53	28	7	33	37	33
Lime	28	30	40	26	18	9	15	17	21	20
Water	44	45	40	54	29	63	78	50	42	47

Recipes R1-R3 incorporated hemp with a particle size of 2-3 mm, whereas recipes R4-R6 and R8-R10 used hemp with a particle size of 0.5-1 mm. Recipe R7 was prepared with hemp particles smaller than 1 mm. The R1-R3 samples exhibited significant differences in consistency and mechanical strength compared to the other recipes. Another factor influencing the mechanical properties of the samples was the type of lime used. For samples R4-R10, hydraulic lime from the industrial construction sector was employed, whereas samples R1-R3 were prepared with commercially available lime. In the case of hydraulic lime, homogenization with water induces an exothermic reaction with heat release, a reaction that did not occur properly with commercial lime.
The obtained samples were dried in molds for 24-72 hours, after which the molds were removed and the samples continued to dry at room temperature for 3-7 days, depending on the size of the mold used.

3. LABORATORY-SCALE TESTING OF THE EXPERIMENTAL MATERIAL, RESULTS AND ANALYSIS

After determining the chemical composition of the experimental recipes, the resulting samples were examined using a stereo microscope and assessed for compressive strength and fire resistance.
The samples were analyzed using a 1.3-megapixel digital stereo microscope, model 520 SZM-D. The resulting images are shown in figure 4.

Figure 4. Samples examined by Stereo microscope

Microscopic analyses of the hemp-based bricks revealed characteristic voids, variations in granulation, and the presence of the incorporated lime-water mixture, which influence the mechanical behavior of the material.
To evaluate compressive strength, the experimental samples were tested using the LabTest 6.50 universal testing machine, equipped with an ASTGmbH KAP-S 50 kN load cell, testing software, flat parallel compression platens, flexible compression platens with spherical joints, and pyramid-grooved grips.
The compressive strength was determined using the following equation:

$$\frac{F}{S} = \frac{N}{L \cdot l} \tag{1}$$

Table 2 presents the initial measurements and observations recorded during the compressive strength testing of the samples.

Table 2. Compression test results

Sample number	Sample size		Breaking section area	Breaking force	Compressive strength
	a	b	A = a x b	"P"	$R_c = P/A$
	[mm]	[mm]	[mm^2]	[N]	[N/mm^2]
1	120	100	12.000	1.770,54	0,15
2	130	90	11.700	1.796,03	0,15
3	110	95	10.450	1.619,47	0,15
4	84	60	5.040	7.157,1	1,42
5	120	100	12.000	2.032,04	0,17
6	83	58	4.814	2.719,63	0,56
7	82	60	4.920	2.290,03	0,47
8	120	100	12.000	2.026,97	0,17
9	110	95	10.450	1.654,14	0,16
10	84	60	5.040	6.445,3	1,28

The analysis of the compressive strength data indicates that recipe R1 exhibits a value of 0.15 N/mm^2 (Figure 5), whereas recipe R4 reaches a significantly higher value of 1.42 N/mm^2 (Figure 6). For recipe R7, the determined compressive strength is 0.47 N/mm^2 (Figure 7).
Compression strength tests showed that the highest value was obtained for sample R4 (1.42 N/mm^2), whereas the lowest values were observed for samples R1-R3 (0.15 N/mm^2).

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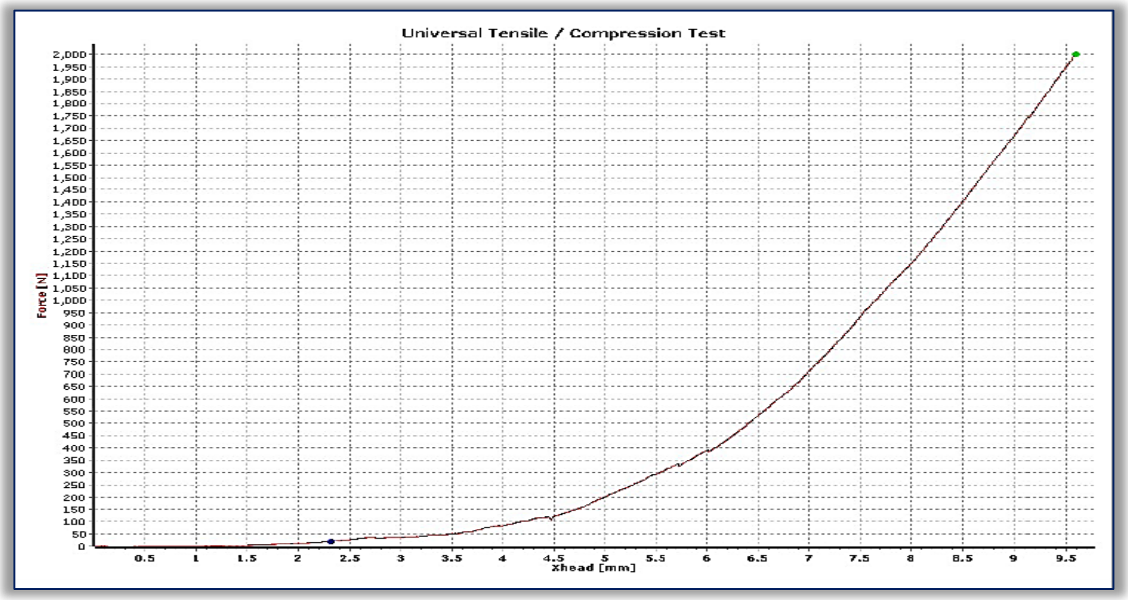

Figure 5. Compressive strength of recipe R1

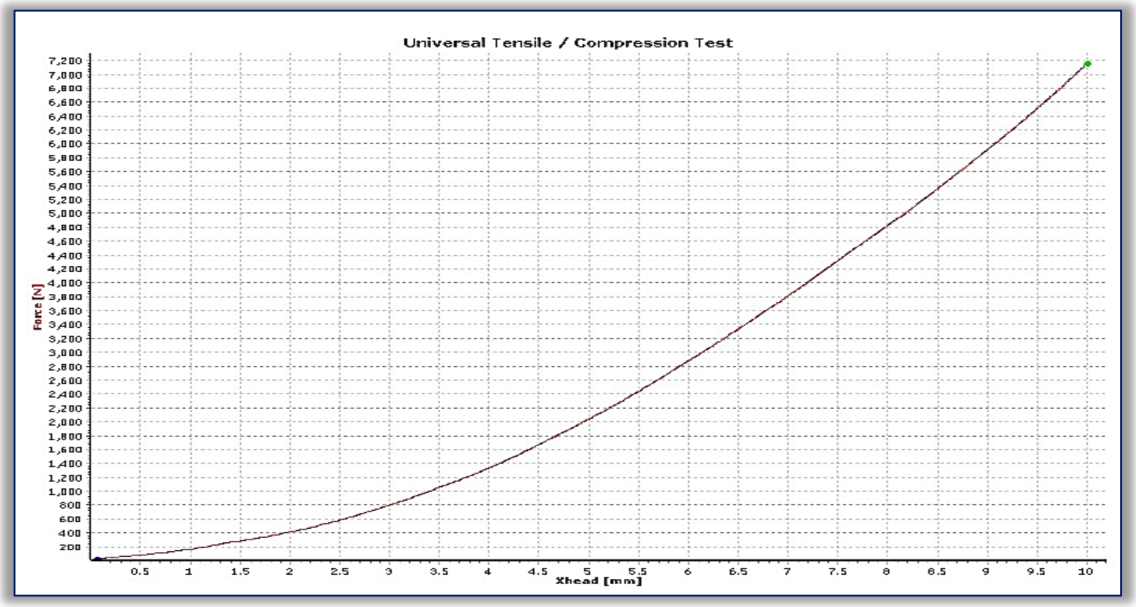

Figure 6. Compressive strength of recipe R4

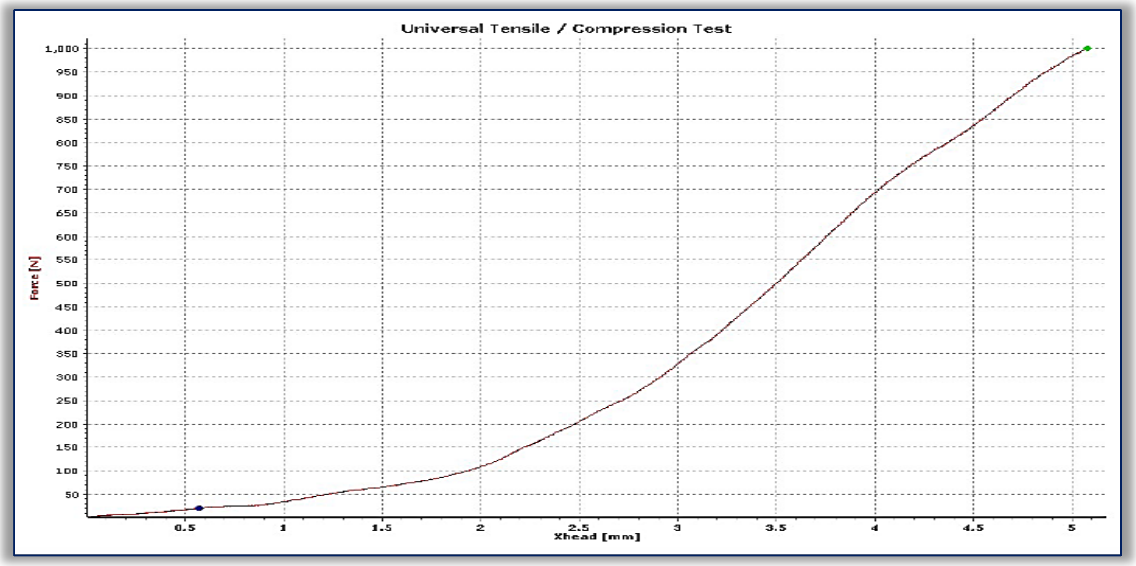

Figure 7. Compressive strength of recipe R7

These compression strength results are consistent with the intended application, considering that a structural wall typically requires a minimum strength of 7.5 N/mm^2. However, this requirement assumes the use of bricks with a thickness of at least 240 mm. The hemp bricks under study are not intended as load-bearing elements but are designed for their excellent insulating properties, which reduces the need for high compressive strength. When installed on a supporting frame, the bricks primarily serve to sustain their own weight.

To evaluate fire resistance, the specimens were exposed to a burner flame for 10 minutes. The results obtained from the tests are presented in Figure 8.

Figure 8. Fire resistance of the tested samples

Fire resistance tests revealed that, although the bricks darkened upon exposure to flame, they did not ignite. A minor mass loss of up to 2% was recorded during burning, indicating that the hemp-based material exhibits high fire resistance.

Despite the evidence of hemp insulation materials being used in construction, these applications remain limited, demonstrating that this is a relatively novel material. Consequently, further research is required to assess its long-term durability and performance.

4. CONCLUSIONS

This experimental study demonstrates the feasibility and potential of hemp-lime composites as sustainable insulating materials in the construction sector. The results highlight that both the mixture composition and particle size distribution of hemp fibers significantly influence the mechanical and thermal performance of the resulting composites. Specifically, finer particle sizes combined with hydraulic lime led to improved compressive strength, while coarser fractions and commercial lime resulted in lower structural performance, yet still adequate for non-load-bearing applications.

Microscopic analyses revealed a heterogeneous internal structure characterized by porosity and variable granulation, which directly affected mechanical behavior. Compression tests indicated a maximum strength of 1.42 N/mm^2, well below structural masonry requirements, confirming that the material is best suited for insulating applications rather than load-bearing elements. Fire resistance tests showed that the hemp-lime samples did not ignite under direct flame exposure, with only minor mass loss, underscoring their high fire performance.

Overall, the study confirms that hemp-based composites represent an environmentally friendly alternative to conventional insulation materials, providing thermal efficiency, fire resistance, and low embodied energy. Despite their low compressive strength, these materials can be successfully integrated into modern construction systems as part of non-structural components, particularly when used in combination with supportive frames. Future work should focus on long-term durability, hygrothermal performance under real-world conditions, and optimization of the binder-to-fiber ratio to enhance both mechanical and insulating properties.

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