

Research Article

Mechanical and Thermophysical Performance of Unfired Clay Bricks Incorporating Recycled Esparto Grass Residues

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Abstract

This article investigates the effects of incorporating recycled plant fibers into raw clay bricks to evaluate the resulting changes in their mechanical and thermophysical properties. The clay used, an illite type (confirmed by its potassium oxide (K₂O) content), originates from the Ifrane region of Morocco and has a high silica (SiO₂) content, making it a suitable building material. Different levels of recycled plant fiber incorporation, from 0% to 20% (0%, 1%, 3%, 7%, 15%, and 20% by weight), were studied. The addition of significant amounts of recycled plant fibers resulted in bricks that were more porous, lighter, and exhibited higher water absorption. A decrease in the compressive strength of the samples was observed, from 12.38 MPa for the



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reference samples to 3.58 MPa for the incorporation of 20% recycled plant fibers. Furthermore, the addition of a fiber-based additive improved the thermal performance of the raw clay bricks: a reduction in thermal conductivity of approximately 43% was observed compared to the reference samples, resulting in better insulating properties. The 29% increase in the specific heat capacity of the bricks indicates a greater capacity to store and release thermal energy. Beyond these thermophysical gains, the valorization of an abundant stream of plant fiber waste into a functional, raw building material reduces the extraction of raw clay, avoids the energy consumption and CO₂ emissions associated with firing, and decreases the energy demand of buildings through improved insulation, thus contributing to the objectives of a circular economy and sustainable development in the construction sector.

Keywords

Unfired clay brick; thermal insulation; waste valorization; circular economy; sustainable construction

1. Introduction

The construction sector is among the most energy-intensive, accounting for 40% of global energy consumption [1] and 33% in Morocco [2]. Nationally, this sector continues to grow, with the World Bank forecasting a 30% increase by 2028 [3]. In light of this trend, the integration of energy efficiency measures in buildings is receiving increasing attention. This led to the adoption, in 2011, of a national decree on the thermal performance of buildings [4], aimed at promoting sustainable development and improving this performance. This growing energy demand is closely tied to environmental pressures such as resource depletion and greenhouse gas emissions, which places the search for low-carbon, resource-efficient building materials at the core of environmental engineering research and of national and international sustainable development agendas. Clay bricks have been one of the most widely used building materials for centuries [5] due to their excellent performance [6]. However, the production of clay bricks generates significant CO₂ emissions [7], which have a direct impact on the environment. To remedy this problem and improve the performance of traditional clay bricks, researchers have turned their attention to eco-friendly bioclimatic materials [8].

Waste-derived additives have been increasingly investigated to improve the sustainability and thermal performance of clay bricks. The incorporation of 4% sisal fibers into unfired bricks reduced thermal conductivity by 11.2% relative to the control [9]. Recycled waste polyethylene foam (WPEF; 0-10%) produced larger reductions in fired bricks, reaching 69.63% at 900°C and 75.84% at 1000°C; the optimum content at 900°C was 7.5% [10]. Neem residues also enhanced thermal insulation: at 4% incorporation, leaf and straw fibers decreased thermal conductivity by 55.2% and 23%, respectively [11]. Compressive strength initially increased with neem-fiber content and subsequently declined, with 2% identified as the optimum proportion. Likewise, incorporating 20 wt.% olive pomace decreased the thermal conductivity of unfired and fired bricks by 43.1% and 39.7%, respectively [12]. The incorporation of recycled *Juncus acutus* fibers at contents ranging from 0 to 10 wt.% produced lightweight unfired bricks and substantially reduced shrinkage, from 8% for

the control formulation to 0.7% at 10 wt.% fiber content [13]. Although compressive strength declined as the fiber proportion increased, the resulting bricks remained suitable for construction applications under DIN 18945 (2013-08) [14].

Beyond material-property assessments, a cradle-to-gate life-cycle assessment of a cementitious composite reinforced with Amazonian jute and malva fibers found that using unprocessed, locally available fibers reduced the environmental burden associated with reinforcement by more than 95%. This result underlines the environmental value of minimizing fiber processing and transport distances [15]. Building on this, the present study investigates the influence of recycled plant-fiber waste on the thermal and mechanical properties of clay bricks for more sustainable building applications.

Collectively, these studies reflect a broader environmental-engineering strategy that converts agricultural, agro-industrial, and plant-fiber residues into value-added construction materials with low embodied energy. Such residues would otherwise be disposed of in landfills, burned, or left to decompose without control. This waste-to-resource approach supports circular-economy principles by creating material linkages between the agricultural and construction sectors. It can also reduce the use of virgin raw materials, including clay. In addition, producing bricks without firing avoids the considerable fuel demand and associated CO₂ emissions of conventional fired-brick manufacturing. This research direction is therefore closely related to several United Nations Sustainable Development Goals, particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Although plant-based additives have been widely investigated for building materials, the present study differs in the selected residue, experimental design, and application-oriented assessment. A locally available esparto residue is ground into powder and incorporated into raw clay bricks through six formulations containing 0-20 wt.% additive. We examine its influence by jointly assessing porosity, apparent density, capillary water absorption, compressive strength, thermal conductivity, and specific heat capacity. This combined assessment quantifies the mechanical-hygrothermal trade-off and determines additive contents that enhance thermal performance while preserving sufficient mechanical strength for the intended building applications. The interfacial mechanisms used to interpret the observed trends are based on established clay-polymer and clay-cellulose interaction models reported in the literature. The contribution of this work lies in establishing a multi-property formulation framework that converts an underused local residue into a functional unfired masonry material and identifies incorporation ranges that balance thermal improvement against strength loss.

2. Materials and Methodology

2.1 Materials

Clay collected from the Ifrane region of Morocco was used as the primary raw material in this study. The clay was purified, refined, and sieved sequentially to obtain a homogeneous powder.

The plant-based additive was prepared from esparto grass (*Stipa tenacissima*) residue. This residue was ground into a heterogeneous fibrous powder with particle sizes ranging from 0.2 to 2 mm, and the powder was incorporated into the clay mixtures at different proportions. In Morocco, esparto residues are generated in considerable quantities through local craft activities and cellulose-

related processes, but they are commonly discarded or burned. Their use as a building additive can limit open burning and the associated release of air pollutants and greenhouse gases, while providing a practical application for an underused natural resource. This recovery route represents a local and cost-effective waste-valorization strategy that can support sustainable development in both rural and urban areas. Figure 1 presents the raw grass, the collected residue, and the ground powder used in this work.

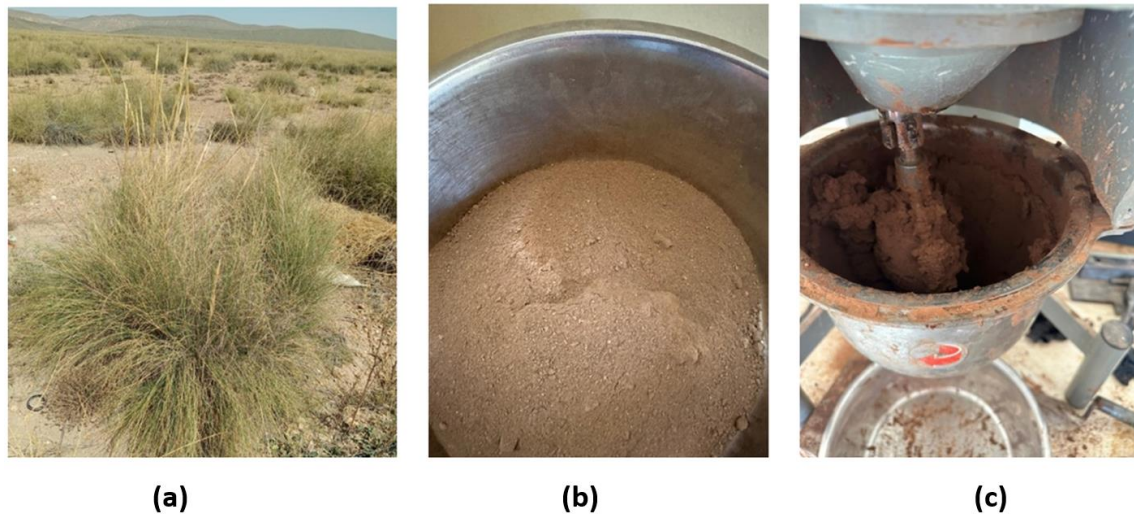


Figure 1 (a) Esparto, (b) Clay used and (c) mixture.

2.2 Samples' Preparation

Several brick samples were manufactured from different compositions, with varying proportions of additives (0%, 1%, 3%, 7%, 15%, and 20%), to evaluate the impact of recycled plant fibers as a reinforcement material in construction. The clay and additive fibers were mixed for 10 min at a speed of 95 rpm using an automated electric mixer under stable conditions. The choice of automated mixing aimed to ensure a homogeneous distribution of the additives within the clay matrix, thus producing bricks with a well-mixed clay-additive reinforcement [16]. To determine the optimal dry density of the soil-fiber mixture while maintaining a minimum water content, the Proctor compaction test (PCT) was performed in accordance with the Moroccan standard NM 13.1.044-2005, which is aligned with ASTM D698 [17]. The Proctor test indicated an optimal moisture content of 17.25%. The prepared mixtures were molded into prismatic test specimens measuring 160 × 40 × 40 mm. After 28 days of air drying at 20°C, the specimens were placed in a programmable oven before testing. The oven temperature was gradually increased from ambient to 96°C at 1.5°C/h and maintained at this temperature for 24 h. After polishing, the bricks were ready for experimental analysis. This air-drying process, carried out without a firing kiln, is in itself a major advantage in terms of sustainable development, as it avoids the combustion of fossil fuels, the use of high-temperature energy, and the direct CO₂ emissions characteristic of traditional fired brick production, thus enhancing the environmental value of the proposed material.

2.3 Testing Standards

A series of experimental tests are carried out before and after the brick samples have been prepared. In accordance with Moroccan national standard NM 00.6.125-2006, X-ray fluorescence tests are performed to analyze the chemical composition of the soil. The porosity of the prepared samples is measured to determine the percentage of void fraction, in accordance with Moroccan standards NM ISO 10545-3 [18] relating to porosity tests. In addition, the bulk density, capillary water absorption coefficient, and compressive strength of the samples are evaluated in accordance with Moroccan test standards NM EN 772-16 [19], NM EN 772-11 [20], and NM EN 772-1-2015 [21]. Thermal evaluation tests are also carried out to measure the thermal conductivity and specific heat capacity of the samples produced, in accordance with the guidelines set out in standard NM EN 1745 [22]. For each test procedure, three separate tests were performed, and the average result was used to obtain a more accurate assessment. The mechanical and thermal measurement devices are shown in Figure 2.

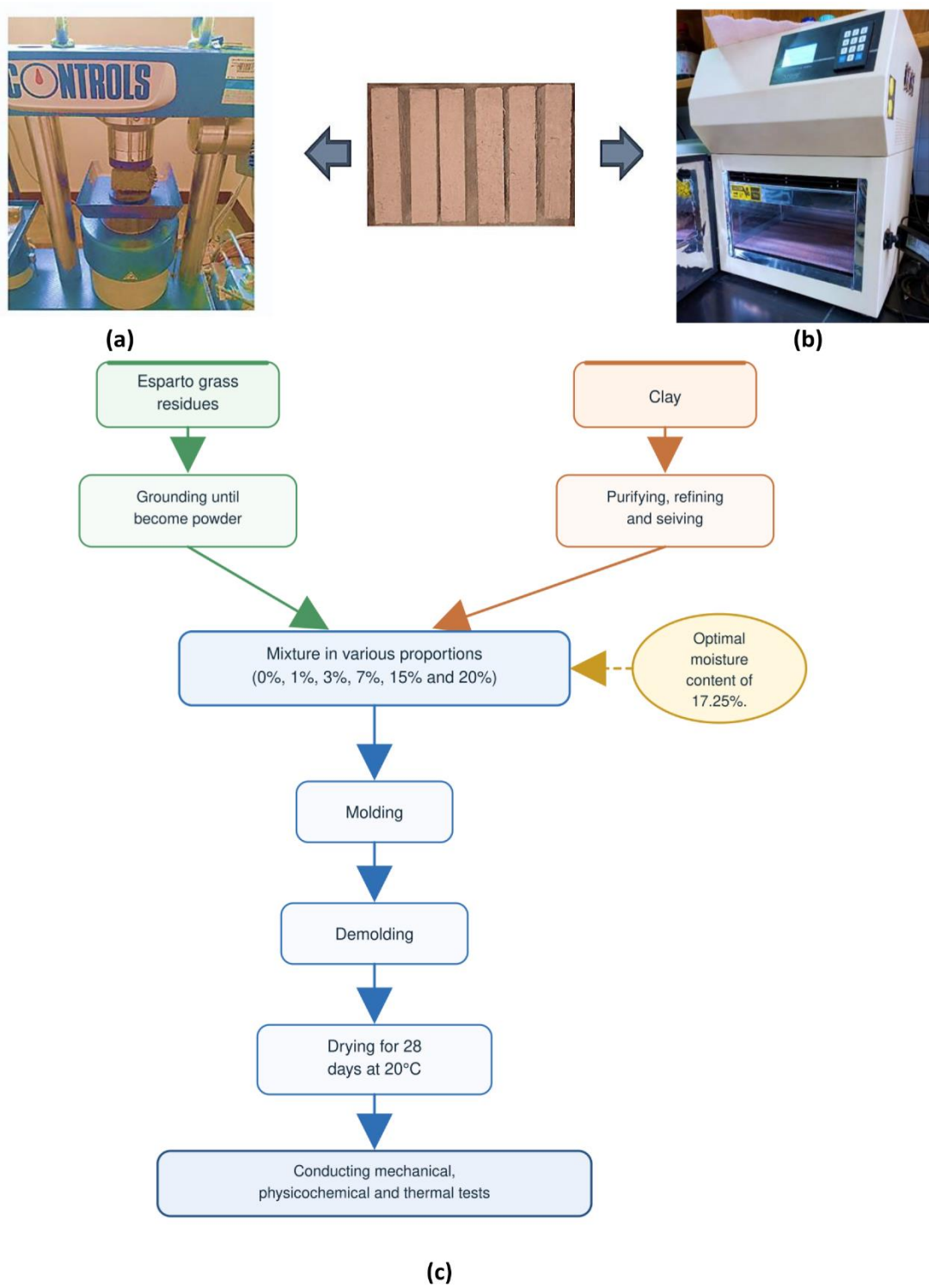


Figure 2 (a) Measurement of mechanical properties (b) measurement of thermal properties and (c) experimental method.

3. Results and Discussion

3.1 Clay Characterization Analysis

Table 1 presents the X-ray fluorescence test, revealing the chemical composition of the powder sample. The presence of clay in the soil is confirmed by the presence of aluminum oxide (Al_2O_3) [23].

Furthermore, the potassium oxide (K₂O) content confirms the illite type. Other oxides such as ferric oxide (Fe₂O₃) influence the color of the bricks, while calcium oxide (CaO) influences structural cohesion and their behavior in the event of failure [24].

Table 1 Chemical composition of the studied earth following X-ray Fluorescence test.

Chemical element	Percentage (%)
SiO ₂	59.60
Al ₂ O ₃	22.41
Fe ₂ O ₃	6.69
CaO	0.08
MgO	0.97
K ₂ O	2.53
TiO ₂	0.83
P ₂ O ₅	0.46
LOI	5.34

3.2 Porosity Analysis

The porosity of the prepared specimens is determined using the gravimetric model based on Archimedes porosity analysis, which is described by Eq. (1):

$$\phi = \frac{W_{ssd} - W_d}{W_{ssd} - W_w} \cdot 100\% \quad (1)$$

Where ϕ is the percentage porosity, W_{ssd} the saturated surface-dry weight, W_d the dry weight (after 24 h of drying), and W_w the weight of the sample immersed in water (buoyancy weight).

Table 2 describes the impact of using the additive based on recycled vegetable fiber waste on the porosity level of brick samples at different percentages. It shows that porosity increases with additive content. Among the additive-containing samples, the lowest porosity (2.25%) is observed at 1% additive, while the reference brick (0%) shows the lowest overall value (1.14%); the highest porosity (14.19%) is observed at 20% additive.

Table 2 Porosity of brick specimens (recycled vegetable fiber waste additive).

Porosity level (%)				
Additive (%)	Trial 1 (%)	Trial 2 (%)	Trial 3 (%)	Mean $\pm$ SD (%)
0%	1.15	1.20	1.08	1.14 $\pm$ 0.06
1%	2.25	2.15	2.36	2.25 $\pm$ 0.11
3%	6.75	6.89	7.01	6.88 $\pm$ 0.13
7%	9.50	8.87	9.01	9.13 $\pm$ 0.33
15%	12.39	11.85	12.05	12.10 $\pm$ 0.27
20%	13.95	14.25	14.36	14.19 $\pm$ 0.21

Vegetable fibers are mainly composed of cellulose, with smaller proportions of lignin and hemicellulose [25, 26]. During sample preparation, in particular at the mixing stage, interactions take place between the silica contained in the clay and the polymeric compounds present in the fibrous additive [27]. During these interactions, the hydroxyl groups of both components are involved: the silanol group in the silica and the hydroxyl groups in the additive [28]. These interactions occur through cationic bridging and hydrogen bonding, leading to adsorption-induced polymerization of the clay-additive mixture. This forms flocculants consisting of clay-additive complexes in the brick matrix [29]. This leads to brick specimens with higher porosity.

Overall, increasing the proportion of plant-fiber waste additive produces bricks with a more porous structure. This behavior is consistent with several studies reported in the literature. In [28], incorporating recycled *Typha* fiber waste into unfired clay bricks increased porosity from 1.14% for the reference formulation to 3.02% and 14.95% for bricks containing 1% and 20% additive, respectively. A similar trend was reported for date-pit waste in [30], where bricks containing 20% additive reached a porosity of 18.51%, compared with 1.17% for the reference bricks. Likewise, [31] found that increasing the content of a rice-husk-based additive increased the porosity of fired clay bricks. In addition, [32] reported that greater tea-waste contents increased the porosity of unfired bricks, from 0.51% for the reference formulation to 1.47% for specimens containing 10% tea-waste additive.

From an environmental engineering perspective, this controlled increase in porosity is a desirable feature rather than a mere side effect: the additional voids are generated using a waste-derived, non-toxic natural fiber rather than synthetic pore-forming agents, so the resulting lightweight bricks combine improved insulation potential with a genuinely bio-based, biodegradable, and low-impact composition, consistent with sustainable material design principles.

3.3 Bulk Density Analysis

Table 3 shows the bulk density measurements of the brick samples. The results show that bulk density decreases as the additive percentage increases in the unfired samples, resulting in lighter samples. In other words, the bulk density of the samples is inversely proportional to the percentage of recycled vegetable fiber waste additive. This correlation may be due to higher porosity levels, which indicate higher void ratios in the samples and, consequently, a lower recorded bulk density. Indeed, the highest bulk density among the samples containing additives, at 1.74 g/cm³, was obtained for the sample containing 1% vegetable fibers, which is the least porous formulation. The reference brick (0% additive) nevertheless exhibited the highest overall apparent density (1.76

g/cm³) and the lowest porosity (1.14%). The lowest apparent density, 1.42 g/cm³, was measured on the unfired samples containing 20% additive, which also had the highest porosity.

Table 3 Bulk density of brick specimens (recycled vegetable fiber waste additive).

Bulk density (g/cm ³)				
Additive (%)	Trial 1	Trial 2	Trial 3	Mean ± SD
0%	1.75	1.79	1.73	1.76 ± 0.03
1%	1.77	1.70	1.76	1.74 ± 0.04
3%	1.65	1.63	1.64	1.64 ± 0.01
7%	1.59	1.60	1.66	1.62 ± 0.04
15%	1.50	1.55	1.51	1.52 ± 0.03
20%	1.39	1.44	1.42	1.42 ± 0.03

Figure 3 illustrates the correlation between the mean values of porosity and bulk density for samples produced with various percentages of additives made from recycled vegetable fiber waste. There is an inverse relationship between bulk density and porosity. This suggests that lower bulk density is associated with higher porosity as reflected in the high R² value of 0.9596. This coefficient indicates a strong correlation between bulk density and porosity.

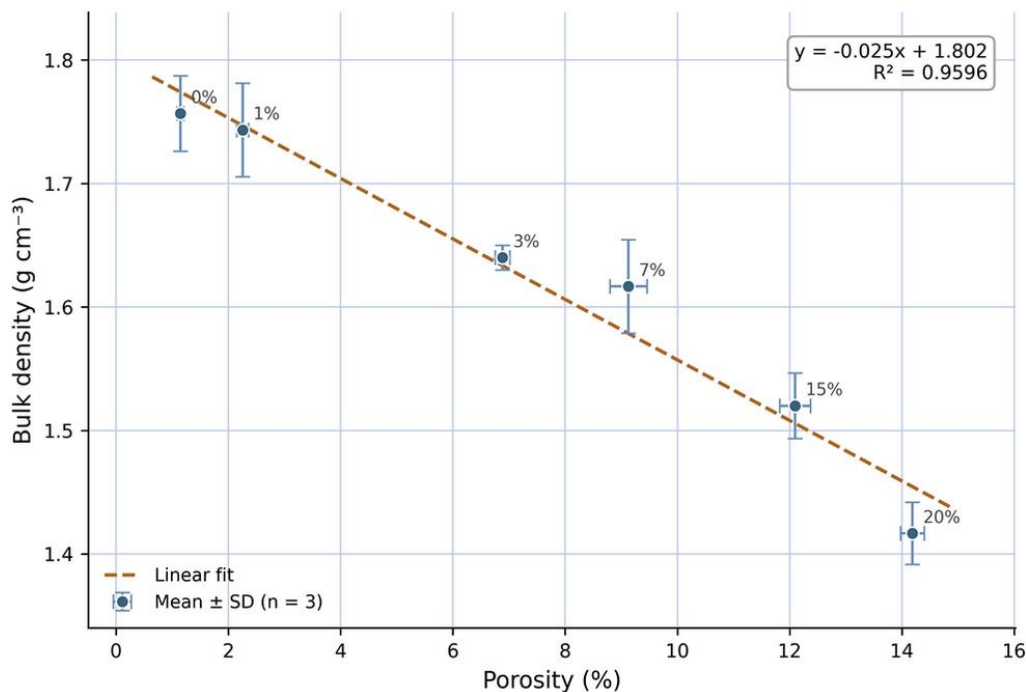


Figure 3 Correlation between bulk density and porosity for specimens containing recycled vegetable fiber waste.

Fe and Al sesquioxides present in clay can contribute to bonding at the clay-fiber interface [28]. By promoting adsorption interactions between cellulose and clay minerals [33], these constituents may favour the formation of clay-additive complexes with a lower density than the clay matrix alone and a more open pore structure [24]. The present results follow this pattern: increasing the

proportion of fibrous additive is accompanied by a lower sesquioxide content in the mixture, higher porosity, and a corresponding decrease in apparent density.

Comparable observations have been reported for other plant-based additives. In [34], the incorporation of pea shell waste into unfired clay bricks decreased bulk density from 1.24 g/cm³ for the reference formulation to 0.85 g/cm³ at an additive content of 20%. Similarly, [35] examined raw clay bricks containing 0%, 1%, 3%, 5%, 7%, and 10% date-palm fibers. Their bulk density declined as the fiber content increased, reaching 1.17 g/cm³ for bricks with 10% additive, compared with 1.26 g/cm³ for the reference brick. In addition, [36] reported an approximately 19.30% reduction in apparent density after incorporating date-palm waste fibers into ecological bricks.

This progressive weight reduction is an additional sustainability lever that is often under-appreciated: lighter unfired bricks reduce the loads to be transported from the production site to construction sites, lowering the fuel consumption and associated CO₂ emissions of logistics, and can also reduce the structural dead-load of buildings, allowing savings in foundation and structural materials. Coupled with the waste-derived nature of the additive, these findings position the developed bricks as a low-carbon alternative to conventional masonry units across their whole life cycle, from raw material sourcing to transport and in-service thermal behavior.

3.4 Water Absorption Analysis

Table 4 describes the results of the capillary water absorption test. The capillary water-absorption coefficient increases with additive content due to higher porosity. Among the samples containing additive, the lowest coefficient (28.05 g/cm²·min^{0.5}) was recorded at 1% additive (porosity 2.25%), with the reference (0%) showing 26.67 g/cm²·min^{0.5}; the highest coefficient (56.53 g/cm²·min^{0.5}) was recorded at 20% additive (porosity 14.19%).

Table 4 Capillary water absorption of brick specimens.

Capillary Water Absorption Coefficient (g/cm ² ·min ^{0.5})				
Additive (%)	Trial 1	Trial 2	Trial 3	Mean ± SD
0%	25.60	25.79	28.63	26.67 ± 1.70
1%	26.25	28.55	29.35	28.05 ± 1.61
3%	37.55	35.66	36.14	36.45 ± 0.98
7%	39.55	40.17	41.67	40.46 ± 1.09
15%	55.15	52.16	53.14	53.48 ± 1.52
20%	57.23	56.24	56.12	56.53 ± 0.61

Figure 4 highlights the correlation between capillary water absorption and porosity ($R^2 = 0.9666$): the most porous samples contain more voids and interconnected channels, which increases capillary flow. These results are consistent with previous research [37] on the effect of incorporating recycled rubber and plastic waste as additives in clay bricks, at different percentages (0%, 1%, 3%, 7%, 10%, and 15%) and for two particle sizes, $\delta < 1$ mm and $1 \text{ mm} < \delta < 3$ mm. The results showed that water absorption by capillary action increased from 41 (cm²·min^{0.5}) for the reference bricks to 60 g/cm²·min^{0.5} for $\delta < 1$ mm and 71 g/cm²·min^{0.5} for $1 \text{ mm} < \delta < 3$ mm at 20% additive. The results also showed a proportional relationship between porosity and capillary water absorption. Another study [38] on Palm kernel shell waste as an additive in fired clay bricks highlighted the correlation

between porosity and water absorption, with water absorption increasing with higher palm kernel shell waste content.

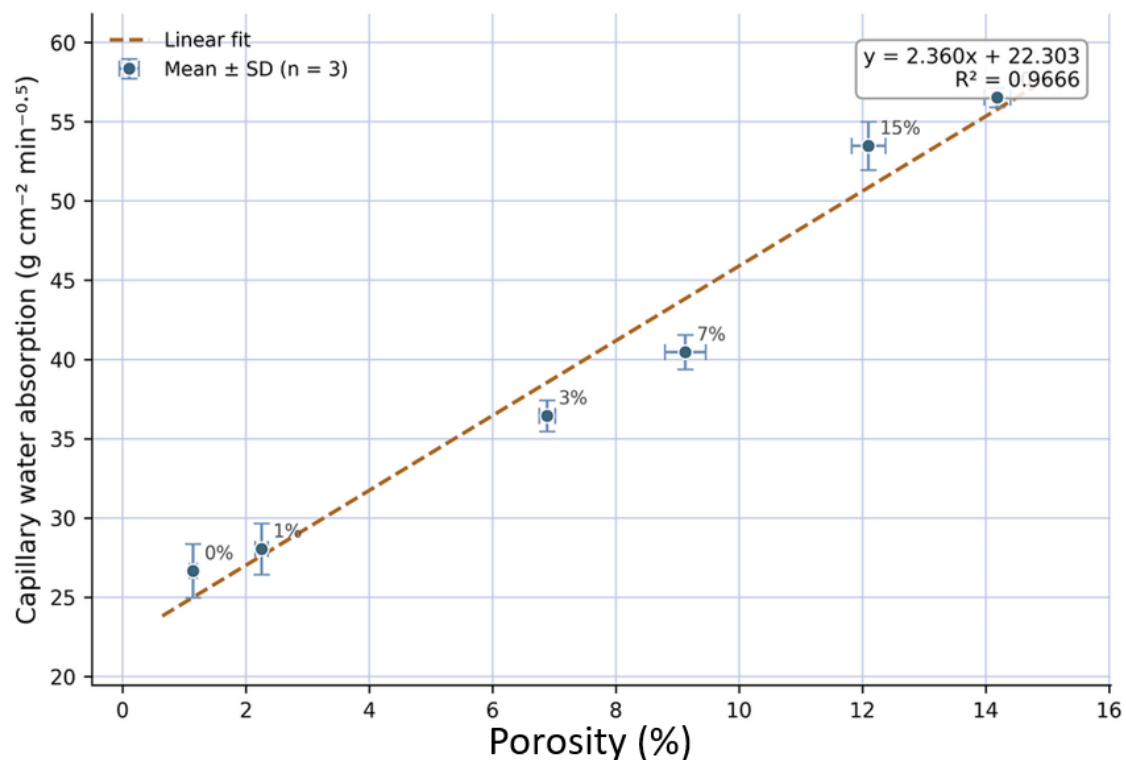


Figure 4 Correlation between capillary water absorption and porosity for specimens containing recycled vegetable fiber waste.

Although increased capillary water absorption represents a technical trade-off to manage, for instance through appropriate rendering, coatings, or restricting use to sheltered or interior applications, it does not offset the environmental benefits identified above. On the contrary, addressing this trade-off through complementary, equally sustainable surface-protection strategies (such as lime- or clay-based renders) would allow the waste-based bricks to combine environmental and durability performance, and is identified here as a promising direction for future environmental engineering research on this material. In practice, reserve formulations with more than 7 wt.% additives for indoor or sheltered applications, and test wetting-drying cycles, erosion resistance, shrinkage and biological durability are recommended before any outdoor or humid use.

3.5 Compressive Strength Analysis

Table 5 presents the results of the compressive strength analysis of the brick samples studied. The compressive strength test was performed using a Controls compression machine at a loading rate of 0.15 MPa/s, with a tolerance of ± 0.0008 MPa, until the samples failed. Increasing the percentage of recycled plant fiber-based additive led to a decrease in the compressive strength of the bricks. Among the samples containing additive, those with the lowest content (1 wt.%) exhibited the highest compressive strength (11.30 MPa), although this was still lower than that of the reference sample (12.38 MPa). Conversely, the sample with the highest percentage of additive (20 wt.%) exhibited the lowest compressive strength (3.58 MPa). This suggests that the reduction in

brick compressive strength is due to incorporating a larger proportion of additive based on recycled plant fibers.

Table 5 Compressive strength of brick specimens.

Compressive strength (MPa)					Classes
Additive (%)	Trial 1	Trial 2	Trial 3	Mean $\pm$ SD	DIN 18945
0%	12.25	12.44	12.45	12.38 $\pm$ 0.11	EB5
1%	11.35	11.45	11.09	11.30 $\pm$ 0.19	EB5
3%	9.95	10.01	9.87	9.94 $\pm$ 0.07	EB5
7%	7.25	7.35	6.99	7.20 $\pm$ 0.19	EB5
15%	5.01	4.95	4.91	4.96 $\pm$ 0.05	EB3
20%	3.60	3.55	3.59	3.58 $\pm$ 0.03	EB2

In the absence of specific standards for raw clay bricks in Morocco, the strength classes of the German standard DIN 18945 (2013-08) [14] are used: EB2 (2.5-3.8 MPa), EB3 (3.8-5 MPa), EB4 (5-6.3 MPa) and EB5 (>6.3 MPa) [39]. The results indicate that bricks containing 20 wt.% additive belong to category EB2, those containing 15 wt.% of additive to category EB3, while samples incorporating 1, 3 and 7 wt.% of additive meet the requirements of the highest class, EB5. The decrease in the clay content of the mixture, as the additive fraction increases, reduces the net electrical charge available for the clay-additive intercalation [40], creating an interlayer spacing that decreases structural compactness and strength [41].

Since there is no unified Moroccan or international standard classifying raw earth bricks, DIN 18945 is used here as the internationally recognized reference framework. Therefore, formulations incorporating up to 7 wt.% by weight of additive are recommended when load-bearing capacity is required, as they maintain the EB5 class while offering a measurable reduction in thermal conductivity. When greater lightness and improved insulation are desired, formulations containing 15 wt.% and 20 wt.% remain usable, provided they are used for non-load-bearing functions such as infill and partitions, or combined with additional reinforcement.

Figure 5 illustrates the correlation between porosity and compressive strength values ($R^2 = 0.9692$) for samples produced with different percentages of additives derived from recycled plant fiber waste. The inverse relationship between porosity and compressive strength is confirmed by the measurements: the most porous bricks exhibit lower mechanical strength. Increasing the proportion of plant fiber-based additives therefore decreases compressive strength. This result is consistent with previous research. El-yahyaoui et al. [42] studied the impact of incorporating doum fibers as additives in unfired clay bricks at different percentages (0, 1, 5, 7, 10, and 12 wt.%).

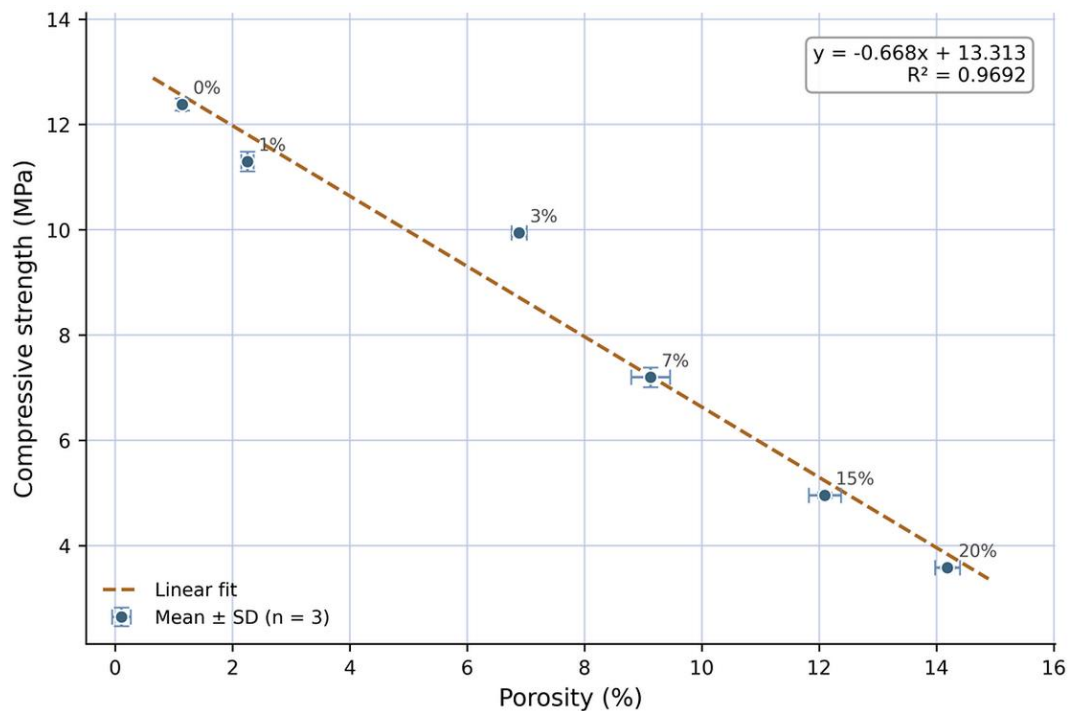


Figure 5 Compressive strength versus porosity for specimens containing recycled vegetable fiber waste.

The results showed that bricks produced with a higher additive content had lower compressive strength: 19.31 MPa for the reference bricks versus 6.52 MPa for bricks containing 12% additives. The results also highlighted a correlation between compressive strength and the apparent density of the bricks containing additives. A previous study by Crespo-López et al. [43] on the impact of adding tea waste to fired bricks showed that a higher additive content led to increased porosity and decreased compressive strength. In another study, Ajouguim et al. [44] examined the impact of incorporating esparto grass fibers at different percentages (1%, 2%, and 3% by volume) and lengths (10 mm, 20 mm, and 30 mm) in the formulation of a mortar-based composite. The results showed that increasing additive content led to an 11% decrease in compressive strength for samples with 1% additive at 10 mm length and an 80% decrease for samples with 3% additive at 30 mm length, compared to the reference samples.

Importantly for the sustainable-construction case made in this study, the reduction in compressive strength does not disqualify the material from real building applications: specimens containing up to 10 wt.% recycled vegetable fiber waste still reach the highest DIN 18945 class (EB5), and even the most heavily loaded formulation (20 wt.%) remains usable for non-load-bearing applications (EB2). This means that a wide range of eco-friendly, waste-valorized bricks can be selected to match specific structural requirements, which broadens the practical adoption potential of this environmentally engineered material in sustainable building projects. However, it should be stressed that compliance with a DIN 18945 strength class is a necessary but not sufficient condition for load-bearing use, which must also be evaluated in light of the applicable structural design rules.

3.6 Thermal Performance Analysis

The thermal performance of the samples produced in terms of thermal conductivity and specific heat capacity is shown in Table 6 and Table 7. The thermal properties of the brick samples, particularly specific heat capacity and thermal conductivity, improved with the incorporation of an additive based on recycled vegetable fiber waste. Specimens having lower thermal conductivity were obtained with the addition of higher proportions of additive. In fact, a thermal conductivity of 0.21 W/m·K was recorded in samples containing 20% additive, against 0.37 W/m·K for the reference specimens. Incorporating a larger amount of additive therefore reduced thermal conductivity by approximately 43%. In addition, higher additive content increased the specific heat capacity of the brick samples. Samples containing 20% additive had a specific heat capacity value of 0.75 kJ/kg·K, while the reference specimens had a specific heat capacity of 0.58 kJ/kg·K. The addition of a high additive content therefore resulted in a significant increase of approximately 29% in the specific heat capacity of the brick samples. These results suggest that the thermal properties of the brick samples are positively affected by the addition of the additive made from recycled vegetable fiber waste, particularly in terms of reduced thermal conductivity and increased specific heat capacity.

Table 6 Thermal conductivity of brick specimens.

Additive (%)	Thermal Conductivity (W/m·K)			
	Trial 1	Trial 2	Trial 3	Mean ± SD
0%	0.37	0.38	0.35	0.37 ± 0.02
1%	0.35	0.35	0.33	0.34 ± 0.01
3%	0.30	0.29	0.32	0.30 ± 0.02
7%	0.27	0.26	0.26	0.26 ± 0.01
15%	0.22	0.23	0.24	0.23 ± 0.01
20%	0.21	0.19	0.22	0.21 ± 0.02

Table 7 Specific heat capacity of brick specimens.

Additive (%)	Specific Heat Capacity (kJ/kg·K)			
	Trial 1	Trial 2	Trial 3	Mean ± SD
0%	0.59	0.58	0.58	0.58 ± 0.01
1%	0.59	0.60	0.59	0.59 ± 0.01
3%	0.63	0.62	0.63	0.63 ± 0.01
7%	0.65	0.67	0.67	0.66 ± 0.01
15%	0.72	0.70	0.70	0.71 ± 0.01
20%	0.75	0.76	0.75	0.75 ± 0.01

These thermal gains have direct, quantifiable environmental engineering significance: a 43% reduction in thermal conductivity translates into lower heat transfer through building envelopes, which in turn reduces the heating and cooling energy demand of buildings constructed with these bricks over their entire service life. Given that the building sector already accounts for a large share of national and global energy consumption, as noted in the Introduction, improving the intrinsic insulating capacity of the wall material itself, using a waste-based additive rather than synthetic

insulation, offers a low-cost, low-carbon route to reducing operational greenhouse gas emissions and advancing energy-efficiency and climate-action objectives in the built environment.

Figure 6 illustrates the correlation between mean porosity and thermal conductivity for samples produced with different percentages of additives made from recycled plant fiber waste. There is an inverse relationship between thermal conductivity and porosity. This suggests that lower thermal conductivity is associated with higher porosity levels, which is reflected in the high R^2 value (0.9923). This indicates a strong correlation between thermal conductivity and porosity.

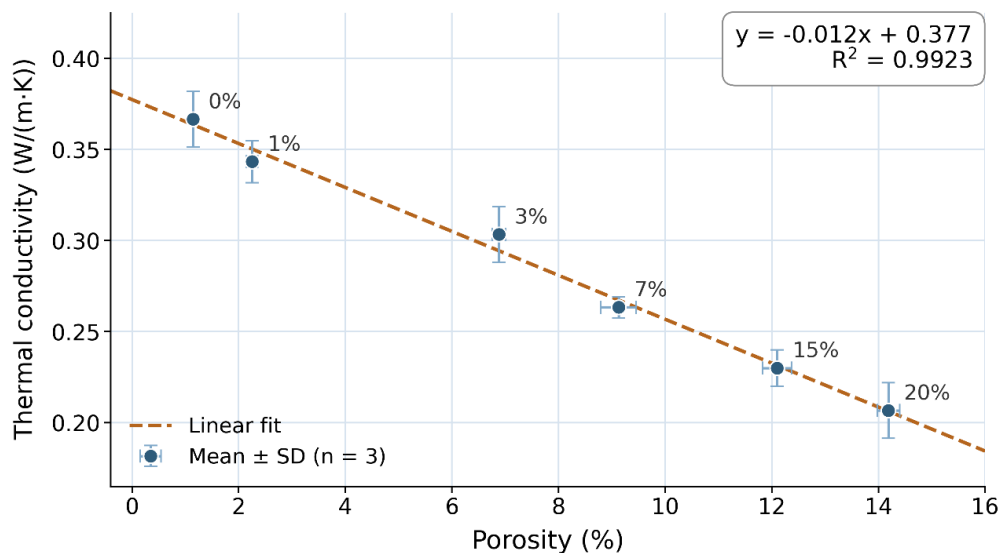


Figure 6 Correlation between thermal conductivity and porosity for specimens containing recycled vegetable fiber waste.

During mixing, the silica particles in the clay are displaced by the additive's fibrous particles, which occupy their place in the brick matrix [45]. This displacement promotes the formation of agglomerating agents [6-32], as it reduces friction between the silica particles of the clay and the cellulose fragments of the fibrous additive [46]. This results in the creation of porous samples with improved thermal performance [47]. Furthermore, the incorporation of the plant fiber-based additive leads to a net reduction in electrical charge, which can induce weak clay-additive intercalation [48, 49]. The formation of voids or pores in the brick matrix can be caused by this weak bonding between the clay and the additive particles, leading to the creation of more porous structures [50]. Heat transmission is hindered by these porous structures, which act as barriers to energy transfer [51]. As a result, the thermal resistance of the bricks increases, leading to a decrease in their thermal conductivity [52, 53]. The specific heat capacity also increases because these voids can store and absorb more thermal energy [54, 55]. Consequently, incorporating larger proportions of plant fiber-based additives allows for the production of more porous bricks with increased thermal resistance, lower thermal conductivity, and a higher specific heat capacity.

This trend is supported by [56], which reported that incorporating plant aggregates, namely barley straw, hempseed, and corn cobs, at 0%, 3%, and 6% reduced the thermal conductivity of bricks. At an additive content of 6%, thermal conductivity values of 0.14, 0.20, and 0.26 W/m·K were obtained for barley straw, hempseed, and corn cobs, respectively, compared with 0.57 W/m·K for the unfired reference sample.

A previous study [57] evaluated clay bricks enriched with mushroom waste and reported a 62% reduction in thermal conductivity, from 0.77 W/m·K for additive-free specimens to 0.29 W/m·K for specimens containing 15% additive. In [58], recycled wastewater-treatment sludge was incorporated into unfired bricks and was likewise found to decrease thermal conductivity while increasing specific heat capacity as the additive content increased. The respective values changed from 0.51 W/m·K and 0.63 kJ/kg·K for the reference bricks to 0.29 W/m·K and 0.82 kJ/kg·K for bricks containing 20% additive.

Taken together, the physical, mechanical and thermal results show that recycled esparto fiber waste can be transformed, by a simple process without cooking, into a building material that combines reduced manufacturing emissions, reduced transport-related emissions thanks to reduced weight and reduced energy consumption in service thanks to improved insulation.

4. Conclusions

This study examines the impact of incorporating recycled plant fiber-based additives on the thermophysical and mechanical properties of raw clay bricks. Adding more additives resulted in bricks with increased porosity. This phenomenon is attributed to floc formation resulting from interactions between clay's silica and the polymeric constituents of the plant-based additive. These results demonstrate that adding plant fiber-based additives allows for the production of lightweight bricks with low apparent density, at the cost of increased capillary water absorption.

The study also revealed that the recorded compressive strength decreased with increasing additive content. In accordance with DIN 18945 (2013-08), the samples belong to classes EB5 (1, 3, and 7 wt.% additive), EB3 (15 wt.%), and EB2 (20 wt.%). Formulations up to 7 wt.% are therefore compatible with load-bearing masonry, while those at 15 and 20 wt.% are better suited to non-load-bearing elements. Thermally, a 43% reduction in thermal conductivity and a 29% increase in specific heat capacity were observed, both of which are explained by a more porous microstructure. Overall, the results demonstrate that recycled esparto fiber waste offers clear potential for improving the thermophysical properties of unfired clay bricks, making them suitable for a range of applications in the building industry, provided that the concomitant reduction in mechanical strength is taken into account in the choice of formulation.

Beyond these mechanical and thermophysical outcomes, this study contributes to environmental engineering and sustainable development. By valorizing an abundant vegetable fiber waste stream, Esparto grass residues, into a functional unfired construction material, the proposed process avoids the firing-related energy consumption and CO₂ emissions of conventional brick manufacturing, diverts an under-used agricultural/plant by-product away from open burning or landfilling, and yields lightweight units that reduce transport-related emissions and structural material demand. The associated 43% reduction in thermal conductivity and 29% increase in specific heat capacity further reduce operational heating and cooling energy demand across the service life of the building, directly supporting building energy-efficiency and climate-mitigation objectives. Taken together, these environmental, economic and technical benefits illustrate how a simple, low-cost waste-valorization strategy can advance circular-economy practice in the construction sector and contribute to United Nations Sustainable Development Goals 9, 11, 12 and 13, reinforcing the relevance of this research to the scope of environmental engineering and sustainability studies. The environmental benefits described above are expressed here in qualitative and comparative terms;

their quantification in terms of embodied energy and CO₂ savings has not been undertaken in the present work and is identified as a necessary future work.

Future work should extend this environmental assessment with a formal life-cycle analysis (LCA) quantifying embodied energy and CO₂ savings relative to conventional fired bricks, together with durability studies addressing the increased water absorption, to fully establish the sustainability credentials of recycled vegetable fiber waste bricks for widespread construction use.

Author Contributions

Amine Azzouzi: Conceptualization, writing - original draft, methodology. Rachid Et-Tanteny: Writing - review and editing, data curation. Imad Manssouri: Supervision, validation, methodology. Aboubakr Bouayad: Supervision. Tajeddine Manssouri: Formal analysis. Houssame Limami: Investigation, resource, writing - review and editing. All authors have read and approved the final version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the authors. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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