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Effect of untreated and treated date palm fibers on the thermomechanical properties of compressed earth bricks for sustainable construction in arid regions

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ABSTRACT

This study aims to use local materials, particularly soil and date palm fibers, to develop a high-performance building material capable of improving the durability of earthen buildings in arid regions, primarily in NKOB-Zagora, located in the Drâa-Tafilalet region of Morocco. The main objective is to study the physical, mechanical, and thermal properties of compressed earth bricks (CEB) reinforced with raw and treated date palm fibers. Two types of fibers were used in this study: fibers from the leaflets (DPLF) and surface fibers (DPSF). These fibers were modified through two treatments: an alkaline treatment and a hydrothermal treatment. Initially, the soil and fibers, in both raw and treated states, were characterized. Then, CEBs reinforced with treated and untreated fibers, varying from 0 to 2% by weight, were prepared. The results show that the addition of both types of fibers, DPSF and DPLF, whether raw or treated, significantly improves the thermal insulation of CEBs while reducing their density. Furthermore, the incorporation of raw DPSF and DPLF results in a significant decrease in compressive strength, by 22.33% and 25%, respectively. Moreover, the results show that the applied treatments substantially mitigated this loss: for DPSF, the decrease was limited to 9.51% with alkaline treatment and 13.83% with hydrothermal treatment, for DPLF, reductions were limited to 13.45% and 16.75%, respectively. These results indicate that the use of date palm fibers as reinforcement improves the thermal performance of CEBs; furthermore, the applied treatments have limited the loss of mechanical properties.

Keywords: earthen buildings, compressed earth bricks, date palm fibers, alkaline treatment, hydrothermal treatment, thermal insulation, compressive strength.

INTRODUCTION

The fabrication of building materials, particularly concrete, is a major contributor to emissions of carbon dioxide (CO_2) into the environment. Furthermore, the building sector as a whole generates about 40% of global greenhouse gas emissions (Lahbabi et al., 2024). Due to their poor thermal insulation performance, most conventional construction materials lead to significant energy consumption, particularly for air conditioning systems, which alone account for approximately 45% of the energy used in buildings (Agoudjil et al., 2011; Mahmoodzadeh et al., 2021). As in many developing countries, the construction sector is one of Morocco's more energy-intensive industries, accounting for approximately 33% of the overall energy consumption (Boumhaout et al., 2017). With the strong growth in global housing, expected to increase by approximately 50% by 2050 (Deetman et al., 2020), reducing the construction industry's environmental impact is becoming crucial to ensuring the sustainability of buildings for future generations. These findings explain the scientific community's interest in less energy-intensive and more eco-friendly materials for construction. In this context, raw earth building materials can be a relevant solution thanks to their excellent insulating properties, affordability, and low environmental impact (Abanto et al., 2017). As Niroumand et al. (2017) point out, earth is a durable material that meets health, thermal insulation, and economic factors. Indeed, earthen construction has been widely used worldwide throughout history (Bhandaree and Tharmarajah, 2023). In some regions, earthen buildings suffer from certain shortcomings, such as strength, impermeability, and durability (Alam et al., 2015). Furthermore, the need for ongoing maintenance and repairs remains a major challenge. The durability and performance of earthen constructions are closely linked to the construction technique employed (Kiki et al., 2023). Rammed earth and adobe are traditional methods widely used in North Africa, particularly in rural areas (Lahbabi et al., 2023). The advances in traditional adobe techniques have contributed to the development of an improved masonry technique: compressed earth bricks (CEBs), which enhance the performance and quality of molded units, yielding buildings that are stronger, more habitable, and more durable (Cid-Falceto et al., 2012). During production, the use of compacting force reduces the porosity and improves the internal cohesion of CEBs. Numerous studies have investigated compressed earth bricks, as demonstrated by the research conducted by (Chehade et al., 2025; Gharbage et al., 2025; Mouih et al., 2025a; Waeytens et al., 2025). To further enhance CEBs' performance, stabilizing agents such as lime or cement are commonly used. In addition, the incorporation of natural fibers as reinforcing agents has received considerable attention. Adding such fibers contributes to better thermal performance of earthen bricks by lowering their thermal conductivity. Because they are biodegradable and reusable, a variety of natural fibers have been incorporated as reinforcements in earth bricks, offering both economic and environmental benefits (Nirmal et al., 2015). In this context, prior studies have examined the effects of natural fibers incorporation on the qualities of earthen building materials. El Bourki et al. (2025) studied the effect of date palm fiber on the mechanical properties of rammed earth, testing different fiber proportions (0.5%, 1%, and 1.5%). The authors demonstrated that incorporating these fibers within the earth matrix enhances compressive strength, with a maximum value observed at a fiber content of 1%. Furthermore, Khrissi and Tilioua (2025) also discovered that incorporating fibers derived from date palm waste to earthen bricks optimizes their thermal behavior across all tested proportions, while mechanical performance increases up to a fiber percentage of 3%. Over this threshold, a reduction in mechanical strength was observed. However, a higher fiber content generally reduces the mechanical performance of the bricks. Khoudja et al. (2021) highlighted that incorporating date palm waste into earth bricks improves their thermal insulation capacity while causing a decrease in mechanical strength, which nevertheless remains within the normative requirements for earthen construction. Similarly, El-Yahyaoui et al. (2023) showed that adding saw palmetto fibers to raw earth bricks leads to a notable decrease in mechanical performance as the fiber proportion increases, while maintaining the bricks' functionality for construction applications. Moreover, Sadouri et al. (2024) reported that adding Juncus fibers to compressed earth bricks stabilized with Portland cement reduces compressive strength by approximately 17% while also decreasing thermal conductivity. Finally, Limami et al. (2021) investigated the performance of clay bricks reinforced with Typha fibers. They found that adding higher proportions of Typha fibers increases the porous fraction of the bricks, which results in a decrease in compressive strength. As reported by Taallah et al. (2014), the reduction in mechanical performance with higher fiber incorporation is linked to insufficient fiber/matrix adhesion. To improve this adhesion by enhancing the irregularity of natural fiber surfaces, alkali and hydrothermal treatments are widely employed to remove undesirable substances including hemicelluloses, lignin, and other constituents from the fibers (Ajouguim et al., 2019a; Elmoudnia et al., 2023). Chemical analyses of date palm fibers have revealed that they mostly consist of cellulose, hemicelluloses, lignin, and trace amounts of other constituents (Alotaibi et al., 2019). Several studies indicate the advantages of fiber treatment in optimizing the mechanical performance of earth bricks. Taallah and Guettala (2016) examined how the addition of date palm fibers subjected to alkaline treatment influences the mechanical characteristics of compressed earth blocks. The authors found that the compressive strength of soil blocks containing treated fibers is high compared to that obtained with untreated fibers. In addition, Bouchefra et al. (2022) investigated the thermophysical and mechanical properties of compressed earth bricks containing doum fibers, used both in their raw state and after alkaline treatment. The authors concluded that fiber treatment helps to limit the decrease in compressive strength, which falls from 35% to 25% for a content of 2% raw and treated fibers, respectively. Similarly, Ajouguim et al. (2019) showed that alkaline and hydrothermal treatments applied to Alfa fibers improve fiber/matrix adhesion, thereby enhancing the mechanical performance of CEBs incorporating treated Alfa fibers. Although these studies demonstrated the beneficial effect of reinforcing earth bricks with natural fibers, whether raw or treated, most investigations have focused on a single fiber type and/or a single treatment method. Consequently, comparative studies involving different fiber categories and treatment techniques remain limited. Furthermore, in order to reduce the grey energy associated with the transportation and processing of materials, it is essential to prioritize the use of locally available resources

Date palms are found in many arid and semi-arid zones worldwide. In Morocco, their population exceeds 5.4 million trees, representing approximately 4.5% of the world's total palm trees (El bourki et al., 2025). Their cultivation is mainly concentrated in the southeastern oases, particularly in the Drâa-Tafilalet region (Rehali et al., 2025). Each year, the maintenance of date palms generates large quantities of waste, estimated to weigh between 33 and 35 kg per tree (Makkawi et al., 2019). This waste can be used as a fibrous reinforcement in earthen building materials, offering an ideal opportunity for its recovery. However, relative to other natural fibers, relatively little research has been conducted on the application of date palm fibers in earth construction materials. Moreover, comparative studies involving different types of date palm fibers, combined with both alkaline and hydrothermal treatments, remain scarce. In addition, the influence of fiber length on the thermomechanical performance of compressed earth bricks has received limited attention. These limitations highlight the need for a comprehensive investigation of the combined effects of date palm fiber type, treatment, content, and length on the performance of compressed earth bricks. Therefore, the objective of the present study is to provide a comprehensive assessment of the effects of date palm fiber type, treatment, content, and length on the physical, mechanical, and thermal properties of compressed earth bricks. The impact of both treated and raw date palm fiber content on the mechanical, thermal, and physical characteristics of compressed earth bricks (CEBs) is examined in this study. Furthermore, the effect of fiber length on the mechanical and thermal performance of CEBs was examined. Two types of date palm fibers were employed: leaflet fibers (DPLF) and surface fibers (DPSF). The CEBs were produced using local soil from the NKOB-Zagora, currently employed by the local population for building and restoring local earthen buildings.

MATERIALS AND METHODS

Soil

The soil employed in this research was obtained from NKOB-Zagora, which is located in Morocco's Drâa-Tafilalet region (Figure 1), an area renowned for its ancient earthen buildings known as Kasbahs. This soil was selected due to its wide local availability and is specifically utilized by local communities for both the construction and restoration of earthen buildings.

Physicochemical and mineralogical analyses

To determine the soil chemical makeup, an analysis was made with X-ray fluorescence spectroscopy. The dried soil was heated to 1000 °C for two hours and to 550 °C for four hours in order to measure the weight loss on ignition (LOI) and the percentage of organic matter, respectively (Heiri, 2001). The carbonate percentage was revealed by the calcimetric technique, based on NF P94-048. Additionally, mineralogical composition of the soil was further investigated using X-ray diffraction (XRD).

Geotechnical characterization

Using dry sieving and sedimentometry, the soil's grain size analysis was determined based on the NM ISO 17892-4 standard. The standard NM ISO 17892-12 was used to determine the Atterberg limits. Furthermore, the soil's methylene blue test (MBV) was measured in accordance with NM 13.1.178, and this value was then employed to calculate the soil's specific surface area using the procedure described in (Cojean et al., 2008). Following NM 13.1.023, the modified proctor test was performed. The water

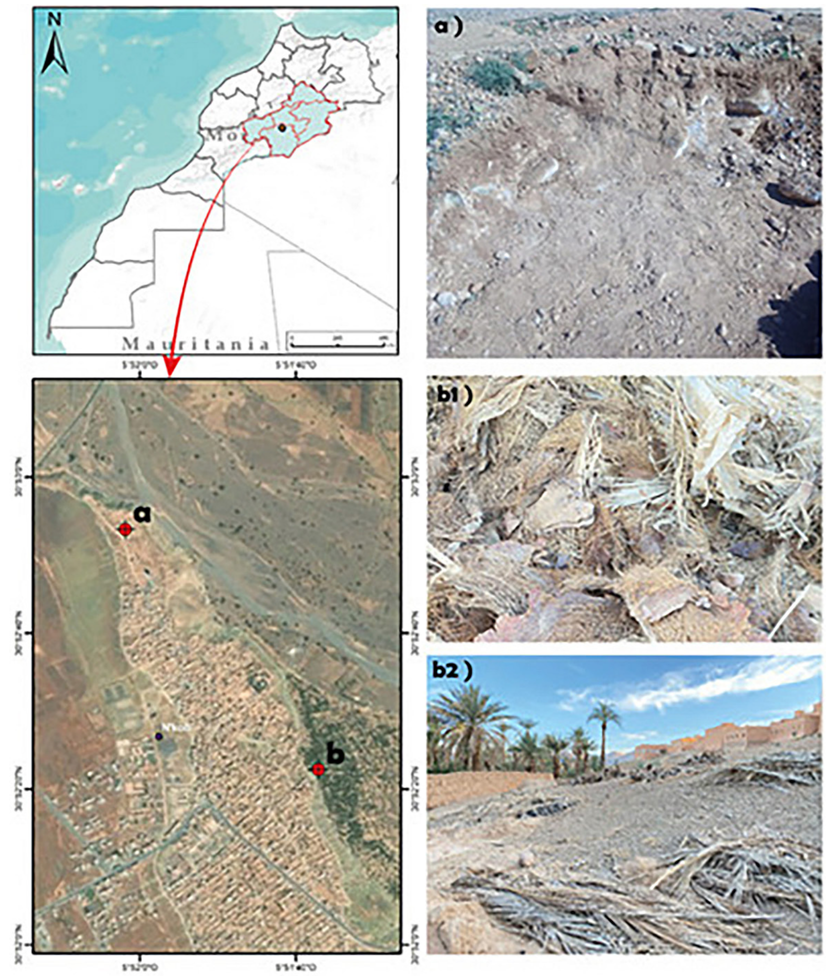

Figure 1. Map of the studied site: a) studied soil, b1) date palm surface fibers, b2) date palm leaflet fibers

contained in the soil was established according to standard NM 13.1.152. Moreover, the distilled water pycnometer method was used to determine soil particle density following the NM 00.8.098.

Palm fibers and treatment

In this study, two types of fibers were used: DPLF and DPSF. These fibers were collected from the NKOB-Zagora palm oases (Figure 1). To eliminate the pollutant particles, the fibers were carefully cleaned then dried in the open air for 72 hours. The fibers underwent two different forms of treatment in order to modify their surface: hydrothermal and alkaline treatments.

- The alkaline treatment, firstly, the fibers were placed in a solution of sodium hydroxide at 6% by mass for 24 hours at laboratory temperature according to the study of Alsaeed et al. (2013). The remaining sodium hydroxide was neutralized by initially washing the fibers in an aqueous solution prepared with 1 wt% acetic acid. Finally, the fibers were then washed with water and dried in the laboratory conditions for 2 days.
- The hydrothermal treatment was conducted according to this protocol: date palm fibers were left 60 minutes in boiling water. After this stage, they were thoroughly rinsed to remove soluble compounds released during the treatment, and then dried under ambient laboratory conditions for 48 hours.

The used fibers were manually cut with scissors to reduce their size (Figure 2). The nomenclature used for the various fibers is shown in Table 1.

Effect of treatments

Analysis with Fourier transform infrared (FTIR)

To examine the effect of the treatments on date palm fiber properties, the two fibers, untreated and treated were characterized using

Table 1. Nomenclature used for raw and treated date palm fibers

Code	Description
RDPSF	Raw date palm surface fibers
RDPLF	Raw date palm leaflet fibers
ATDSF	Alkali treated date palm surface fibers
ATDPLF	Alkali treated date palm leaflet fibers
HTDPSF	Hydrothermal treated date palm surface fibers
HTDPLF	Hydrothermal treated date palm leaflet fibers

FTIR analysis. Spectra were recorded following the same protocol employed for soil analysis. To this end, 1 mg of ground fibers and 99 mg of KBr are mixed and compacted into pellets for analysis.

Chemical composition

The chemical analysis of fibers was carried out based on the experimental protocols published in literature (Boopathi et al., 2012; Elmoudnia et al., 2022; Sanjay et al., 2017). The analysis was used with the aim of determining the percentages by weight of cellulose, lignin and hemicellulose prior to and following treatment of the fibers with the aim of discovering the results of both treatments on their chemical composition.

Preparation of CEBs

The preparation of the CEBs was started by passing the soil through a 3 mm sieve, then, it was dried for twenty-four hours at 105 °C. Date palm fibers were incorporated with contents of (0.5–2%) at a fixed length of 0.5 cm, 2% ATDPSF and ATDPLF were used to determine the effect of fiber length (0.5 and 2.5 cm) on thermomechanical properties of CEBs. The soil and fibers were mixed manually, then the optimum quantity of water found previously by the Proctor was added. The combination was homogenized, molded, and compressed using a hydraulic compacting machine at 2.7 MPa based on the NM 13.1.023. Cylindrical bricks measuring (2 × 4 cm) and (6 × 2 cm) were prepared for the various tests (Figure 3). After demolding, the CEBs were stored during 28 days in the laboratory. Finally, the obtained CEBs were dried at 60 °C until a constant mass was reached. Three bricks were fabricated for every percentage of fiber in order to obtain average findings.

Tests on compressed earth bricks

In this research, produced specimens underwent testing for thermal conductivity and compressive strength. In addition, their density was measured.

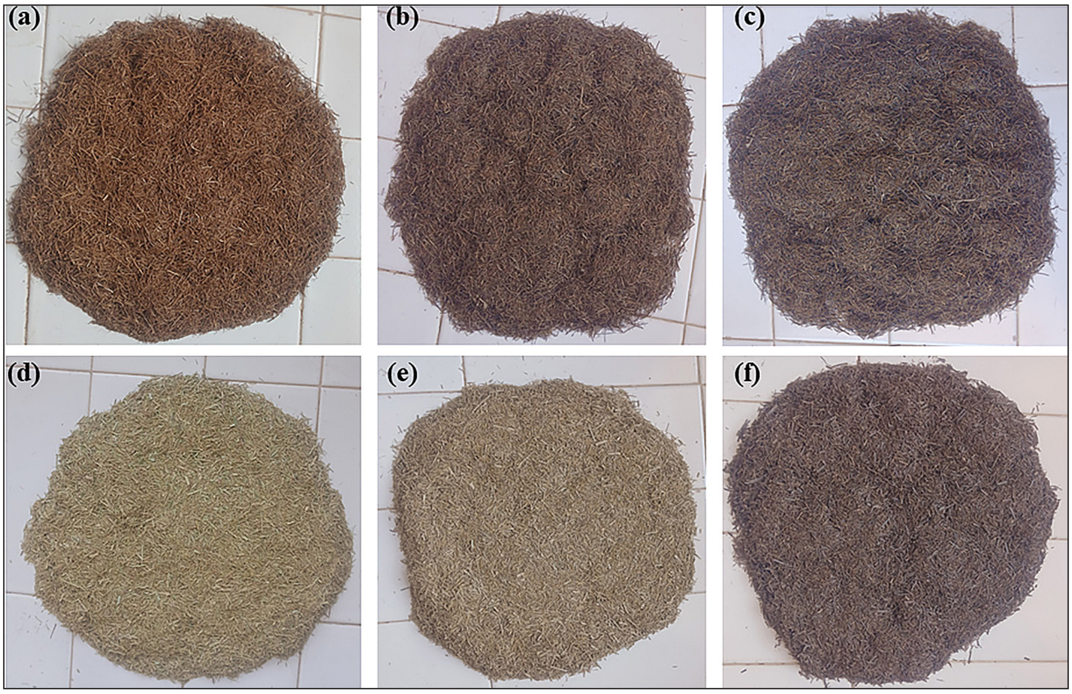

Figure 2. Prepared raw and treated date palm fibers. (a) RDPSF; (b) HTDPSF; (c) ATDPSF; (d) RDPLF; (e) HTDPLF; (f) ATDPL

Figure 3. Preparation of CEBs

Figure 4. Compressive strength test of CEBs

To measure the compressive strength of samples, the prepared bricks were subjected to a compressive force until failure using a Multiplex Universal Electromechanical Testing Machine at a speed of 0.5 mm/min to conduct the test (Figure 4).

Thermal conductivity λ (W/m·K) was evaluated using the Hot Disk TPS 1500n by placing its sensor between two surfaced bricks to prevent any contact with air (Figure 5).

RESULTS AND DISCUSSION

Physicochemical and mineralogical analysis of soil

Table 2 illustrates the soil's organic matter (OM), carbonate content (CC), loss on ignition (LOI), and chemical composition. The chemical composition consists mainly of calcium oxides CaO, silica SiO_2, and alumina Al_2O_3. An abundance of calcium oxides in the soil will act as a cementitious product in the manufacture of CEBs (Taypondou et al., 2022). The high loss on ignition (LOI) results from carbonate decomposition, leading to the release of CO_2 (Rodriguez-navarro et al., 2009). Calcimetric analysis confirmed the existence of these carbonates.

Soil XRD analyses are presented in Figure 6. The soil XRD diagram shows that the soil is composed mainly of calcite, as confirmed by the prominent peaks at 3.84 Å (23.12°), 3.03 Å (29.46°), 2.28 Å (39.46°), and 2.10 Å (43.1°). In addition, this diffractogram shows quartz peaks at 3.34 Å (26.64°), 4.25 Å (20.88°), and 1.82 Å (50.18°), albite peaks at 4.02 Å (22.12°), 3.23 Å (27.58°), 3.19 Å (27.94°), and illite at 4.45 Å (19.94°) appearing in small quantities. These results highlight the effect of mineralogical constituents contained in the soil on the characteristics of the produced building material and their manufacturing process (Boukili et al., 2021). Quartz contributes to enhanced compaction properties (Gökalp, 2009; Kamga Djoumen et al., 2023) while calcite is known for its cementitious effects in earth concrete (Lahbabi et al., 2024; Satone et al., 2023).

Geotechnical analysis

The soil's geotechnical behavior was analyzed taking into account various factors, which includes, absolute density (ρs), Atterberg limits, moisture content, methylene blue value (MBV), and particle size distribution. The soil has a low water content of 1.3% by weight. Furthermore, the soil's absolute density (ρs) is 2.75 g/cm³. Regarding the Atterberg limits, the values obtained are: a liquidity limit (WL) of 29 %, a plasticity limit (WP) of 19 %, and a plasticity index (PI) of 10%, this plasticity index falls inside the interval determined by the XP P 13-901, confirming that the soil is suitable for manufacturing high-quality compressed earth bricks (CEBs).

Table 2. Chemical composition of soil (%)

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	OM	CC
14.176	0.375	3.3	2.935	0.0580	0.677	48.87	0.193	0.927	0.198	28.29	2.3	61.55

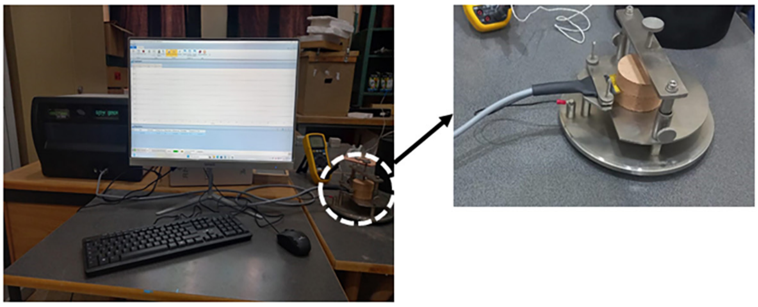

Figure 5. Thermal conductivity measurement

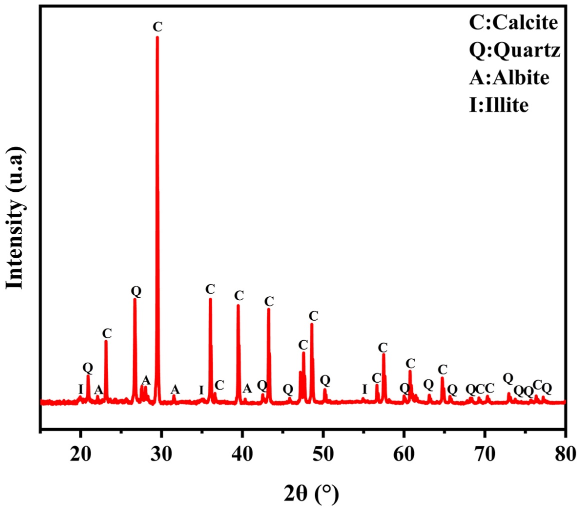

Figure 6. XRD patterns of the studied soil

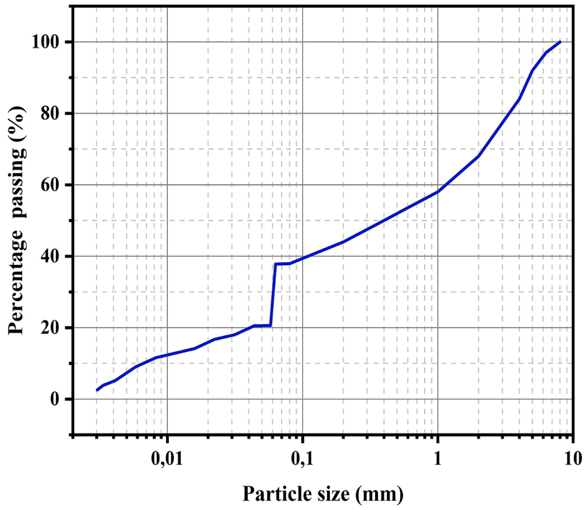

Figure 7. Particle size distributions of the soil

The grain size distribution of the soil is given in Figure 7: 32% gravel, 14% sand, 47% silt, and 7% clay. Since the clay content is below the recommended range for CEBs (9% to 31%), a 3 mm sieve will be used to increase the clay fraction. This method contributes to the enhancement of the mechanical qualities of CEB, since the clay naturally acts as a binding agent. (Lahbabi et al., 2024). The methylene blue test performed on the soil showed that the MBV is 1.25 g. According to NF P11-300, the soil is classified as a sandy loam soil. A high MBV reflects an increased capacity to retain water, which helps limit the formation of cracks during drying and, consequently, minimizes the material's surface imperfections. The soil's specific surface area is 26.12 m²/g. This parameter has a significant impact on cohesion, with elevated values resulting in greater soil cohesion because of the strong attraction among its particles. The Proctor test was performed to evaluate the soil's compaction capacity and to determine the appropriate molding parameters. The modified Proctor curve, shown in Figure 8, indicates a maximum dry density value of 2.05 g/cm³ at an optimum water percentage of 9.5%. According to Panagiotou et al and Doat et al. (Panagiotou et al., 2022; Silva et al., 2013), soils suitable for building should exhibit a dry density between 1.76 and 2.10 g/cm³, which confirms that the investigated soil has good potential for CEB production.

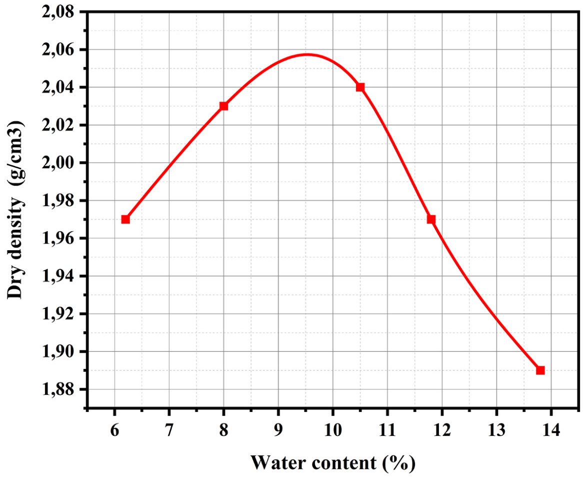

Figure 8. Modified Proctor curve for the soil employed in CEB preparation

Effect of date palm fiber treatment

Figure 9 displays FTIR spectra of both untreated and treated DPLF and DPSF fibers. A comparative analysis indicates that both treatments induced significant microstructural modifications in both fiber types. Firstly, the intensity of the band at 1734 cm^{-1} is reduced, characteristic of the C=O stretching of hemicellulose, is observed after hydrothermal treatment, and the band disappears after alkaline treatment. This modification results from the elimination of hemicellulose, which is attributed to the breaking of C–O–C between two monomers (Oushabi et al., 2017). The same behavior is observed for the bands at 1511, 1606, and 770 cm^{-1} for DPSF, and at 1515, 1650, and 833 cm^{-1} for DPLF. This is explained by the partial elimination of lignin in the fibers (Ajouguim et al., 2019a; Elmoudnia et al., 2022). Moreover, the decrease in band intensity observed at 3300 cm^{-1} (DPLF) and 3400 cm^{-1} (DPSF), compared to that of raw fibers, indicates a partial degradation of substances rich in these functional groups, such as lignin and hemicellulose. The results of both treatments indicate that alkaline treatment is more efficient at eliminating amorphous components compared to hydrothermal treatment. These findings are confirmed by an analysis of the chemical makeup of the fibers after treatment (Table 3), which reveals a reduction in amorphous components, particularly hemicellulose and lignin. The partial reduction of these fractions during treatment has led to an important increase in the percentage of cellulose.

Tests on compressed earth bricks

Effect of date palm fibers content on the bulk density of CEB

The impact of fibers percentage on the characteristics of CEBs can be better understood through a density study. As illustrated in Figure 10, the incorporation of raw or treated fibers causes a gradual decline in density. Bricks are lighter as a result of this reduction, which is advantageous for building because it makes handling easier and reduces the structural load. The addition of 2% fibers decreased the density by 15.76%,14.28%, and 11.33%, respectively, for samples reinforced with RDPLF, HTDPLF, and ATDPLF. A similar trend is observed in samples reinforced with date palm surface fibers, showing decreases reaching 14.77%, 13.30%, and 11.82% for RDPSF, HTDPSF, and ATDPSF. The reduction in density is mainly associated with the substitution of a portion of the dense soil matrix with lightweight date palm fibers. In addition, fiber incorporation increases the porosity of the composite through the formation of internal voids and fiber–matrix interfacial pores, even after compaction of the earth bricks. Nevertheless, the densities obtained remain within the usual range for CEB, between 1700 and 2200 kg/m^3 (El and Kabasy, 2013). These results are consistent with those of El bourka et al. (El bourki et al., 2025), who also reported a reduction in density as the fiber content increased. Furthermore, compressed earth bricks incorporating treated fibers, whether from the leaflet or the surface of the date palm, generally exhibit higher density than those reinforced with untreated fibers. Both treatments remove waxes and impurities, enhancing fibers/matrix adhesion and reducing the formation of internal pores, which limits the density decline. This effect is more pronounced with alkaline treatment, these observations align with those published by Ajouguim et al. (2019b), who noted that bricks stabilized by using treated Alfa fibers exhibited higher density than those incorporating untreated fibers.

Table 3. Chemical composition of raw and treated palm fibers

Fibers	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Ash (wt%)
RDPSF	47.33	11.74	32.76	5.15
HTDPSF	52.12	10.48	31.57	5.92
ATDPSF	57.23	8.76	29.27	5.42
RDPLF	43.14	16.43	28.73	9.21
HTDPLF	43.78	12.87	27.13	8.43
ATDPLF	53.24	10.09	24.67	7.21

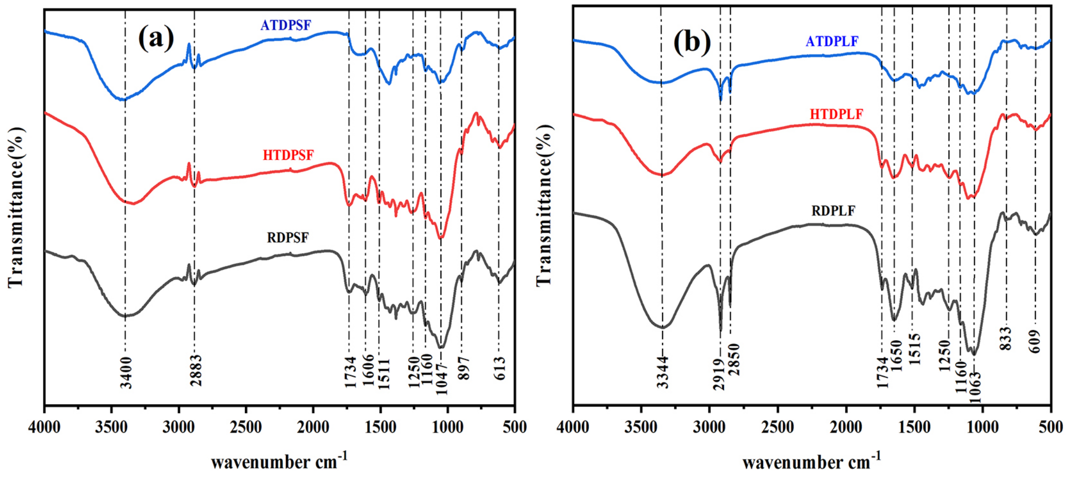

Figure 9. FTIR spectra of raw and treated fibers: (a) DPSF; (b) DPLF

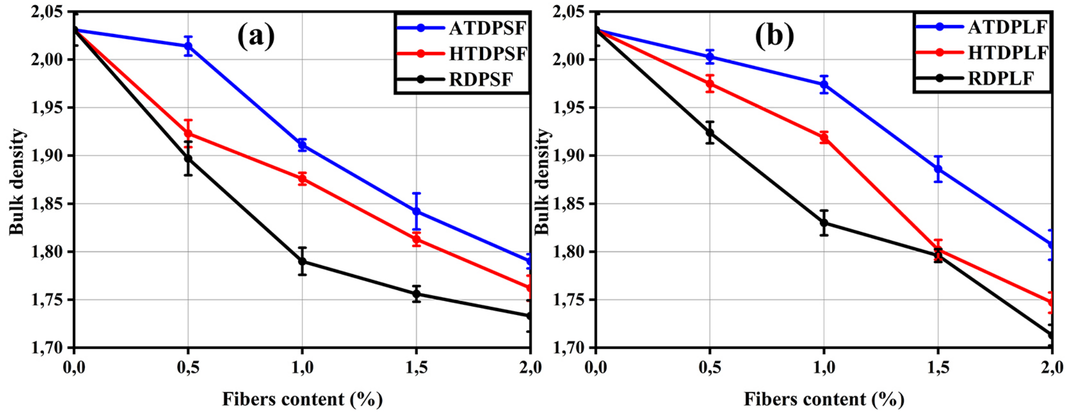

Figure 10. Effect of raw and treated date palm fibers content on the bulk density of CEBs: (a) DPSF; (b) DPLF

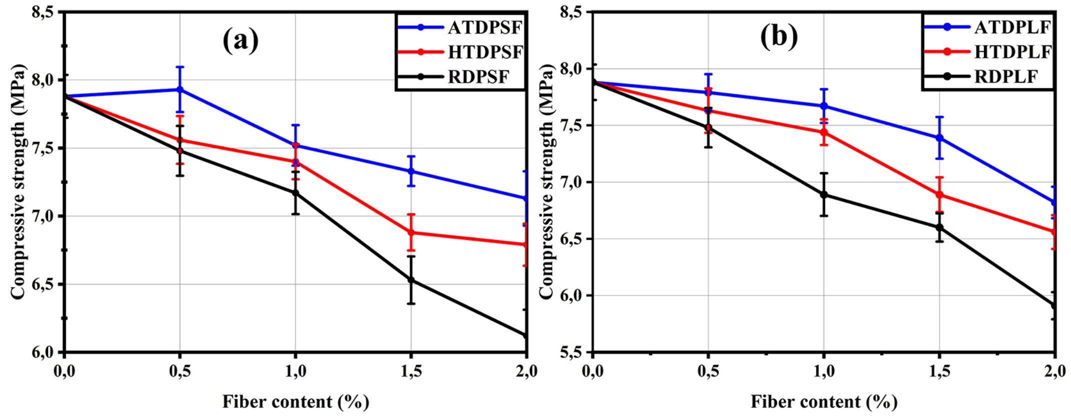

Figure 11. Effect of raw and treated date palm fibers on compressive strength: (a) DPSF; (b) DPLF

Effect of date palm fibers on compressive strength

Figure 11 describes the compressive strength variation of compressed earth bricks as a function of fiber percentage after 28 days of curing under laboratory conditions. The results show that the mechanical quality of CEBs was influenced by the incorporation rate and the nature of the treatment applied. Apart from a 0.63% enhancement in the compressive strength of CEBs reinforced with 0.5% ATDPSF compared to the bricks without fibers, for all fiber contents, an elevation in fiber percentages reduced the compressive strength. This reduction is significantly more marked in the samples reinforced with leaflet fibers compared to those incorporating surface fibers. It is worth noting that for zero fiber content, the compressive strength obtained was 7.88 ± 0.16 MPa. The decline in compressive strength could be interpreted by the porosity of the reinforced samples. As observed by El Bourki et al. (2025), a large percentage of fibers forms a higher volume fraction of fibers within the matrix, generating more pores. Additionally, uneven fiber dispersion can cause localized porous zones, which reduces the density of the samples and further weakens their mechanical strength (Khelifa et al., 2018). A clear explanation of the relationship between the mechanical behavior of CEBs and the variation in their density is highlighted by analyzing the correlation between these two parameters. Figure 12 shows a clear positive correlation between compressive strength and bulk density for all fiber types. The coefficients of determination (R^2) were 0.87, 0.95, and 0.98 for RDPSF, HTDPSF, and ATDPSF, respectively, and 0.97, 0.99, and 0.95 for RDPLF, HTDPLF, and ATDPLF, respectively. These high R^2 values indicate that bulk density is strongly correlated with the compressive strength of the compressed earth bricks, emphasizing that the variation in density can clearly explain the mechanical behavior of the CEBs. This reduction may also result from low fiber/matrix adhesion (Taallah et al., 2014). In fact, when the raw fiber percentage elevates from 0% to 2%, the compressive strength of CEBs decreases to 5.91 ± 0.12 MPa for RDPLF and to 6.12 ± 0.19 MPa for RDPSF, corresponding to reductions of 25% and 22.33%, respectively. Several studies have reported similar findings. For instance, Khoudja et al. (2021) observed an 80% decrease in compressive strength when earth blocks reinforced with 10% palm waste. Similarly, Limami et al. (2021) reported that a percentage of 20% Typha fibers in earth bricks leads to a 40% loss in compressive strength.

The reduction in compressive strength is mitigated when the fibers are pretreated, with losses of 16.75% and 13.45% for HTDPLF and ATDPLF fibers, respectively. In the case of treated DPSF fibers, the decrease in strength is even lower, reaching only 9.51% for ATDPSF and 13.83% for HTDPSF. Both treatments applied to the fibers helped limit the reduction in compressive strength of CEBs, with a more noticeable effect observed for fibers subjected to alkaline treatment. The observed improvement results from the partial removal of hemicellulose, lignin, waxes, and other amorphous constituents present on the fiber surface during the treatment process. These modifications enhance the fiber–soil matrix interfacial adhesion, thereby improving the internal cohesion of the compressed earth bricks, which limits the loss of compressive strength. These findings align with previous research. Taallah and Guettala (2016) evaluated the impact of alkaline treatment of palm fibers on the physicomechanical behavior of CEBs. In addition, Bouchefra et al. (2022) examined how the alkaline treatment of doum fibers on the thermomechanical performance of CEBs. It is worth noting that, despite the reduction in compressive strength observed in the fiber-reinforced samples, all the tested bricks exhibited compressive strength values exceeding the minimum requirements specified by the

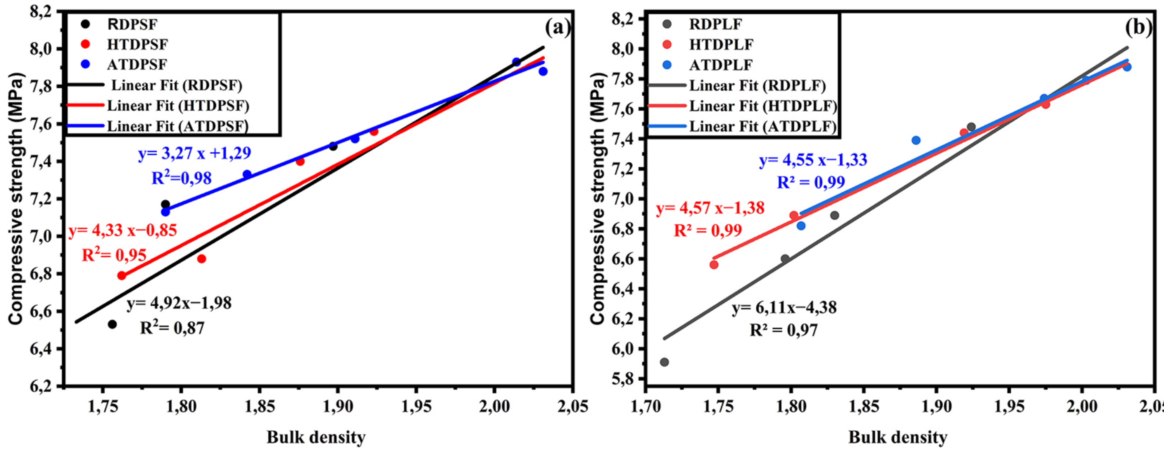

Figure 12. Correlation between compressive strength and density: (a) DPSF; (b) DPLF

major international standards for compressed earth bricks (CEBs) intended for construction applications. In particular, they comply with the minimum compressive strength requirements established by the New Mexico Code (2.07 MPa), the French guideline Earth Construction: A Comprehensive Guide (2–2.4 MPa), the Australian Earth Building Handbook (2 MPa), and the Spanish regulations for compressed earth brick construction (1.3 MPa). (Gharbage et al., 2025).

Effect of date palm fibers on thermal conductivity

Figure 13 depicts the measured thermal conductivity of the prepared composites. These findings indicate that as the content of fibers (raw and treated) rises, a notable reduction in thermal conductivity is observed. A small difference is noted between the two fibers, CEBs reinforced with DPSF exhibiting slightly lower thermal conductivity than those made with DPLF. The thermal conductivity of the unreinforced sample is 0.909 ± 0.015 W/m·K. By increasing the fiber content from 0% to 2%, this value decreases by 39.38%, 36.41%, and 35.75% for RDPSF, HTDPSF, and ATDPSF, respectively. This decrease is 41.80%, 39.05 %, and 37.07% for RDPLF, HTDPLF, and ATDPLF fibers, respectively. The minimum thermal conductivity value is observed at a fiber content of 2% for both fiber types. These results can be interpreted firstly by the thermal conductivity of date palm fibers, which is low compared to the soil. According to (Al-Oqla and Sapuan, 2014), date palm fibers exhibit a thermal conductivity value of 0.083 W/m·K. Secondly, the inclusion of fibers creates air-filled pores within the matrix, which causes a decrease in density (Taallah et al., 2014). Consequently, thermal conductivity is reduced. Figure 14 highlights a marked correlation linking thermal conductivity and density, attesting to the existence of a strong relationship between these two parameters. Similar findings have been obtained by other studies. Recently, Khrissi et al. (Khrissi and Tilioua, 2025)

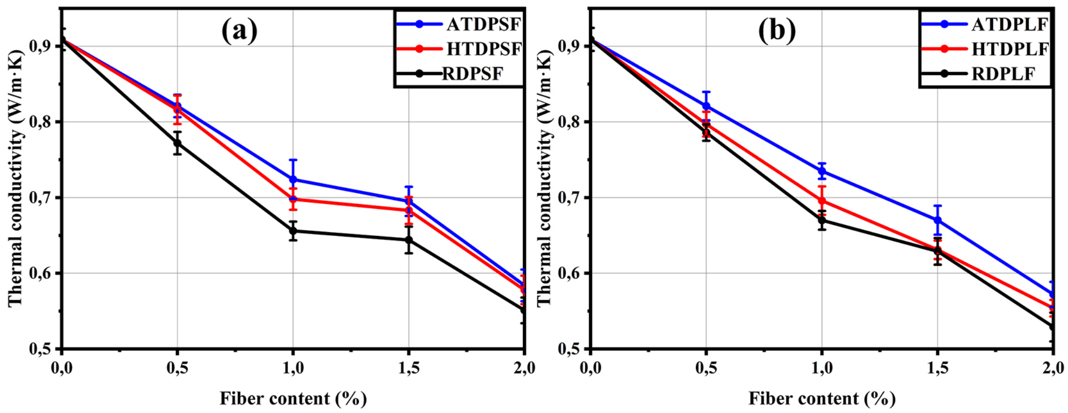

Figure 13. Influence of raw and treated date palm fiber content on the thermal conductivity of compressed earth bricks: (a) DPSF; (b) DPLF

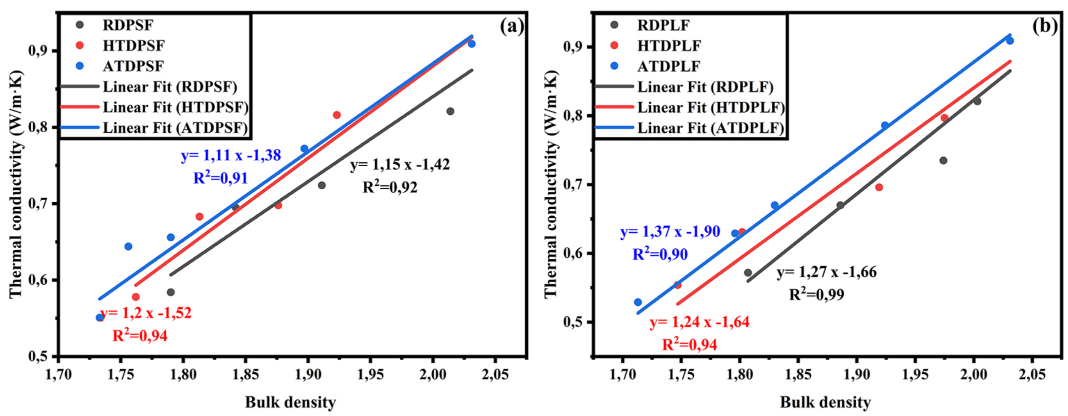

Figure 14. Correlation between thermal conductivity and density: (a) DPSF; (b) DPLF

reported a 54.85% decrease in thermal conductivity in earth bricks containing 5% date palm waste. Khoudja et al. (Khoudja et al., 2021) noted a reduction of 49.48% when adding 10% date palm waste to raw earth bricks. Likewise, Bali et al. (Bali and Kriker, 2025) noted an approximate 56.41% reduction in thermal conductivity for the soil matrix containing 15% by weight of date palm wood powder.

It is also noted that CEBs reinforced with treated fibers exhibit a slightly higher thermal conductivity than those reinforced with raw fibers. Both treatments remove amorphous compounds and clean the date palm fibers, which enhances fibers/matrix adhesion, thus causing an elevation in thermal conductivity. These results indicate that, despite this slight increase in thermal conductivity, treated fibers contribute overall to a remarkable improvement in the behavior of compressed earth bricks. These observations align with those published by several researchers. Bouchefra et al. (Bouchefra et al., 2022) analyzed the role of alkaline treatment of doum fibers on the mechanical and thermophysical properties of compressed earth bricks. The same applies to Ajouguim et al. (Ajouguim, Talibi, et al., 2019), who evaluated the role of alfa fibers treated by alkaline and hydrothermal treatments on the thermo-mechanical characteristics of CEBs.

Effect of fiber length on the mechanical and thermal performance of CEBs

A content of 2% was selected for each of ATDPLF and ATDPSF, to study the impact of their length on the thermomechanical quality of CEBs. Figure 15 shows the variation in compressive strength according to fiber length. Increasing the fiber length within the CEB matrix decreased the compressive strength. Replacing 0.5 cm fibers with 2.5 cm fibers caused compressive strength to drop from 7.13 ± 0.2 MPa to 5.31 ± 0.39 MPa for ATDPSF, and from 6.82 ± 0.14 MPa to 4.78 ± 0.29 MPa for ATDPLF, corresponding to decreases of 25.52% and 29.91%, respectively. This result is explained by the tendency of longer fibers to agglomerate, which reduces the fibers/matrix adhesion, thus creating voids. This observation was also reported by Mouih et al. (Mouih et al., 2025b), who found that substituting date palm fibers of 500 µm length with 2.5 mm fibers in the brick matrix reduced compressive strength by 6.60%. Similarly, Alioui et al. (Alioui et al., 2024) observed that substituting crushed straw (5–25 mm) with long straw (100–200 mm), at 4% by weight, decreased the compressive strength of bricks from 13.63 MPa to 3.08 MPa.

Figure 16 shows how the length of the fibers influences the thermal insulation of CEBs. Increasing the fiber length from 0.5 cm to 2.5 cm in the studied samples decreases the thermal conductivity, decreasing from 0.584 ± 0.021 W/m·K to 0.514 ± 0.029W/m·K for ATDPSF and from 0.572 ± 0.017 W/m·K to 0.505 ± 0.031 W/m·K for ATDPLF. This corresponds to a significant improvement of 11.98% and 11.71%, respectively, in insulating properties. These findings can be interpreted by the tendency of long fibers to curl and form voids that trap more air within the CEB matrix. The presence of air decreases thermal conductivity, which is beneficial for applications in the building sector, as it promotes greater

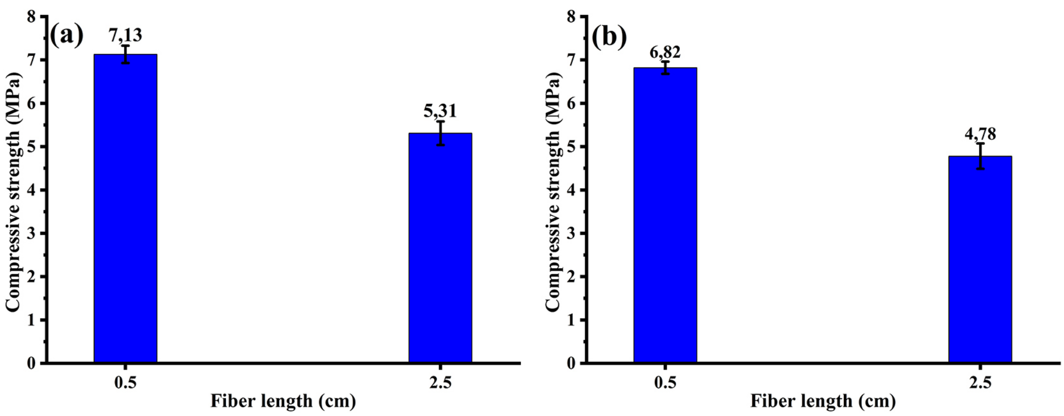

Figure 15. Effect of fiber length on the compressive strength of CEBs reinforced with 2% alkali-treated date palm fibers: (a) ATDPSF, (b) ATDPLF

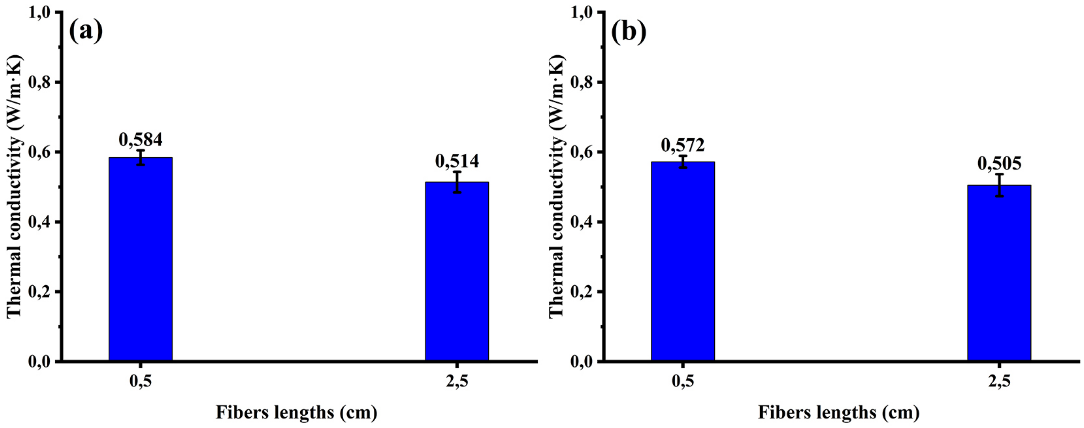

Figure 16. Effect of fiber length on the thermal conductivity of CEBs reinforced with 2% alkali-treated date palm fibers: (a) ATDPSF, (b) ATDPLF

energy efficiency. In the same context Millogo et al. (Millogo et al., 2014), observed that adobe incorporating long fibers has a higher volume than those containing short fibers, resulting in an improvement in thermal insulation.

CONCLUSIONS

This study focuses on the analysis of the physico-mechanical and thermal behavior of compressed earth bricks produced using a local soil from NKOB-Zagora and reinforced with raw and treated date palm fibers. Two types of fibers were incorporated: surface fibers (DPSF) and leaflet fibers (DPLF). The main objective is to develop a high-performance earth-based construction material suitable for the sustainable reconstruction and restoration of earthen buildings, in arid and semi-arid oasis regions. The main results of this work are presented below:

- The properties of the soil used demonstrated that it meets the essential criteria for the production of CEBs
- An increase in percentage date palm fiber, whether treated or untreated, enhances the thermal insulation of compressed earth bricks by reducing their thermal conductivity. The incorporation of 2% RDPSF, HTDPSF, and ATDPSF decreases thermal conductivity by 39.38%, 36.41%, and 35.75% respectively, while this reduction reaches 41.80%, 39.05 %, and 37.07% for RDPLF, HTDPLF, and ATDPLF, respectively.
- The bulk density of CEBs decreases with the incorporation of date palm fibers, regardless of the fiber type or treatment applied. The non-reinforced CEBs have a density of 2.03 g/cm³. Adding 2% by weight of date palm surface fibers (DPSF) reduces the density to 1.71 g/cm³ for RDPSF, 1.74 g/cm³ for HTDPSF, and 1.80 g/cm³ for ATDPSF. Similarly, incorporating 2% of leaflet fibers (DPLF) results in a density decrease to 1.73 g/cm³ for RDPLF, 1.76 g/cm³ for HTDPLF, and 1.79 g/cm³ for ATDPLF.
- Except for a slight 0.63% increase in dry compressive strength observed in CEBs containing 0.5% alkali-treated date palm surface fibers (ATDPSF) compared to samples without fibers, the addition of fibers with different percentages decreased in mechanical performance. For surface fibers, the addition of 2% RDPSF, HTDPSF, and ATDPSF reduces compressive strength by approximately 22.33%, 13.83%, and 9.51%, respectively. As for leaflet fibers, the incorporation of 2% RDPLF, HTDPLF, and ATDPLF leads to decreases of 25%, 16.75%, and 13.45%, respectively.
- The treated fibers helped to limit the mechanical losses as well as the decrease in density of the compressed earth bricks (CEBs), with a more pronounced effect observed for fibers subjected to alkaline treatment.
- Changing the fiber length from 0.5 cm to 2.5 cm leads to a decrease in compressive strength of 25.52% and 29.91%, respectively, for ATDPSF and ATDPLF, as well as a corresponding reduction in thermal conductivity, from 0.584 to 0.514 W/m·K for ATDPSF and from 0.572 to 0.505 W/m·K for ATDPLF.

This study demonstrated that incorporating date palm fibers promotes the development of an eco-friendly construction material with satisfactory mechanical and thermal performance. Further investigations on the long-term durability of these materials under environmental exposure conditions constitute an important perspective for future research.

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