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Sheep Wool Composite Mortar for Thermo-Mechanical Retrofitting

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Abstract

The construction sector plays a significant role in heavy resource consumption and waste production, directly or indirectly leading to environmental pollution or ecosystem disruption. In efforts to reduce the sector's carbon footprint and combat climate change's effects, the use of sustainable and eco-friendly building materials is gaining importance. This study highlights the integration of locally available (Sardinian) sheep wool fibres into mortar as an alternative construction product. Experimental findings indicate that incorporating sheep wool enhances the flexural strength of the mortar, suggesting improved durability under bending forces compared to conventional mortar mixtures. However, this addition results in a slight reduction in both compressive strength and thermal conductivity. While a decrease in compressive strength may suggest limitations for specific load-bearing uses, the lower thermal conductivity indicates better insulation properties. Notably, this improvement in thermal performance highlights the boost in the insulation property of the composite mortar. The results show that the composite mortar fabricated with sheep wool fiber can provide an optimum balance between structural performance and improved insulation properties, if selected for integrated retrofitting.

Keywords: thermo-mechanical retrofitting, thermo-mechanical properties, composite mortar, sheep wool, natural fiber, circular economy.

1 Introduction

Climate change, largely driven by greenhouse gas emissions, is heavily influenced by the carbon footprint associated with human activities. Among the primary contributors is the construction and building (C&B) sector, which is responsible for a significant portion of global emissions—estimated at around 39% worldwide. Within the European Union (EU), the sector's share is similarly high, contributing approximately 36% of total emissions [1].

The construction sector has a significant environmental impact, not only due to direct emissions during construction but also because of its substantial energy consumption. Globally, construction accounts for about 36% of total energy use, and this figure rises to nearly 40% in the European Union [2]. The use of more sustainable building materials, like natural fiber composite materials, can reduce energy consumption and emissions throughout the lifecycle of a building, therefore minimizing the environmental effects of construction practices.

By transitioning to eco-friendly alternatives, the industry can significantly contribute to achieving climate goals and easing the strain on natural ecosystems.

In recent years, the use of natural fibre composite building materials has become a hot topic among various research groups [3–6]. Notably, there is an urgent need for sustainable, eco-conscious, green, renewable, and biodegradable construction materials with adequate thermal and mechanical properties.

Studies have demonstrated that the natural fibre composites offer dual benefits, they reduce environmental impact while improving mechanical/structural performance and thermal efficiency [7,8]. As the construction industry shifts toward more sustainable practices, incorporating natural fiber reinforcements emerges as a promising option. This approach supports the global sustainability goals and offers a practical response to the growing demand for high-performance, low-impact building materials.

This integrated strategy aims to broaden the use of natural fibres in construction, offering an environmentally responsible method to improve overall building performance [9]. The study presented in this paper centres on an experimental evaluation of the thermo-mechanical behaviours of mortars reinforced with natural fibres. The Sardinian sheep wool fibres are incorporated into a natural hydraulic mortar matrix, aligning with the goal of developing sustainable and high-performing building materials.

The structure of the paper is as follows: Section 1 introduces the topic, Section 2 describes the materials and methods adopted for testing. Section 3 presents the experimental results. Finally, the conclusive remarks are summarized in section 5.

2 Materials and Methods

2.1. Materials

During this experimental campaign, the thermo-mechanical properties of the composite mortar specimens made using Tarmac Limelite Natural Hydraulic Lime (NHL-5), natural sand, and Sardinian sheep Wool (SW) fibres have been evaluated, as illustrated in Figure 1. To study the effect of sheep wool fibre incorporation, the thermo-mechanical properties of the fiber-reinforced mortar samples were tested and compared against control samples made without any fiber reinforcement. The comparative analysis aimed to evaluate thermal insulation and mechanical performance variations.

(a) *(b)* *(c)*

Figure 1. (a) NHL(5), (b) sheep wool, and (c) sand

Table 1 outlines the different mix ratios used in the preparation of the sheep wool composite mortar samples, providing a clear overview of the formulation parameters explored during testing.

Sample nomenclatures	Binder used	Aggregates used	SW Fiber percentage used
Reference Sample	NHL5	sand	0% by Vol
S1	NHL5	sand	1.0% by Vol
S1.5	NHL5	sand	1.5% by Vol
S2	NHL5	sand	2.0% by Vol

Table 1. Compositions of reference and fiber-reinforced composite mortar samples.

2.2. Water absorption test

For the preparation of the SW composite mortar, the SW fibres were first submerged in water until fully saturated, ensuring optimal integration into the mix. This was done due to the fact that natural fibres need certain hours to get saturated; therefore, when they are used in a mixture instantaneously and the water is added, the fibres tend to form fiber balls and do not distribute uniformly in the mixture. It has been found experimentally that SW fibres get saturated after about 2 hours from the time of immersion, and 5 g of SW fiber can approximately absorb 88% of water when fully saturated.

F_{Dry}	Water absorbed percentage
g	%
5	88

Table 1. SW fiber water absorption percentage when fully saturated.

Therefore, to avoid all aforementioned problems, it has been decided to use fully saturated SW fibres for composite mortar preparation. The grout has been prepared following the standard EN 1015-2[10], a shaking table test was employed to evaluate the workability (EN 1015-3 [11]) of the mortar. Specimens were cast using a hollow conical bronze mold. To ensure even distribution of the material, 15 strokes were applied to the mix after the mold was half-filled. Once fully filled, another 15 strokes were performed before the excess mortar was levelled off and the mold carefully removed. Subsequently, the shaking table was operated for 15 cycles at a frequency of one rotation per second to simulate workability conditions. The resulting spread of the mortar was then measured along two orthogonal diameters using a digital vernier calliper. To maintain consistency and reliability in the testing procedure, a tolerance of ±10% between measurements was allowed; if the spread fell outside this range, the test was repeated to ensure the accuracy and uniformity of the mortar mixtures.

(a) (b)

Figure 2. (a) Dry SW fiber, and (b) Saturated SW fiber.

Two distinct mold types were employed for fabricating the test specimens, accommodating both fiber-reinforced and non-reinforced mortar mixes. Specimens measuring 160 mm × 40 mm × 40 mm (Figure 3.a) were designated for mechanical testing, including flexural and compressive strength assessments. Larger specimens, sized at 160 mm × 140 mm × 40 mm (Figure 3.b), were prepared for evaluating thermal conductivity.

(a) (b)

Figure 3. (a) Mechanical test samples, and (b) Thermal conductivity test sample.

During the casting process, special care was taken to eliminate entrapped air, which could affect the integrity of the results. Mechanical test samples received 25 uniform tamping strokes, while thermal conductivity samples, due to their larger volume, were compacted with 75 strokes. This step ensured consistent compaction and minimized internal voids, contributing to reliable and reproducible test outcomes.

2.3. Mechanical and Thermal properties

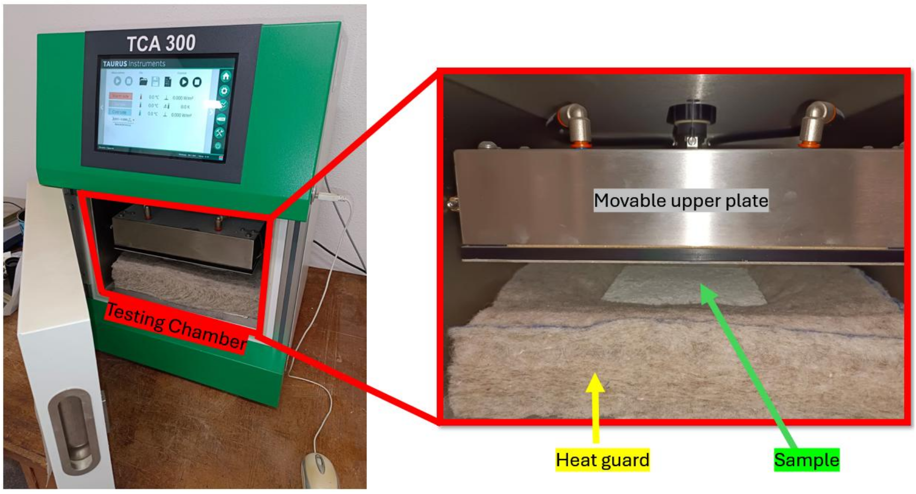
The mechanical and thermal properties of the mortar samples were evaluated following recognized international standards to ensure accuracy and reliability. Flexural and compressive strength tests (Figure 4) were performed in accordance with EN 1015-11[12], while thermal conductivity assessments adhered to ISO 8301:1991 [13], EN 12939 [14]. Flexural strength tests were carried out using the three-point bending method on prismatic specimens measuring 160 mm × 40 mm × 40 mm, and for this, a universal testing machine operating in displacement-controlled mode was used, set at a loading rate of 1.5 mm/min. The equipment featured a maximum load capacity of 4.9 kN and a sensitivity of 0.02 kN, enabling precise measurement of load-deflection behaviours and ensuring accurate determination of flexural strength. Following the flexural tests, compressive strength was measured using the fractured halves of the same specimens. These tests were performed with a Metrocom-2 universal load-controlled testing machine. It has a maximum capacity of 100 kN.

(a) (b)

Figure 4. Mechanical tests: (a) Flexural test, and (b) Compression test.

The thermal conductivity of both plain mortar and sheep wool fiber-reinforced composite samples was measured using a heat flow meter (TAURUS TCA 300), as shown in Figure 5.a. This device features hot and cold plates, each with a total surface area of 300 mm × 300 mm.

The measuring active zone is located at the centre of each plate, which is a 100 mm × 100 mm, and they are equipped with a symmetrically positioned heat flux sensor, allowing for precise measurement of heat transfer. Surrounding these active zones are protective areas designed to minimize losses and ensure stable thermal conditions during testing. Measurements were carried out over a 300-minute period, with thermal conductivity values recorded at one-minute intervals, providing detailed and time-resolved data. To ensure accuracy, all samples were oven-dried at 50°C prior to testing, following the procedure outlined in [15]. Drying times varied from 5 to 14 days, depending on the initial moisture content of the samples. Samples were dried as even slight residual moisture can greatly affect the thermal conductivity value of the specimen. By standardizing the moisture content across all specimens, the test ensured that the measured values accurately represented the inherent thermal performance of the materials under dry conditions. Samples were placed inside a woollen heat-guard (Figure 5.b) to have mono-directional heat flow, and minimize heat loss due to edging effect.

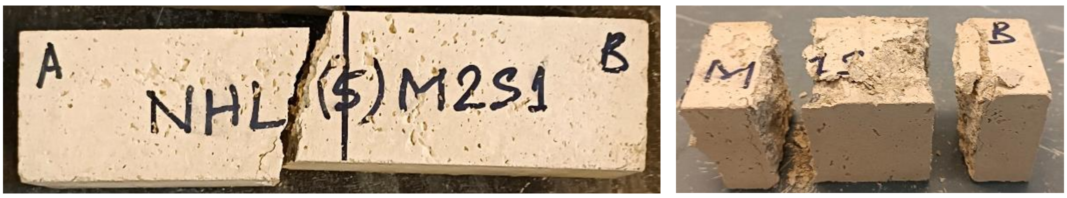


(a) (b)

Figure 5. Thermal conductivity test: (a) Heat flow meter, and (b) Sample placed inside the testing chamber.

3 Results

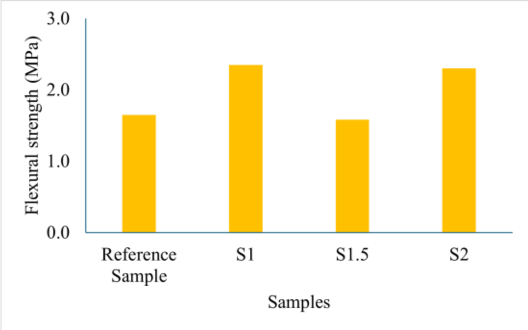
Figure 6 shows the one of the reference samples without fiber after flexural (Figure 6.a) and compressive (Figure 6.b) collapse.



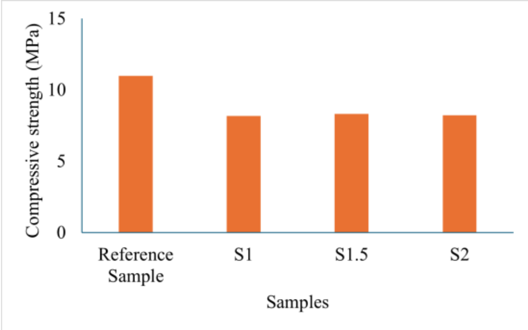
(a) *(b)*

Figure 6. Samples after (a) flexural and (b) compressive collapse.

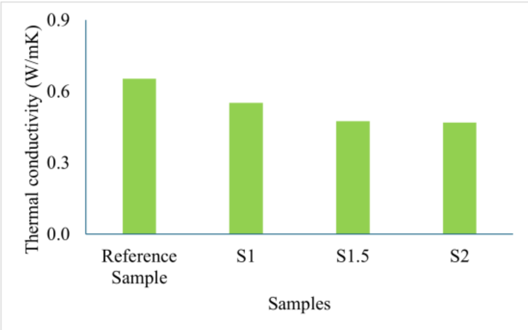
Figure 7 presents the comparative evaluation of composite samples containing sheep wool fibres at different weight percentages 1% (S1), 1.5% (S1.5), and 2% (S2) alongside a reference sample without any fiber. The analysis focuses on three key parameters: flexural strength (Figure 7a), compressive strength (Figure 7b), and thermal conductivity (Figure 7c).



(a)



(b)



(c)

Figure 7. Samples without (Reference) and with sheep wool fiber (Composite samples): (a) Flexural strengths, (b) Composite strengths, and (c) Thermal conductivity values.

The flexural strength results shown in Figure 7a indicate a clear trend of improvement with the addition of sheep wool fibres. With the addition of 1% fiber (S1), the flexural strength increased by 0.70 MPa with respect to the reference sample, indicating improved resistance to bending. Interestingly, at 1.5% fiber content (S1.5), the flexural strength slightly decreased by about 0.70 MPa, possibly due to poor fiber dispersion or localized agglomeration that reduces effective stress transfer. However, at 2% fiber content (S2), the flexural strength improved by about 0.65 MPa.

Interestingly, the compressive strength results, shown in Figure 7b, follow a slightly different pattern. In all cases, a reduction in compressive strength was observed when compared with the reference sample. At 1% fiber content (S1), at 1.5% fiber (S1.5), and 2% fiber content (S2), the compressive strength decreased by about 2.80 MPa, 2.66 MPa, and 2.75 MPa, respectively. This drop in compressive strength can be attributed to voids or weak fiber-matrix bonding.

Thermal conductivity data in Figure 7c reveal a consistent and favourable trend with fiber addition. The reference sample exhibited the highest thermal conductivity. After adding 1% fiber (S1), the thermal conductivity dropped significantly by about 0.101 W/m·K. While this decrease is about 0.179 W/m·K in the case of samples with 1.5% fiber (S1.5). The highest reduction of about 0.184 W/m.K has been observed for samples with 2% (S2) fibre content. This demonstrates the effective insulating properties of wool fibres, likely due to their natural hollow structure and ability to trap air.

In summary, incorporating sheep wool fibres has demonstrated improvements in flexural strength and thermal insulation properties. The compressive strength was slightly affected by the addition of fibres. These findings demonstrate the potential of sheep wool fiber as a sustainable additive in composite materials, especially when an optimal balance of mechanical strength and thermal performance is required.

4 Conclusions

This study confirms the potential of sheep wool fiber-reinforced mortar as a sustainable solution for thermo-mechanical retrofitting in the construction sector. Flexural strength and thermal insulation improvements were observed by incorporating Sardinian sheep wool fibres into a natural hydraulic lime mortar matrix. The highest flexural strength occurred at 2% fiber content, while optimal thermal performance was achieved at 1.5%. Although compressive strength slightly decreased, it remained within acceptable limits for non-load-bearing applications.

The results obtained from this experimental campaign suggests that the correct composition of composite mortar can effectively balance mechanical performance and improve insulation properties, making it suitable for retrofitting existing masonry. Additionally, using a renewable, biodegradable, and locally sourced material like sheep wool supports circular economy principles. Further, using greener building materials can lower the overall environmental impact. With appropriate fiber dispersion and processing, this natural fiber composite presents a promising option for sustainable building upgrades and conservation projects.

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