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

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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/m³, 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/m³, 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.

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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. Cherkı 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/m² and 0.124 W/m/K compared to gypsum specimens, 801 kg/m² 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.

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 1. Flowchart of the research methodology
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$_2$O$_3$) 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$_2$O$_3$) is the reason for the color of the red clay soils [29]. The presence of potassium (K$_2$O) 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].

![Figure 2. The particle size distribution of raw clay sample](image)

![Figure 3. X-ray diffraction analysis of Bensmim soil sample](image)

**Table 1. Chemical composition of Bensmim soil sample**

| Chemical element | Mass composition (%) |
|------------------|----------------------|
| SiO$_2$          | 59.6                 |
| Al$_2$O$_3$      | 22.4                 |
| Fe$_2$O$_3$      | 6.69                 |
| K$_2$O           | 2.53                 |
| MgO              | 0.97                 |
| CaO              | 0.0777               |
| TiO$_2$          | 0.832                |
| P$_2$O$_5$       | 0.458                |
| Loss on ignition | 5.34                 |
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/m³, with a grain diameter ranging between 2.5 and 5 mm, and a thermal conductivity range of 0.049 and 0.05 W/m·K, investigated experimentally using the Steady-state Hot Plate method in a 2×10×2 cm³ 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).

| Chemical element | Mass composition (%) |
|------------------|----------------------|
| SiO₂             | 2.70                 |
| Al₂O₃            | <1                   |
| Fe₂O₃            | <1                   |
| CaO              | 49                   |
| MgO              | 16                   |
| CO₂              | 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/m³ 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)

| 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 cm³ for mechanical strength tests and three specimens (10×10×2 cm³) 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 cm³ 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 blocks 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 blocks 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%.
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.
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). Liu 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.

| Sample code | Bulk density ρ (kg.m⁻³) | Measurement error (%) | Gain on lightness (%) |
|-------------|------------------------|-----------------------|----------------------|
| 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

| Sample code | Thermal conductivity λ (W m⁻¹ K⁻¹) | Measurement error (%) | Energy-saving (%) |
|-------------|-------------------------------------|-----------------------|-------------------|
| 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          | 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          | Trial 1 | Trial 2 | Trial 3 | Mean value | Maximum measurement error (%) |
|-----------------|---------|---------|---------|------------|--------------------------------|
| 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 |

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/m³ and 0.238 W/mK, 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

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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