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SUSTAINABLE UNFIRED CLAY MASONRY INCORPORATING AGRICULTURAL WASTE: PHYSICAL AND MECHANICAL PROPERTIES

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Abstract

Sustainable societal development requires practical solutions that promote the use of traditional and locally available materials, particularly for vulnerable rural communities. In this context, unfired clay represents an environmentally friendly construction material due to its low embodied energy, recyclability, and local availability. Compared to conventional fired materials, it reduces energy consumption and environmental impact, supporting sustainable construction practices. At the same time, the valorization of plant-based waste generated by agricultural and wood-processing activities represents an effective strategy for improving resource efficiency and reducing environmental pollution. According to the National Institute of Statistics, agriculture accounted for approximately 2.5% of Romania's GDP in 2025 and generated over 50% of total municipal waste as vegetal residues. As consumption increases, the management of such waste becomes increasingly challenging, while its decomposition releases greenhouse gases such as methane, contributing to climate change. The incorporation of plant-based waste into clay-based construction materials represents a promising approach for waste valorization and the development of sustainable building materials. This study investigates the effect of hemp fibers and sawdust on the physical and mechanical properties of unfired clay mixtures.

Key words*: hemp fibers, plant-based waste, sawdust, sustainable construction, unfired clay.*

INTRODUCTION

The development of sustainable construction materials has become a strategic research direction in civil engineering, driven by the urgent need to reduce the environmental impact of the construction sector and to address the growing challenges associated with global climate change (Hegyi et al., 2016). Over the past decades, the construction industry has been identified as a major contributor to global greenhouse gas emissions, both through the industrial processes involved in material production and through the extensive consumption of natural resources required for construction activities.

In particular, the production of conventional construction materials such as cement and fired bricks involves energy-intensive technological processes that generate significant amounts of carbon dioxide emissions. These environmental concerns have stimulated increasing research efforts aimed at identifying alternative construction materials and technologies capable of reducing environmental impact while maintaining adequate structural performance and energy efficiency (Bradu et al., 2025).

Within this context, the use of locally available natural materials has gained considerable attention as part of sustainable construction strategies. Materials such as unfired earth, wood, and other natural resources offer significant advantages in terms of reduced embodied energy and lower carbon footprint during production. Moreover, the use of local materials reduces transportation-related environmental impacts and facilitates the adaptation of buildings to specific climatic and geographical conditions (Walker et al., 2005; Minke, 2012).

Masonry elements produced from natural materials such as clay soil, sand, local aggregates, and plant-based waste represent one of the oldest construction technologies used

worldwide (Hegyi et al., 2023). These materials provide several sustainability-related advantages, including local availability, low energy consumption during processing, recyclability, and environmental compatibility. In addition, unfired clay masonry elements contribute to improved hygrothermal comfort in buildings due to their ability to regulate indoor humidity and their high thermal inertia, which helps stabilize indoor environmental conditions (Houben & Guillaud, 1994; Tomaževič, 1999).

The use of clay soil for masonry construction has a long tradition in Romania, particularly in rural areas where traditional building techniques have been developed according to local climatic conditions and available resources (Petcu et al., 2023). The geological diversity of Romania provides significant reserves of clay soils, sands, and natural aggregates that can be utilized for producing environmentally friendly masonry materials (Calatan et al., 2020).

At the same time, the agricultural sector and the wood-processing industry generate considerable amounts of plant-based waste, including sawdust resulting from timber processing and hemp fibers obtained from the cultivation of this traditional crop (Mircea et al., 2021). The incorporation of these materials into masonry compositions can lead to the development of natural composite materials with improved thermal insulation performance and enhanced mechanical behavior. Furthermore, this approach supports the valorization of renewable resources while reducing the amount of biodegradable waste that could otherwise contribute to greenhouse gas emissions during decomposition (Walker et al., 2005; Ashour et al., 2010).

Hemp is characterized by high ecological adaptability, being able to grow under a wide range of climatic and soil conditions without requiring intensive use of fertilizers or pesticides. Due to its ability to absorb and neutralize certain soil contaminants, hemp cultivation can contribute to reducing soil pollution and improving soil quality. In addition, the deep root system of this plant improves soil structure and promotes aeration, facilitating the development of subsequent agricultural crops (Binici et al., 2007).

Moreover, hemp plays an important role in carbon sequestration, capturing atmospheric carbon dioxide from the early stages of plant growth. Hemp-based products are non-toxic, biodegradable, and renewable, making them particularly attractive for the development of sustainable construction materials (Lachheb et al., 2023).

Historically, Romania was one of the major global producers of industrial hemp. In the 1990s, with a production exceeding 72,000 tons, Romania ranked third worldwide in hemp production. However, increasingly restrictive regulations significantly reduced interest in this crop. In recent years, a gradual revival of hemp cultivation has been observed in Romania, supported by investments in processing facilities, access to European Union funding, and its higher economic potential compared to traditional crops such as cereals and oilseeds (Neacșu, 2022).

In parallel, Romania has a well-developed forestry and wood-processing sector, generating significant quantities of wood residues, particularly sawdust. This type of waste represents an important resource within the framework of the circular economy and is increasingly used in various applications, including energy production, wood-based panel manufacturing, and sustainable construction materials (Bailly et al., 2024). The incorporation of sawdust into construction materials contributes both to the efficient reuse of industrial by-products and to the improvement of certain physical properties such as density reduction and enhanced thermal insulation.

In recent years, increasing research interest has been directed toward the use of sawdust in ecological construction materials. The integration of this by-product into building materials not only facilitates the valorization of wood waste but also improves certain physical and mechanical properties of composite materials. Furthermore, this approach supports the development of locally sourced, low-cost construction materials while promoting environmentally sustainable building solutions, particularly in rural areas (Toader et al., 2025).

Despite the growing interest in plant-based additives for earthen construction materials, limited research has been conducted on the combined use of locally available clay soils with vegetal residues such as sawdust and hemp fibers in masonry elements. In particular, there

is still insufficient experimental data regarding the influence of these additives on the physical and mechanical properties of clay-based composites produced from locally available materials.

Therefore, the present study aims to investigate the influence of plant-based waste additives on the performance of clay masonry materials. A comparative experimental study was conducted on clay-based compositions intended for masonry elements, produced from locally available sustainable materials and modified by the addition of plant-based waste in the form of sawdust and hemp fibers. The main objective of this research is to evaluate the influence of these vegetal additives on the physical and mechanical properties of the resulting composites and to identify sustainable construction solutions based on locally available natural resources.

MATERIALS AND METHODS

The mixtures used for the production of masonry elements were composed of locally available materials, including clay soil, sand, aggregates, and agricultural waste in the form of sawdust and hemp fibers, together with a natural additive (Figure 1). The formulations of the mixtures are presented in Table 1.

Table 1. Composition of the evaluated clay-based mixtures

Constituents	Unit	S1	S2	H1	H2
Clay soil	g	10,758	10,758	10,758	10,758
Sand 0-1 mm	g	220	220	220	220
Sand 0-4 mm	g	2,289	2,289	2,289	2,289
Aggregate 4-8 mm	g	2,102	2,102	2,102	2,102
Hemp	g	-	-	1,537	3,074
Sawdust	g	1,537	3,074	-	-
Additive	g	107.6	107.6	107.6	107.6
Clay/water ratio	-	0.28	0.29	0.28	0.22
Spread	mm	108.9	106.9	110.6	105.1

The clay soil used as a binder consisted of 52% clay fraction, 44% silt, and 4% sand.

The sand incorporated into the clay mixture was coarse construction sand with particle size distributions of 0-1 mm and 0-4 mm. In addition, natural alluvial aggregates with particle sizes ranging from 4 to 8 mm were used.

The amount of water was determined experimentally for each mixture in order to ensure optimal workability of the fresh material. To obtain smoother and more uniform surfaces of the self-supporting elements and to improve the workability of the mixtures, rabbit glue was used as a natural additive. This additive enhances the elasticity and cohesion of the clay matrix.

Plant-based waste in the form of hemp fibers and sawdust was incorporated into the material composition as additives in order to valorize renewable resources.



a) Hemp fibers



b) Sawdust



c) Rabbit glue

Figure 1. Constituent materials

The incorporation of fibers in a saturated state improves the adhesion between the fibers and the clay matrix. Moistening the fibers helps eliminate entrapped air, reducing the risk of void formation and ensuring a stronger bond between the constituent materials.

The preparation of the clay mixture followed several stages. First, the clay soil and the vegetal waste were mixed in a large container until a homogeneous mixture was obtained. The rehydrated rabbit skin glue was dissolved in the required amount of water and added to the composition, while mixing continued until a uniform consistency was achieved. Finally, sand with particle sizes of 0-1 mm and 0-4 mm, together with aggregates (4-8 mm), were added to the mixture, and mixing was continued until a homogeneous texture was obtained.
The consistency of the fresh clay mixture was determined according to SR EN 1015-3:2001/A2:2007 (Figures 2 and 3).



a) 10% sawdust content



b) 20% sawdust content

Figure 2. Spread of the clay mixture with sawdust addition

The principle of this method is as follows: the conical mold is placed on the circular flow table, using a manual flow table manufactured by MATEST (Italy), and filled with the fresh mixture in two layers. Each layer is compacted using a metal tamper. After removing the mold, 15 drops are applied to the flow table within 15 seconds, after which the average diameter of the spread specimen is measured.



a) 10% hemp fiber content



b) 20% hemp fiber content

Figure 3. Spread of the clay mixture with hemp fiber addition

The mixture was cast into standardized molds, using cubic molds for concrete sample preparation manufactured by UTEST (Turkey), with dimensions of 150 × 150 × 150 mm, intended for compressive strength testing after 28 days. In addition, part of the mixture was cast into molds measuring 300 × 300 × 50 mm for thermal conductivity testing.
The specimens were demolded after 5 days and conditioned at a temperature of 23 ± 5°C. The stages of specimen preparation are illustrated in Figure 4.
The drying time of the specimens varies depending on the mixture composition and environmental conditions. Mixtures containing sawdust or hemp tend to require a longer drying period due to their higher moisture retention capacity.
This time can be reduced by exposing the mixtures to air circulation or controlled temperatures; however, excessive acceleration of the drying process should be avoided in order to prevent cracking.



a) Mixing of the materials



b) Casting of the specimens



c) Conditioning of the specimens

Figure 4. Stages of specimen preparation

The density of the elements was determined in accordance with SR EN 1015-10:2002/A1:2007 - Methods of test for mortar for masonry. Part 10: Determination of the apparent density of hardened mortar.
The density of the hardened material was calculated using Eq. (1):

$$\boldsymbol{D = \frac{m}{V}} \quad (1)$$

where:
D - density of the hardened material, kg/m³;
m - mass of the specimen in saturated state, kg;
V - volume determined by measurement, m³.
The compressive strength was calculated using Eq. (2):

$$\boldsymbol{f_c = \frac{F_c}{A}} \quad (2)$$

where:
f_c - compressive strength, MPa;
F - maximum load at the moment of rupture, N;
A - area of speciment, mm².

The thermal conductivity was determined in accordance with SR EN 12667:2002 - Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods, using a thermal conductivity measuring device (HESTO Lambda Control A 90) manufactured by HESTO Elektronik GmbH (Germany). Products of high and medium thermal resistance. The thermal resistance was calculated using Eq. (3):

$$\boldsymbol{R = \frac{d}{\lambda}} \quad (3)$$

where:
R - thermal resistance, m²K/W;
d - thickness of the layer, mm;
λ - thermal conductivity of the material, W/mK.

RESULTS AND DISCUSSIONS

The determination of the geometric characteristics of unfired clay specimens after the drying process is essential for evaluating the shrinkage behavior of the material and its ability to maintain the initial mold geometry. The dimensional stability of masonry elements plays an important role in ensuring proper placement within masonry structures, contributing to the uniform distribution of vertical loads and adequate contact with the bonding mortar. Significant dimensional deviations may lead to local stress concentrations, crack initiation, and a reduction in the overall structural stability.
The experimental measurements indicated relatively small dimensional deviations compared to the initial nominal dimensions of the specimens, suggesting a good dimensional stability of the studied mixtures. For specimens containing 10% vegetal waste addition, both sawdust and hemp fibers exhibited a maximum shrinkage of 3.5 mm, corresponding to 2.33% of the initial dimension.
For mixtures incorporating 20% sawdust, the measured shrinkage was 3.2 mm, while specimens containing 20% hemp fibers showed

a slightly higher shrinkage value of 4.1 mm. This behavior may be associated with the higher water absorption capacity and greater volumetric variability of hemp fibers compared to sawdust, which can influence the drying process and dimensional stability of the clay matrix (where H represents the specimen height, l the specimen width, L the specimen length, and Δ the longitudinal/transversal shrinkage of the specimen).

The corresponding experimental results are presented in Tables 2 and 3, where samples 1, 2, and 3 represent the three tested specimens for each composition (10% and 20% addition of sawdust or hemp fibers).

Table 2. Geometrical characteristics of the specimens with sawdust addition after 28 days

Sample no.	Dimensions, mm				
	10% sawdust				
	H mm	l mm	L mm	% Δ_l	% Δ_L
1	142.2	147.5	146.9	2.5	3.1
2	143.4	146.9	146.5	3.1	3.5
3	143.1	146.7	146.9	3.3	3.1
Sample no.	Dimensions, mm				
	20% sawdust				
	H mm	l mm	L mm	% Δ_l	% Δ_L
1	143.8	146.9	147.1	3.1	2.9
2	143.1	146.8	146.8	3.2	3.2
3	142.9	147.0	147.2	3.0	2.8

Table 3. Geometric characteristics of the specimens with hemp fiber addition after 28 days

Sample no.	Dimensions, mm				
	10% hemp				
	H mm	l mm	L mm	% Δ_l	% Δ_L
1	145.6	147.3	147.2	2.7	2.8
2	145.9	147.1	146.5	2.9	3.5
3	145.7	147.1	147.1	2.9	2.9
Sample no.	Dimensions, mm				
	20% hemp				
	H mm	l mm	L mm	% Δ_l	% Δ_L
1	142.0	146.2	146.1	3.8	3.9
2	141.8	145.9	145.9	4.1	4.1
3	142.6	146.3	146.0	3.7	4.0

The determination of the density of clay-based mixtures represents an important indicator in the evaluation of the physical and mechanical performance of construction materials, as it directly influences both the structural behavior and the thermal insulation properties of the material. The analysis of density allows the assessment of the degree of compaction and homogeneity of the mixture, as well as the identification of an optimal balance between mechanical strength and thermal insulation capacity.

An increase in material density is generally associated with a higher degree of compaction of the clay matrix and improved mechanical strength. However, it simultaneously leads to an increase in thermal conductivity, which reduces the material's insulating capacity. From a practical perspective, construction elements with densities exceedingly approximately 1200 kg/m³ become more massive and more difficult to handle and install, potentially requiring additional construction measures to prevent settlement or deformation during construction.

Therefore, optimizing the density of the material represents an important aspect in the design of clay-based mixtures intended for construction applications.

The experimental density results obtained for the four analyzed mixtures indicate a coefficient of variation below 5%, highlighting a relatively high degree of homogeneity of the materials produced under laboratory conditions.

The highest density value was recorded for the sample containing 10% sawdust addition, reaching 1643 kg/m³, with a coefficient of variation of 2.92%. Increasing the amount of sawdust to 20% of the total aggregate mass led to a density reduction of approximately 8%, resulting in a value of 1509 kg/m³.

The specimens produced with 20% hemp fiber addition exhibited the lowest density among all analyzed samples, namely 1383 kg/m³, with a coefficient of variation of 3.43%, representing a 14.3% decrease compared to the values recorded for the specimens containing 10% hemp fibers.

The overall range of experimentally determined densities, illustrated in Figure 5, varies between approximately 1362 and 1642 kg/m³. These values fall within the range characteristic of conventional construction materials, being comparable to the density of solid bricks (approximately 1600-1900 kg/m³) and close to the density range of hollow ceramic blocks (700-1400 kg/m³).

This comparison suggests that the analyzed clay-based materials may present significant

potential for use in construction applications, offering a favorable balance between mechanical performance and thermal insulation properties.

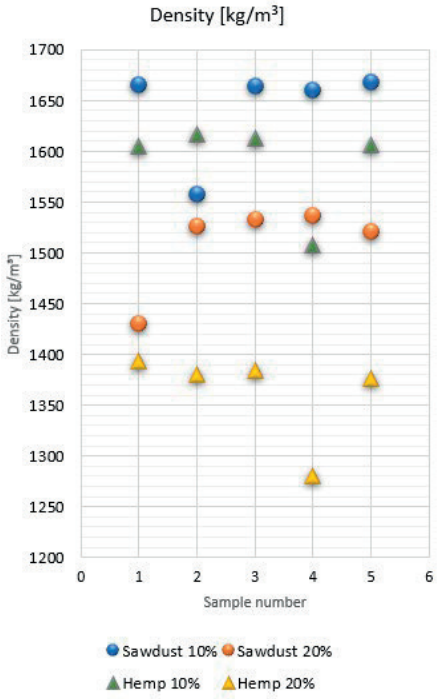


Figure 5. Density of clay-based mixtures

The compressive strength of clay-based elements is influenced by several factors, including the type and quantity of clay, the particle size distribution of the mixture, the preparation technology of the mixture, and the casting process of the specimens. These parameters determine the degree of cohesion of the matrix and the way stresses are transmitted within the material. According to data reported in the literature, the compressive strength of unfired clay materials generally ranges between 0.2 and 5 N/mm², depending on the composition and production conditions of the mixture (Ashour et al., 2011).

The compressive strength values obtained experimentally are presented in Figure 6. The compositions containing sawdust recorded the lowest compressive strength values, particularly in the case of the 20% addition, for which the experimentally determined average value was 1.46 MPa, with a coefficient of variation of 4.02%. The specimens containing 10% sawdust showed an average compressive strength of 1.602 MPa and a coefficient of variation of 8.95%.

Mixtures incorporating hemp fibers exhibited better mechanical behavior, with compressive strength values slightly varying depending on the proportion of fibers added. The compressive strength reached 2.03 N/mm² for the composition containing 10% hemp fibers and 1.912 MPa for the mixture with 20% hemp fiber addition.

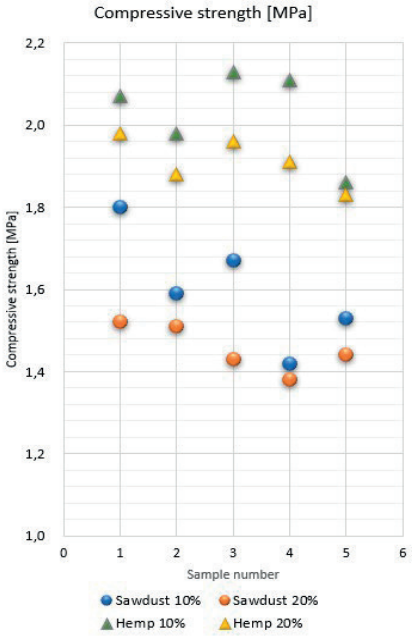


Figure 6. Compressive strength of clay-based mixtures

The comparative analysis of the results reveals a general trend of decreasing compressive strength with the increase in the percentage of vegetal material incorporated into the clay matrix. This behavior can be explained by the reduction in the structural continuity of the clay phase and by the occurrence of discontinuities or additional porosity within the material, which lead to a reduced capacity of the material to uniformly absorb and transmit mechanical stresses.

Following the compressive strength tests, all clay specimens containing vegetal additives exhibited a failure mode characterized by the appearance of vertical cracks distributed over the entire surface of the tested elements, a phenomenon typical for brittle materials subjected to axial compressive loading. This type of cracking indicates the progressive

development of internal stresses and the propagation of cracks in the direction of the applied load until the structural integrity of the specimens is lost.

The failure mode of the specimens subjected to axial compression is illustrated in Figures 7 and 8.



Figure 7. Failure mode of the specimens containing hemp fibers under axial compression



Figure 8. Failure mode of the specimens containing sawdust under axial compression

The determination of the thermal conductivity of materials is essential for the design and efficient use of building products and structures involving heat transfer, ensuring optimal thermal performance, safety, and energy efficiency.

In the construction sector, the evaluation of the thermal conductivity of unfired clay-based materials with fiber additives is particularly important for assessing their thermal insulation performance.

Such materials can contribute to improving the energy efficiency of buildings by reducing heat losses during winter and limiting heat gains during summer.

Consequently, thermal conductivity represents a key parameter in determining indoor thermal comfort and reducing energy consumption associated with heating and cooling.

The experimentally determined values of thermal conductivity and thermal resistance for the analyzed clay-based specimens are presented in Table 4.

Table 4. Experimental values of thermal conductivity and thermal resistance

Specimen type	Dimensions	Thickness	Thermal conductivity λ	Thermal resistance
	[mm]	[mm]	λ[W/mK]	[m^2K/W]
R1 (10% sawdust)	280x295	26.67	0.19099	0.140
R2 (20% sawdust)	290x295	31.16	0.18369	0.169
R3 (10% hemp)	294x292	26.12	0.17503	0.149
R4 (20% hemp)	295x260	26.39	0.17258	0.152

The data presented in Table 4 indicate that the specimens containing sawdust exhibited higher thermal conductivity values (λ). At the same time, increasing the content of vegetal additives contributed to improved thermal insulation performance of the clay-based composite.

CONCLUSIONS

The incorporation of vegetal waste into the composition of construction materials influences both the physical behavior and the mechanical and thermal insulation properties of the material. Based on the comparative study of the clay-based mixtures, the following conclusions can be drawn:

- From the perspective of the dimensional stability of the specimens, the relatively small deviations of the geometric characteristics, ranging between 1.98% and 2.6%, indicate a relatively uniform shrinkage during the drying process, suggesting good dimensional stability of the analyzed mixtures.
- The density coefficient of variation below 5% confirms the production of relatively homogeneous materials. The determined density values, ranging between 1362 and 1642 kg/m³, demonstrate that the studied materials fall within the density range characteristic of commonly used construction materials. The results indicate that vegetal additives contribute to reducing the density of the clay matrix, an effect more pronounced in the case of hemp fiber compositions, while the addition of sawdust leads to comparatively higher density values.
- From the perspective of mechanical behavior, a general tendency of decreasing compressive strength was observed with increasing vegetal additive content. This phenomenon can be associated with increased porosity and the presence of discontinuities within the clay matrix structure. Nevertheless, the mixtures containing hemp fibers exhibited slightly higher compressive strength values compared to the specimens containing sawdust. The observed failure mode, characterized by vertical cracks distributed across the surface of the specimens, confirms the typical behavior of brittle materials subjected to axial compressive loading.
- Regarding thermal insulation performance, the experimental results indicate that increasing the vegetal additive content contributes to the reduction of thermal conductivity for both types of vegetal additives, although this improvement is accompanied by a reduction in mechanical performance.

Overall, the experimental data suggest the existence of a trade-off between density, mechanical strength, and thermal conductivity, highlighting the need to optimize the proportion of vegetal additives in order to obtain a clay-based material with balanced properties suitable for construction applications.

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