Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 12, December, 2021

Unfired Clay-Cork Granules Bricks Reinforced with Natural Stabilizers: Thermomechanical Characteristics Assessment

Fatima Zohra El Wardi [1*], Sara Ladouy [1], Abdelhamid Khabbazi [1], Khalid Ibaaz [2], Asmae Khaldoun [3]

[1] EMDD_CERNE2D, Mohammed V University in Rabat, EST Salé, 227 Avenue Prince Héritier, Salé, Morocco.

[2] Engineering for Smart and Sustainable Systems Research Center. Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco.

[3] Laboratory of Sustainable Energy Materials, Al Akhawayn University, Ifrane, Morocco.

Received 06 September 2021; Revised 18 October 2021; Accepted 08 November 2021; Published 01 December 2021

Abstract

Cork is an ecological, natural, and renewable additive, an excellent thermal and acoustic insulator. All these attributes encourage its use in the building sector. Adding this additive to the Earth leads to a more lightweight composite with better thermal performance than the Earth alone. Unfortunately, the mechanical performance of this composite is degraded significantly, limiting its use in construction applications. The authors propose in this study to stabilize the clay-cork composite using natural stabilizers. A chemical stabilization was tested using local quick-lime, in addition to a physical stabilization using natural sheep-wool fibers. The primary purpose is to propose eco-friendly construction material with enhanced thermal and mechanical properties and the lowest environmental impact based on local and ecological raw materials to encourage more sustainable and low-energy constructions. First, physicochemical and mineralogical characterization of used clay was investigated. Then, an experimental investigation was conducted to identify the lime content that allows the optimal stabilization for the used clay. In this context, many different specimens of Bensmim soil stabilized with lime at six many contents 0, 10, 20, 30, 40, 50, and 70% were prepared and tested. The obtained results showed that the optimal lime content for the better stabilization of the used soil is about 30%. Next, an experimental study of thermomechanical properties was conducted on unfired clay bricks mixed with expended cork granules and stabilized by the addition of variable proportions of quick-lime 0, 10 and 30% and sheep-wool fibers 0, 1, and 2%. The mechanical performance of the specimens was investigated in terms of compressive and flexural strengths. At the same time, thermal quality was qualified through evaluating thermal conductivity using the steady-state Asymmetrical Hot Plate test method. The very encouraging experimental findings showed that using lime and sheep-wool fibers at the studied addition content resulted in lightweight composites with lower thermal conductivity and higher compressive and flexural strength than reference samples. The highest thermomechanical performances are obtained with clay-cork blocks reinforced with 30% lime content and 2% sheep-wool fibers. This block recorded values of 583 kg/m^3, 0.155 W/m/K, 1.55 MPa, and 3.91 MPa, for bulk density, thermal conductivity, flexural and compressive strength respectively, compared to 765 kg/m^3, 0.238 W/m/K, 0.96 MPa and 2.29 MPa for control samples. New material presents lightweight material for both improved thermal and mechanical qualities encouraging its use in building applications.

Keywords: Unfired Clay Bricks; Expended Cork Granules; Quick-lime; Sheep-wool Fibers; Physicochemical and Mineral Identification; Thermal Conductivity; Mechanical Strength.

* Corresponding author: fatima.zohra.elwardi@gmail.com

http://dx.doi.org/10.28991/cej-2021-03091778

1. Introduction

In the last few decades, an increased interest has appeared in sustainable building materials with higher thermal efficiency and a low environmental impact. The biggest challenge is developing new building materials with improved thermal insulation, low environmental impact, and good mechanical properties. The main purpose of the current study is to develop and propose an eco-friendly construction material of high thermal performance and an appropriate mechanical strength based on local and ecological raw materials. According to available literature, many research works considered incorporating cork granules in building materials like clay, mortars, concrete, and gypsum [1-5]. That leads to lighter composites with significantly improved thermal properties. That refers to many advantages, mainly the exceptional thermal and acoustics properties that exhibit this additive encouraging its use in construction applications [6, 7]. Unfortunately, the mechanical qualities of cork-based composite materials are impoverished, limiting their use as construction materials. Cherki et al. [8] investigated the thermophysical properties of cork-gypsum composite saturated on cork granules. Developed composites with 2.5-5 mm cork's grains size presented improved bulk density and thermal conductivity, 470 kg/m^3 and 0.124 W/m/K compared to gypsum specimens, 801 kg/m^3 0.299W/m/K, respectively. A work of El Wardi et al. [9] characterized thermomechanical characteristics of a multilayer material based mainly on clay-cork composite. The outcome showed that cork granules resulted in lightweight specimens with a 68% gain in thermal conductivity and a 59% gain in bulk density for a 65% cork volume fraction in the composite compared to the clay sample. Indeed, the cork granules mortars tested by Borges et al. [1] showed a flexural strength of 0.64 MPa and compressive strength of 1.37 MPa. The addition of cork to mortar binder reduces flexural strength between 72-75%, compressive strength between 84- 97%, and thermal conductivity of 45% relative to the control blocks without cork. Adding cork fibers to the plaster binder reduces flexural strength from 3.12 MPa to 0.014 MPa and lowers the compressive strength by 7.25 MPa, to reach 0.17 MPa [10]. In another study [4], the involvement of cork-gypsum in construction materials indicated that the mechanical properties of the cork-gypsum composite are inferior, even if the properties could be enhanced using fibers (glass as an example).

The present work aims to improve the composite clay-cork's mechanical qualities while maintaining enhanced thermal insulation performances to explore opportunities in the building sector. In this context, the authors investigated the effect of Lime and sheep-wool fibers on the thermal and mechanical characteristics of the clay-cork composite experimentally. Since antiquity, lime and natural fibers have been used as stabilizers for building materials, especially clay soil. On the one hand, many studies reported that lime-stabilized soil blocks present enhanced durability and mechanical strength compared to reference ones [11-13]. This enhancement refers to the chemical reactions when adding Lime to clay soils, forming hydrated aluminate and calcium silicate[14], which, in return, provide a durable strength gain [13, 15]. While an optimum lime dosage corresponding to the natural soil is detected, beyond which the mechanical strength decreases [11, 12, 14, 16]. For that, the authors in this study conducted an experimental investigation to identify the optimum lime content that permits the maximum Bensmim soil stabilization.

On the other hand, although the technological development and the appearance of a variety of synthetic fibers, the trends of using natural fibers instead of synthetic fibers continue to increase due to their availability, economic and energetic cost, and their ecological aspect, as well as the low technicity necessary for their production [17, 18]. In this context, sheep wool fibers have comparable characteristics with rock wool and mineral wool in thermal insulation [19]. In addition, it is more eco-friendly and has a lower negative health impact compared to mineral wool. Few researchers have studied sheep wool as reinforcing fibers in mineral composites, usually in concrete and mortar. These natural fibers are characterized by a high elastic modulus, in the range of 1 to 4 GPa, equivalent to that of plastic fibers used as reinforcement fibers in the cementitious mix [20]. It has proved that sheep wool composites' mechanical and thermal performance has improved significantly [17, 20-22]. Generally, using sheep-wool fibers negatively affects the mechanical qualities of composites [18, 23, 24]. The hydrophobic character of the sheep-wool can explain this adverse effect. Indeed, the wool absorbs water from the mixture, which requires adding water for good workability (mixing water), reducing the reference material's mechanical performance. The fiber content of 2% by weight of the dried raw materials is recommended as the optimal content; in terms of workability, mechanical and thermal performance [18, 24]. Other works have demonstrated that using fibers content around 0.35-1% by weight leads to a 7 to 18% improvement in flexural strengths [20].

Furthermore, excessive long sheep-wool fibers cause agglomeration inside the mixture, leading to poor adhesion and a decline in strength. Fiore et al. [17] reported that sheep-wool fibers having a 1 mm fiber length and less could not significantly improve the strength. Still, sheep-wool fibers having 6mm fibers length result in reinforced mortars with improved compressive strength. Therefore, an appropriate choice of fibers content and length is strongly recommended to have enhanced mechanical qualities. In this context, the authors tested sheep-wool reinforcement fibers at 2-3cm length and two different fibers content (1 and 2%) in this present work.

This study focused on characterizing mechanical strength in terms of flexural and compressive strengths and bulk density without neglecting the thermal conductivity of clay-cork specimens containing lime and sheep-wool fibers at many different contents. First, the physicochemical and mineralogical identification of used clay was investigated.

Then, an experimental investigation was conducted to identify the lime content that allows the optimal stabilization for the used clay. In this context, many different specimens of Bensmim soil stabilized with lime at six different ranges (0, 10, 20, 30, 40, 50, and 70%) were prepared and tested. Results revealed that 30% lime content refers to the optimal lime content of Bensmim soil stabilization characterized by the highest values of flexural and compressive strengths. Next, the authors prepared and tested many different samples of clay-cork granules blocks reinforced with lime at two different contents (0, 10, and 30% by weight) and sheep-wool at two different fibers contents (0, 1, and 2% by weight). The thermal characterization was made by the steady-state Asymmetrical Hot Plate test method to identify the tested block's thermal conductivity. The resistance to flexural stress is characterized according to the three-point flexural test. The resistance to compression is measured by applying a simple compression test on the two parts resulting from the rupture of the specimens already subjected to the flexural test. New material presents lightweight material for both improved thermal and mechanical qualities encouraging its use in building applications. This novel idea could help reduce waste from forestry and livestock husbandry activities by effectively utilizing them as building materials.

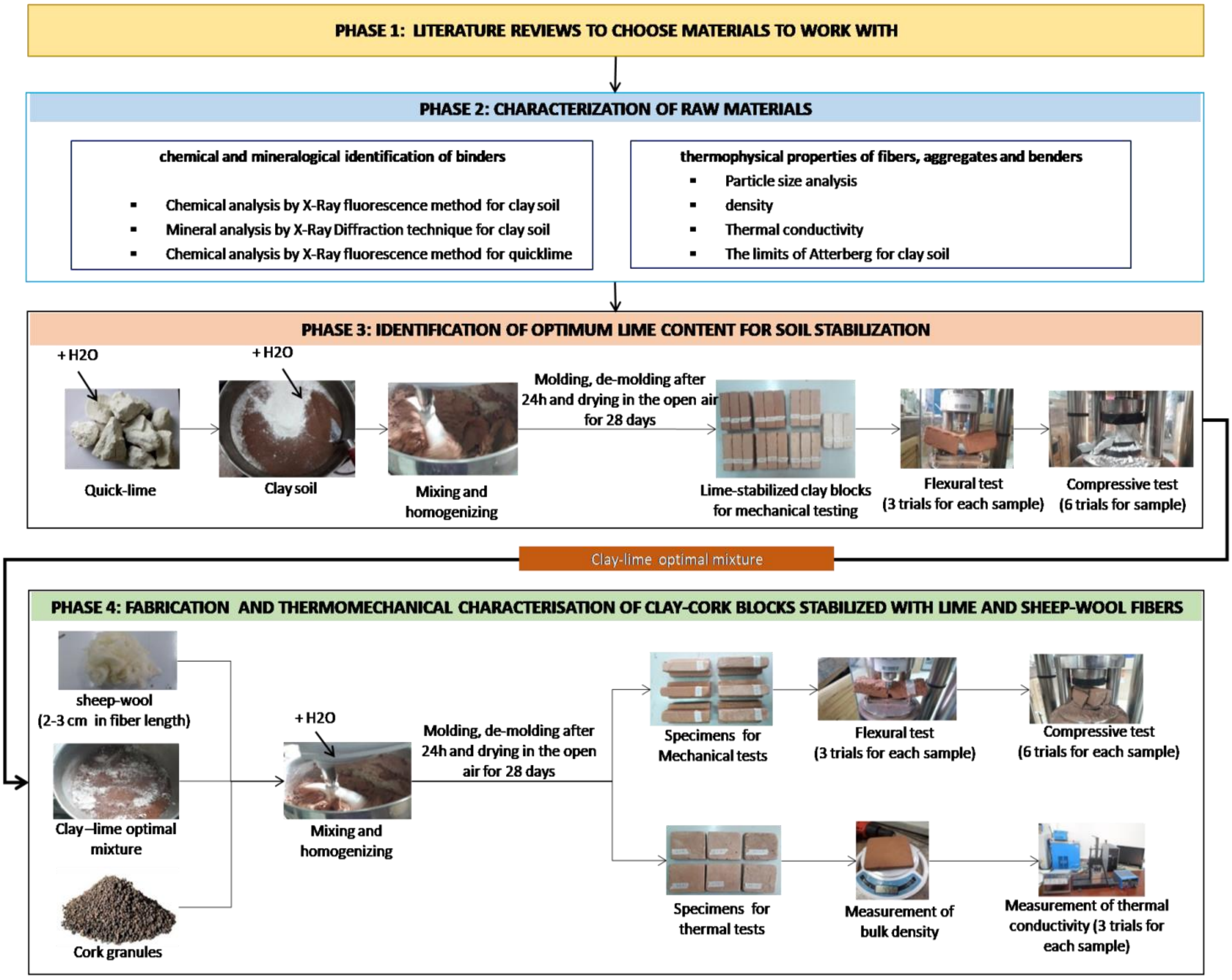

Figure 1. Flowchart of the research methodology

2. Materials and Methods

2.1. Clay

The investigated clay is the red one of the Bensmim area in the Middle Atlas of Morocco, near the Ifrane region. Particle size distribution was carried out by a wet sieving analysis method. The particle size distribution curve of Bensmim soil is between the lower and upper limits of the Adobe raw earth blocks [25], as shown in Figure 2. The limits of Atterberg were investigated using the apparatus Casagrande according to the NF P94-051 standard. The recorded values of liquid limit (LL), plastic limit (LP), and plasticity index (IP) are, respectively, 37.4%, 21.2%, and 16.2%, allowing it to be classified as low plastic clay [26].

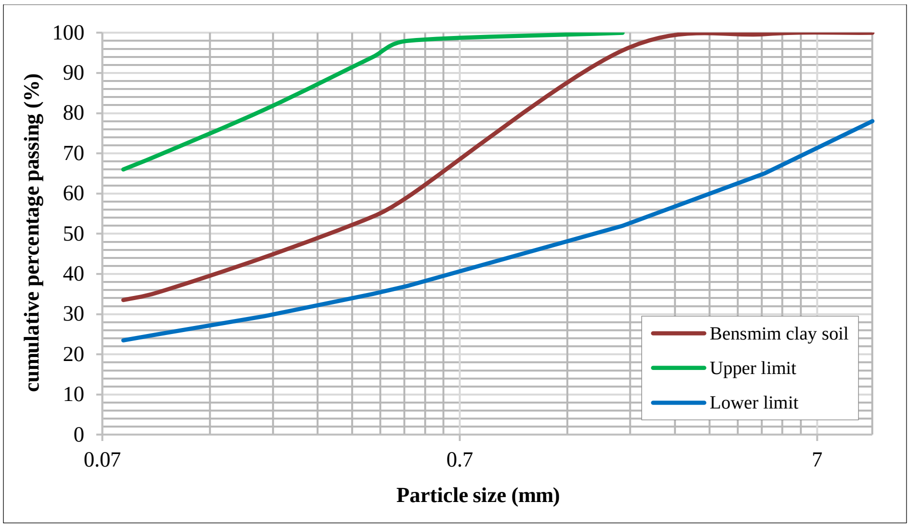

Figure 2. The particle size distribution of raw clay sample

The X-ray fluorescence spectrometry method was deployed to define the chemical composition of clay samples and their loss on ignition. Besides, a mineral analysis of Bensmim soil was performed by the X-Ray Diffraction technique. Obtained results are displayed in Table 1 and Figure 3. The results of X-Ray Diffraction analysis revealed that quartz SiO_2 is the most representative mineral with a spacing of d=3.36Å, as seen in Figure 3. The clay part is composed of Illite identified by its prominent peak at d=10.17 Å, confirming the presence of K^+ potassium in microstructure level, preventing the clay's swelling [27].

The chemical composition shows that silica (SiO_2) and alumina (Al_2O_3) are the most abundant oxides in the Bensmim soil sample (Table 1) with proportions that respect the ranges specified for the manufacturing of regular bricks [28]. Iron content (Fe_2O_3) is the reason for the color of the red clay soils [29]. The presence of potassium (K_2O) classifies the clay as an Illite type. Calcium (CaO) low content (0.08%) indicates that the studied clay is non-calcareous and endorses the management of its structure and rupture threshold [30].

Table 1. Chemical composition of Bensmim soil sample

Chemical element	Mass composition (%)
SiO_2	59.6
Al_2O_3	22.4
Fe_2O_3	6.69
K_2O	2.53
MgO	0.97
Cao	0.0777
TiO_2	0.832
P_2O_5	0.458
Loss on ignition	5.34

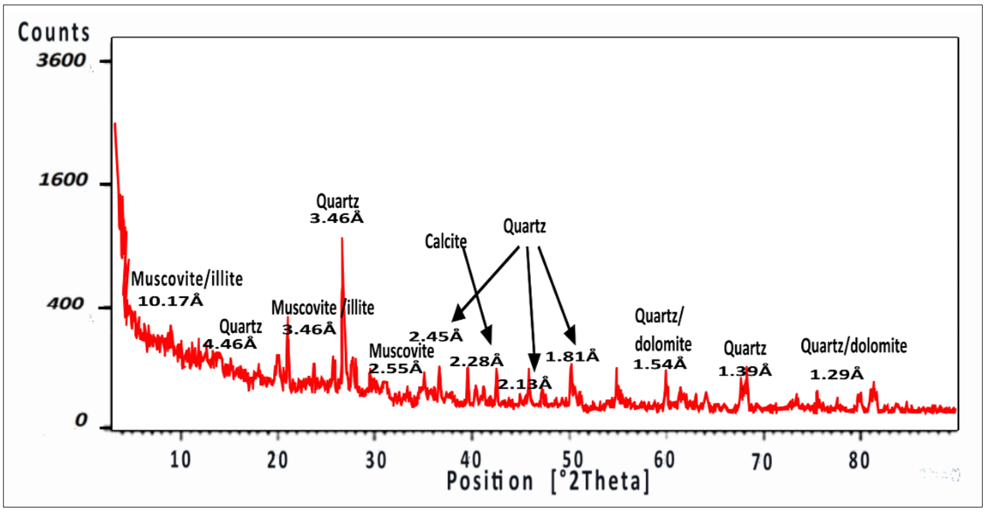

Figure 3. X-ray diffraction analysis of Bensmim soil sample

2.2. Cork Granules

Cork granules are a by-product, resulted from the cork manufacturing process or forestry residue. The authors work on developing the circular economic use of this by-product of the Moroccan Maâmora forest by using it as additives. Its density is 160 kg.m^{-3}, with a grain diameter ranging between 2.5 and 5 mm, and a thermal conductivity range of 0.049 and 0.05 Wm^{-1}K^{-1}, investigated experimentally using the Steady-state Hot Plate method in a 2×10×2 cm^3 prepared sample (Figure 4).

2.3. Lime

Quick-lime (CaO) tested as a stabilizer in the present work was extracted from the Sefrou region. Thermal and mechanical characteristics of used lime were measured experimentally in this work on prepared specimens. The chemical composition of lime was established using the technique of X-ray Fluorescence (Table 2).

Table 2. Chemical composition of lime using X-ray Fluorescence test

Chemical element	Mass composition (%)
SiO_2	2.70
Al_2O_3	<1
Fe_2O_3	<1
Cao	49
MgO	16
CO_2	0.64
Loss on ignition	31.32

2.4. Sheep-wool Fibers

Sheep-wool reinforcing fibers are natural fibers composed mainly of 90% keratin, a polymer made of ordinary natural α-amino acids. While the complexity of its chemical structure, sheep-wool is composed only of five chemical components, as presented by Table 3 [31]. Sheep-wool used in the current study has a bulk density of 20 kg/m^3 and a thermal conductivity of 0.044 W/m/K. Its fibers length ranges from around 2-3 cm (Figure 4).

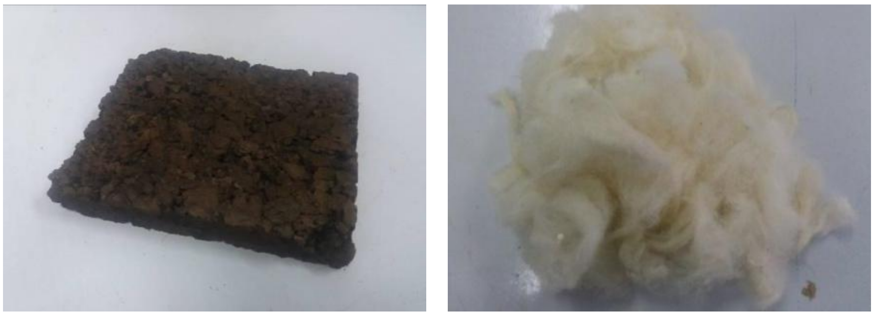

Figure 4. Cork sample for thermal test (left), sheep-wool fibers (right)

Table 3. Chemical composition of the sheep-wool fibers

Chemical element	Mass composition (%)
Carbon	50
Oxygen	22
Nitrogen	16
Hydrogen	7
Sulfur	5

3. Samples Preparation Procedure

Phase 4 of the flowchart presented by Figure 1 showcases the methodology followed to fabricate the tested blocks for the thermomechanical measurement. Many different samples of clay-cork granules (C-CO) specimens reinforced with lime (L) at two different contents (0, 10, and 30% by weight) and sheep-wool (SW) at two different fibers contents (0, 1, and 2% by weight) were prepared. Clay-cork granules, the object of this work, are a composite saturated in cork granules, leading to the best achievable thermal characteristics. While the cork granules fill the mold's apparent volume, clay paste -with a 0.25 water-clay ratio- is added to fill the intergranular space left until the mold is completely stuffed. For each type of mixture, two kinds of specimens were realized; three specimens of dimensions 16×4×4 cm^3 for mechanical strength tests and three specimens (10×10×2 cm^3) for thermal conductivity tests.

As specified in Figure 1, the authors used a clay-lime optimal mixture of 30% of lime content because it refers to the ratio that leads to the best Bensmim soil stabilization. It is characterized by the highest values of flexural and compressive strengths, as resulted from an experimental investigation on many different specimens of Bensmim soil stabilized with lime (C-L) at six different contents (0, 10, 20, 30, 40, 50, and 70%). After this ratio, the mechanical qualities of lime-stabilized soil decrease. In order to prepare lime-soil specimens, the required proportion of lime is mixed with Bensmim soil in a dry condition until a homogeneous paste is obtained. Then, the mixtures were homogenized using a mechanical mixer for 5 ± 1 min at a velocity of 40 rpm. A water ratio of 0.3 by mass was gradually added based on preliminary qualitative tests- to ensure the maneuverability of the molding step. Obtained mixtures are then molded to manufacture 16×4×4 cm^3 specimens for mechanical properties testing, as presented in Figure 5. Then the molds are left to rest for 24 hours.

A 10% lime content was also investigated according to an intensive bibliographic study that revealed that this proportion is very used to stabilizing clay soil [11, 14, 16, 32, 33]. After de-molding, prepared specimens were air-cured in laboratory conditions of a controlled temperature at 23 ± 2°C and relative humidity at 60 ± 10% for a curing period of 28 days. Before the experimental measurements, the samples were dried for a whole day in a drying oven until a constant mass was reached; this step is crucial to eliminate any moisture that could falsify the measurements.

Figure 5. Stabilized soil specimens for mechanical properties testing

4. Testing Procedures

The bulk density of tested specimens was determined by directly measuring their weight and dimensions, according to the standard NM EN 772-16. Thermal conductivity was estimated using the steady-state Asymmetrical Hot Plate method [3, 34]. The flexural test is conducted with the CONTROLS PILOT COMPACT-Line machine (Figure 6 (a)), conformed to EN 196-1 standard, applied at a loading speed of 50 N s^{-1} (Figure 6 (c)). To ensure an acceptable accuracy, mean values are a result of three manipulations. The same machine is used again for compression characterization by applying a loading speed of 500 N s^{-1} to the specimens (Figure 6 (b)). The presented results are the average of six compression tests.

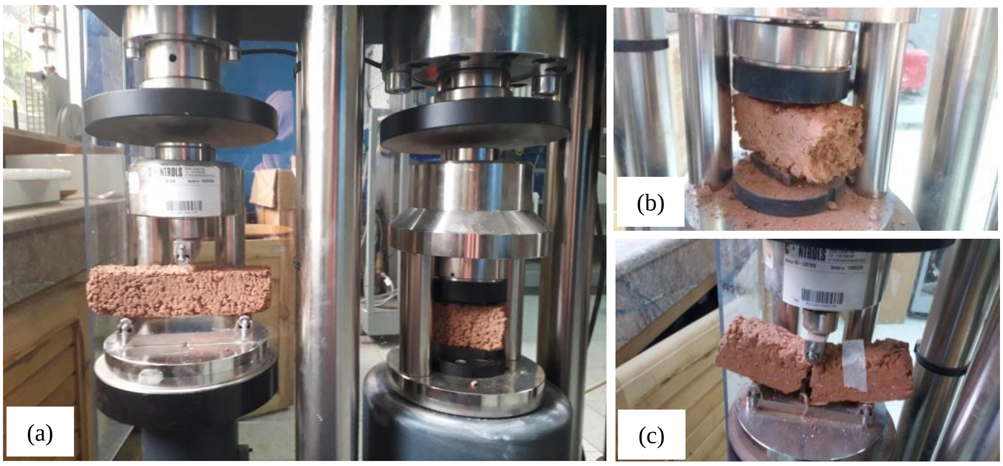

Figure 6. View of a) Controls Pilot Compact-Line; b) compressive test, and c) flexural test

5. Results and Discussion

5.1. Identification of Optimum Lime Content for Soil Stabilization

The estimation of optimum content of lime to achieve the highest values of flexural and compressive strengths for the lime-stabilized Bensmim soil was performed experimentally obtained; results are illustrated in Figure 7. Compressive test findings reflected a range from 3.76-5.88 MPa registering a 56% increase. After an optimum content of lime of 30%, any further lime increase will not be as beneficial to the blocks' strength gain, and at the same time, flexural strength is following the same trending.

Findings reflected that replacing soil with lime increased their flexural strength from 1.65 to 1.90 MPa, registering a 15% increase against the control samples until a lime content addition of 30%. Samples displayed a slow increase in the resistance till reaching its peak at a lime content of 30%, after which the decrease started. In other words, the compressive and flexural properties were found to increase proportionally with the increase of lime percentage until showing high values of 5.88 and 1.90 MPa, respectively, at 30% lime stabilization. After 30% lime content, a drop in compressive and flexural strengths was observed with the increase of lime dosage percentage. The results obtained from this study agree well with those reported by several previous works investigating soil stabilization with lime.

The evaluated strength of blocks under dry state reported by a study of Guettala et al. [11] is about 9.4 MPa for 5%, 14.2 MPa for 8%, and 16 MPa for 12%. It is clear from this study that any further increase in the lime ratio after an optimum value will not be as advantageous for the strength enhancement of the block specimens. In research carried out by Raheem et al. [12], the strength gain of the blocks reaches 3.2 MPa for cement-stabilized blocs and 1.2 MPa for blocks made with lime for a maximum content of stabilizer, about 25%. The maximum compressive strength value of samples with cylindrical form, stabilized with 18% of lime content, was about 13 MPa in a work of Miqueleiz et al. [35]. An evaluation of the physical and mechanical characteristics of compressed clay blocks stabilized with lime was carried out in a study conducted by Taallah and Guettala [36]. The results show that the increase in lime rate from 8% to 10% leads to a gain of compressive strength of bocks tested by 5%. A decrease in compressive strength of 8.15% is observed when increasing the lime rate from 10 to 12%. It is concluded that the optimal lime rate for the tested soil stabilization is about 10%.

In theory, adding lime to clay leads to chemical reactions at the microscopic level. The calcium minerals present in the lime react with the silicates and aluminates of the clayed fraction of the soil. This reaction leads in the short-term to flocculation of the particles. In the long-term, it leads to forming hydrates of calcium silicate and calcium aluminates. These reaction products have binding properties and play the role of an adhesive allowing to consolidate the cohesion and the adhesion between the particles of the clay matrix, which leads at the macroscopic level to an improvement of its mechanical performances [15]. The experimental tests confirm these theoretical considerations on soil blocks stabilized with lime carried out during the present study and previous studies [11-13, 15]. Literature shows that the difference in the improvement rate of mechanical performance in different soils depends on the percentage of the clayed, particularly silicates and aluminates proportion that will play the role of the adhesive agent in the presence of lime. That explains the results of the experimental tests indicating that there is not a fixed dosage of lime to be applied for soil stabilization.

However, each type of soil has its optimum dose of lime for better stabilization. This optimum corresponds theoretically to the proportion of lime necessary to ensure a complete reaction of all the silicates and aluminates present in the soil. The degradation of the mechanical performance of the soil after this optimum is well explained at the microscopic level by an excessive lime dosage. This overdosing of lime results in non-hydrated lime particles that lead to the formation of a heterogeneous microstructure. The non-hydrated particles can be seen clearly at the macroscopic level by observing the tested specimens at 40%, and 70% of lime content destroyed after the compression test shown in Figure 8. Besides, these interpretations are well confirmed at the level of scanning micrographs of clay blocks stabilized with different proportions of lime developed as part of a research work elaborated by Millogo et al. [14] analyzing the physical properties and the microstructure of adobe blocks stabilized with lime. Therefore, the importance of this experimental part of the work consists of identifying the optimal ratio of lime to achieve the optimal stabilization of the Bensmim soil, namely 30%.

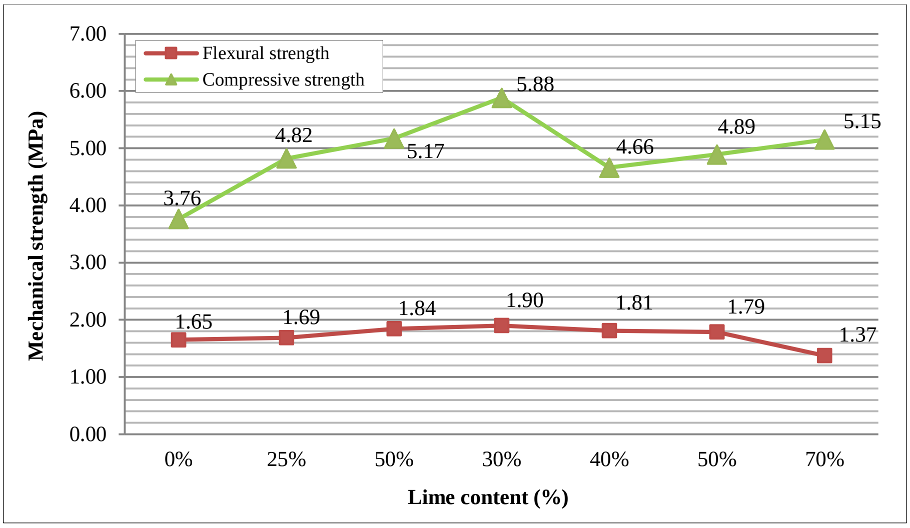

Figure 7. Compressive and flexural strength of stabilized soil samples versus lime content

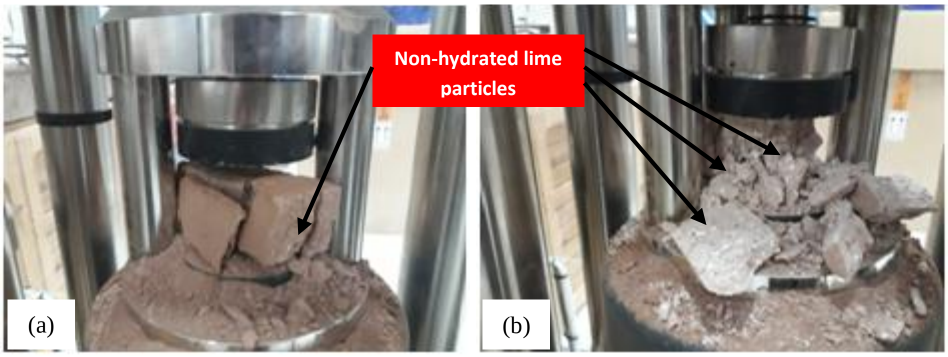

Figure 8. Compressive test for stabilized soil blocks at a) 40% and b) 70% lime content

5.2. Bulk density

Table 4 showcases the results of the prepared specimen's bulk density. Table 4 shows a decrease in specimen's bulk density with increased lime and sheep-wool fibers percentage. Collected findings revealed that the bulk density of the composite clay-cork granules improved by 4% and 14%, respectively, incorporating 10 and 30% of lime. This result is perfectly logical because a part of clay soil is replaced with lime (ρ=1101 kg.m^{-3}), which is lighter than soil (ρ=1885 kg.m^{-3}). A similar trend was noticed in the literature review. Temga et al. [32] investigated mechanical behavior, water resistance, and durability of clay soil consolidated with lime and sand. The results showed that adding lime to clay from 4 to 12% allows decreasing the bulk density of specimens from 1.98 to 1.4 g.cm^{-3}. They explain this decrease in bulk density by the reorganization of clay particles by the flocculation of aggregation. This result can be explained theoretically by the mass conservation and the law of mixtures. According to this law, the density of a mixture equals the sum of each component's multiplication with its volume fraction in this mixture [3]. Therefore, replacing part of the clay (which is denser (ρ=1885 kg.m^{-3})) with lime which is lighter (ρ=1101 kg.m^{-3}), decreases the density of the lime-stabilized cork-clay blocks. Moreover, adding 1-2% sheep-wool fibers to clay-cork composite improves its lightweight from 657 to 611-583 kg.m^{-3} for the same lime content of 30%, representing a significant gain in the range of 20-24% compared to the reference composite clay-cork granules.

Obtained results correlate with results reported in previous literature studies that investigated the use of natural fibers for the physical stabilization of soil. A work carried out by El Wardi et al. [37] showed that the density of soil blocks reinforced with straw fibers decreases from 1209 to 934 kg.m^{-3} when increasing the mass fraction of straw fibers from 4 to 8%. A similar result was reported by Mounir et al. [21] showing that the volume occupied by sheep wool fibers in the clay matrix decreases its density and improves its iso-thermal qualities. The density of the clay decreases by 10 and 12% for a wool content of 3 and 5%, respectively. Besides, Cardinale et al. [18] showed that incorporating 2, 5, and 7% of sheep-wool fibers resulted in a 17, 46 and 48% decrease in the bulk density of cement mortar, respectively. Another study by Florea and Manea [38] reported that sheep-wool improves the lightness of plaster blocks by recording a 69% decrease in bulk density with a 12.2% additive. This decrease refers to the fact that sheep-wool fibers create additional porosity inside the binder matrix. That leads to an increase in the pores' number (filled with air) inside the composite leading to this reduction.

Table 4. Bulk density results

Sample code	Bulk density ρ (kg.m^{-3})				Measurement error (%)			Gain on lightness (%)
	Trial 1	Trial 2	Trial 3	Mean value	Trial 1	Trial 2	Trial 3	
C-CO	766	763	765	765	0.2	0.2	0.0	-
L10%-C-CO	734	730	728	731	0.5	0.1	0.4	4
L30%-C-CO	658	661	651	657	0.2	0.7	0.9	14
L10%-SW1%-C-CO	679	670	674	674	0.7	0.6	0.0	12
L10%-SW2%-C-CO	642	648	639	643	0.2	0.8	0.6	16
L30%-SW1%-C-CO	607	611	616	611	0.7	0.1	0.8	20
L30%-SW2%-C-CO	587	583	579	583	0.7	0.0	0.7	24

5.3. Thermal Conductivity

Experimental results of brick samples' thermal conductivity are presented in Table 5. On the one hand, results show that increasing the content of lime from 10 to 30% improves the thermal conductivity of stabilized clay-cork blocks from 6 to 13% compared to reference blocks. This result comes in line with a previous study by Barbero-Barrera et al. [33] discussed the stabilization of compressed earth bricks with two different natural hydraulic lime types, NHL3.5 and NHL2, in a percentage ranging from 3 to 12%. The results showed that thermal conductivity and lime are inversely proportional. Also, the sample's bulk density was reduced by 12.8%. Ouedraogo et al. [39] tested clay bricks stabilized with low mineral binder percentages (2-4%) using two different soils. The results obtained for soil B showed that increasing lime percentages from 0 to 4% caused a decrease in thermal conductivity (from 0.752 to 0.650 W/m/K). Liuzzi et al. [40] showed a decline in thermal conductivity because of dry bulk density reduction. It can be seen from this review of literature that there is a proportional relationship between the bulk density of the material and its thermal conductivity. The thermal conductivity decreases with the decrease of the material bulk density. The origin of this reduction of thermal conductivity of lime-stabilized clay-cork blocks can be explained by the increase of the number of pores filled with air, which is an excellent thermal insulator with a low thermal conductivity of 0.025 W/m/K [41].

On the other hand, natural fibers of sheep-wool improved the thermal performance of lime-stabilized clay-cork specimens by decreasing thermal conductivity. Specimens stabilized with 30% lime content, reflecting the lowest recorded thermal conductivity values, 0.171 to 0.155 W/m/K, with 28 and 35% gain, for 1 and 2% sheep-wool content, respectively. Similar results in anterior studies investigating the thermal insulation performances of building materials on the base of natural fibers [21, 22, 37, 38, 42]. Mounir et al. [21] investigated the thermal characteristics of unfired clay blocks with sheep-wool additives. Thermal conductivity recorded 53 and 63% thermal gains for 3 and 5% wool percentages versus control samples.

Moreover, Florea and Manea [38] showed an attractive thermal gain of 89% for a 12.2% sheep-wool percentage compared to gypsum specimens. This reduction in thermal conductivity can be explained by creating an additional porosity inside the clay-cork matrix stabilized with lime due to the introduction of sheep wool fibers. This explanation is well confirmed at the microscopic level by observing the microstructure of the gypsum blocks reinforced by the Alpha fibers carried out by Maaloufa [43]. The observed spectrometers clearly show the existence of air pores inside the fiber-reinforced gypsum blocks. Besides, this reduction can also be referred to as the low thermal conductivity of the sheep-wool insulation fibers (0.044 W/m/K) compared to the clay-cork composite stabilized with lime (0.206-0.224 W/m/K). To summarize, the use of lime and sheep-wool fibers enhance the thermal insulation performances of clay-cork composite. The highest value of thermal conductivity, 0.155 W/m/K with a gain of 35%, is obtained using 30% lime content and a 2% sheep-wool additive.

Table 5. Finding results of thermal conductivity characterization

Sample code	Thermal conductivity λ (W m^{-1} K^{-1})				Measurement error (%)			Energy-saving (%)
	Trial 1	Trial 2	Trial 3	Mean value	Trial 1	Trial 2	Trial 3	
C-CO	0.235	0.241	0.237	0.238	1.1	1.4	0.3	-
L10%-C-CO	0.220	0.226	0.227	0.224	1.9	0.7	1.2	6
L30%-C-CO	0.202	0.205	0.211	0.206	1.9	0.5	2.4	13
L10%-SW1%-C-CO	0.184	0.189	0.193	0.189	2.5	0.2	2.3	21
L10%-SW2%-C-CO	0.175	0.173	0.179	0.176	0.4	1.5	1.9	26
L30%-SW1%-C-CO	0.168	0.175	0.171	0.171	1.9	2.1	0.2	28
L30%-SW2%-C-CO	0.151	0.154	0.161	0.155	2.8	0.9	3.6	35

5.4. Flexural and Compressive Strengths

Tables 6 and 7 regroup experimental findings of three-point flexural and compressive strength tests. As seen in Tables 6 and 7, the mechanical quality of clay-cork composite is remarkably improved by the lime addition. The highest increase of flexural strength, 1.06 MPa with 10.5% gain percentage, and compressive strengths, 3.35 MPa with 29% gain percentage, is obtained for clay-cork specimens with 30% lime content. This experimental finding aligns with many literature studies that investigate the use of lime for soil stabilization. An investigation by Temga et al. [32] discussed soil stabilized by lime and sand. The findings revealed that the stabilized clay-lime compressive strength increases as the rate of lime addition increases, with the highest values, obtained being 0.4 to 5.1 MPa for a lime content of 4 to 12%. Another work of Barbero-Barrera et al. [33] assessed the effect of natural hydraulic lime on the stabilization of compressed earth bricks indicated that replacing soil with lime has increased flexural strength by 48-56% and compressive strength by 12-35%, for the NHL2 and NHL3.5 samples, respectively, in comparison to the control samples. These findings reconfirm the results obtained in section (5.1), showing the beneficial effect of the addition of lime on enhancing the mechanical characteristics of the clay. Also, it is well explained by the formation of hydrated products with adhesive properties following pozzolanic reactions between the calcium in the lime and the silica and alumina in the clay. These reaction products play the role of an adhesive agent, allowing a better consolidation and adherence between the cork and the clay. Therefore, they permit the improvement of the mechanical qualities of the material of reference clay-cork composite, which is well confirmed by the experimental results obtained in the present study. In other words, the results obtained show the effectiveness of lime stabilization in the consolidation of inter-granular adhesion of the clay-cork structure, allowing optimum exploitation of valuable properties of cork granules, as flexibility and elasticity, to boost the composite mechanical performances, which is the purpose of the present work. Under a mechanical load, the cork imitates the behavior of spring and absorbs the mechanical shock received by the clay-cork composite. Vasconcelos et al. [44] observed the same behavior during the compressive tests; the composite gypsum-cork revealed an exceptional dissipative nature that characterizes cork-based composites, which, minimizes structure damage [45].

Besides, one can see clearly from the finding results that sheep-wool fibers additive improves the mechanical performance of the composite's specimens in terms of flexural and compressive strengths. The highest mechanical strength values are obtained for specimens with 2% sheep-wool content and 30% lime, with a recorded flexural and compressive strength of about 1.55 and 3.91 MPa, respectively. In other words, the use of 2% of sheep-wool additive resulted in a 46% gain in flexural strength and 21% in compressive strength. The literature review shows that the obtained results agree with those reported by previous works that tested the physical stabilization of building materials with fibers. According to a study by Fantilli et al. [20], using 1% of sheep-wool fibers improved the flexural strength of cement mortar by about 18% and 23% when wool fibers were untreated and treated with the atmospheric plasma, respectively. An increase of 300% in fracture strength of this mortar was observed in both cases, improving the ductility of the mortar matrix. This improvement in mechanical qualities of the clay-cork composite can be explained by the fact that sheep-wool fibers, thanks to their flexibility, can reinforce the adhesion between clay and cork particles and the flexibility of the composite, leading to increased mechanical strength and durability [46]. This conclusion is well confirmed by Maaloufa [43] via observation of the microstructure of the gypsum reinforced with Alpha fibers. The resulted spectrometers show a good adhesion between the Alpha fibers and the gypsum matrix, allowing the absorption of the solicitations in the fiber direction during the flexural test.

However, the addition of sheep's wool in inappropriate proportions causes a decline in the mechanical properties of the based material. This decline in mechanical properties is explained by the increase in the water/mixture ratio due to the hydrophobic character of the wool for good workability, which increases the water content in the composite and therefore reduces its mechanical performance, particularly the compressive strength. Fiore et al. [17] reported that sheep-wool fibers having a length of 1 mm (or less) could not significantly enhance strength, but sheep-wool having 6mm fibers length results in reinforced mortars with enhanced compressive strength. Those excessively long sheep-wool fibers caused agglomeration inside the mixture, led to poor adhesion with cement paste, and caused an unwanted decline in strength. Cardinale et al. [18] tested experimentally the thermal and mechanical characteristics of cement mortar panels reinforced with sheep's wool fibers at 2, 5, and 7% fiber content by weight. Mortar was observed in both cases, improving the ductility of the mortar matrix. Authors recommend using fiber content of 2% by weight of dry raw materials as optimum dosage in terms of workability, mechanical and thermal performances.

Throughout the mechanical tests particularly compressive one, the authors observed that the obtained specimens maintain their integrity even beyond the maximum load as seen in Figure 9. The same behavior is observed in a study conducted by Mansur et al. [47] that investigated fiber-reinforced mortar. It is reported that specimens tested in three-point bending keep their integrity even beyond the maximum load and continue to support a significant load in the post-peak portion. At the same time, the pure cementitious matrix exhibits brittle linear elastic behavior. This behavior can be explained by the fact that the sheep-wool fibers distribute the stresses caused by the shrinkage of the clay and other mechanical forces over the entire mass of the material, strengthening the structure of the material and avoiding cracking. Ordinary soil can only support small bending forces, while reinforced soil can resist large deformations without cracking. In addition, fibers increase the tensile strength and, therefore, the flexibility of the material.

Compressive strength improvement is more critical than flexural strength when using lime stabilization. Flexural strength is doubled compared to compressive strength when using sheep-wool reinforcement fibers. An approximative 61% gain on flexural strength and 71% gain on compressive strength were obtained for bricks with 30% lime content and 2% sheep-wool additive.

Table 6. Variation of flexural strength of unfired clay-cork blocks with lime and sheep-wool fibers reinforcement

Sample	Flexural strength σ_{flex} (MPa)				Measurement error (%)		
	Trial 1	Trial 2	Trial 3	Mean value	Trial 1	Trial 2	Trial 3
C-CO	0.92	1.01	0.94	0.96	3.8	5.6	1.7
L10%-C-CO	0.92	1.02	0.99	0.98	5.8	4.4	1.4
L30%-C-CO	0.99	1.05	1.13	1.06	6.3	0.6	6.9
L10%-SW1%-C-CO	1.22	1.31	1.26	1.26	3.4	3.7	0.3
L10%-SW2%-C-CO	1.27	1.36	1.41	1.35	5.7	1.0	4.7
L30%-SW1%-C-CO	1.36	1.42	1.29	1.36	0.2	4.7	4.9
L30%-SW2%-C-CO	1.54	1.61	1.49	1.55	0.4	4.1	3.7

Table 7. Variation of compressive strength of clay-cork blocks with lime and sheep-wool fibers reinforcement

Sample	Compressive strength σ_{comp} (MPa)							Maximum measurement error (%)
	Trial 1		Trial 2		Trial 3		Mean value	
	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2		
C-CO	2.18	2.21	2.24	2.32	2.43	2.36	2.29	6.1
L10%-C-CO	2.76	2.69	2.82	2.75	2.64	2.91	2.76	5.4
C-CO_L30%	3.25	3.16	3.05	3.34	3.22	3.35	3.23	5.5
C-CO_L10%-SW1%	3.22	3.16	3.27	3.44	3.32	3.11	3.25	5.7
C-CO_L10%-SW2%	3.56	3.67	3.48	3.37	3.74	3.64	3.58	5.8
C-CO_L30%-SW1%	3.85	3.71	3.82	3.64	3.69	3.88	3.77	3.3
C-CO_L30%-SW2%	3.94	3.86	3.99	3.79	4.01	3.88	3.91	3.1

Figure 9. View of C-CO_L30%-SW2% specimens resulting from the compressive test

6. Conclusions

This paper investigates the thermal conductivity and the mechanical strength of the clay-cork composite reinforced with lime and sheep-wool fibers. The main purpose is to contribute to more sustainable and eco-friendly construction materials with improved thermal and mechanical qualities based on clay and local and ecological additives such as cork granules, lime, and sheep-wool fibers. The clay-cork granules composite presents exciting thermal performances; unfortunately, it has weaker mechanical properties that need to be improved for potential use as a construction material in building applications. Therefore, lime and sheep-wool fibers are mainly used to improve this composite's mechanical qualities and durability. The results of the experimental investigation in this research study can be concluded as follows:

- The combination of cork granules and clay matrix resulted in lightweight composites with significantly improved thermal properties. The recorded bulk density and thermal conductivity, respectively, reached 765 kg/m^3 and 0.238 W/m/K, representing a 59 and 68% gain compared to reference samples. This gain comes at the expense of the mechanical strength that showed a 42% decrease in flexural strength and a 39% decrease in compressive strength compared to clay matrix;

- The lime addition resulted in changes mechanical properties of the Bensmim clay soil. The optimal lime content to gain the highest flexural and compressive strength and reach maximum soil stabilization, in the present work, is obtained at a lime rate of 30%;
- Lime positively influences the lightness, thermal conductivity, and mechanical strengths of lime-stabilized clay-cork specimens. The highest values are reached for 30% lime content recorded a 14% improvement in bulk density, 13% in thermal conductivity, 41% in compressive strength, and 10% in flexural strength, compared to unstabilized clay-cork composite;
- In addition to the beneficial impact of sheep wool on the lightness and the thermal properties of block samples, they also positively influence their mechanical properties. An approximative 11% gain on lightness, 25% gain on thermal conductivity, 46% gain on flexural strength, and 21% gain on compressive strength were obtained for bricks with 30% lime content and 2% sheep-wool additive compared to reference specimens stabilized with 30% lime without fibers reinforcement;
- The improvement of compressive strength is more critical than the flexural strength when using lime stabilization; while flexural strength is two times enhanced compared to compressive strength when using sheep-wool reinforcement;
- The enhanced specimens are obtained with 30% lime content and 2% fibers additive having a 24% gain on lightness, 35% gain on thermal conductivity, 61% gain on flexural strength, and 71% gain on compressive strength, compared to clay-cork specimens.

7. Declarations

7.1. Author Contributions

Conceptualization, F. Z. E. and A.Khab.; methodology, F. Z. E., A.Khab. and A.K.; software, F. Z. E. and A.Khab.; validation, A.Khab. and A.K.; formal analysis, F. Z. E.; investigation, F. Z. E., ; resources, A.Khab. and A.K.; data curation, F. Z. E. and S.L.; writing—original draft preparation, F. Z. E.; writing—review and editing, F. Z. E., S.L. and K.I.; visualization, F. Z. E. and S.L.; supervision, A.Khab. and A.K.; project administration, A.Khab. and A.K.; funding acquisition, F. Z. E., S.L. and K.I. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data sharing is not applicable to this article.

7.3. Funding and Acknowledgements

Particular recognition is given to Centre National pour la Recherche Scientifique et Technique (CNRST) for its financial support during the project Grant Number 33UM5R2017.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Borges, Andreia, Inês Flores-Colen, and Jorge de Brito. "Physical and Mechanical Performance of Cement-Based Renders with Different Contents of Fly Ash, Expanded Cork Granules and Expanded Clay." Construction and Building Materials 191 (2018): 535–43. doi:10.1016/j.conbuildmat.2018.10.043.

[2] Mounir, Soumia, Abdelhamid Khabbazi, Fatima Zohra Elwardi, Khalid Elharrouni, and Youssef Maaloufa. "Energy Efficiency and Impact Carbon of a Multilayer Material Composed of Ecological Additives." In Energy Procedia, 157:419–27, 2019. doi:10.1016/j.egypro.2018.11.206.

[3] Wardi, Fatima Zohra El, Abou Bakr Cherki, Soumia Mounir, Abdelhamid Khabbazi, and Youssef Maaloufa. "Thermal Characterization of a New Multilayer Building Material Based on Clay, Cork and Cement Mortar." In Energy Procedia, 157:480–91, 2019. doi:10.1016/j.egypro.2018.11.212.

[4] Hernández-Olivares, F., M. R. Bollati, M. Del Rio, and B. Parga-Landa. "Development of Cork-Gypsum Composites for Building Applications." Construction and Building Materials 13, no. 4 (1999): 179–86. doi:10.1016/S0950-0618(99)00021-5.

[5] Wardi, Fatima Zohra El, Abdelhamid Khabbazi, Asmae Khaldoun, and Ghita El Boukili. "Thermal Behavior of a New Eco-Friendly Sandwich Material Based on Clay Combining with Granular Cork." In Proceedings of 2019 7th International Renewable and Sustainable Energy Conference, IRSEC 2019, 1–6, 2019. doi:10.1109/IRSEC48032.2019.9078214.

[6] Cooke, Bussler W. “GB: Cork and the Cork Tree (Kork und Korkeiche).” Pergamon Press, Oxford-London-New York-Paris, (1961).

[7] Pereira, Helena. “Cork: Biology: Production and Uses.” Elsevier, (2011).

[8] Cherki, Abou Bakr, Benjamin Remy, Abdelhamid Khabbazi, Yves Jannot, and Dominique Baillis. “Experimental Thermal Properties Characterization of Insulating Cork-Gypsum Composite.” Construction and Building Materials 54 (2014): 202–9. doi:10.1016/j.conbuildmat.2013.12.076.

[9] Wardi, Fatima Zohra El, Abdelhamid Khabbazi, Abou Bakr Cherki, and Asmae Khaldoun. “Thermomechanical Study of a Sandwich Material with Ecological Additives.” Construction and Building Materials 252 (2020): 119093. doi:10.1016/j.conbuildmat.2020.119093.

[10] Sair, S., B. Mandili, M. Taqi, and A. El Bouari. “Development of a New Eco-Friendly Composite Material Based on Gypsum Reinforced with a Mixture of Cork Fibre and Cardboard Waste for Building Thermal Insulation.” Composites Communications 16 (2019): 20–24. doi:10.1016/j.coco.2019.08.010.

[11] Guettala, A, H Houari, B Mezghiche, and R Chebili. “Durability of Lime Stabilized Earth Blocks.” Courrier Du Savoir-N°02, (2002).

[12] Raheem, A A, O A Bello, and O A Makinde. “A Comparative Study of Cement and Lime Stabilized Lateritic Interlocking Blocks.” The Pacific Journal of Science and Technology-27 11, no. 2 (2010): 27–34.

[13] Al-Hasan, Soleen Jaber Ahmad, R. Balamuralikrishnan, and Motasem Altarawneh. "Eco-Friendly Asphalt Approach for the Development of Sustainable Roads." Journal of Human, Earth, and Future 1, no. 3 (2020): 97-111. doi:10.28991/HEF-2020-01-03-01.

[14] Millogo, Younoussa, Mohamed Hajjaji, and Raguilnaba Ouedraogo. “Microstructure and Physical Properties of Lime-Clayey Adobe Bricks.” Construction and Building Materials 22, no. 12 (2008): 2386–92. doi:10.1016/j.conbuildmat.2007.09.002.

[15] Al-Mukhtar, Muzahim, Abdelmadjid Lasledj, and Jean Francois Alcover. “Behaviour and Mineralogy Changes in Lime-Treated Expansive Soil at 20°C.” Applied Clay Science 50, no. 2 (2010): 191–98. doi:10.1016/j.clay.2010.07.023.

[16] Hubert guillaud, Hugo Houben. Traité de Construction En Terre. Journal Des Africanistes. Vol. 60. Éditions Parenthèses: Marseille, 2015.

[17] Fiore, V., G. Di Bella, and A. Valenza. “Effect of Sheep Wool Fibers on Thermal Insulation and Mechanical Properties of Cement-Based Composites.” Journal of Natural Fibers 17, no. 10 (2020): 1532–43. doi:10.1080/15440478.2019.1584075.

[18] Cardinale, Tiziana, Giuseppe Arleo, Franco Bernardo, Andrea Feo, and Piero De Fazio. “Thermal and Mechanical Characterization of Panels Made by Cement Mortar and Sheep’s Wool Fibres.” Energy Procedia 140 (2017): 159–69. doi:10.1016/j.egypro.2017.11.132.

[19] Zach, Jiří, Azra Korjenic, Vít Petránek, Jitka Hroudová, and Thomas Bednar. “Performance Evaluation and Research of Alternative Thermal Insulations Based on Sheep Wool.” Energy and Buildings 49 (2012): 246–53. doi:10.1016/j.enbuild.2012.02.014.

[20] Fantilli, Alessandro P., Silvio Sicardi, and Francesca Dotti. “The Use of Wool as Fiber-Reinforcement in Cement-Based Mortar.” Construction and Building Materials 139 (2017): 562–69. doi:10.1016/j.conbuildmat.2016.10.096.

[21] Mounir, Soumia, Abdelhamid Khabbazi, Asmae Khaldoun, Youssef Maaloufa, and Yassine El Hamdouni. “Thermal Inertia and Thermal Properties of the Composite Material Clay-Wool.” Sustainable Cities and Society 19 (2015): 191–99. doi:10.1016/j.scs.2015.07.018.

[22] Atbir, Aziza, Fatima Zohra El Wardi, Abdelhamid Khabbazi, and Moha Cherkaoui. “Thermophysical Study of a Multi-Layer Brick of Grids Made of Sheep’s Wool Yarn and Clay.” AIP Conference Proceedings 2123, no. 1 (2019): 30002. doi:10.1063/1.5117033.

[23] Corscadden, K. W., J. N. Biggs, and D. K. Stiles. “Sheep’s Wool Insulation: A Sustainable Alternative Use for a Renewable Resource?” Resources, Conservation and Recycling 86 (2014): 9–15. doi:10.1016/j.resconrec.2014.01.004.

[24] Alyousef, Rayed, Hisham Alabduljabbar, Hossein Mohammadhosseini, Abdeliazim Mustafa Mohamed, Ayesha Siddika, Fahed Alrshoudi, and Abdulaziz Alaskar. “Utilization of Sheep Wool as Potential Fibrous Materials in the Production of Concrete Composites.” Journal of Building Engineering 30 (2020). doi:10.1016/j.jobe.2020.101216.

[25] Doat, Patrice, Alain Hays, Hugo Houben, Silvia Matuk, and François Vitoux. “Construir En Terre, Par Le CRATerre.” Paris: Editions l’Harmatta. Collection AnArchitecture, (1979): 265.

[26] NF-P 11-300. “Classification Des Materiaux Utilisables Dans La Construction Des Remblais et Des Couches de Forme d’infrastructures Routiers,” (2008).

[27] Olphen, Hendrik Van. "An Introduction to Clay Colloid Chemistry, for Clay Technologists, Geologists, and Soil Scientists." (1977).

[28] Muñoz Velasco, P., M. P. Morales Ortíz, M. A. Mendívil Giró, and L. Muñoz Velasco. "Fired Clay Bricks Manufactured by Adding Wastes as Sustainable Construction Material - A Review." Construction and Building Materials 63 (2014): 97–107. doi:10.1016/j.conbuildmat.2014.03.045.

[29] Muñoz V., P., M. P. Morales O., V. Letelier G., and M. A. Mendívil G. "Fired Clay Bricks Made by Adding Wastes: Assessment of the Impact on Physical, Mechanical and Thermal Properties." Construction and Building Materials 125 (2016): 241–52. doi:10.1016/j.conbuildmat.2016.08.024.

[30] Carretero, M. I., M. Dondi, B. Fabbri, and M. Raimondo. "The Influence of Shaping and Firing Technology on Ceramic Properties of Calcareous and Non-Calcareous Illitic-Chloritic Clays." Applied Clay Science 20, no. 6 (2002): 301–6. doi:10.1016/S0169-1317(01)00076-X.

[31] Kozlowski, Ryszard M. "Handbook of Natural Fibres." Edited by Ed. Handbook of Natural Fibres. Woodhead Publishing in Association with the Textile Institute, Series in Textiles. Oxford-Cambridge-Philadelphia-New Delhi, 2012. doi:10.1533/9780857095510.

[32] Temga, Jean Pierre, Achille Balo Madi, Simon Basga Djakba, Philemon Zo o. Zame, Monique Abessolo Angue, Jacques Richard Mache, Jean Pierre Nguetnkam, and Lucien Dieudonné Bitom. "Lime – and Sand – Stabilization of Clayey Materials from the Logone Valley (Lake Chad Basin) for Their Utilisation as Building Materials." Journal of Building Engineering 19 (2018): 472–79. doi:10.1016/j.jobe.2018.06.003.

[33] Barbero-Barrera, M. Mar, Félix Jové-Sandoval, and Sonia González Iglesias. "Assessment of the Effect of Natural Hydraulic Lime on the Stabilisation of Compressed Earth Blocks." Construction and Building Materials 260 (2020): 119877. doi:10.1016/j.conbuildmat.2020.119877.

[34] Jannot, Yves. "Théorie et pratique de la métrologie thermique." Lab. D'Energétique Mécanique Théorique Appliquée LEMTA. (2011).

[35] Miqueleiz, L., F. Ramírez, A. Seco, R. M. Nidzam, J. M. Kinuthia, A. Abu Tair, and R. Garcia. "The Use of Stabilised Spanish Clay Soil for Sustainable Construction Materials." Engineering Geology 133–134 (2012): 9–15. doi:10.1016/j.enggeo.2012.02.010.

[36] Taallah, Bachir, and Abdelhamid Guettala. "The Mechanical and Physical Properties of Compressed Earth Block Stabilized with Lime and Filled with Untreated and Alkali-Treated Date Palm Fibers." Construction and Building Materials 104 (2016): 52–62. doi:10.1016/j.conbuildmat.2015.12.007.

[37] Wardi, Fatima Zohra El, Abdelhamid Khabbazi, Chaimaa Bencheikh, Houda Ennaceri, and Asmae Khaldoun. "Insulation Material for a Model House in Zaouiat Sidi Abdessalam." In Proceedings of 2017 International Renewable and Sustainable Energy Conference, IRSEC 2017, 1–6. Tangier: IEEE, 2018. doi:10.1109/IRSEC.2017.8477582.

[38] Florea, Iacob, and Daniela Lucia Manea. "Analysis of Thermal Insulation Building Materials Based on Natural Fibers." In Procedia Manufacturing, 32:230–35. Tirgu Mures, Romania, 2019. doi:10.1016/j.promfg.2019.02.207.

[39] Ouedraogo, Kouka Amed Jeremy, Jean Emmanuel Aubert, Christelle Tribout, and Gilles Escadeillas. "Is Stabilization of Earth Bricks Using Low Cement or Lime Contents Relevant?" Construction and Building Materials 236 (2020): 117578. doi:10.1016/j.conbuildmat.2019.117578.

[40] Liuzzi, S., M. R. Hall, P. Stefanizzi, and S. P. Casey. "Hygrothermal Behaviour and Relative Humidity Buffering of Unfired and Hydrated Lime-Stabilised Clay Composites in a Mediterranean Climate." Building and Environment 61 (2013): 82–92. doi:10.1016/j.buildenv.2012.12.006.

[41] Wardi, Fatima Zohra El, Soumia Mounir, Aziza Atbir, Abdelhamid Khabbazi, and Khalid Ibaas. "Effect of Artificial Porosity on the Thermal Behavior and the Lightness of an Eco-Friendly Building Material Based on Clay and Granular Cork." AIP Conference Proceedings 2345, no. 1 (2021): 20008. doi:10.1063/5.0049385.

[42] Elhamdouni, Yassine, Abdelhamid Khabbazi, Chaimaa Benayad, Abdallah Dadi, and Oumar Idriss Ahmid. "Effect of Fiber Alfa on Thermophysical Characteristics of a Material Based on Clay." In Energy Procedia, 74:718–27, 2015. doi:10.1016/j.egypro.2015.07.807.

[43] Maaloufa,Youssef. "Étude de comportement thermique et mécanique de nouveaux matériaux composites à additifs écologiques destinés a l'efficacité énergétique plâtre + fibre alpha/plâtre + liège." PhD thesis, Mohammed V University in Rabat, Morocco, 2019.

[44] Vasconcelos, G., P. B. Lourenço, A. Camões, A. Martins, and S. Cunha. "Evaluation of the Performance of Recycled Textile Fibres in the Mechanical Behaviour of a Gypsum and Cork Composite Material." Cement and Concrete Composites 58 (2015): 29–39. doi:10.1016/j.cemconcomp.2015.01.001.

[45] Vasconcelos, G., P. B. Lourenço, P. Mendonça, A. Camões, R. Mateus, L. Bragança, A. G. Brito, and E. Poletti. "Proposal of an Innovative Solution for Partition Walls: Mechanical, Thermal and Acoustic Validation." Construction and Building Materials 48 (2013): 961–79. doi:10.1016/j.conbuildmat.2013.07.079.

[46] Dénes, Orsolya, Iacob Florea, and Daniela Lucia Manea. "Utilization of Sheep Wool as a Building Material." In Procedia Manufacturing, 32:236–41. Tirgu Mures, Romania, 2019. doi:10.1016/j.promfg.2019.02.208.

[47] Aziz, M. A., P. Paramasivam, and S. L. Lee. Concrete Reinforced With Natural Fibres. New Reinf Concr. Surrey University Press, (1984).