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NATURAL FIBRE COMPOSITES IN GREEN CONSTRUCTIONS: EXPERIMENTAL TESTS ON LIME-BASED MORTARS WITH HEMP AND RECYCLED AGGREGATES

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Abstract

In response to the increasing demand for sustainable and low-impact construction materials, this study investigates the mechanical and physical performances of lime-based mortars reinforced with hemp fibres and hurds, agricultural by-products sourced from local Italian cultivation, and recycled aggregates. The research is structured in two experimental phases.
In the first phase, hemp fibres and hurds were incorporated into mortars at three weight percentages (0.25%, 0.50%, and 1.00%) relative to the lime content. Four mix configurations were tested: a control mix without hemp (CNTL), fibre-only (F), hurd-only (H), and a combination of fibres and hurds (F+H). Each mix was evaluated for workability, using the slump test, and for mechanical performance through compressive and three-point bending testing.
Building upon the findings of the initial phase, a second experimental campaign was designed to further investigate the potential of improving mortar sustainability by integrating recycled concrete aggregates into the hemp-reinforced mixtures. In this phase, the selected hemp content, based on optimal compressive strength performance in the first phase, was combined with varying percentages of recycled concrete aggregates to evaluate their joint effect on compressive strength. The objective was to determine whether the use of these secondary raw materials could not only reduce the consumption of virgin resources but also maintain or improve the mechanical performance of the composite material.

Keywords: Green constructions, Hemp, Mechanical tests, Natural fiber composites, Recycled aggregates.

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1 INTRODUCTION

In recent years, the global push toward sustainability and the transition to a green economy have significantly impacted the construction sector, prompting a reevaluation of traditional building materials [1]. As seismic resilience and environmental responsibility become parallel priorities, the integration of natural fibres into construction materials has emerged as a compelling solution [2]. Conventional reinforcements, such as steel, pose environmental concerns due to high resource consumption and emissions [3]. In contrast, natural fibres, derived from renewable plant sources, offer promising mechanical properties, including flexibility and tensile strength, making them suitable alternatives in structural applications [4].

The construction industry has a significant environmental footprint, ranking among the largest consumers of global raw materials and a major contributor to primary energy consumption and CO_2 emissions across all stages of the building lifecycle, from raw material extraction to waste management [5]. These figures highlight the urgent need for environmentally friendly alternatives and more efficient building practices.

In response, researchers have increasingly turned to bio-based materials and renewable components to replace toxic and polluting inputs in construction. Natural fibre composites (NFCs), especially those reinforced with plant-based fibres, are gaining attention for their affordability, biodegradability, and low ecological impact [6]. Their adoption is justified not only by performance metrics, such as high strength and stiffness, but also by the imperative to preserve natural resources and reduce the carbon footprint. Additionally, their use aligns with sustainable agricultural development and supports the "Reuse-Reduce-Recycle" principles [7].

Among natural fibres, hemp has shown particular promise due to its outstanding mechanical and thermal properties [8, 9]. Beyond its structural performance, hemp cultivation is environmentally advantageous as it requires minimal pesticide use and can absorb up to four times more CO_2 per hectare than a forest [10].

This study contributes to that emerging body of work by investigating the mechanical performance of hemp fibres and hurds in lime-based mortars. Two mortar configurations were examined. The first configuration used M5-class lime mortar with varying hemp percentages, which was subjected to three-point bending and compression tests on 4×4×16 cm and 4×4×4 cm specimens, respectively. The second configuration was based on 15×15×15 cm M15 mortar specimens in three configurations: basic (without raw materials), with a fixed percentage of hemp fibres and hurds, and with the same hemp content plus recycled aggregates, to evaluate compressive strength.

2 PHASE 1

2.1 Materials and mix design

The plain mortar was manufactured using a fine-grained structural geo-mortar composed of pure natural NHL range and geo-binder. The mortar falls within resistance class M5 according to the EN 998-2 standard, and CSIII, as per the EN 998-1 classification. Hemp fibres and hurds, derived directly from agricultural waste sourced from a local cultivation in Italy, were incorporated into the matrix in varying percentages. The preparation of the hemp particles involved separating the fibres from the hurds and removing any impurities. The fibres were then combed, and both fibres and hurds were cut to an approximate length of 3 cm (Figure 1).

Figure 1: Hemp fibres (a) and hurds (b).

The amount of water added to the mixture was determined based on the technical data sheet of the premixed mortar and the water absorption capacity of the hemp fibres and hurds. Specifically, before defining the mix design, the absorption capacity of the hemp was assessed by immersing a known weight of dry hemp in water and recording the weight at regular intervals. Water absorption was calculated as the difference between the wet and dry weights. Saturation was considered reached when no further weight increase was observed. This absorbed water was accounted for and included in the total water content of the reinforced mixture.

Various mix designs were tested, including a control mix without hemp (CNTL), mortars reinforced exclusively with fibres (F), mortars reinforced only with hurds (H), and mortars reinforced with both fibres and hurds (F+H). In all cases, three levels of hemp addition were investigated, corresponding to 0.25%, 0.50%, and 1.00% by weight of lime. Table 1 recaps the mix designs implemented.

Table 1: Mix design of phase 1.

ID	Premix [g]	Hemp,tot [%]	Hurd [%]	Hurd [g]	Fibre [%]	Fibre [g]	Water [g]
CNTL	1000	-	-	-	-	-	200.0
F_0.25%	1000	0.25	-	-	0.25	2.50	207.9
F_0.50%	1000	0.50	-	-	0.50	5.00	215.7
F_1.00%	1000	1.00	-	-	1.00	10.00	231.4
H_0.25%	1000	0.25	0.25	2.50	0.00	0.00	204.3
H_0.50%	1000	0.50	0.50	5.00	0.00	0.00	208.6
H_1.00%	1000	1.00	1.00	10.00	0.00	0.00	217.1
F+H_0.25%	1000	0.25	0.13	1.25	0.13	1.25	206.1
F+H_0.50%	1000	0.50	0.25	2.50	0.25	2.50	212.1
F+H_1.00%	1000	1.00	0.50	5.00	0.50	5.00	224.3

2.2 Workability tests

Among the various available testing methods, this study utilized a shaking table to evaluate the workability of the mixtures, following the procedure specified in the UNI 7044 standard. The primary aim of this test was to assess the spread of the mortar by observing its flow behavior under vibratory motion. After subjecting the mortar to 15 shakes, the spread was measured by averaging two orthogonal diameters. The results of the workability tests for all analyzed mixtures are presented in Figure 2.

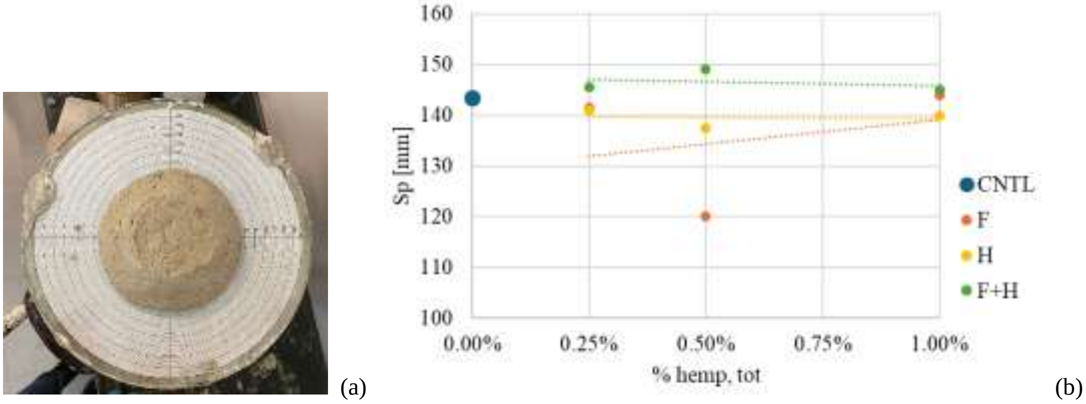

Figure 2: Workability test execution (a) and results (b), with the linear trend indicated by a dashed line – phase 1.

Fibre-only mortars (F) show an increasing trend, with workability improving as fibre content rises. In contrast, hurd-only mixes (H) demonstrate a slightly decreasing but overall stable trend. The combination of fibres and hurds (F+H) maintains the highest and most consistent workability among the hemp-reinforced mixes, despite a mild downward trend.

2.3 Three-point bending tests

The mechanical testing began with the evaluation of flexural strength through three-point bending tests, conducted after 28 days of curing on 40×40×160 mm prismatic specimens prepared in accordance with the UNI EN 196-1 standard. Three specimens were prepared for each mix design. The average flexural strength results for each mix design, relative to increasing hemp content, are presented in Figure 3, which also includes images of a specimen during testing and after failure.

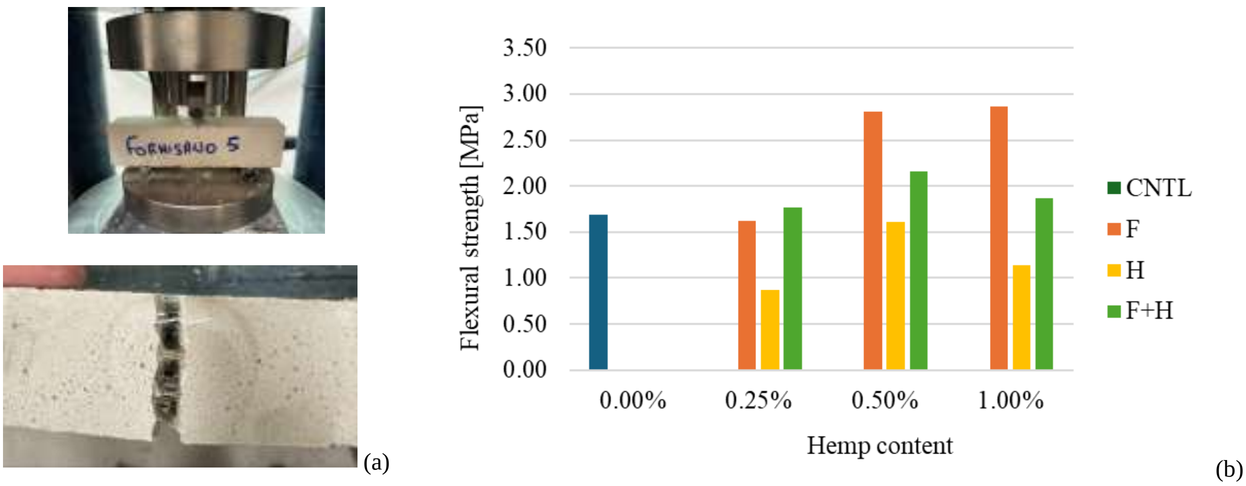

Figure 3: Three-point bending test execution (a) and results (b) – phase 1.

The results indicated that mortars reinforced exclusively with hemp fibres exhibited an increase in flexural strength with rising fibre content. This strength was higher than that of the control mortar for all fibre contents except at 0.25%. Notably, the highest flexural strength among all tested mixes was recorded for the mortar containing 1.00% hemp fibres with a 69.2% increase compared to the control mix.

In contrast, mortars reinforced solely with hemp hurds showed a reduction in flexural strength compared to the control, indicating that hurds alone may not contribute positively to tensile resistance. Finally, the mortars incorporating both fibres and hurds exhibited intermediate behaviour, with flexural strength values consistently exceeding those of the control mix. The best performance in this category was observed for the mixture with a total hemp content of 0.50% (0.25% fibres and 0.25% hurds), which achieved a maximum flexural strength increase of 27.8% compared to the control specimen.

2.4 Compression tests

One of the two halves of each prismatic specimen, obtained after the flexural strength test, was subsequently used to perform compressive strength tests on the mortar mixes. The average compressive strength results for each mix design, relative to increasing hemp content, are presented in Figure 4.

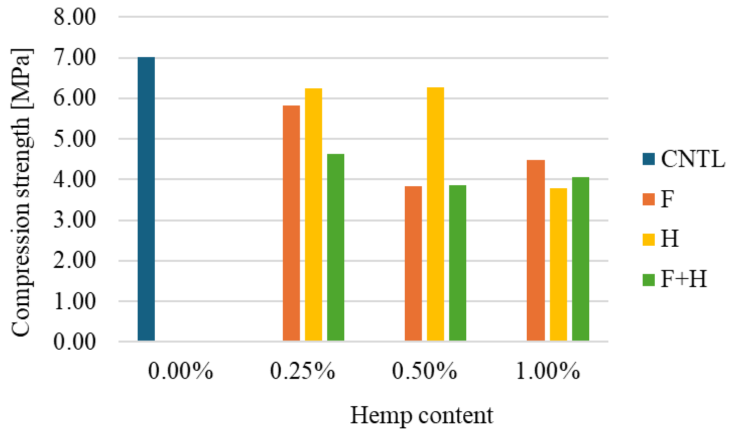

Figure 4: Compression test results – phase 1.

The results indicated that all mortars mixes containing hemp exhibited lower compressive strength compared to the control mixture. In general, a decreasing trend in compressive strength was observed with increasing hemp content across all configurations. The smallest reduction was recorded for the mix containing 1.00% hemp hurds, which showed a 46% decrease compared to the control. Among the tested formulations, only the mixes reinforced with 0.25% and 0.50% hemp fibres maintained a compressive strength above 5 MPa, thus preserving the M5 classification of the mortar useful for seismic applications. Furthermore, the mixtures incorporating both hemp fibres and hurds demonstrated an almost stable compressive strength regardless of the total hemp content, indicating a balanced mechanical response when both components are combined.

3 PHASE 2

3.1 Materials and mix design

The plain mortar was manufactured using a coarse-grained structural geo-mortar composed of pure natural NHL range and geo-binder. The mortar falls within resistance class M15 according to the EN 998-2 standard, and R1, as per the EN 1504-3 classification. For the hemp-reinforced formulation, the mix containing 0.50% of both hemp fibres and hurds was selected based on the outcomes of the previous experimental phase. This choice was guided not only by the overall performance in terms of physical and mechanical properties, but also by practical considerations. Specifically, using both fibres and hurds in combination eliminates the need to separate the components, offering a more efficient and scalable approach for utilizing agricultural waste in large-scale production. In the second phase of the research, the addition of recycled aggregates was also tested in the hemp-reinforced mortar formulation. These aggregates were sourced from the demolition of existing buildings, aligning with circular economy principles and aiming to further enhance the sustainability of the mix.

Therefore, three mix designs were tested, including a control mix without hemp (CNTL), mortars reinforced with fibres and hurds (F+H), and mortars reinforced with fibers, hurds and recycled aggregates (A+F+H). Table 2 summarizes the mix designs used.

Table 2: Mix design of phase 2.

ID	Premix [g]	Hurd [%]	Hurd [g]	Fibre [%]	Fibre [g]	Aggregates [%]	Aggregates [g]	Water [g]
CNTL	25000	-	-	-	-	-	.	5100
F+H_0.5%	25000	0.25	62.5	0.25	62.5	-	-	5641
A+F+H_0.5%	25000	0.25	62.5	0.25	62.5	25	6250	5641

3.2 Compression tests

Three specimens for each mix design, measuring 15×15×15 cm, were prepared to perform compressive strength tests after 28 days of curing. The average results for each mix are presented in Figure 5, accompanied by images of a specimens during the test and after failure to illustrate the fracture patterns.

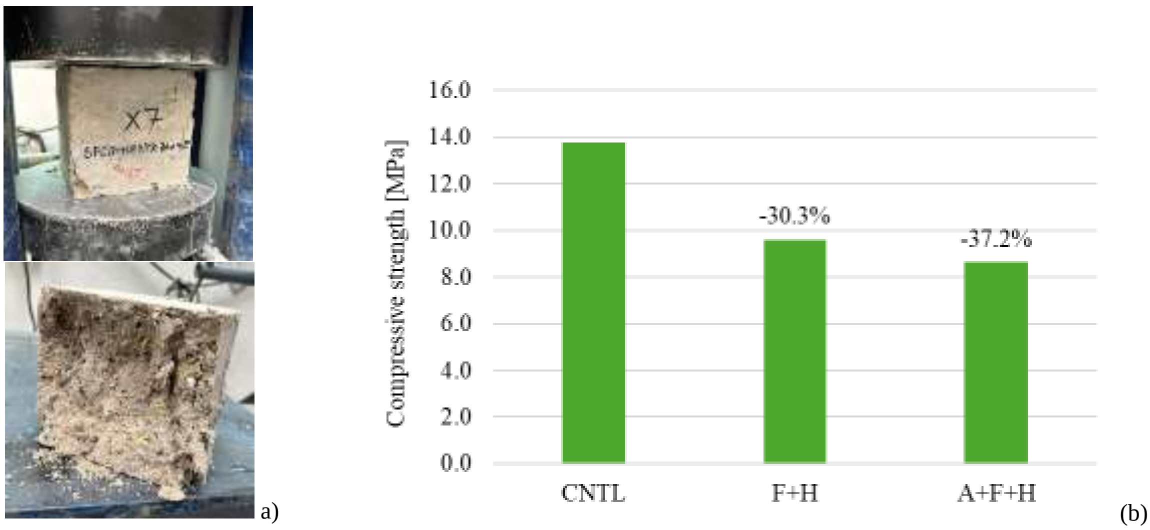

Figure 5: Compression test execution (a) and results (b) with labels indicating strength variations compared to control specimen – phase 2.

The results indicated that the inclusion of hemp in the mortar led to a reduction in compressive strength. Specifically, the control mixture achieved an average compressive strength of 13.8 MPa. In comparison, the mix containing only hemp fibres and hurds reached 9.6 MPa, while the mix incorporating both hemp and recycled aggregates recorded 8.7 MPa. The greater reduction observed in the latter suggests that the addition of recycled aggregates further compromises compressive strength. However, since it remains above 5 MPa, it can still be effectively used as a sustainable seismic block. These findings highlight the need for future research to recalibrate and optimize the proportions of recycled aggregates in order to achieve compressive strengths comparable to or exceeding that of the control mix.

4 CONCLUSIONS

This study explored the potential of using natural fibers and recycled materials to develop sustainable lime-based mortars with improved mechanical performance and reduced environmental impact. Specifically, it assessed the incorporation of hemp fibers and hurds, locally sourced agricultural by-products, along with recycled aggregates from building demolition waste. The research was divided into two experimental phases, each providing valuable insights into the behavior of these eco-friendly materials in structural applications.

In Phase 1, M5 lime-based mortars were prepared with varying amounts of hemp fibers and hurds in different configurations: fiber-only (F), hurd-only (H), and a combination of both (F+H). These mixes were compared against a control mix without hemp. Workability tests showed that fiber-only mortars exhibited improved flowability as the fiber content increased, while hurd-only mixes showed a slight decrease. The combined fiber-hurd mix demonstrated the most consistent workability across all percentages, indicating a balanced influence of both components on fresh-state behavior.

Flexural strength results revealed that hemp fibers positively contributed to the tensile resistance of the mortar. The mix with 1.00% fiber achieved the highest flexural strength, showing a 69.2% increase compared to the control. In contrast, the addition of hurds alone resulted in reduced flexural strength, while the F+H mixes showed intermediate values, with a notable 27.8% increase at the 0.50% content (0.25% fibers + 0.25% hurds).

However, compressive strength results highlighted the trade-off between sustainability and mechanical performance. All hemp-reinforced mortars exhibited a decrease in compressive strength compared to the control, with strength diminishing as hemp content increased. Notably, the F+H configuration showed stable behavior across different hemp contents, indicating a more uniform internal structure when both fibers and hurds were combined.

In Phase 2, based on the promising performance of the 0.50% F+H mix in Phase 1, a new series of M15-class mortars were developed, incorporating this mix both with and without recycled aggregates. Compressive strength tests confirmed that the addition of hemp alone reduced strength from 13.8 MPa (control) to 9.6 MPa. When recycled aggregates were added, compressive strength dropped further to 8.7 MPa, but the resistance remained above the 5 MPa threshold, which is the minimum requirement for blocks used in seismic areas. Therefore, further optimization of mix design, particularly the proportion of aggregates, will be explored in future research to improve or match the performance of traditional mortars.

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