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Comparative study of the effects of natural fibers on the physical, thermal and mechanical properties of soil building blocks

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ABSTRACT: With a view to valorizing local resources, juncus fibers have recently been used as reinforcements in building materials. The aim of this study is to compare their thermophysical and mechanical behavior in adobe with that of coconut fibers, which are generally imported and not available locally. Raw materials were subjected to chemical, geotechnical, mineralogical and microstructural characterization. Different volumetric percentages of the two types of fiber (0%, 10%, 20%) were incorporated into the adobes. The thermal conductivity, apparent density and mechanical strength of the adobes were determined for each sample. The microstructure was analyzed by scanning electron microscopy (SEM). The addition of 20% juncus fibers improves thermal performance by 12.34%, compared with 10.6% for coconut fibers, with a decrease in mechanical strength due to poor fiber–matrix adhesion observed by SEM.

KEY WORDS: Adobes; Thermo-physical properties; Mechanical properties; Coconut; Juncus; Microstructure.

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RESUMEN: *Estudio comparativo de los efectos de las fibras naturales en las propiedades físicas, térmicas y mecánicas de los bloques de construcción de suelos.* Con el objetivo de valorizar los recursos locales, las fibras de junco se han usado recientemente como refuerzo en materiales de construcción. Este estudio compara su comportamiento termofísico y mecánico en el adobe con el de las fibras de coco, generalmente importadas y no disponibles localmente. Las materias primas se sometieron a una caracterización química, geotécnica, mineralógica y microestructural. Se incorporaron diferentes porcentajes volumétricos de los dos tipos de fibra (0%, 10%, 20%) a los adobes. Para cada muestra se determinaron la conductividad térmica, la densidad aparente y la resistencia mecánica de los adobes. La microestructura se analizó mediante microscopía electrónica de barrido (SEM). La adición de un 20% de fibras de junco mejora el rendimiento térmico en un 12,34%, en comparación con el 10,6% de las fibras de coco, con una disminución de la resistencia mecánica debida a una mala adhesión fibra-matriz observada por SEM.

PALABRAS CLAVE: Adobes; Propiedades termofísicas; Propiedades mecánicas; Coco; Junco; Microestructura.

1. INTRODUCTION

The human being has been looking for building methods able to ensure a stable structure and comfort, the need for safety and comfort in housing triggering a cultural debate on energy and environmental issues. Earthen construction is a traditional architectural method that, in recent years, has gained in popularity thanks to its ecological and aesthetic advantages. Over the years, men of the art of building (architects, engineers and builders) have adopted this approach more and more as a solution for originality and for creating more sustainable built environments, in response to the challenges posed by variations in climatic conditions, resource depletion and the environmental impact of industrial materials (1). Architects are always developing new ideas for shapes and orientations, but with doubts about the value of this option. Recent studies have shown the relationship between the well-being of residents and the orientation and shape of the building (2).

The exterior envelope attracts the attention of researchers, the choice of materials that make up this envelope and their structural arrangements depend on the resources available on the building site. Providing adequate housing with thermal and acoustic comfort in developing countries has become a pressing concern. Traditional building methods have long been reliable and widely used. However, with increasing environmental concerns and the imperative to adopt more sustainable building practices have contributed considerably to the evolution of building materials (3). Economic concerns are also present in the choice of building materials, the purchase price of cement is still rising, this product poses a major challenge due to the significant energy required to produce clinker, and environmental preservation has become a crucial priority worldwide. Studies show that the production of cement used in the formulations of various types of concrete and mortar is responsible for 5% to 7% of global carbon dioxide (CO_2) emissions (4), which makes the use of ecological materials a necessity, and the retreat to the use of traditional materials, such as clay, presents a number of advantages, both ecologically and in terms of comfort and socio-economic impact. Clay materials reduce the energy required for their extraction, manufacture and transport, contributing to almost zero embodied energy (5, 6).

Restoration work on historic monuments and old buildings constructed using clay-based materials requires appropriate repair methods. This notion of restoring and repairing deterioration in earthen buildings is not new, and has been cited in the literature, the characterization of earthen materials is important to preserve our architectural heritage and keep the same appearance and regidity of constructions. A methodological note to characterize adobes of historical construction from mechanical, physicochemical and durability properties has been cited by Adrià Sánchez Calvillo et al (7). Historic and ancient buildings require an ongoing diagnosis to assess their condition and conformity with current safety standards, based on literature, an explorative study of risk identification and mitigation measures appropriate to green residential building projects (8), Diagnostics and experience feedback on damage observed in buildings constructed with pure earth have identified non-conformities in the mixtures. The researchers thus highlighted the limits of the exclusive use of earth alone. Clay, made up mainly of different minerals combined, has played an important role in architecture and construction through the years and across civilizations. Its reputation as an advantageous local material for use in building, and its availability in large quantities in all locations, makes it easily accessible and economical for local construction. In areas where town plans permit the use of clay, most builders resort to its use, reducing the cost and imprint of man-made materials and assuring an original aesthetic, however clay alone shows degradation during its lifetime and during construction operation, making it fragile against cutting and mechanical stresses, over the years men of art have been incorporating clay with various natural fibers without theoretically understanding their effects, for example, Straw has been used as an additive to the clay matrix since the beginning of earth construction, making the use of natural fibers as building materials an antiquated idea. With scientific evolution, composite materials made of clay reinforced with natural fibers are more and more recommended by studies for their thermal performance and environmental respect (9).

For centuries, natural fibers have been used in construction, benefiting from their tensile strength, low thermal conductivity, compressive strength and durability, to improve the performance of clay based materials. This approach makes these materials more efficient than conventional building materials (10). The fibres most frequently used are coconut and glass fibres (11), palm fibers (12), alfa fibers (13), sisal fibers (14), jute fibers (15, 16), sugar cane fibers (17), bamboo fibers (18), kenaf fibers (19) and other scientific work on the possibility of integrating natural fibers to replace conventional reinforcements (20). Research into the stabilization and reinforcement of clay, as a largely available building material, using natural wastes is an emerging area. Evaluation of their potential as building materials for bio-construction not only reduces raw material consumption, but also cuts the costs associated with waste and by-product elimination (21). The focusing on fibers as an additive to building materials has given rise to a new branch which is interested in the treatment of these elements to improve the adhesion and characteristics of matrices. For example, the analysis of the impact of alkaline treatments on palm fibers has shown that the thermal conductivity of earth blocks stabilized with lime decreases with the increase in the proportion of palm fibers (22).

Juncus fibers are new to the construction industry. New scientific research has investigated the effect of these fibers on the thermal and mechanical behavior of cement mortars, and found that juncus fibers increased the porosity of mortars, improving their thermal properties (23), and used chemical treatment to improve the mortars' mechanical properties (24). For Omrani et al. (25) studied the thermal and mechanical behavior of clay mortars (60% clay and 40% sand) incorporated by juncus fibers, they found that these fibers decreased the compressive and flexural strengths of the mortars, but they have a positive effect on the mortars' physical and thermal properties. Recently, Sadouri et al. (26) found that juncus fibers have a favorable impact on ultrasonic pulse velocity, which will improve the acoustic insulation of composites. Amazal et al. (27) studied the impact of these fibers on the thermal and mechanical behavior of the gypsum matrix. Based on these encouraging results on the properties of juncus fibers, this study aims to use these local fibers as an alternative to commercial coconut fibers.

The first objective of this study is to compare the thermal, physical and mechanical characteristics of adobes reinforced with different types and

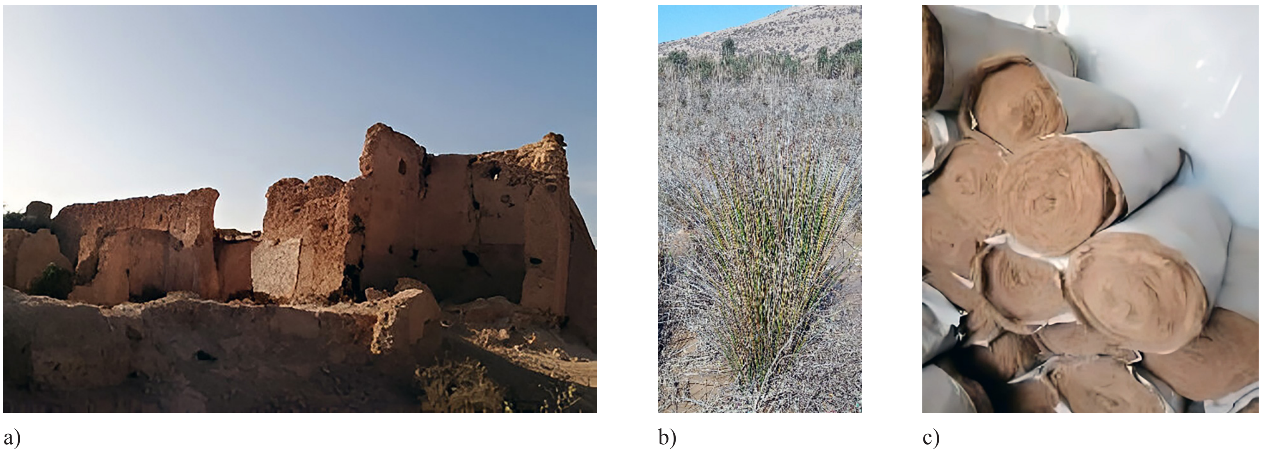
content of fibers (coconut and juncus). Taking into consideration the good reputation of coconut fiber as one of the fibers marketed with regard to their thermal and acoustic performance discussed with litter (28), and because this type of fiber is not available locally, the transport and supply of these fibers is reserved for specific projects. The aim is to characterize and find a variant with similar characteristics. The fibers were added to the clay matrix with a volume fraction of 0, 10 and 20%. Juncus and coconut fibers were selected as two competing natural fiber products, one being locally available and requiring only standard climatic conditions, and the other being commercially available in roll form. The main reason for this research is the use of local fibers and the possibility of replacing commercial fibers, in this case coconut, which can generally be used in potential applications for repairing and treating cracks in wall infills. Finally, this study compares the thermal and mechanical aspects associated with the use of natural and commercial fibers in order to promote the use of low-cost fibers for building materials.

2. MATERIALS AND PROCEDURES

2.1. Materials used

2.1.1. Soil

The soil studied was obtained from the Sous Massa region in southern Morocco. The coordinates of the site of origin of the raw material are (N 30°23' 20.8314", W 8°41' 27.9126"), and the location is illustrated in Figure 2b. This village is known for its traditional clay construction techniques (Figure 1a). The clay soil of the Souss region was selected for this study because of its abundance and its traditional use by the local population for the production of high-quality adobes. The material was extracted by collecting samples from several locations in the selected area, at depth, after removing the top layer containing organic matter. This step was essential to ensure that the collected soil accurately represents the village soil. A sufficient quantity of raw material was then collected for the study. This study needs to characterize the soil and examine its impact in terms of mechanical strength, as well as its suitability for use with other natural additives.



a) b) c)

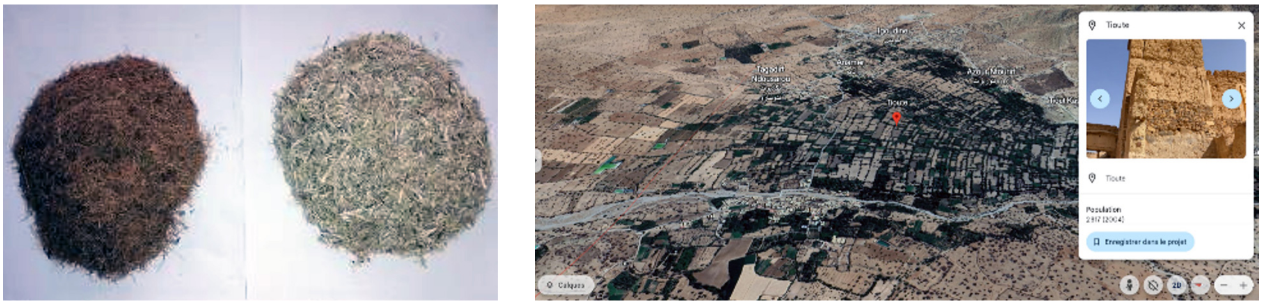
Figure 1. Raw material extraction site, a) soil extraction site, b) juncus fibers extraction site, c) delivered coconut fiber stock.

2.1.2. Juncus fibers

The Juncus plant, harvested in the Tamri region (30°41′42″ North, 9°49′30″ West), was studied to compare its characteristics with those of commercial fibers used on the market, particularly in construction. This plant is widely planted in the Tamri region, appearing as a tuft of grass with a white spongy substance (Figure 1b), surrounded by a cylindrical stem averaging around 1 meter long and 4-8 mm in diameter. It is frequently found in humid and saline areas. The juncus fibers were ground after a preparation process, to obtain small sections of fiber refusing to 2 mm sieve as shown in Figure 2a.

2.1.3. Coconut fibers

Coconut fibers, in general, are natural fibers that are extracted from the outer husk of coconuts. The planting of these fibers requires special climatic conditions, which makes them rare in Morocco, mainly grown in tropical regions. The main producing countries include India, Brazil, Indonesia and the Philippines. The coconut fibers used in this research are presented on the market in the form of compacted rolls (Figure 1c). For use under concrete screeds to improve acoustic performance by minimizing the effect of vertical noise in special-purpose buildings such as singing rooms and dens, these commercialized fibers have been prepared and dispersed manually to obtain elements of the same dimensions Figure 2a. Coconut fibers are a natural material with multiple applications, offering significant advantages in terms of performance, durability and respect for the environment. Due to their scarcity, compensating for this lack in different paid by another alternative, constitutes a real need in developing countries. The aim of this comparative research is to identify a fiber with characteristics similar to those of coconut, in order to propose a more accessible ecological alternative better suited to local contexts, where coconut fiber is not naturally available and is mainly obtained through commercial channels.



a) b)

Figure 2. Different fibers after preparation, a) manually dispersed coconut fibers and juncus fibers after grinding, b) location of soil extraction site.

2.2. Characterization of prepared samples

2.2.1. Geotechnical and physico-chemical soil characterization

The clay sample designed for the study was subjected to geotechnical identification (Figure 3), i.e. atterberg limit in accordance with standard NM 13.1.007 [28], methylene blue index and specific surface following NF P 94-068 [29] and sand equivalent following NM 10.1.147 [30]. Plasticity index (PI), plasticity limit (PL) and the liquidity limit (LL) of the soil studied were found to be equal to 38.05%, 23.34% and 14.71% respectively, these values are found within the range of soils recommended for the production of adobes, as shown in Table 1. According to the plasticity diagram, we can conclude that the soil studied can be considered a moderately plastic inorganic clay (29). Table 2 also shows the physical and chemical properties of the soil studied. PH and salinity tests measured respectively by an inoLab™ 7110 benchtop pH meter and a Thermo Scientific Orion portable conductivity meter.

Table 1. Geotechnical properties of the soil studied.

Atterberg limit	Value (%)	Recommended limits of adobe (30)
Plastic limit PL	23.34	10%-25%
Liquid limit LL	38.05	25%-45%
Plasticity index PI	14.71	10%-25%

Table 2. Geotechnical, chemical and physical characteristics of soil.

MBV	Specific surface (m^2/g)	Porosity (%)	Bulk density (kg/m^3)	SE	Absolute density (kg/m^3)	PH	Salinity (ppT)
1.48	30.97	39.54	1615	2.77	2671	7.96	0.91

*MBV: Methylene blue value, *SE: Sand equivalent

Figure 3. Soil identification tests carried out in the laboratory.

2.2.2. Mineralogical and chemical composition of the soil

The soil under study was ground, passed through a 2 mm mesh sieve, and then dried at 60°C for 24 hours, then prepared in sample molds for mineralogical characterization using a Bruker D8 Advance Twin diffractometer (Figure 6). The aim of this analysis is to roughly determine clay minerals qualitatively and semi-quantitatively (31). The diffractogram (Figure 4) shows that the soil studied contains two principal minerals, quartz (SiO_2) and calcite ($CaCO_3$) with percentages 34.3 % and 39.4% respectively, and the other minerals chlorite and murdochite are almost present but less abandoning. The chemical composition of the soil was determined by dispersive X-ray fluorescence spectrometry using the Panalytical 4 Kw Axios Dy 1856 (Figure 6) (Table 3). The oxides present in the soil are SiO_2 (24.78%), CaO (33.59%), however (Al_2O_3,Fe_2O_3, MgO...) are present in small quantities. The loss on ignition was evaluated after calcination of the sample at 1000°C, the value obtained is 31.37%.

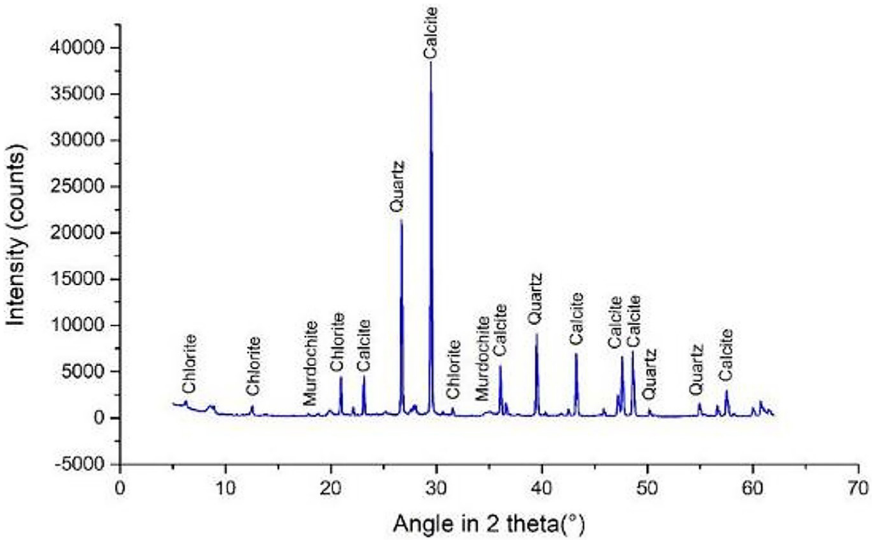


Figure 4. Mineralogical composition of the soil studied.

Table 3. Chemical analysis of the soil studied

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	L.O. I
Mass %	24.78	5.91	2.30	33.59	2.13	0.04	1.07	0.10	0.06	31.37

2.2.3. Microstructure of the soil studied

The structural morphology of the raw materials was visualized by scanning electron microscopy (SEM) using by JEOL JSM IT-100 scanning electron microscopy (Figure 6). SEM enables the surface topography of the sample to be observed by scanning its surface with an electron beam and collecting the image formed. As the samples (soil and fibers) are non-conductive, surface metallization is required by coating them with a thin layer of gold. This can be achieved by two methods. For this study, sputtering was used. This involves depositing atoms torn from a piece of metal (gold) onto the sample using ionized argon in a partial vacuum chamber. The SEM image of the soil in Figure 5 illustrates a porous structure which is one of the main characteristics that allow a high sorption capacity and low thermal conductivity of unfired clay bricks. SEM analysis was combined with energy dispersive X-ray spectroscopy (EDS) to determine the chemical composition of the sample analyzed. As the spectra in Figure 5 show, SiO_2 and $Al_2\ O_3$ contents are generally related to clay contents. SiO_2 is also a function of quartz percentages. EDS results indicate that the soil contains an average content of around 48.05% Si, Fe and Al. with an average content of around 49.36% SiO_2, 10.44% Al_2O_3 and 20.25% CaO. The high oxygen and silicon content explains the high quartz (SiO_2) peaks.

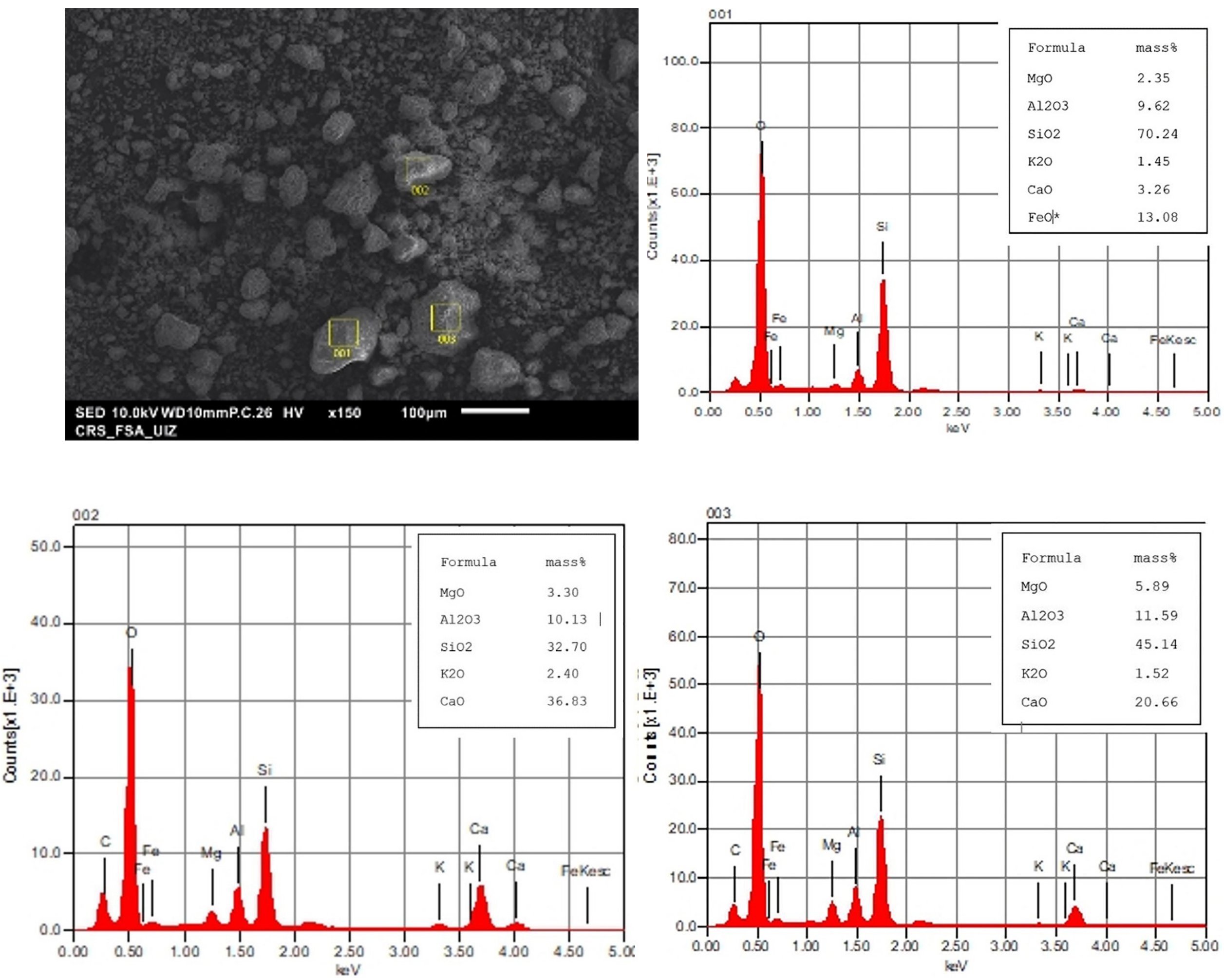


Figure 5. SEM results and EDS analysis of the soil studied.

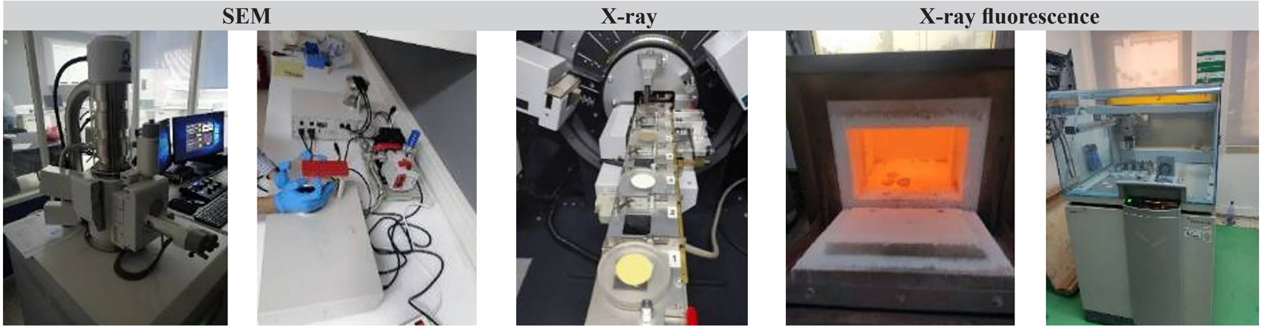


Figure 6. Soil characterization tests carried out in the laboratory.

2.2.2. Characterization of fibers

X-ray diffraction analysis has been adopted to obtain qualitative information on the cellulose content of plant fibers. Cellulose is an essential parameter for evaluating the effectiveness of fibers in the mechanical stabilization of building materials, the diffraction pattern of coconut and juncus fibers shown in Figure 7 shows three main peaks at 2θ of 15.6, 22.19 and 34.7, corresponding to the main cellulose signals of plant fibers. The crystallinity index is one of the main properties of cellulosic fibers, which can be calculated empirically from the XRD spectrum as follows:

$$C_r I = \frac{I_{200} - I_{am}}{I_{200}} \times 100 \qquad [1]$$

With I_{200} corresponds to the maximum intensity of the crystalline part 2θ of the cellulose I, and I_{am} corresponds to the intensity of the peak which corresponds to the amorphous.

The crystalinity index of juncus is 42% compared with coconut fibre, which has a crystalinity index of 38.52%. This finding indicates that juncus fibers contain a significant amount of cellulose, which could be advantageous for developing effective building materials.

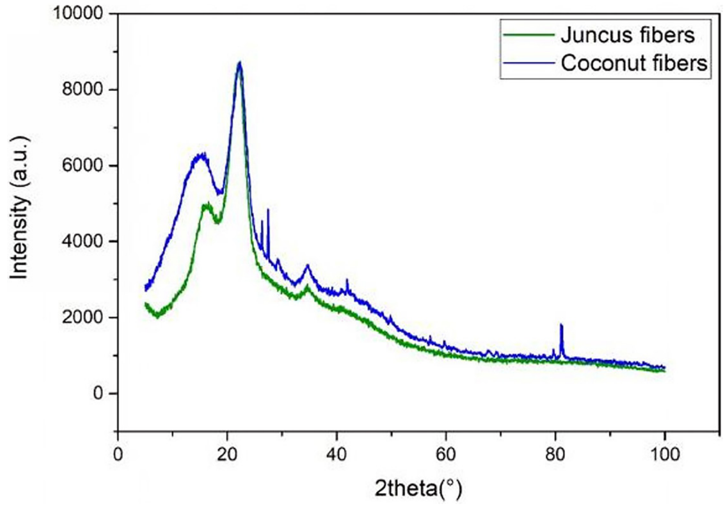


Figure 7. Mineralogical composition of coconut and juncus fibers.

Table 4 below summarises some of the mechanical and physical characteristics of the fibres that were used in this research, and compares the various characteristics, i.e. tensile strength, thermal conductivity, water absorption and apparent density of each fiber, this comparison prioritizes the choice of the most suitable fiber for use as a construction material, with coconut fiber presenting more satisfactory characteristics than juncus, while the hydrophilic behavior of juncus fibers in the matrix may improve the composite's characteristics, a hypothesis that will be treated as part of this study.

Table 4 . Mechanical and physical characteristics of the fibres employed in this research

Property	Fiber type	
	Coconut	Juncus
Apparent density (in kg/m³)	80	130
Tensile strength (in MPa)	110	40
Water absorption (in %)	175	260
Thermal conductivity (in W/m.K)	0.041	0.092

2.2.3. Microstructural characterization of fibers

The microstructure of juncus and coconut stems was determined by JEOL JSM IT-100 scanning electron microscopy (SEM), and a semi-quantitative analysis of chemical elements was carried out using an energy dispersive X-ray spectrometer (EDS). The microstructure of the outer surface of each rod presented in Figure 8 (R) shows the dimensions and external appearance of the coconut fibers, we observe linear lines in the form of roots parallel to the length of the fiber, which provides a rough surface, which can improve the mechanical coupling of the fibers with the clay matrix, influencing the behavior of the composite material after pointing. SEM observations of the cross-section of each rod show a porous structure for juncus fibers Figure 8 (W) and a firm structure for coconut, the pores contributing effectively to the thermal performance and lightness of the composites (Figure 12 and Figure 13), which explains the lower conductivity of the composite incorporated by juncus fibers (Figure 13a). The cross-section of coconut fibers remains smaller, with a difference of around 140 µm between the two cross-sections. Figure 9c and Figure 9d show the curves obtained from the EDS cross-section spectra of juncus and coconut respectively, each fiber revealing a significant amount of oxygen and carbon as the main constituents of these fibers. The amount of these two components remains lower for coconut fibers, which may be due to the porous structure of juncus fibers, and chlorine is another component observed in the coconut cross-section, which may be a contaminant from the outside.

R W

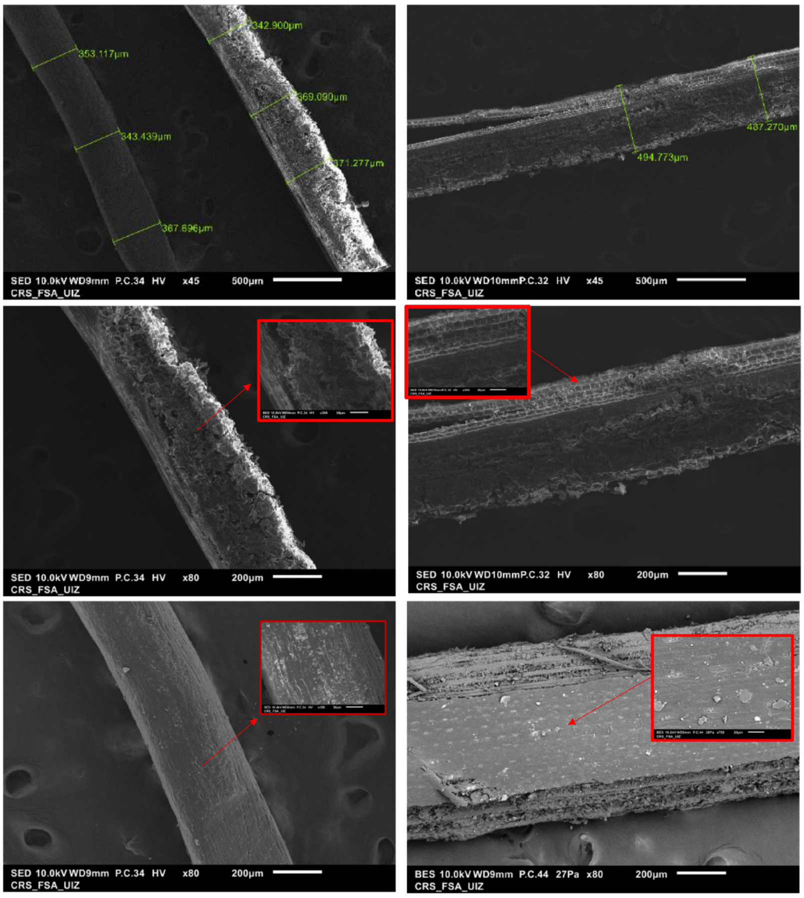


Figure 8. Fiber microstructure, (R) coconut fiber microstructure, (W) juncus fiber microstructure.

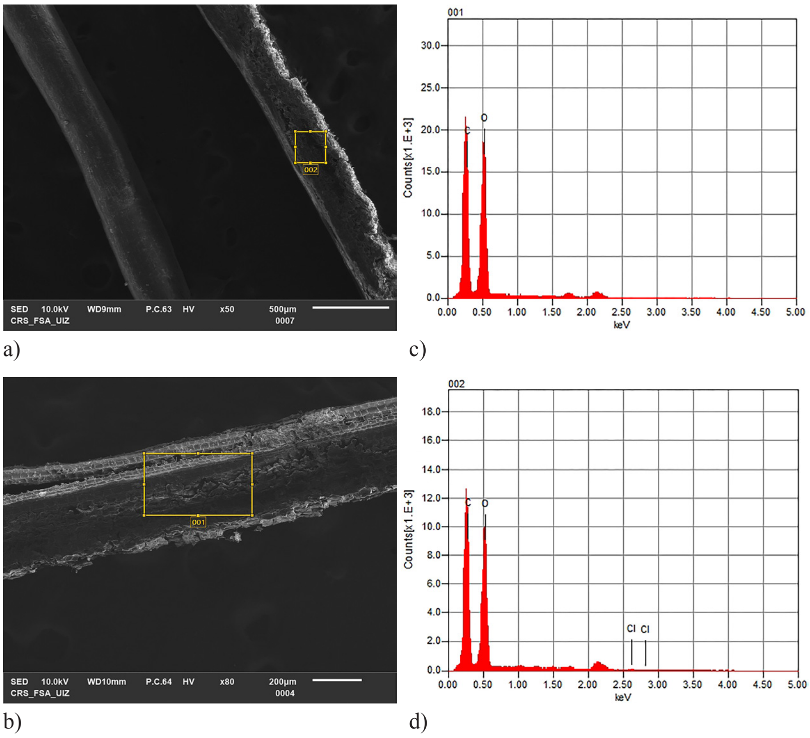


Figure 9. SEM results of studied fiber stems, (a) longitudinal section of juncus stem, (b) longitudinal section of coconut stem, (c) EDS analysis of juncus, (d) EDS analysis of coconut fiber stem.

2.3. Adobe formulation and preparation procedure

The adobes were prepared by hand-mixing dry clay soil (< 2 mm) with different percentages by volume of the fibers (coconut and juncus fibers). The composites were prepared using the following process: First, the coconut fibers were immersed in water for 24 hours to saturation before being blended and for the local juncus fibers were dried naturally for 25days, then broken and ground, then the fibers were sieved through a sieve with a mesh size of 2 mm and a maximum length of 1.5 cm. first, the soil and fibers were mixed homogeneously, then water was added. The mixture was then stirred until a homogeneous blend was obtained. This operation was repeated for each type of mixture. The tests were carried out in the laboratory under conditions of temperature between 19°C and 23°C and relative humidity between 60% and 64%. Details of the proportions used in the composition of the mixture are given in Table 5. Contrary to current studies on agro-based (32, 33) small fiber/clay ratios were taken into account in this study (0, 10, 20% by volume). The composites were produced manually in the laboratory using parallelepiped molds with dimensions (4 × 4 ×16) cm^3 and cylinder molds with dimensions (D= 100 cm and thickness = 4 cm). For compacting, the same ratio water/soil (w/s) was used for each mixture. As discussed by (34) the required (W/s) ratio was calculated using Equation [2] :

$$(\text{w/s})\text{ratio} = \frac{LL + PL}{2} \qquad [2]$$

With : PL and LL are the calculated plasticity limit and liquidity limit, respectively, in %. The steps involved in preparing biobased adobes are illustrated in the Figure 10.

Table 5. Details of the proportions used in the composition of the mixture.

Mixture code	Clay	Fibers	(w/s) ratio
adobe		0	
10% coconut-adobe		10	
20% coconut-adobe	100	20	Eq1 (34)
10% juncus-adobe		10	
20% juncus-adobe		20	

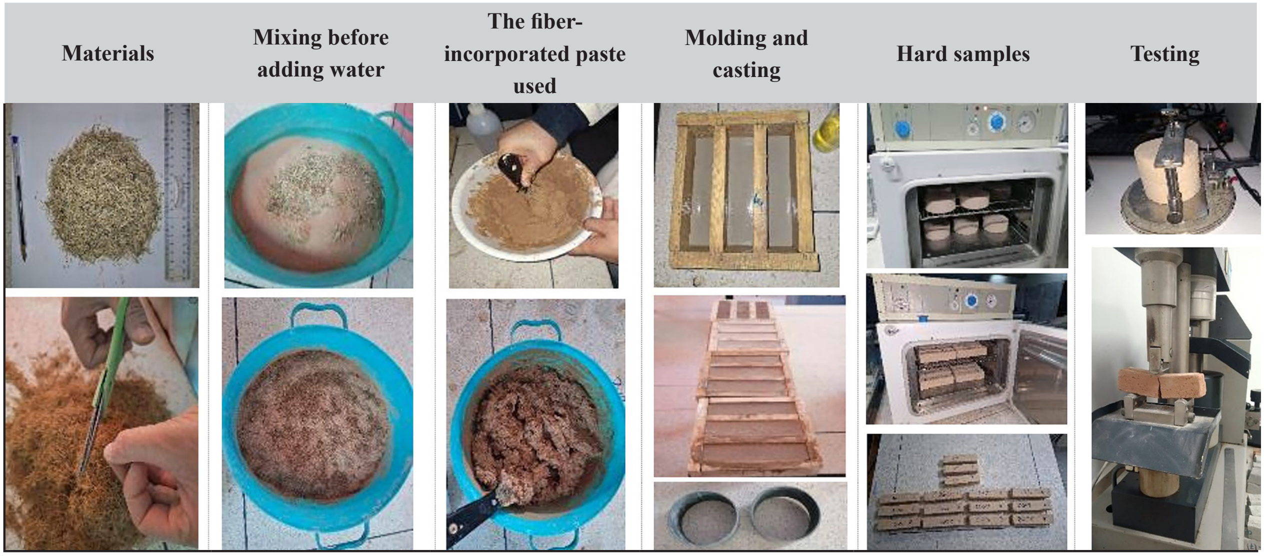


Figure 10. The steps involved in preparing biobased adobes.

3. TESTS AND METHODS

3.1. Physical test

In the last few years, the lightness of building materials has become a critical parameter in minimizing greenhouse gas emissions associated with transportation. Measured in the dry state, the apparent density of the samples was calculated as the ratio of the dry mass to the apparent volume of the sample, which was deduced from the dimensions measured using 0.01 mm precision calipers. Three samples were prepared for each percentage to conduct various tests and obtain multiple analyses.

3.2. Thermal test

The thermal conductivity of the composites developed is measured using a TPS 1500 hot disk apparatus marketed by Thermo-Concept. This method is based on a transient planar source (TPS) technique, which involves studying the rapid transient response of samples in accordance with ISO 22007-2 (35). The measurement protocol is based on tracking the time-dependent evolution of temperature across samples via a double spiral sensor, which serves both as an electrical heater and as a temperature sensing element (Figure 11).

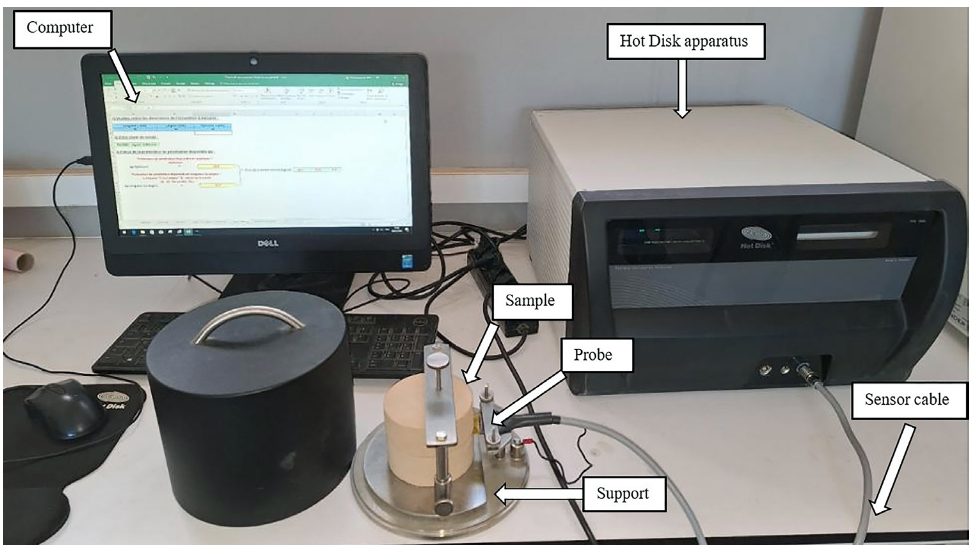


Figure 11. Hot Disk slide.

First, the sensor is inserted between two samples of the material to be characterized. The dimensions of the material must be sufficient to allow the assumption of a semi-infinite medium. Then, after thermal stabilization, the samples are heated through the sensor with a direct electric current. The theoretical framework as well as the governing equations of the hot disk method are detailed in (36, 37).

3.3. Mechanical Test

For each specimen developed, mechanical strengths were obtained at 28 days of age, on three 16x4x4 cm^3 prisms for the bending test and 4cm*4cm*8cm for the compression test, using Controls Automax5 machine equipped with the Microdata Autodriver software, according to standard NF EN 196-1(38). The specimens were dried in an oven at a uniform temperature of 60°C until a constant mass was obtained. For bending tests, the specimens were subjected to a uniform loading rate of 50 N/s until failure. The flexural strength of the specimens was calculated using the following expression:

$$R_f = \frac{1.5 \times F_{flex} \times l}{b^3} \quad [3]$$

With,

- (F_{flex}) measured in Newtons, is the bending force.
- (l) is the distance between the two points where the sample is seated, expressed in millimeters.
- (b) length in millimeters of the prism under the effect of the bending force.

The transverse half of the specimen have been subjected to compressive stress. A compression test plate 40.0 mm (± 0.1) in width and 40.0 mm (± 0.1) in length receives the specimen halves, with a load rate of 2400 N.s-1 (± 200) applied. Compressive strength is determined using the following formula:

$$R_{Comp} = \frac{F_{Comp}}{1600} \quad [4]$$

With :

- F_{comp} representing in Newtons the compressive force, and the value 1600 in square millimeters (4 × 4 cm^2) is the contact surface of the plates on either side of the sample.

4. RESULTS AND DISCUSSION

4.1. Apparent density

The variation in dry composite bulk density as a function of fiber volume is shown in Figure 12. As fiber volume increases, the dry density of the composites decreases. For composites incorporated with coconut fibers, the density varies from 1598.83 kg/m^3 for the composite without fibers to 1549.63kg/m^3 for the composite containing 20% of fibers, corresponding to a reduction of around 3.07%, and for composites incorporated with juncus fibers, the density varies from 1598.83 kg/m^3 for the reference sample to 1501.83 kg/m^3 for the composite incorporated

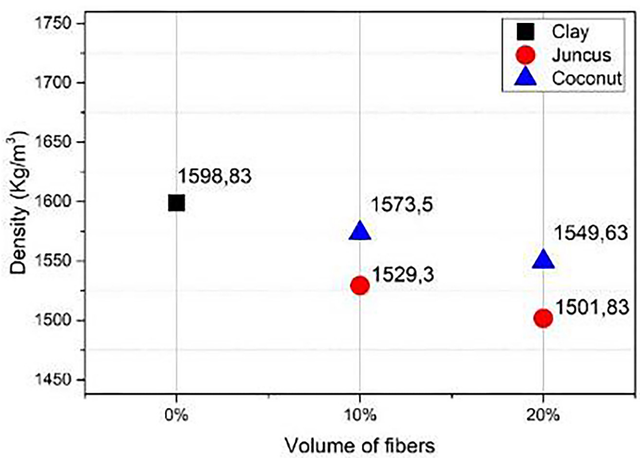
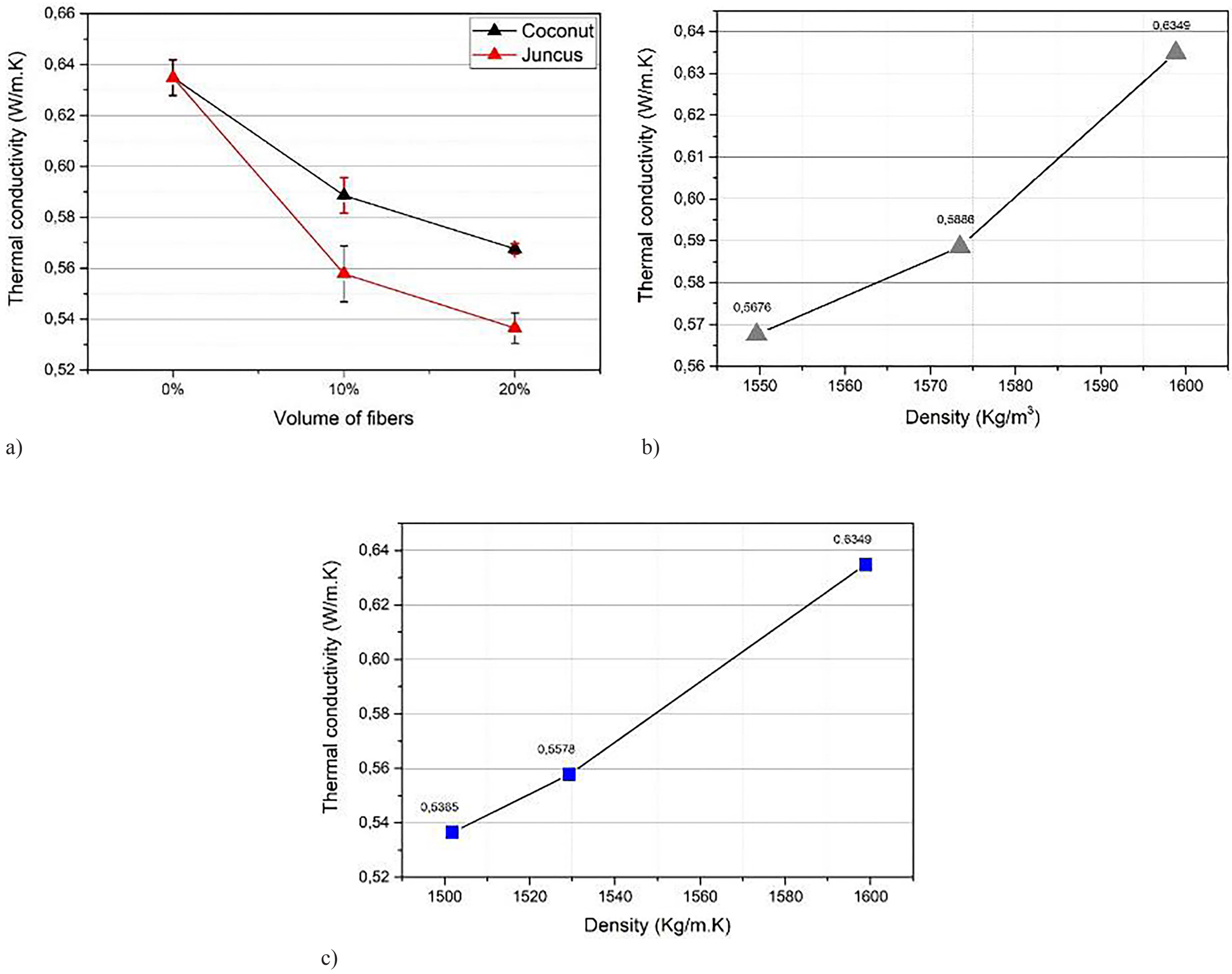


Figure 12. Bulk density of composites incorporated with different percentages of juncus and coconut fibers.

with 20% of fibers, with a rate of decrease of 6.06%. Similar trends have been observed in previous studies (25, 39) earth blocks/bricks reinforced with other natural fibers. The decrease in density was expected, as the fibers have a low fiber density (130 kg/m^3 for juncus fibers and 80 kg/m^3 for coconut fibers) compared to the density of the soil (1615kg/m^3) (Table 2), Consequently, the increase in fiber content displaced the heavier soil content, resulting in a decrease in adobe density. In fact, the bulk densities of composites incorporated by juncus fibers improved more than those incorporated by coconut fibers, and these results are due to the greater water absorption capacity of juncus fibers (260%) compared to that of coconut fibers (175%), which would cause high matrix porosity during the drying process.

4.2. Thermal properties

Thermal conductivity is a crucial thermophysical characteristic of construction materials (40), It quantifies how readily heat is able to transfer through a material under steady-state conditions (41), Thermal conductivity for both juncus and coconut fibers is illustrated in Figure 13a. According to the conductivity curves previously quoted, it is evident that conductivity decreases with increasing fiber volume, varying from 0.6349 W/m·K for the reference sample to 0.5565 W/m·K for the composite incorporated with 20% juncus fibers, and 0.5676 W/m·K for coconut fibers. Consequently, the addition of 20% juncus fibers improved the thermal performance of the material by around 12.34%, and 10.6% for coconut fibers. This can be due to the low thermal conductivity of the juncus and coconut plant fibers compared to that of the clay matrix, and by the increased porosity of the material when the fibers were added. The use of additives with low thermal conductivity leads to the manufacture of low-conductivity composites(42-44). In fact, the decrease in thermal conductivity is relatively small for juncus incorporated adobes compared with those incorporated by coconut fibers, as we have seen from the microstruc-



c)

Figure 13. (a) Variation in thermal conductivity of composites. Relationship between thermal conductivity and bulk density for different fiber types and volume contents: (b) coconut fiber, (c) juncus fiber.

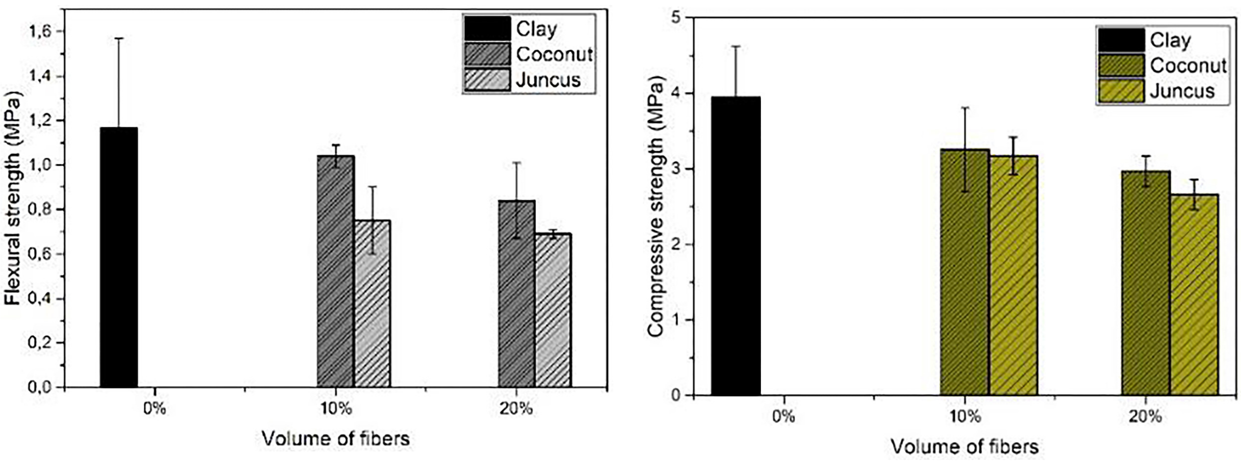
ture of coconut and juncus fibers (Figure 9), juncus fibers have a more porous structure than coconut fibers, allowing juncus fibers to absorb a significant amount of water (Table 4). The presence of water in the pores of the fibers increases the contact surface between fiber and matrix due to the stress exerted by the water trapped in the pores after drying. The stripping of the water causes the contact surface of the fibers to detach from the matrix, a large gap between the fiber/matrix contact surface is noted for juncus fibers, indicated by the microstructure Figure16b. The development of porosity in composites through the insertion of natural fibers reduces the apparent density of composites. However, the lightness of the samples contributes efficiently to the decrease in thermal conductivity. This dependency between lightness and thermal conductivity (conductivity as a function of density) is always confirmed for materials based on mineral matrix and vegetal fibers. According to Khoudja et al. (45) and Saghrouni et al. (24) which used a clay matrix and Portland cement respectively. The corresponding relationships between dry bulk density and the thermal conductivity of composites with different volumes of coconut and juncus fibers are shown in Figure 13b and Figure 13c respectively. The thermal conductivity of the composites decreases with increasing bulk density. The variation observed is comparable to that described by various authors in past studies on lightweight materials, using different types of vegetal materials as palm, coconut, oil palm, bagasse, wood chips and jute fibers (46).

4.3. Mechanical properties

Figure 14b illustrates the results of mechanical tests on composites based on clay incorporated with juncus and coconut fibers, while indicating their errors, calculated from the difference between the maximum and average values of the measurements obtained for each percentage. According to these figures, a decrease in flexural strength was observed for all fiber-reinforced samples Figure14a. The highest strength value was recorded for the clay-based composite with 10% coconut fiber, reaching 1.166 MPa, followed by the same blend with 20% coconut fiber reaching 0.84 MPa, a decrease of 0.3 MPa compared to the reference sample. However, the clay incorporated by the 10% and 20% juncus fibers has a value close to that recorded for 20% coconut, which remains quite modest with a decrease of 0.5 MPa compared to the value obtained by the samples reinforced with 10% coconut. Nevertheless, in Figure 14b. The compressive strengths of the two samples with 10% and 20% are lower than those of the reference sample, and the values obtained by the two fibers approach each other for the same percentages with a reduction rate of 24.71% and 32.57% for a percentage of 20% of coconut and juncus fibers respectively compared to the reference sample.

The contact surface between the clay and the coconut fibers and their orientation in the matrix, as well as the good tensile strength of the coconut fibers, are key factors contributing to the improved flexural strength of coconut reinforced composites compared to juncus reinforced samples, this observation is justified by the microstructural analysis in Figure 16, with the coconut fibers protruding from the matrix oriented perpendicular to the applied stress, making the coconut reinforced samples more cost effective in terms of flexural strength compared with juncus fibers.

From the results concluded, a decrease in the mechanical strengths of composites reinforced with coconut and juncus was observed, the decrease in flexural strength when adding natural fibers, has been detected by sever-



a) b)

Figure 14. Results of mechanical tests on prepared samples, (a) flexural strength test results, (b) compression test results.

al authors (27, 47, 48). The decrease in compressive strength observed for both composites containing juncus fibers is justified by the presence of pores and voids in the volume of the matrix, which accentuates its porosity reduction in densities Figure 12. Also poor fiber distribution has a direct impact on the mechanical stress performance of the samples, as illustrated by the microstructures shown in Figure 15, Several studies have shown that increased porosity redu has been cited in the literature, the characterization of earthen materials is important to preserve our architectural heritage and keep the same appearance and regidity of constructionsces mechanical strength while improving thermal performance (49, 50).

The non-destructive samples recovered after the mechanical test are put under observation to explain the mechanical results obtained, we noticed bar-like fibers protruding from the inner surface of the matrix as shown in the images in the Figure 15. These bars make a major contribution to the adhesion of the transverse faces of the clay composite, the coconut fibers are detached from the matrix, this observation can be explained by the external face of coconut which is smooth compared to that of juncus as shown in the figure Figure 16b, the morphology of the fibers impacts on the degree of adhesion of the additives and composites, also the dosage of the different fibers and their orientations destroys the homogeneity of the matrices as shown in Figure 15 below.

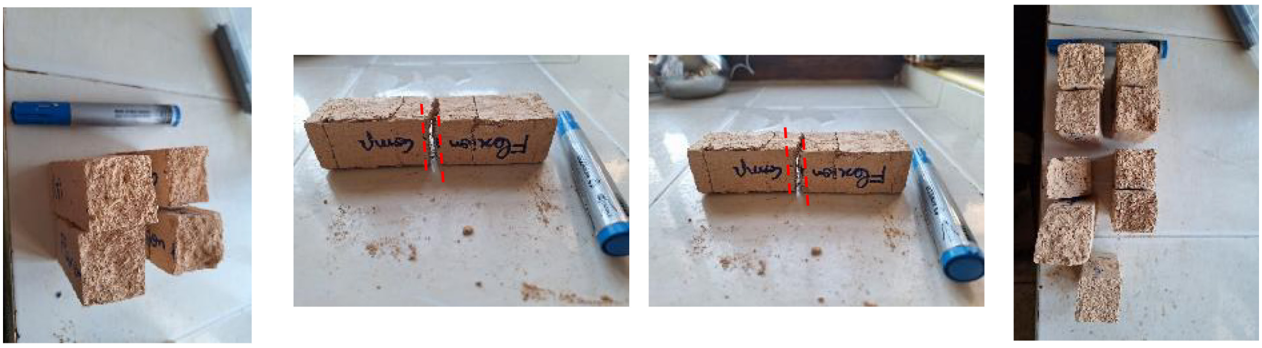
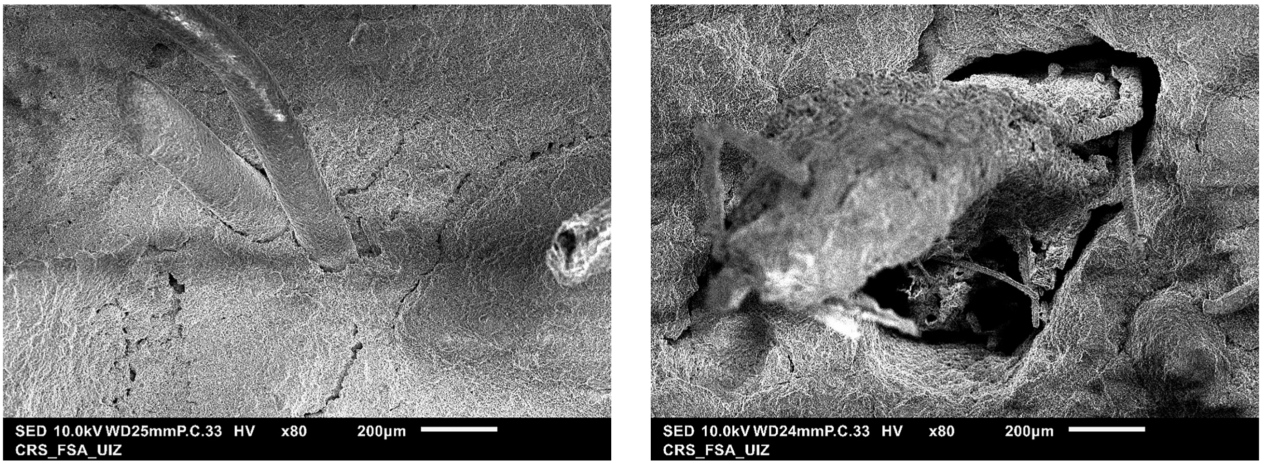


Figure 15. Observation of sample break-up surface after destructive testing.



a) b)

Figure 16. SEM images of samples after bending tests, (a) coconut fiber salient from matrix, (b) juncus fiber salient from matrix.

4.4. Microstructure

Figure 16 shows SEM images of the internal surfaces of the clay-based composite sections obtained from the bending test. The clay composite reinforced with coconut fibers Figure 16a shows a better bonding surface, illustrated by negligible cavities and pores between the fiber surface and the matrix. An approximately uniform distribution of fibers in the matrix, with no noticeable accumulation at specific points. This is due to the behavior of coconut fibers towards water, which tend to absorb some water during the preparation of the blends, unlike juncus fibers. The absorption of water by these juncus fibers generates cavities after evaporation of the post curing water. This phenomenon has been observed by several researchers and can be attenuated by chemical treatment of the fiber contact surface (51).

The microstructures (SEM images) of the samples after bending tests are shown in Figure 16 in the mechanical testing section, the images show a large void between the clay matrix and the juncus fibers Figure16b which contributed to the decrease in adhesion that negatively affects mechanical strengths, on the other hand image Figure 16a a shows a small void between the clay and the coconut fiber, Juncus fibers have a porous structure with a large geometry and high water absorption. After drying, the water escapes from the clay matrix, leaving voids between the matrix and the fibers. These observations explain the reduction in mechanical properties, which depend essentially on adobe porosity. The higher the number of pores in the adobe, the greater the reduction in mechanical strength (25). The increase in pores as the percentage of fibers in the clay matrix increases, as observed in these SEM images, also justifies the decrease in bulk density and the thermal properties of the composites obtained.

5. CONCLUSIONS

The objective of this research is to analyze how the addition of juncus and coconut fibers affects adobes manufactured mainly from clay extracted in the Sous Massa region of Morocco. The fibers chosen are natural, one planted under standard climatic conditions and the other commercialized and imported from abroad in the form of rolls. Different proportions of each fiber (0%, 10%, 20%) were studied to determine the feasibility of replacing commercial fibers with local fibers, and the thermo-physical and mechanical behavior of adobes reinforced with each fiber (juncus and coconut) was compared, with the results summarized as follows:

- The smooth interface of juncus fibers reduces adhesion, making the bricks more insulating but less resistant, requiring fiber treatment.
- The roughened interface of the coconut fibers helped improve adhesion, resulting in more homogeneous brick samples that are more resistant to cracking, more resistant to impact and have a lower transport loss coefficient.
- All samples show acceptable performance levels, making them suitable for adobe construction.
- Samples reinforced with 10% juncus have satisfactory mechanical properties, enabling them to be used as adobes.
- The addition of 20% juncus fibers improved the thermal performance of the material by around 12.34%, and 10.6% for coconut fibers.
- The two samples reinforced with 10% and 20% juncus and coconut fibers have lower compressive strengths than the reference sample, and the values obtained by the two fibers approach each other for the same percentages with a reduction rate of 24.71% and 32.57% for a percentage of 20% of coconut and juncus fibers respectively compared to the reference sample.

This research presents the results of a comparative study on the physical, thermal and mechanical behavior of adding juncus and coconut fibers to the clay matrix. Based on the findings and discussions cited in this research, we can conclude that juncus fibers are recommended for use as insulating materials, and the mechanical results obtained are satisfactory, the challenge remains to seek further improvements in their mechanical resistance and test their acoustic performance, while replacing commercialized natural fibers which require specific plantation conditions, and also to replace synthetic fibers. Researchers will be focusing on the acoustic and lighting aspects.

Although the results of this study demonstrate the effectiveness of natural fibers in improving the thermal properties of composites, future research should focus on improving the mechanical strength of these fibers. This could enable them to be used in applications requiring greater robustness. In addition, it would be interesting to explore the acoustic performance of composites made from natural fibers, in order to assess their potential in sound insulation and comfort-enhancing applications in buildings.

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Authorship contribution statement:

Slimane Oubeddou: Conceptualization; Data cleansing; Formal analysis; Fund raising; Research; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Write-up - original draft; Write-up - review & editing.

Mina Amazal: Conceptualization; Methodology; Resources; Software; Supervision; Validation; Visualization; Write-up - review & editing.

Soumia Mounir: Conceptualization; Methodology; Resources; Supervision; Validation; Visualization.

Asma Souidi: Conceptualization; Methodology; Validation; Visualization. Malika Atigui: Conceptualization; Methodology; Validation; Visualization.

Hassan Demrati: Supervision; Validation; Visualization.

Youssef Maaloufa: Supervision; Visualization.

Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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