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Orginal Article

Performance of compressed earth blocks reinforced with natural fibres

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Abstract: In contemporary times, governments prioritise the construction of structures that are both durable and cost-effective. Compressed earth blocks (CEB), known for their low environmental impact, excellent thermal insulation, and water resistance, have consistently met these criteria while seamlessly blending modernity with tradition. This study aims to investigate the mechanical and thermal properties of CEB stabilised with cement, compressed at 3 MPa, and reinforced with fibres derived from alfa and vine shoots. The fibres underwent chemical treatment, employing an alkali-acrylic process, to enhance their bond with the matrix, thereby bolstering the mechanical strength of the CEB. Results indicate a notable reduction in water absorption for treated alfa and vine shoot fibres, with reductions of 45% and 33%, respectively, compared to untreated fibres. Optimal compression resistance was achieved with a composition of 1.5% vine shoot fibres and 2.5% alfa fibres. Moreover, surface treatment of fibres led to a 5% and 20% increase in compressive strength for alfa and vine shoot fibres, respectively. Additionally, employing both fibre types resulted in decreased thermal conductivity and density, albeit with a slight adverse effect on thermal conductivity in CEBs containing treated fibres of both types.

Keywords: compressed earth blocks, alfa fibres, vine shoots fibres, mechanical properties, thermal conductivity

1. Introduction

Sustainable construction is considered a way to ensure the comfort and health of inhabitants, limit the environmental impacts of constructions, and seek to make maximum use of natural and local resources.

Currently, the major concern of construction companies is to create thrifty and environmentally friendly habitats. According to Balaras et al., the energy expended in the use of buildings represents almost 40% of the total energy consumption in the European Union. However, on average, we use 11 times more energy for heating, 8 times more primary energy for our electricity consumption, 10 times more for industry, and 11 times more for transportation. Heating alone absorbs around two-thirds of the world's energy [1].

Heating during winter and summer air conditioning consume more energy, which prompts researchers to minimise heat exchange between buildings and the environment. This depends on the building's shape, the nature of the building materials, and the climate in which the building is located.

The choice of building material depends mainly on its availability and cost, which leads to the encouragement of using eco-friendly materials such as raw earth reinforced with vegetable fibres (wood, straw, hemp, flax, earth, etc.).

Raw earth has been used as a building material since ancient times, such as in the tower houses of Shibam in Yemen. This raw material is considered one of the most widely used materials in the world; it is available everywhere and does not require a lot of processing.

Mud construction techniques are not popular nowadays. There are few rules or standards regarding this material. CRAterre (International Centre for Earth Construction) constitutes the principal state of raw earth development in the world [2], while many researchers are working on the development of this material.

Raw earth with plant fibres constitutes a natural and breathable mortar. It is used as a construction method for thermal and sound insulation, and even in the restoration of old buildings to repair mud walls.

Recycling plant waste is the best solution instead of burning it. The burning of vegetable waste is extremely polluting and harmful to the environment and human health. Among the plant waste are certain elements such as wood residue, branches, and leaves that can be used in other construction areas.

Numerous studies have investigated the use of agricultural waste as fibres in compressed earth bricks (CEB) and demonstrated an enhancement of brick performance with this waste. Boussaa et al. studied the effect of the recovery of two biomass ashes, resulting from domestic wood heating, on the mechanical, thermal, and durability properties of compressed earth bricks. These blocks were obtained by partially substituting a silty-clay soil with biomass ashes, in various proportions (0, 5, 10, 15, and 20 % wt). The results show that adding 20 % biomass ashes to CEB improved its compressive and flexural strength [3]. Kiki et al. examined the impact of adding 0 to 1.5 wt% quack-grass straw to CEB composition. The results testify to the durability of stabilised CEB [4]. Junior et al. studied the incorporation of industrial and demolition waste in the production of CEBs. The results show that these waste materials can improve the mechanical, durability, and thermal insulation properties of CEB. Factors like particle size distribution, chemical composition, and processing techniques significantly influence block performance [5]. Nshimiyimana et al. characterised the suitability of clay materials from four sites in the vicinity of Ouagadougou for the production of stabilised compressed earth blocks (CEB). The study also characterised by-products of industry: calcium carbide residue, and of agriculture: rice husk ash and okra plant fibres for the stabilisation of CEB. All clay materials are suitable for the production of CEB with a compressive strength of 4 MPa. Furthermore, the stabilisation of the earthen material from Kamboinse using novel binders improved the structural efficiency of CEB: an increase in compressive strength and a decrease in bulk density. It also improved the hygro-thermal efficiency: a decrease in thermal diffusivity, conductivity, and diffusivity, and an increase in thermal specific capacity and water vapour absorption [6]. According to these studies, plant fibres generally improve the properties of the soil blocks. It should be noted that three essential parameters can affect the quality of CEB: its composition, its binder content, and the compaction force. The combination of these three factors gives the best results.

Previous studies have used plant fibres as reinforcement for CEB [7-14]. According to these studies, plant fibres generally improve the properties of the soil blocks. It should be noted that three essential parameters can affect the quality of CEB: its composition, its binder content, and the compaction force. The combination of these three factors gives the best results [15].

This study aims to evaluate the economic and ecological benefits of CEB reinforced with vegetable fibres. Two types of fibres were used in this investigation: alfa fibres and vine shoots, with percentages of 0.5, 1, 1.5, 2, 2.5, and 3%, by adding cement in amounts of 3, 7, 9, and 11%, a sand content of 30%, and compaction stresses of 3 MPa.

This study is part of the process of recycling and reusing plant waste in the construction of raw earth, including alfa and vine shoots fibres, in order to reduce CO2 emissions released during the manufacture of fired red bricks, which is very advantageous from both an ecological and financial point of view. According to the literature review, several studies have been conducted on the effect of using plant fibres in the manufacture of CEB. This study was conducted to evaluate the effect of using alfa fibres and grapevine shoots as reinforcement on the density, compressive strength, tensile strength, porosity, and thermal conductivity of CEB.

2. Methods and materials

2.1. Materials

2.1.1. Cement

To stabilise the CEB, we employed "Matine" CEM II / B 42.5 N Portland cement compound, which is certified and compliant with both Algerian (NA 442) and European (EN 197-1) standards [16,17]. The chemical composition of the cement used is detailed in Tab. 1. The mineralogical composition of the cement used is detailed in Tab. 2.

Table 1. Chemical composition of cement. *Source*: own study

Chemical composition											
Oxides	SiO_2	AL_2O_3	Fe_2O_3	CaO	K_2O	MgO	Na_2O	SO_3	Cl^-	CaO	P.F
	%	%	%	%	%	%	%	%	%	%	%
Content	20.34	5.37	3	61.69	0.76	1.80	0.14	2.20	0.027	0.07	11.26

Table 2. Mineralogical composition of cement. *Source*: own study

Mineralogical composition				
Minerals	C_3S	C_2S	C_3A	C_4AF
Contents (%)	58.3	14.6	8.7	11.26

2.1.2. Sand

The sand used in this study originates from quarries in the Hassi Bahbah region, situated in the northern part of Djelfa, Algeria. The mineralogical composition is illustrated in Fig. 1, while Tab. 3 provides a summary of the physical characteristics of the sand employed.

Table 3. Physical properties of sand. Source: own study. *Source*: own study

Properties		Sand
Apparent density (kg/m^3)		1350
Specific density		2.810
Water absorption (%)		1.01
Sand equivalent	SE (%)	83.3
	SE_t(%)	80.3
Fineness modulus (FM)		0.91
Compactness (%)		52.55
Porosity (%)		47.45

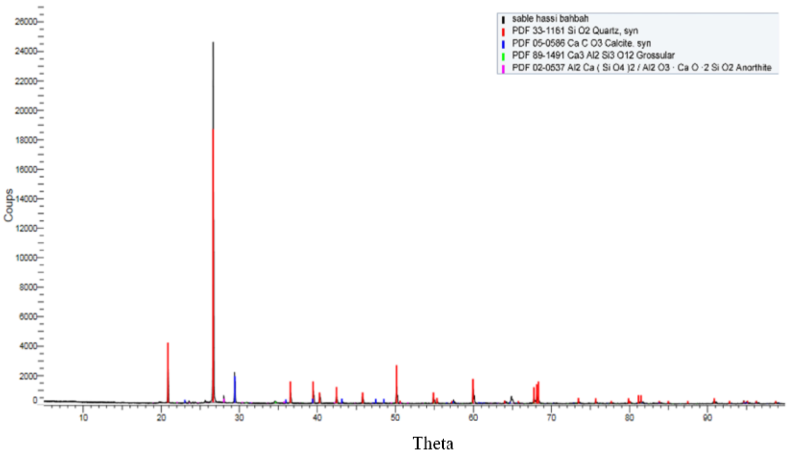


Fig. 1. X-Ray diffraction of sand used. *Source*: own study

2.1.3. Soil

The soil used in this research was sourced from the Medea region, situated approximately 90 km southwest of the capital city of Algiers. Its coordinates are 36°16'19.0"N latitude and 2°43'56.4"E longitude (Fig. 2). Table 4 presents the physical properties of the soil used in the study.

Fig. 2. GPS location of the soil used. *Source*: own study

Table 4. Physical properties of the soil used. Source: own study

Characteristics	Soil
Water content (%)	5.56
Apparent density (kg/m^3)	1320
specific density	2.570
Liquid limit (%)	37
Plastic limit (%)	19
Plasticity index (%)	18

The chemical composition of the soil used is presented in Tab. 5. The mineralogical composition shows that the soil contains a high concentration of quartz, calcite, illite, and a low kaolin content (Fig. 3). The mineralogical composition of the soil used is detailed in Tab. 6.

Table 5. Chemical composition of the soil used. Source: own study

Oxides	SiO_2 %	AL_2O_3 %	Fe_2O_3 %	CaO %	MgO %	SO_3 %	MnO %	T_iO_2 %	LOI %
Content	15.85	3.72	12.76	62.06	2.04	2.06	0.11	0.92	0.59

Table 6. Mineralogical composition of the soil used. Source: own study

	Mineralogical composition					
Minerals	Quartz	Calcite	Illite	Kaolinite	Dolomite Ferroan	Calcium Sulfate Hydrate
Contents (%)	34.4	23.7	28.9	2.6	6.5	3.8

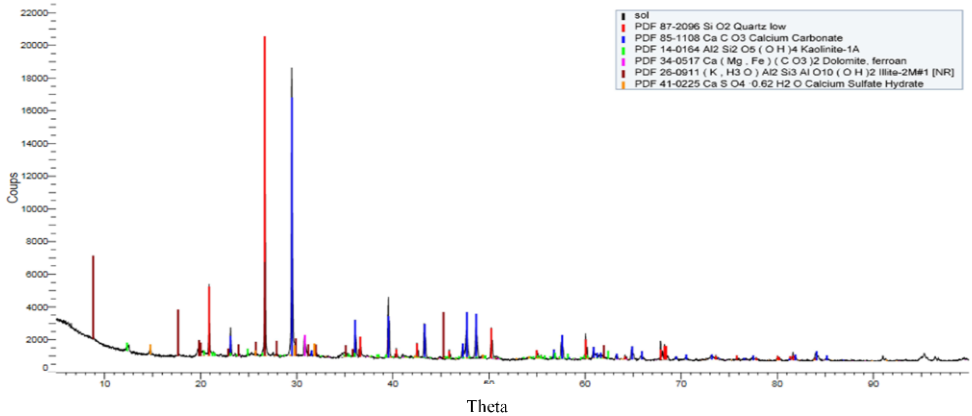


Fig. 3. X-Ray Diffraction of soil Position (°2Θ). Source: own study

The particle size distribution of the soil was determined through particle size analysis and sedimentometry, following the standards NFP 18-560 and NFP 94-057, respectively [18,19]. Figure 4 illustrates the particle size analysis curves of the soil under study, along with the soil amended with dune sand, and depicts the recommended zone limits for CEBs.

It is noteworthy that the soil curve used in this study falls outside the recommended limit zones for CEBs [20], necessitating correction with dune sand. Various authors have employed dune sand for soil correction in CEB production [21-25]. Consequently, soil curves amended with 30% and 40% sand content fall within the recommended limit zones, whereas those amended with 10% and 20% sand content exceed these limits. Moreover, the 30% sand content was selected by several researchers [9,10,15,20,21], and thus was also chosen for this case study.

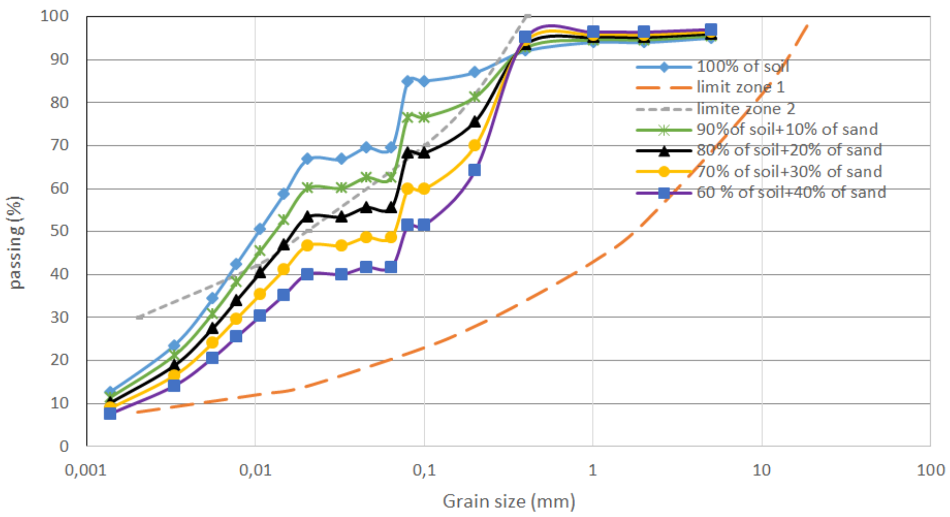


Fig. 4. Particle size distribution of the soil used. *Source*: own study

2.1.4. Water

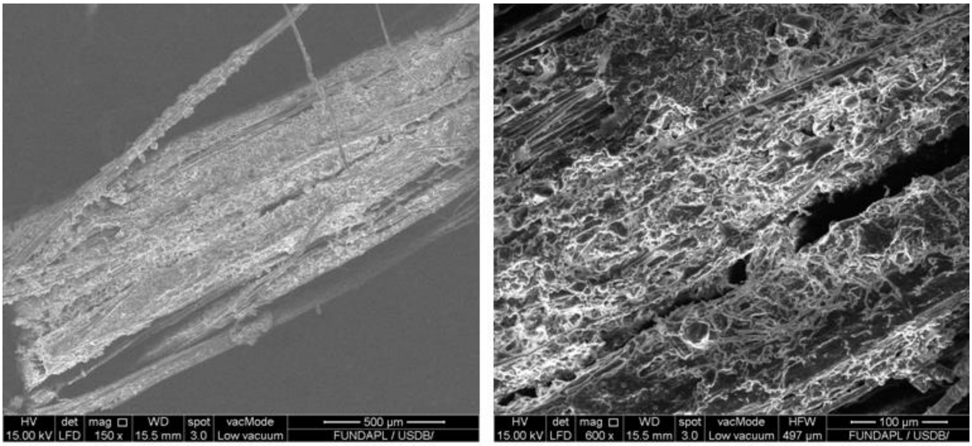
Potable tap water from the civil engineering laboratory of the University of Medea, with a pH between 6.5 and 8, in accordance with NF EN 1008, was used [26].

2.1.5. Fibres

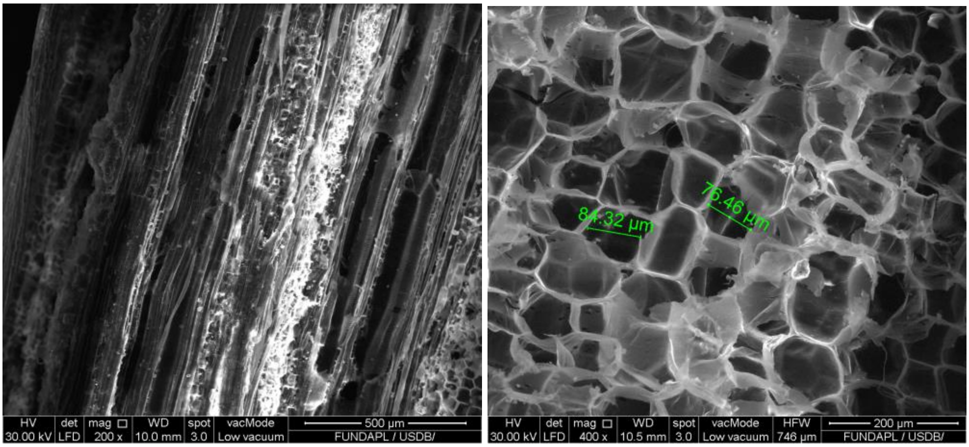
Two types of fibres were employed in the study: vine shoots and alfa fibres. Vine shoot fibres were obtained from vine pruning waste sourced from the Medea region of Algeria, known for vine production. SEM analysis revealed that vine shoot fibres exhibit an elongated, rectangular shape with a fibrous structure (Fig. 5a). Additionally, smaller spherical particles were observed, primarily composed of 41% cellulose, 26% hemicelluloses, and 20.3% lignin [22].

The alfa fibres used are from the region of Djelfa (Algeria). The electron scan of a section in the longitudinal direction of an alfa rod shows the presence of small parts in the fibres, which are the fibrils (Fig. 5b). For the transversal section, the fibres are porous and circular in cross section with low density (Fig. 5c).

The porosity of these fibres is quite high, and their water absorption can reach 90% after immersion. These fibres are heterogeneous, composed mainly of 47% cellulose, 2% hemicelluloses, and 17% lignin [27], which is similar to that of vine shoots. In our work, all fibres are washed and cut into short lengths (40 mm). It should be noted that untreated alfa and vine shoot fibres are soaked in water for 24 hours before use.



a) Longitudina section of vine shoots



b. Longitudinal section of alfa fibres c. Transversal section of alfa fibres

Fig. 5. Scanning electron microscopy (SEM) observations of alfa fibres and vine shoot fibres. *Source*: own study

2.1.6. Treatment of fibres

Numerous studies have indicated that the properties of composites reinforced with natural fibres rely heavily on the interfacial bond between these fibres and the matrix. The adhesion between fibres and the matrix is pivotal in enhancing the mechanical properties of composite systems, facilitating a more effective transmission of forces from the matrix to the fibres. Weak adhesion between the fibres and the matrix can lead to increased porosity and water absorption. Therefore, the treatment of natural fibres is an important area of research that has garnered significant attention.

2.1.6.1. Alkali treatment of fibres

The aim of alkaline treatment is to remove undesirable components of the fibre, such as hemicelluloses, lignin, and pectin. This process alters the morphology of the fibres, leading to the emergence of micro-fibrils and an increase in surface roughness, which facilitates physical bonding with the matrix. Indeed, poor adhesion between the fibre and matrix can elevate porosity, consequently diminishing the mechanical properties of the composite [24,25].

Alsaeed et al. found that treating date palm fibres with 6% NaOH enhances the adhesion between the fibre and the polymer matrix [28]. Mwaikambo et al. investigated fibres from hemp, jute, and kapok treated with various NaOH concentrations, including 6%. They observed that the majority of non-cellulosic constituents degrade under these conditions, leaving the cellulose in a crystalline form and improving adhesion between the matrix and the different fibres [29]. Rokbi et al. noted that a 10% NaOH solution concentration improves bending stresses by 60% and 62%, respectively, compared to composites with untreated reinforcement [25]. In the study by Davila et al., vine shoot alkaline pretreatment was conducted using 12% NaOH for 105 minutes [30].

In this study, treated alfa fibres (TA) were immersed in a 10% NaOH solution for approximately 24 hours at room temperature (25°C). Similarly, treated vine shoot fibres (TV) underwent the same treatment conditions for 24 hours. Subsequently, all fibres (TA and TV) were thoroughly rinsed with distilled water to eliminate any traces of the NaOH solution, followed by neutralisation of the latter with a dilute sulfuric acid (H2SO4) solution for 10 minutes. Finally, the fibres were rinsed again with distilled water and dried in an oven at 60°C for 24 hours [24,31]. Following the alkaline treatment, both types of fibres underwent acrylic treatment.

2.1.6.2. Acrylic waterproofing treatment of fibres

To isolate the fibre or plant aggregate from the cementitious medium, one solution is to coat it with an acrylic polymer. Chafei et al. utilised a treatment designed to protect concrete from water, effectively reducing the water saturation rate of flax fibres [32]. This resulted in improved consistency of the cement mixture and reduced initial setting time, leading to increased flexural and compressive strengths due to the enhanced rheological properties of the composite. Similarly, Chamoin et al. employed a treatment with an acrylic polymer in their study of concrete reinforced with hemp fibres [33]. According to Taallah et al., methods of impregnating fibres with hydrophobic agents such as epoxy and polyester resins, bituminous products, linseed oil, or cashew nuts can slow down or delay fibre embrittlement, but they may not completely inhibit it [27]. However, Gram et al. point out that these impregnation methods tend to reduce the bond between the matrix and fibres, thus decreasing performance in the short term [34].

The resin employed in this study is an acrylic waterproofing resin coating known as STARPROOF WF-AC-600. It was thoroughly mixed for 3 to 5 minutes at low speed using an electric stirrer (rotation less than 300 rpm). The treated fibres, TA and TV, were soaked for approximately 3 minutes at room temperature (25°C) and subsequently air-dried for 24 hours at room temperature in the final step. These fibres were meticulously separated by hand for future use. The treatment process of both treated and untreated fibres is illustrated in Fig. 6.

Fig. 6. The treatment process of fibres. *Source*: own study

Table 7 gives the physical characteristics of different fibres. Plant fibres are hydrophilic materials, which can absorb significant amounts of water. This important absorption is reduced by adequate treatment using "Alkali – Acrylic" treatment. The water absorption of TA and TV is 45% and 33% lower than that of UA and UV, respectively.

Table 7. Physical properties of the fibres used. *Source*: own study

Characteristics	Diameter (mm)	Length (mm)	Water absorption (%)	Specific density
F_1: TA	0.05-0.09	4-5	21.5	0.833
F_2: UA			98	0.769
F_3: TV	0.39-0.5	4-5	11.5	0.892
F_4: UV			37	0.862

2.2. Testing procedures

2.2.1. Preliminary test

Preliminary tests were conducted on CEB to assess compressive strength in both dry and wet states, varying the cement content from 0% to 11% by weight relative to the soil, aiming to determine the optimal percentage for producing durable and cost-effective CEB. Raw soil was dried and sieved to obtain particles smaller than 5 mm. The soil was then mixed with 30% dune sand and different percentages of cement for 30 minutes. Water was added to achieve normal consistency (to facilitate the shaping of the dough), maintaining a water-to-soil ratio of 20% by weight, followed by an additional 30 minutes of kneading. The resulting mixtures were poured into moulds measuring (160 x 40 x 40) mm and compacted under a constant weight, applying a pressure of approximately 3 MPa. After 24 hours, the specimens were demoulded, wrapped in plastic film, and stored in the laboratory for 28 days at room temperature (approximately 22°C, with a humidity of 65%) (Fig. 7).

When cement hydrates with the water present in the soil, it forms stable crystals that create bonds between the soil grains. This reaction necessitates an adequate amount (the right amount of water is the optimal water content) of water. However, since cement achieves its hardness and maximum strength within 28 days, it's essential to maintain moisture by covering the blocks with plastic wrap during this period. After 28 days, the plastic film is removed, and the blocks are placed in an oven at 40°C until their mass stabilises. This method is employed by various researchers who have investigated CEB [10,20,35].

Fig. 7. Mixing process of CEB mixtures. *Source*: own study

2.2.2. *Influence of cement content on CEB*

According to Fig. 8, it is observed that the dry compressive strength decreases from 2.32 to 2.02 MPa with an increase in cement content from 0 to 3%. This reduction of around 13% is likely due to the formation of calcium silicates, which are few and not interconnected due to the low cement percentage. The increase in cement content up to 3% results in an increase in dry compression strength up to 7.63 MPa. This can be attributed to the formation of hydration products within the pores of the matrix, creating a continuous skeleton. Similar observations have been made by other researchers [35,36].

Regarding wet compressive strength, when CEB with 0% cement is used, it dissolves in water. There is also an increase in strength from 1.04 to 4.73 MPa when cement content is increased from 3% to 11%. However, for the same cement percentages, the dry compressive strength is higher than the wet compressive strength (compressive strength of specimens stored in water for 28 days) for all mixes. This finding is consistent with several studies [10,15,36,39]. Additionally, it was observed that the ratio of dry compressive strength to wet compressive strength decreases with increasing cement content.

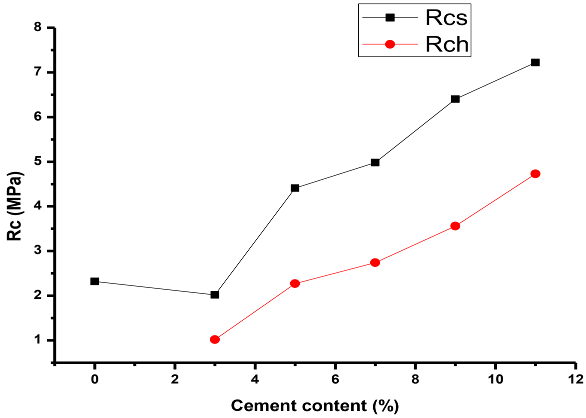


Fig. 8. Dry and wet compressive strength of CEB as a function of cement content. *Source*: own study

Figure 9 shows that the highest compressive strength ratio (R_{cd}/R_{cw}) was obtained for 3% cement: 1.94%, (less than 2%), which is recommended for CEBs.

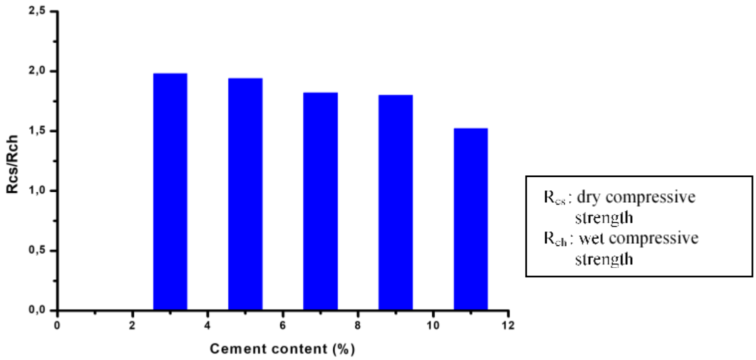


Fig. 9. Dry and wet ratio of compressive strength of CEB as a function of cement content. *Source*: own study

Boulekbach et al. suggest that cement is one of the most effective stabilisers for Compressed Earth Blocks (CEB) due to its superior adhesion with gravel and sand. Therefore, Algeria's National Center for Studies and Research in Integrated Building (Centre National d'Etudes et de Recherche en Bâtiment intégré CNERIB) has drawn up guidelines for the local production of CEB, probably based on extensive testing. These guidelines aim to optimise the composition of CEB, taking into account the characteristics of the local soil and guaranteeing the strength and durability of the blocks [40].

To obtain acceptable compressive strength results for CEB, a cement content of 5 to 6% is typically required. However, with 2 to 3% cement, certain soils may exhibit poorer behaviour when stabilised. An 8% cement dosage is considered an economically acceptable limit [30]. Based on these considerations and the results obtained from the preliminary tests, a cement dosage of 9% was selected. According to Fig. 8, the dry compressive strength for this cement percentage is 6.5 MPa, exceeding the values recommended by major standards for CEB [41].

2.2.3. *Preparation of fibre CEB*

The CEBs with 9% cement content were manufactured following the same procedure as described in paragraph § 2.2.1. However, in this case, natural fibres were incorporated into the CEBs at varying percentages (0.5%, 1%, 1.5%, 2%, 2.5%, 3%). The compositions of the different mixtures are presented in Tab. 8. It is important to note that CEBs with untreated fibres were prepared using the same mixing percentages as those with treated fibres.

Table 8. Mixture proportions of CEB. *Source*: own study

CEB	Soil (%)	Cement (%)	Sand (%)	TAF (%)	TVSF (%)	Water/soil (-)
CEBW	61	9	30	0	-	0.26
CEBTA0.5	60.5	9	30	0.5	-	0.26
CEBTA1	60	9	30	1	-	0.26
CEBTA1.5	59.5	9	30	1.5	-	0.26
CEBTA2	59	9	30	2	-	0.26
CEBTA2.5	58.5	9	30	2.5	-	0.26
CEBTA3	58	9	30	3	-	0.26
CEBTVS0.5	60.5	9	30	-	0.5	0.26
CEBTV1	60	9	30	-	1	0.26
CEBTV1.5	59.5	9	30	-	1.5	0.26
CEBTV2	59	9	30	-	2	0.26
CEBTV2.5	58.5	9	30	-	2.5	0.26
CEBTV3	58	9	30	-	3	0.26

UA: Untreated alfa fibres.
CEBW: Compressed earth blocks with 0 % fibres.
CEBTA: Compressed earth blocks with treated alfa fibres.
CEBUA: Compressed earth blocks with untreated alfa fibres.
CEBTV: Compressed earth blocks with treated vine shoots fibres.
CEBUV: Compressed earth blocks with untreated vine shoots fibres.
TA: Treated alfa fibres.
UV: Untreated vine shoots fibres.
TV: Treated vine shoots fibres.

2.2.4. *Testing methods*

2.2.4.1. *Dry compressive strength test*

This test aims to assess the resistance to simple compression of CEB specimens measuring (40 x 40 x 80) mm, following standard XP P 13-901 [42]. It involves subjecting a sample composed of two superimposed half blocks bonded with cement mortar to a compressive load until failure occurs.

2.2.4.2. Dry tensile strength test

The tensile strength of CEBs is determined using the three-point bending test as per standard NFP 18-407 [43]. This test is conducted on specimens measuring (40 x 40 x 160) mm^3.

Measurements are performed using a mechanical press with a capacity of 50 kN, and the travel speed is set at 0.1 mm/min (Fig. 10).

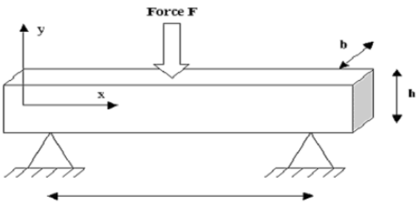


Fig. 10. Three-point bending assembly diagram of CEB. *Source*: own study

2.2.4.3. Porosity accessible to water

The accessible porosity to water of the CEB samples was determined by hydrostatic weighing according to NF P 18-459 [44]. The procedure is to saturate the pores of specimens (Fig. 11), after determining the apparent mass of the samples immersed (M_{wet}), their mass in air (M_{sat}), and the dried mass (M_{dry}). The porosity is given by:

$$\varepsilon = \frac{M_{sat} - M_{dry}}{M_{sat} - M_{wet}} \cdot 100\% \tag{1}$$

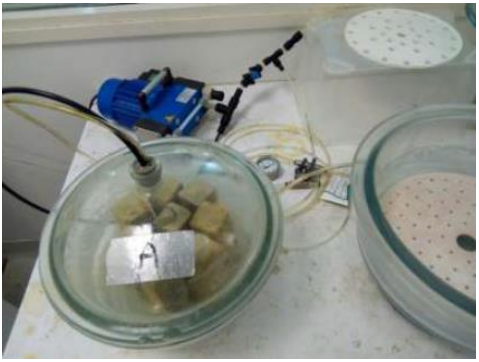


Fig. 11. Saturation device for determining porosity of CEB. *Source*: own study

2.2.4.4. Thermal conductivity

For each type of fibre and each treatment method, three identical specimens of (40 x 40 x 160) mm^3 were used. These specimens were placed in the oven to dry at 40°C until a constant weight was reached. The thermal conductivity for each type of CEB was measured by the hot wire method using a CT-meter (Fig. 12) according to standard NF EN 993-15 [45].

Fig. 12. Experimental device used for measuring thermal properties of CEB. *Source*: own study

2.2.4.5. XRD, TGA and SEM analyses

In order to evaluate the effects of incorporating alfa and vine shoot fibres on the microstructural properties of CEB blends, XRD and SEM analyses (Fig. 13a-b) were performed on the cured samples of some CEB blends, both with and without fibres. Scanning electron microscopy (SEM) analysis was performed using a VEGA3-TESCAN SEM with an accelerating voltage of 25 kV (Fig. 13a) to study the raw material morphology and microstructure of some cured CEB blends, including hairline cracks, surface morphology, and voids. To make the sample electrically conductive, it was placed in a cutter and then a thin layer of gold was applied. X-ray diffraction (XRD) analysis was used to determine the mineral phase composition of the raw materials used. Samples for XRD testing were collected and immersed in anhydrous ethanol. After sample preparation, a mass of 2 or 3 g of prepared powder was obtained and subjected to XRD testing with an X-ray tube (Cu 1.54 Å) using a BRUKER, AXS, D8 instrument, as shown in Fig. 13b. The diffractogram was obtained in a range of 2θ, between 20° and 90°, and at a speed of 1 s for 50 min.

a) b)

Fig. 13. Microstructural tests, a) Scanning electron microscopy SEM analysis, b) XRD analysis. *Source*: own study

3. Results and discussion

3.1. The impact of natural fibres on the specific density of CEB

From Fig. 14, it is evident that the density of different compositions of CEBs decreases with an increase in the percentage of fibre. This phenomenon has been observed in several studies [27,46-49]. The substitution of the matrix with fibres leads to an expansion in the total volume of the mixture, even after compaction, resulting in a decrease in sample weight and density. Notably, the density of CEBW is recorded at 2103.5 kg/m³, decreasing to 2016.33 kg/m³ for CEBTA (a reduction of 4.15%) with 3% fibres. This decrease is 5.57% for CEBUA, 6.85% for CEBTV, and 17% for CEBUV. It is observed that bricks reinforced with alfa fibres exhibit higher densities than those reinforced with vine shoot fibres. This disparity may be attributed to the higher solid content in alfa compared to vine. Additionally, there is no significant difference in mass loss between CEBs reinforced with treated and untreated alfa fibres. However, for CEBs with vine shoot fibres, the density of blocks with untreated fibres decreases by approximately 24.44% compared to those with treated fibres. This discrepancy is attributed to the fibre treatment, which reduces pores within the brick matrix, resulting in higher densities than other CEBs, consistent with findings by Ouedraogo et al. [50]. (Fig. 5 shows SEM images of untreated alfa fibres).

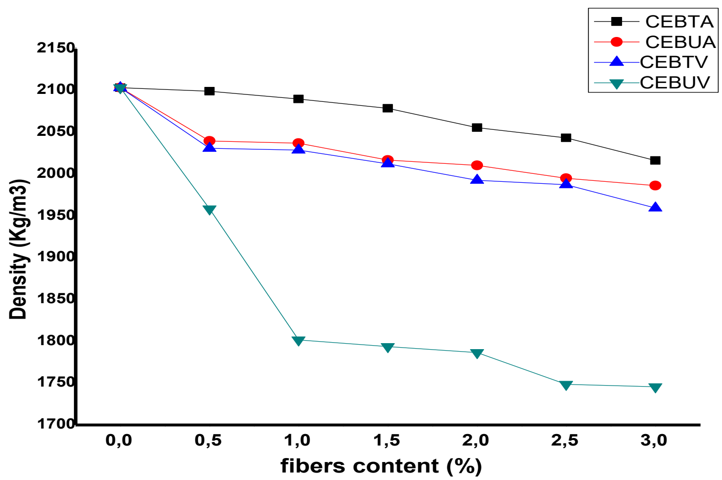


Fig. 14. Density of CEB as a function of fibres content. *Source*: own study

3.2. The impact of natural fibers on the compressive strength of CEB

From Fig. 15, it is apparent that the compressive strength of fibre-reinforced CEB decreases with increasing fibre incorporation rate compared to BTCW. This trend has been observed by other authors [14,36-38]. For CEBUV, a reduction of approximately 36% in compressive strength is recorded compared to that of CEBW for 0.5% UV, followed by a slight increase of 10% for 1.5% UV, then a subsequent decrease to 14% for 3% UV. CEBTV exhibits the highest compressive strengths (RCmax = 4.82 MPa), indicating that the treatment of vine shoot fibres enhances compressive strength by 5% for 1.5% fibre volume fraction.

For CEBUA, a decrease in compressive strength of 38% compared to CEBW is observed with 1% UA, followed by an increase of 13% for 2.5% UA, and then a decrease of

13% for 3% UA. CEBTA records the highest compressive strengths (RCmax = 5.48 MPa) with an improvement in compressive strength of 20% compared to CEBUA with 2.5% fibres, confirming once again the significant role of fibre treatment.

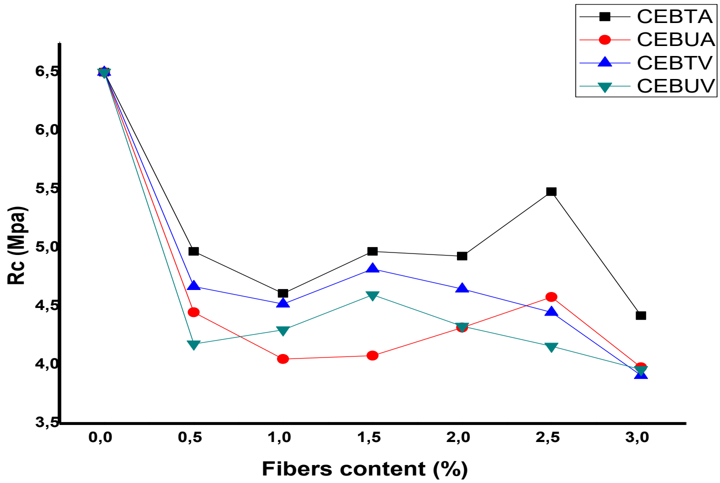


Fig. 15. Compressive strength of CEB as a function of fibre content. *Source*: own study

The increase in compressive strength at a certain percentage is likely attributable to the presence of fewer pores, which are occupied by fibres. The combination of fibres and the matrix impedes crack propagation, thereby contributing to enhanced compressive strength. However, at certain fibre ratios, compressive strength may decrease due to soil matrix degradation caused by bulky fibres. As the fibres become entangled and overlap, cohesion is reduced, weakening the soil-fibre composite. Millogo et al. observed a similar phenomenon in adobes reinforced with 6 cm long Hibiscus cannabinus fibres, recording an RC max of 2.7 MPa [21]. Ouedraogo et al., who utilised Kenaf fibres to reinforce adobes, achieved approximately 3.4 MPa [51]. Similar results were also reported by Bahar et al., who employed various fibre types to reinforce CEB and achieved an RC max of 3 MPa [39].

3.3. The impact of the percentage of natural fibres and their treatments on the tensile strength of CEB

From Fig. 16, it is evident that for all fibre-reinforced CEBs, tensile strength increases with increasing fibre incorporation. This is attributed to the fact that alfa and vine shoot fibres exhibit resistance to tensile stress and demonstrate good adhesion with the matrix, particularly for the treated fibres.

For CEBUA, an increase in tensile strength (Rt) of 96% compared to CEBW with 2.5% UA was observed, followed by a reduction of 11% for 3% UA. CEBTA achieves the highest tensile strengths (Rtmax = 1.94 MPa), representing a 70% improvement in Rt compared to CEBUA with a fibre percentage of 2.5%.

For CEBUV, an increase in Rt of 57% compared to CEBW with 2.5% UV was observed, followed by a reduction of 19% for 3% UV. CEBTV achieves the highest tensile strengths (Rtmax = 1.3 MPa), representing a 43% improvement in Rt compared to CEBUV with a fibre percentage of 2.5%.

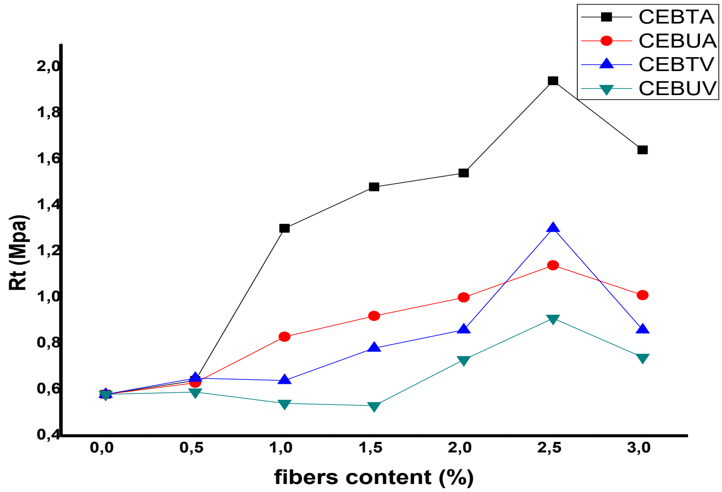


Fig. 16. Tensile strength of CEB as a function of fibre content. *Source*: own study

From a fibre content of 2.5% onwards, there is a decrease in tensile strength due to the low adhesion between the fibres and the matrix as fibre content increases. Elhamdouni et al. observed a similar phenomenon, but with an increase in Rt up to 2% for both alfa and straw fibres [52]. Conversely, there is an improvement in Rt for CEBs with treated fibres compared to those with untreated fibres, especially for alfa fibres. This is attributed to the fact that fibre treatment increases their surface roughness, thereby enhancing adhesion between the fibres and the matrix. Similar results have been observed in other studies [50,53-55].

3.4. The impact of the percentage of natural fibres and their treatments on the thermal conductivity of CEB

According to Fig. 17, the thermal conductivity of CEBs decreases with an increase in fibre incorporation, a trend consistent with findings from several authors [9,21,27,39,46,51,56]. For CEBTA, the thermal conductivity coefficient decreases from 1.1615 to 0.8382 W/m·K as fibre content varies from 0% to 3%. Conversely, for CEBUA, thermal conductivity decreases to 0.7936 W/m·K. These results suggest that CEBUA exhibits better insulation properties than CEBTA. This difference is likely due to the decrease in porosity of CEBTA resulting from fibre treatment and the increase in porosity of CEB reinforced with untreated fibres. According to Lima et al., an increase in porosity leads to lower density, which in turn results in decreased thermal conductivity [57]. Conversely, a decrease in porosity is associated with compaction force, where increasing the impact pressure reduces air content [58].

Indeed, cement hydration facilitates the formation of compounds that reinforce the bonds between constituents (soil and sand), thereby promoting a reduction in porosity. This results in a homogeneous and continuous internal structure, which is favourable for heat transfer [59].

For CEBTV, thermal conductivity decreased from 1.1615 to 0.7196 W/m·K as fibre content varied from 0% to 3%. Conversely, for CEBUV, it decreased to 0.6761 W/m·K. Additionally, the thermal conductivity of CEBs reinforced with vine shoot fibres is lower than that of CEBs with alfa fibres. This is attributed to the shape of vine shoot fibres, which allows a large number of empty voids to be stored inside the matrix. The results obtained suggest that vine shoot fibres improve thermal insulation better than alfa fibres.

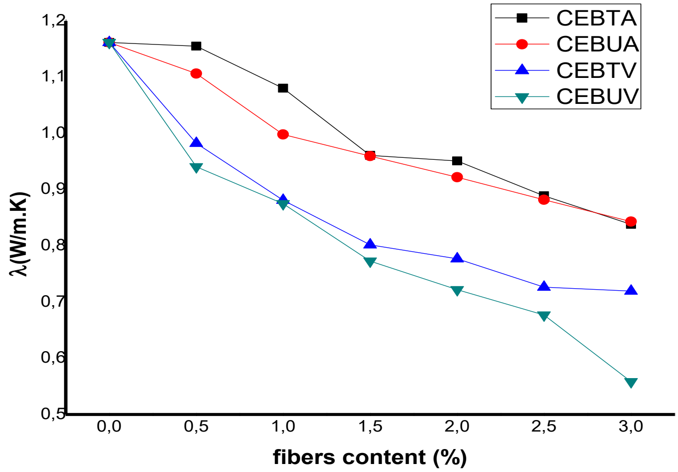


Fig. 17. Thermal conductivity coefficient of CEB as a function of fibre content. *Source*: own study

3.5. The impact of the percentage of natural fibres and their treatments on the porosity of CEB

The addition of fibres typically leads to an increase in the porosity of earth blocks [48,51,60], as observed in Fig. 18. Across all CEBs reinforced with the two types of fibres, porosity increases with the percentage of fibres. Notably, for CEBTA and CEBUA, there is a decrease in porosity with 2.5% alfa fibres, followed by an increase. Conversely, for CEBTV and CEBUV, there is a slight decrease in porosity with 1.5% vine shoot fibres, followed by an increase.

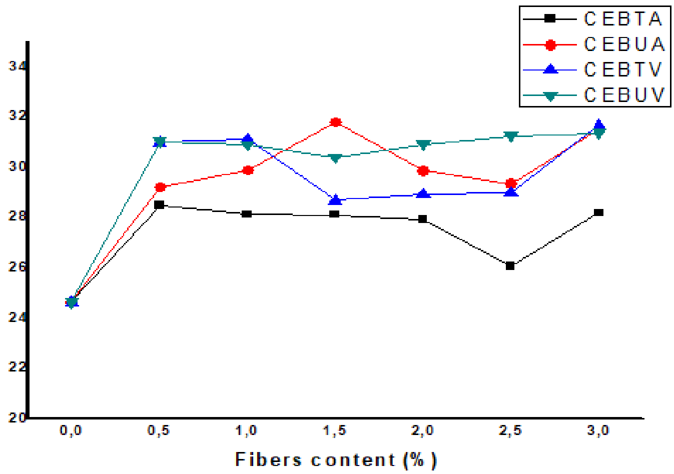
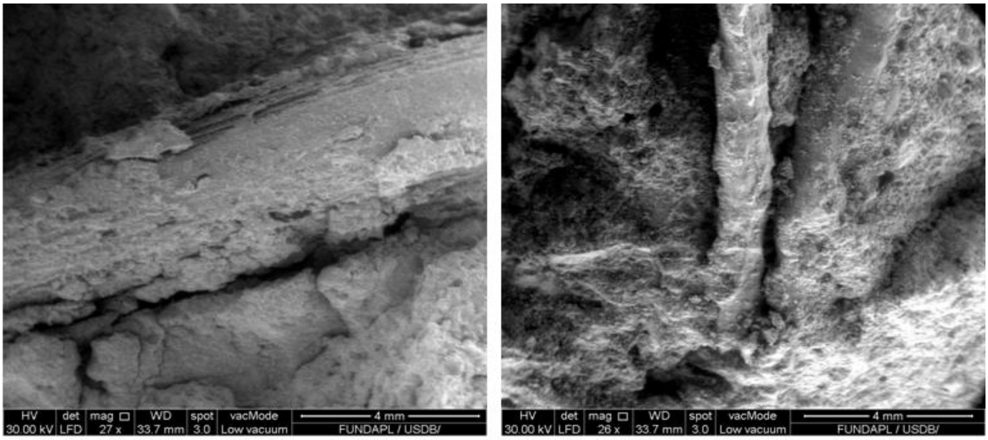


Fig. 18. Porosity of CEB as a function of fibre content. *Source*: own study

According to Namango et al., the addition of certain percentages of sisal fibres to the soil results in a reduction in voids and consequently a decrease in the porosity of the blocks. This leads to an improvement in compression resistance, particularly noticeable at a fibre percentage of 0.75% [61]. Similarly, Mansour et al. suggest that increasing the compaction of CEBs causes a rearrangement of the internal structure of the grains, resulting in a reduction in the quantity of microscopic pores and, consequently, a decrease in porosity. For a compaction force of nearly 3 MPa, the porosity is measured at 24.1%, which is similar to that found for the control CEBs [56].

In Fig. 19, SEM observations of the fibre-matrix interaction for both alfa and vine shoot fibres are depicted. These observations further confirm the impact of fibre treatment on reducing porosity and enhancing adhesion between fibres and the matrix.



a) Matrix -alfa fibers **b) Matrix -Vine shootd fibers**

Fig. 19. SEM observation of alfa and vine shoots fibers. *Source*: own study

4.6. Influence of the porosity on the compressive strength of CEB

The variation in compressive strength of CEBs as a function of porosity (ε) is shown in Fig. 20 and Fig. 21. It can be seen that the compressive strength decreases with an increase in the porosity of CEB.

The relationships between strength and porosity for CEB reinforced with all fibres are given in Tab. 9.

Table 9. Empirical relations of strength and porosity of CEB. *Source*: own study

CEB	Empirical relations	R^2
CEBTA	$R_c = 50.2e^{-0.048\varepsilon}$	0.8732
CEBUA	$R_c = 34.844e^{-0.069\varepsilon}$	0.9286
CEBTV	$R_c = 0.3549\varepsilon^2 - 19.305\varepsilon + 266.69$	0.8474
CEBUV	$R_c = 0.073\varepsilon^2 - 4.4421\varepsilon + 71.412$	0.9515

Table 9 reveals a strong correlation between compressive strength and porosity across all models, as evidenced by their high correlation coefficient values. This finding aligns with similar relationships observed by other researchers [56,62-64].

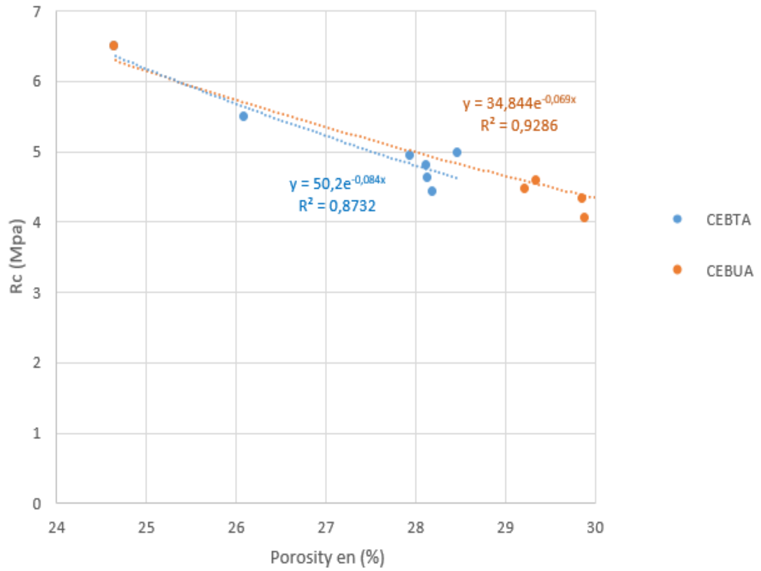


Fig. 20. Compressive strength of CEB with alfa fibres as a function of porosity. *Source*: own study

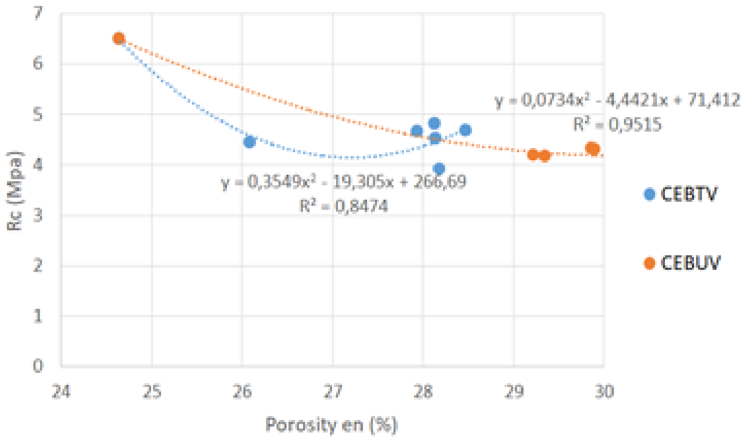


Fig. 21. Compressive strength of CEB with vine shoot fibres as a function of porosity. *Source*: own study

The data presented in Fig. 21 illustrate that the porosity of CEB falls within the range of 23% to 30%. Specifically, for CEBTA, with a porosity of 28.19%, the compressive strength (Rc) is measured at 4.42 MPa. Meanwhile, for CEBUA, with a porosity of 31.54%, Rc is recorded at 3.98 MPa. Regarding CEB reinforced with vine shoot fibres, CEBTV exhibits a porosity of 28.19%, with an Rc of 3.9 MPa, while CEBUV, with a porosity of 31.54%, shows an Rc of 3.96 MPa.

These findings meet acceptable constraints, as outlined by Mansour et al., who suggest that practical stress should be limited to a value equal to or greater than 1 MPa [56]. Accordingly, CEBs should ideally possess a porosity degree of less than 35%, a criterion satisfied by the results of our study.

4. Conclusions

In summary, the study investigated the impact of alfa and vine shoot fibre content and treatment on the mechanical and thermal properties of CEBs. Here are the key conclusions drawn from the research:

- 30% dune sand is required to adjust the soil and ensure it aligns with the recommended standards for CEBs.
- For strong and cost-effective CEBs, a 9% cement content is required for soil treatment.
- Alkali-acrylic treatment of alfa and vine shoot fibres enhanced the compressive strength of fibre-reinforced CEBs by 15% and 4%, respectively, compared to untreated fibres.
- Treatment of the fibres reduced porosity, leading to increased densities in the treated CEBs.
- The compressive strength of fibre-reinforced CEBs decreases as the fibre content increases. CEBs with treated vine shoot fibres show a 5% improvement in compressive strength compared to untreated ones at 1.5% fibre content. Similarly, CEBs with treated alfa fibres exhibit a 20% increase in compressive strength compared to untreated alfa fibre CEBs at 2.5% fibre content, highlighting the significant impact of fibre treatment.
- A 70% improvement in tensile strength can be achieved with treated alfa fibres, while treated vine shoot fibres provide a 43% increase in CEB tensile strength.
- At fibre contents above 2.5%, tensile strength decreases due to reduced adhesion between the fibres and the matrix as the fibre content increases.
- The thermal conductivity of CEBs is a function of treated fibres. The thermal conductivity of CEBs reinforced with vine shoot fibres is lower than that of CEBs with alfa fibres.
- The porosity of CEB (TA & UA) and CEB (TV & UV) decreases, respectively, with 2.5% alfa fibre content and 1.5% vine shoot fibres.
- A content of 2.5% alfa fibres and 1.5% vine shoot fibres is sufficient to produce CEBs with both good strength and insulation properties. These blocks offer a viable alternative to fired bricks in construction and can be classified as eco-friendly materials.

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