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Thermophysical, Mechanical and Durability Properties of Adobes Incorporated with Juncus Maritimus Fibres

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ABSTRACT

The aim of this research is to study the thermophysical, mechanical, and durability behaviour of adobes reinforced with Juncus maritimus fibres, which have recently been used in building materials. This composite consists of a mixture of clay incorporated with different percentages of fibres by volume of 20%, 40% and 60%. The raw materials were characterised physically, chemically, thermally, geotechnically and mineralogically. The thermal and mechanical properties of the adobes elaborated were determined by Hot disk method, compressive strength and flexural strength tests. A capillary water absorption test was used to assess the effect of fibre content on the durability of the adobes. The outcomes showed that adding 60% fibre to the clay matrix reduced the thermal conductivity, thermal effusivity and thermal diffusivity of the composites by 49.07%, 34.65% and 39.26% respectively, coupled with a 16.34% increase in specific heat capacity. But that a reduction in compressive and flexural strength was obtained as the amount of fibre in the clay matrix increased. In addition, to understand the durability of the composites produced, the evaluation of their behaviour when exposed to water shows that increasing the percentage of Juncus maritimus fibres in the adobe increased the water resistance of the composites. These results confirm the potential of Juncus maritimus-reinforced adobes as durable, thermally efficient building materials.

1. INTRODUCTION

Construction methods have always evolved, whether in terms of the modern building materials used (concrete, cement, wood and steel) or in terms of the latest techniques that are continually appearing. This continuous evolution is making buildings faster and more aesthetic, but at a high cost, with considerable energy consumption and a high environmental impact. This impact is linked to the use of clinker, which is a main component of the cement used in concrete, the manufacture of which requires a great deal of energy, and to the pollution resulting from this manufacture [1]. Studies show that the cement industry is responsible for between 5% and 7% of CO_2 emissions [2, 3]. Cement production relies heavily on the use of fossil fuels, mainly to heat the high-temperature kilns needed to make the clinker. This process not only generates CO_2 emissions due to the combustion of fossil fuels, but also contributes to the significant decarbonation of limestone. It will therefore be essential to develop innovative solutions to meet the growing demand for affordable housing in developing countries, while taking environmental issues into account. So, the use of earthen construction is still a recognised method that dates back a long time, particularly adobes, which are a frequently used construction method, given the simplicity of this type of technique and the availability of shaping and demoulding tools. In addition, earth walls have the ability to retain heat and regulate indoor air humidity levels effectively, offering significant advantages in terms of thermal insulation and humidity [4, 5]. However, studies have shown that using only raw clay bricks in the production process cannot guarantee all the desired performance because adobe construction has disadvantages in mechanical properties, in particular low tensile strength and brittle behaviour [6]. Adobes also have low water resistance, which can lead to further reduced mechanical strength or cause them to disintegrate [5]. Several techniques have been used to improve their mechanical strength, such as incorporating natural fibres [6-10] or mineral stabilisation with cement [11-13]. Although cement stabilisation generally offers superior mechanical reinforcement, most researchers rarely recommend this technique because of the pollution generated by cement production, its high cost and high energy consumption [5, 14]. Cement also tends to mineralise the plant fibres contained in the clay matrix over time due to its alkaline nature [15]. According to Ashour et al. [16], an increase in the quantity of cement in unfired earth bricks leads to a slight decrease in thermal resistance. Indeed, when cement is increased from 0 to 10% by weight, the thermal conductivity of unfired earth bricks incorporated with 3% barley straw fibre and 3% wheat increases by 24% and 8% respectively. Dao et al. [17] have shown in their study that the thermal conductivity of adobes initially decreases with the addition of 2% and 4% cement, then increases above these percentages. The decrease in the thermal conductivity of adobes with low cement content could be due to inhomogeneity between the earth and the cement [16, 17]. These results contradict those of many authors who have shown that adding fibres to the clay matrix reduces thermal conductivity [5-7, 18, 19]. Several researchers have advised that it is very important to use raw earth bricks incorporated with plant fibres to ensure thermal comfort in the building, since these earth bricks save energy compared with other construction materials. Also, the use of thermally insulating materials can reduce energy consumption for cooling and heating buildings [4]. Binici et al. [20] revealed after a study of a fibre-incorporated mud house that the latter is 41.5% cooler in winter and 56.3% cooler in summer than a house built with concrete bricks. They concluded that the house built with fibre-reinforced mud has an energy savings of 57% in summer and 69% warmed in winter.

Several studies have examined the effect of incorporating plant fibres on the thermophysical and mechanical behaviour of construction materials [4, 9, 21-25]. Khoudja et al. [9] and Mellaikhafi et al. [26] investigated the impact of date palm fibre reinforcement on the mechanical and thermal characteristics of adobe. The Fanio straw fibres have been studied by Ouedraogo et al. [6] to improve the thermal and mechanical properties of adobes, they found that the addition of these fibres to adobes reduced their thermal conductivity and that optimum mechanical properties were obtained for quantities of fibres between 0.2% and 0.4% of the mass. Millogo et al. [22] improved the physical and mechanical properties of pressed adobes by reinforcing them with 30 mm Hibiscus cannabinus fibres, and observed a negative impact on the compressive strength of pressed adobes with a length of 60 mm of fibres with a percentage of 0.8% by weight. In the same context, Danso et al. [19] examined the properties of pressed earth bricks stabilised with coconut fibres, sugarcane bagasse fibres and oil palm fruit fibres, and found that the incorporation of these fibres improved the mechanical and physical properties of the brick materials. A new clay brick incorporated with rice husks has been developed by Chiang et al. [27]. A recent study by Jové-Sandoval et al. [28] compared three types of plant fibre with wheat straw. All these studies have revealed that the addition of fibres can improve the thermal properties of unfired bricks and effectively reduce their cracking during drying. Nevertheless, further research is needed to explore the use of new local additives to design more efficient and economical bricks. Ba et al. [29] studied the effect of adding Typha australis fibres on the thermomechanical properties of clay bricks, using higher fibre percentages. The results show that the use of 55% 1 cm long fibres reduced the thermal conductivity of the clay from 1.03 W/m. K to 0.146 W/m. K. However, the addition of fibres had a negative impact on the mechanical properties of the clay. In order to address the low mechanical properties of clay bricks reinforced with plant fibres, this study proposes a novel approach involving the use of high-fibre clay bricks for building facades.

Fibres of the Juncaceae family are newly used in the construction. Recent scientific research has dealt with the effect of these fibres from the Juncaceae family on the thermophysical and mechanical behaviour of plaster, cement and clay mortar. Two studies were carried out by Saghrouni et al. [30, 31], in the first study, they examined a composite consisting of cement mortar and Juncus maritimus fibres, and found that the incorporation of these fibres improved the thermal properties of the composite. In the second study, the authors applied a chemical treatment to the fibres to improve the mechanical properties of the composites. They found that the flexural and compressive strengths of composites reinforced with treated fibres were higher than those of composites containing untreated fibres. Amazal et al. [32] have developed a new material based on gypsum and Juncus maritimus fibres. They have shown that these fibres improve the thermal properties of biocomposites, and have found that an optimum fibre content of 20% improves the flexural strength of composites. Another type of Juncus acutus fibre was studied by Omrani et al. [25] they found that these fibres improved the thermal conductivity of clay mortar composites by partially replacing the sand with 5 to 20% fibre. Furthermore, this study seems to focus only on the thermal conductivity of clay mortar reinforced with Juncus acutus fibres. However, for a complete analysis of the effects of Juncus fibres, it is also necessary to examine other thermal properties, including thermal diffusivity, thermal effusivity and specific heat, which will be studied as part of this research. The purpose of this research is to develop a new material with a zero carbon footprint, using local fibres that are available but not yet integrated into construction practices in our region. This represents an opportunity to reduce dependence on traditional materials, reduce construction costs and contribute to more sustainable building practices.

This study evaluates the thermophysical and mechanical properties of adobes reinforced with Juncus maritimus fibres. The thermal capacity of the adobes developed was examined, being considered a crucial thermal parameter that reflects the thermal inertia of the material [33, 34]. In addition, this study assessed the durability of adobes reinforced with Juncus maritimus fibres using a capillary absorption test, highlighting the essential role of fibres in the durability and water resistance of adobes.

2. MATERIALS AND METHODOLOGY

2.1 Raw materials

The soil studied comes from the small town of Tafraout, located to the southeast of Agadir in the Souss Massa region Figure 1(a). This soil is traditionally used to make mud bricks, proving that it has a sufficient clay content to ensure the cohesion of the adobes. This raw material was extracted from abandoned buildings in the town to ensure the right choice of material used by builders in the region at the time. When clay was extracted from the site studied, we observed cohesion between the components of this material (the grains with the dominant clay), hence the need to study the thermophysical and mechanical behaviour of this sample.

Juncus maritimus of the Juncaceae family, with around 200 species, grows particularly in wet and saline areas [25]. This plant is found in the form of a hollow cylindrical stem averaging 1m in length and 4-8 mm in diameter [15]. It is rich in cellulose products (around 40%) [30] and abundant in several countries, particularly in Africa [35, 36]. The Juncus maritimus plant used in this study was extracted from the village of Tameri (30°41′42″ North, 9°49′30″ West). This plant is very common in this region, which is why we chose this area. It is characterized by its high cellulose content, which provides good mechanical strength and enhances the reinforcement of the material's structure. Its low density also helps to lighten the adobe blocks, contributing to improved thermal performance while reducing their overall density. Most Moroccans use them to make carpets and baskets. In this study, we will investigate the feasibility of using them in construction. The chemical composition of the juncus maritimus plant extracted from two different Tunisian regions is presented in Table 1 [37]. The Juncus maritimus plant is illustrated in Figure 1(b).

Figure 1. a) Studied soil extraction site b) Juncus maritimus plant

2.2 Geotechnical, chemical and physical soil characterisation

A series of laboratory tests were used to determine the geotechnical properties of the soil (Figure 2), namely the methylene blue value and the specific surface following NF P 94-068 [38], the sand equivalent following NM 10.1.147 [39], and the Atterberg limit test following NM 13.1.007 [40] (Table 2). The latter provided us with a value for the liquidity limit at the Casagrande Cup (WL) of 35.452%, a value for the plasticity limit at the roller (WP) of 22.345%, and a plasticity index (PI) of 13.107%. Based on the plasticity diagram [41], we can conclude that the soil studied can be considered as a medium plastic inorganic clay. The soil studied has a specific surface area of 48,80 m^2/g, and taking into account the significance of this value in terms of adsorption of water and water vapour, the sample will not present problems of swelling [41].

Table 2 also shows the physical properties of the soil in terms of absolute density, bulk density and porosity.

Table 2 shows the PH value, salinity, and electrical conductivity, which have been measured by a Consort™ C3010 benchtop multi-parameter analyser (Figure 3). Salinity is one of the characteristics that affect the mechanical and chemical properties of construction materials. According to Calvet [42], soil is considered saline when the electrical conductivity of solutions exceeds 4000 µS/cm. According to Table 2, the soil studied is non-saline (1651 µS/cm) and alkaline (7,78) (Table 3), and is classified as a non-calcareous material since its calcium carbonate content does not exceed 10% [41].

Table 4 presents the mass percentages of soil oxides determined by the dispersive X-ray fluorescence spectrometry technique using the Panalytical 4 Kw Axios Dy 1856. A significant amount of silica was detected in the soil studied, mainly from quartz and alumina silicates, and also an interesting content of Al_2O_3 which corresponds to clay silicates and contributes to good plasticity [41], the presence of calcium oxides with a percentage of 12.04%, which makes the soil stable, and other traces of oxides (MgO,SO_3,P_2O_5 …) were found in the soil studied. After calcination at 1000°C for 24 hours, the loss on ignition (L.O.I) of the soil was 7.48%.

Figure 2. Techniques used to measure geotechnical soil properties: a. b) Atterberg limits, c) Methylene blue, d) Sand equivalent

Figure 3. a. b) Materials used to measure pH, salinity, electrical conductivity, c) Calcium carbonate content, d) Organic matter

Table 1. Chemical composition of Juncus maritimus plants collected in Tunisian regions

Rush	Chemical Composition				
	Cellulose (%)	Holocellulose (%)	Lignin (%)	Hemicellulose (%)	Ash (%)
JM (region 1)	40.99	68.84	18.54	27.84	7.3
JM (region 2)	53.10	88.46	13.05	35.36	5.29

Table 2. The geotechnical and physical properties of the soil

Atterberg Limit			MBV	Specific Surface (m^2/g)	Sand Equivalent (%)	Absolute Density (kg/m^3)	Bulk Density (kg/m^3)	Porosity (%)
WP	WL	PI						
22,345	35,452	13,107	2,332	48.80	16,72	2640,7	1416,53	46.35

MBV: Methylene blue value

Table 3. Chemical properties of soil

Chemical Properties of Soil	Unit	Results
PH	-	7,78
Electrical conductivity	$\mu S/cm$	1651
Salinity	ppT	0,89
Content of $CaCO_3$	%	8,79
Organic matter	%	1,2

Table 4. Chemical analysis of the soil

Oxides	Mass %
SiO_2	54,67
Al_2O_3	13,82
Fe_2O_3	3,77
CaO	12,04
MgO	1,14
SO_3	0,16
K_2O	4,08
Na_2O	0,99
P_2O_5	0,07
L.O.I	7,48

2.3 Physical and thermal properties of Juncus maritimus fibres

The physical and thermal characteristics of Juncus maritimus fibres were determined and are presented in Table 5.

2.4 Microstructure and mineralogical phases of the soil studied

Figure 4(a) shows the crystalline nature of the sample, determined by X-ray diffraction (XRD) using a Bruker D8 Advance Twin diffractometer, equipped with a copper anti-cathode, using Kα_1-rays, wavelength =1,5418Å with a scan of 5 to 80° and a step of 0.02°. The results were analysed using X'Pert High Score Plus software. The sample shows that it is mainly composed of quartz, albite, phengite, and a few traces of calcite and garronite. The microstructure of the soil shown in Figure 4(b) was determined by JEOL JSM IT-100 scanning electron microscopy and shows scattered structures in the studied soil and a random orientation that leaves visible voids in the sample structure. The EDS spectra of soil composition in Figure 4 reveal very high levels of oxygen, silica, aluminum, iron, and negligible proportions of magnesium and potassium, with an average content of approximately 45.60% SiO_2, 24.65% Al_2O_3 and 17.59% FeO.

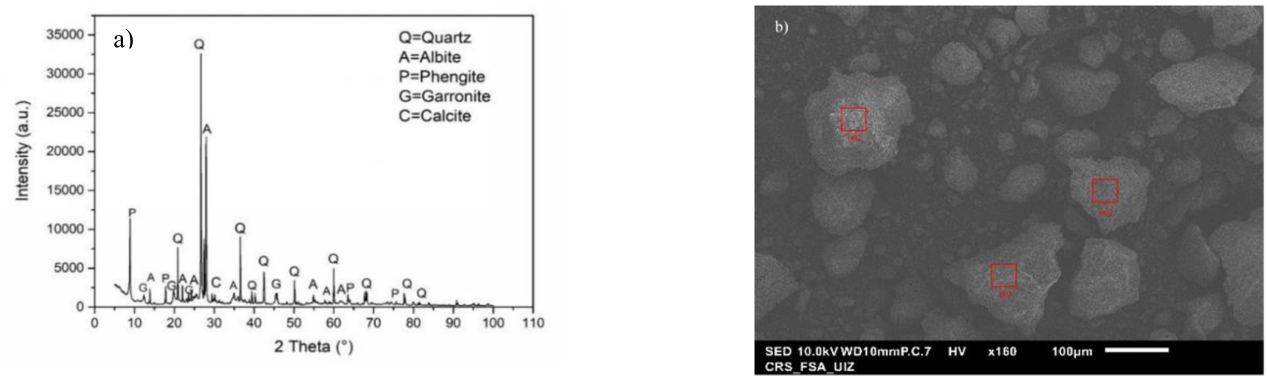
2.5 Water absorption of crushed and sieved Juncus maritimus fibres

Concerning the process for calculating the water absorption rate of Juncus maritimus fibres, these fibres were first ground and sieved, then dried at 70°C in the oven until a constant mass of fibres was obtained (a variation of less than 0,1 g between two weighings at an interval of 24 hours). We obtained a constant mass over a period of two days (m_d), this mass of dried fibres was then immersed in water. The saturated mass is the mass trapped in the pores of the fibres and was obtained by using a filter paper to remove the water trapped between the fibres (m_{sat}). The absorption rate is calculated using the following formula:

$$Wa\ (\%) = \frac{m_{sat}-m_d}{m_d} * 100 \quad (1)$$

Table 5. Physical and thermal properties of Juncus maritimus fibres

Property	Apparent Density (Kg/m³)	Specific Heat (MJ/m³K)	Thermal Effusivity ($Ws^{1/2}$/(m²K))	Thermal Diffusivity (mm²/s)	Thermal Conductivity (W/m. K)
Value	100.5	0,3187	170,9	0,2874	0,0916



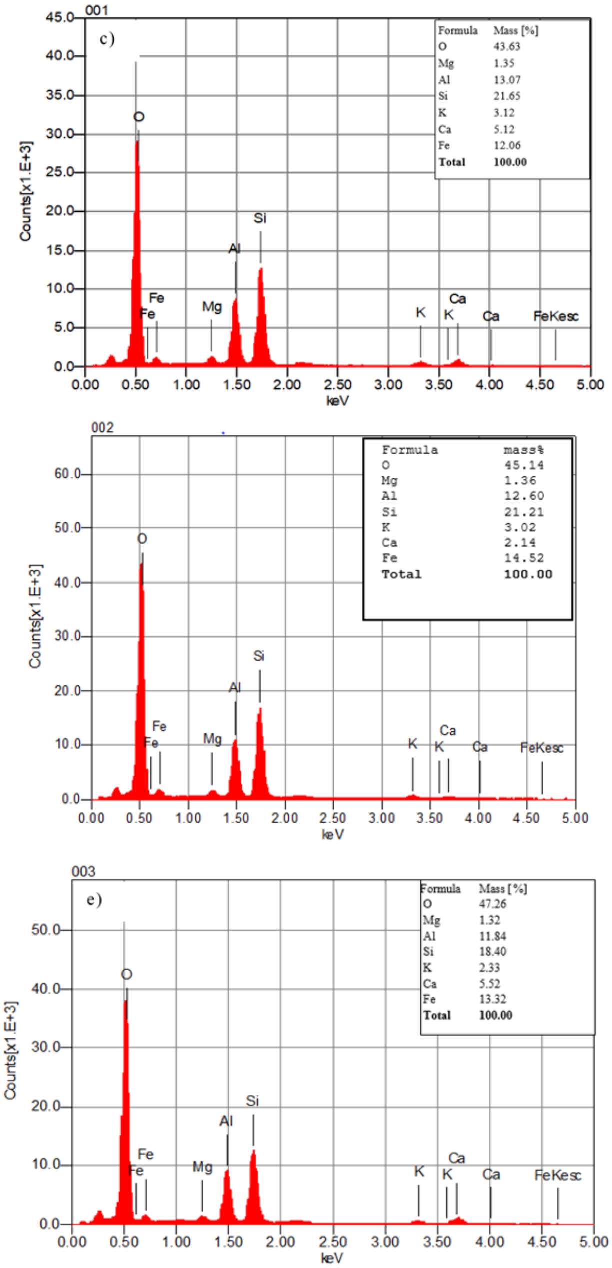


Figure 4. a) Diffractogram of soil studied, b) SEM secondary electron images of the soil examined, c-e) EDS of three different spectra

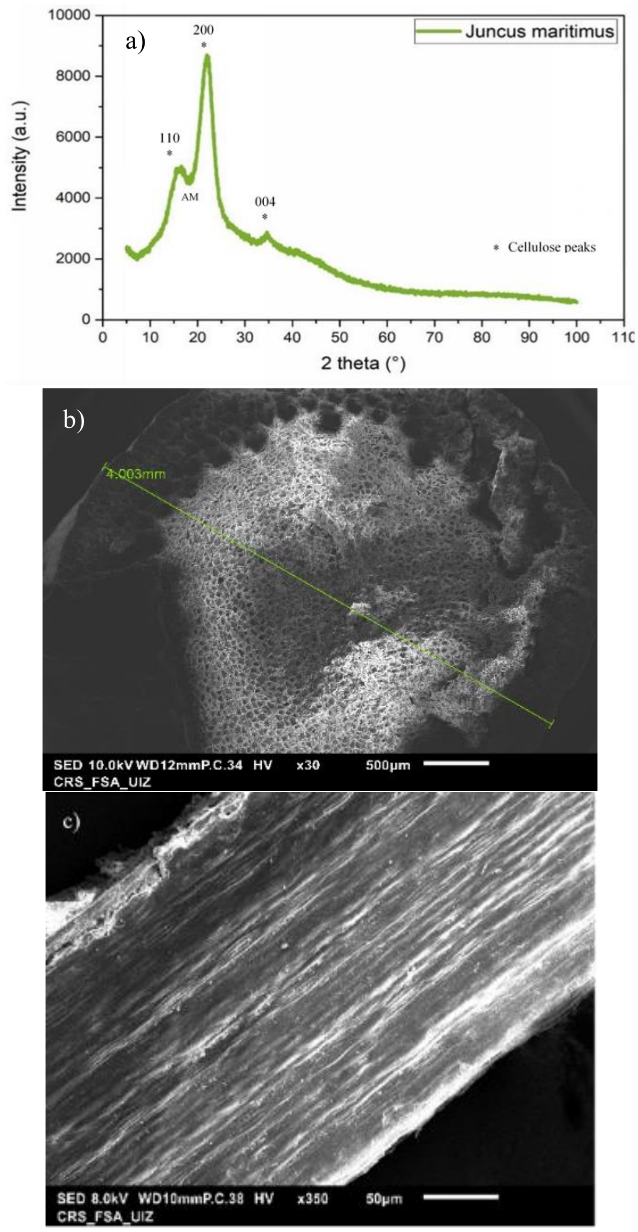
Three measurements were carried out to evaluate the average absorption rate and saturation of the ground fibres. A value of 250% was found, which is lower than the value of the water absorption coefficient of Juncus maritimus fibres in Tunisia (280.59%) [31]. This difference is due to the type of fibres and the variation in the diameter and length of the fibres, as indicated by Migneault et al. [43] which is also lower than that of Banana and eucalyptus fibres, which have values of 407% and 643% respectively [44].

2.6 Microstructure and mineralogical phases of Juncus maritimus fibres

Figure 5(a) illustrates the X-ray diffraction analysis of Juncus maritimus fibres, which is characterised by 3 major reflection peaks: an intense peak appears at 2θ = 22,19◦ and two less defined peaks at 2θ=15,6◦ and 34,7◦ [35]. According to the XRD reference models, these peaks correspond to cellulose I ($C_6H_{10}O_5$). The value of the crystallinity index was determined using Segal's formula (Eq. (2)) [45], where I200 corresponds to the maximum intensity of the crystalline part 2θ=22,19◦ of the cellulose I, and I_{am} corresponds to the intensity of the peak which corresponds to the amorphous part around 2θ=18◦. The value of Cr I obtained is 42.45%, higher than the value of the crystallinity index found for date palm fibres (19.9%) [46], and Juncus effusus fibres (33.4%) [47].

$$\text{Cr I} = \frac{I_{200} - I_{am}}{I_{200}} * 100 \qquad (2)$$

The microstructure of the Juncus maritimus plant is illustrated in Figure 5. Microscopic observation of a cross-section of the dry Juncus maritimus stem presented in Figure 5(b) showed that the stem has a diameter of 4.003 mm and contains lignin, hemicellulose cells, and cellulose fibre grouping. This stem cannot be used directly as a reinforcing material in composite materials; the lignin and hemicelluloses must first be removed to obtain the cellulose fibres, most of which are found on the periphery of the stem Figure 5(c). The microstructure of the external surface of the stem is presented in Figure 5(c), it appears on the surface of the shiny particles that can contaminate.



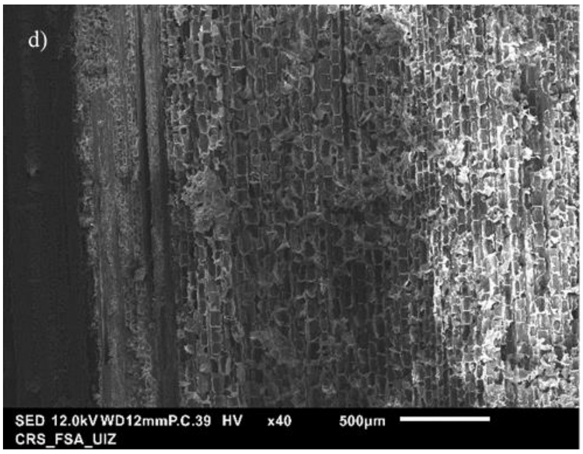


Figure 5. a) Diffractogram of Juncus maritimus fibres, b) SEM observation of a cross-section of Juncus maritimus plant stems, c) SEM observation of the outer surface of Juncus maritimus plant stems, d) SEM observation of a longitudinal section of Juncus maritimus plant stems

Veins parallel to the axis of Juncus maritimus were also observed on the outer surface of the plant, this grooved structure of the fibres can improve the mechanical coupling of the fibres with the clay, which can influence the post-peak behaviour of the composite material [6]. A longitudinal section of the Juncus maritimus plant is illustrated in Figure 5(d), revealing a porous microstructure.

3. EXPERIMENTAL METHODS

3.1 Preparing the adobes

Adobe bricks are produced by reinforcing clay soil with Juncus maritimus fibres as an ecological additive, varying the percentage by volume of fibres from 20% to 60%. To ensure the homogeneity of the grains constituting the soil, a 2 mm sieve was used to remove any coarse components that could cause complications during the elaboration of the samples. The Juncus maritimus fibres were dried in natural air for a period of 20 days, afterwards, the stems were manually broken into small pieces and then placed in an oven at a temperature of 60°C to facilitate grinding. The resulting fibres were then sieved to mesh sizes between 0,315mm and 2mm. Figure 6 shows the steps followed to obtain crushed and sieved fibres. For the quantity of water chosen, the same water/fibre+soil (w/s+f) ratio was used for all the percentages of fibre added, As conducted by Ouedraogo et al. [6]. This ratio was calculated according to Eq. (3). Table 6 shows the different formulations used.

$$w/(s+f) = \frac{W_P - W_L}{2} \qquad (3)$$

where, W_P and W are respectively the plasticity limit and the liquidity limit of the soil, in %. The dry soil was first mixed to homogenise all the grains making up the soil. The dry fibres were then gradually added to the mixture of soil to obtain a homogeneous mixture. Once the water had been added, the mixture was placed in parallelepiped moulds with a volume of $4 \times 4 \times 16$ cm^3 for the mechanical tests and moulds with a volume of $10 \times 10 \times 2.5$ cm^3 for the thermal tests. To ensure good consistency, a layer-by-layer compaction was carried out manually using a plunger manufactured for this type of process, and the face exposed to the air was shaved with a trowel until a smooth face was obtained. The samples were air-dried under controlled laboratory conditions (20 ± 2°C, 65 ± 2% RH) for 72 hours before demoulding. Drying was carried out away from any source of direct heat or solar radiation, to ensure gradual evaporation of moisture and limit the risk of cracking. These conditions were chosen to ensure homogeneity between the samples and to reproduce realistic drying in a traditional construction context. The manufactured bricks were then dried under laboratory conditions for a period of 60 days before being characterised in order to avoid cracks in the samples that may appear as a result of thermal shock.

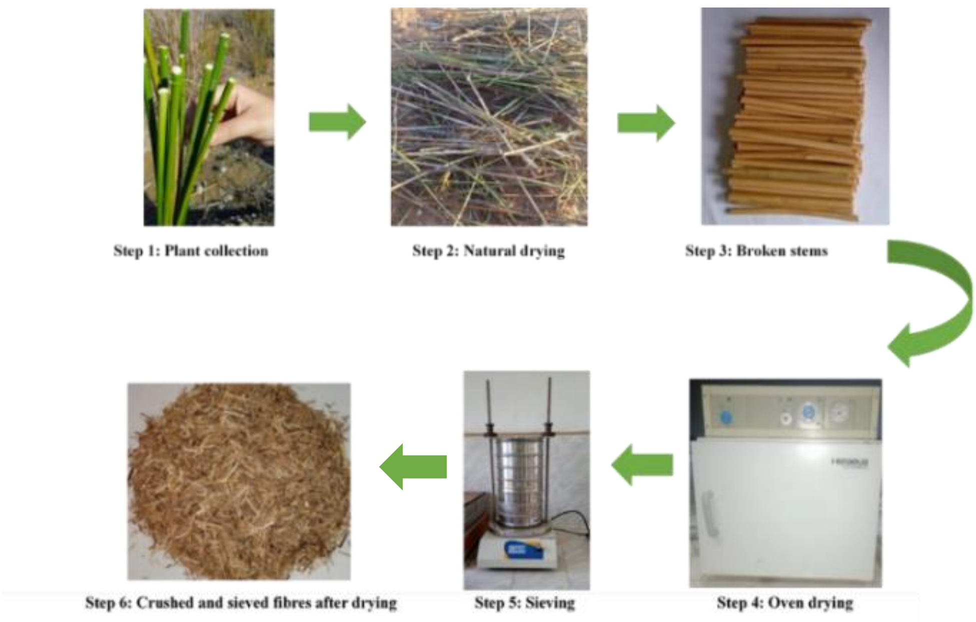


Figure 6. Steps followed to obtain crushed and sieved fibres

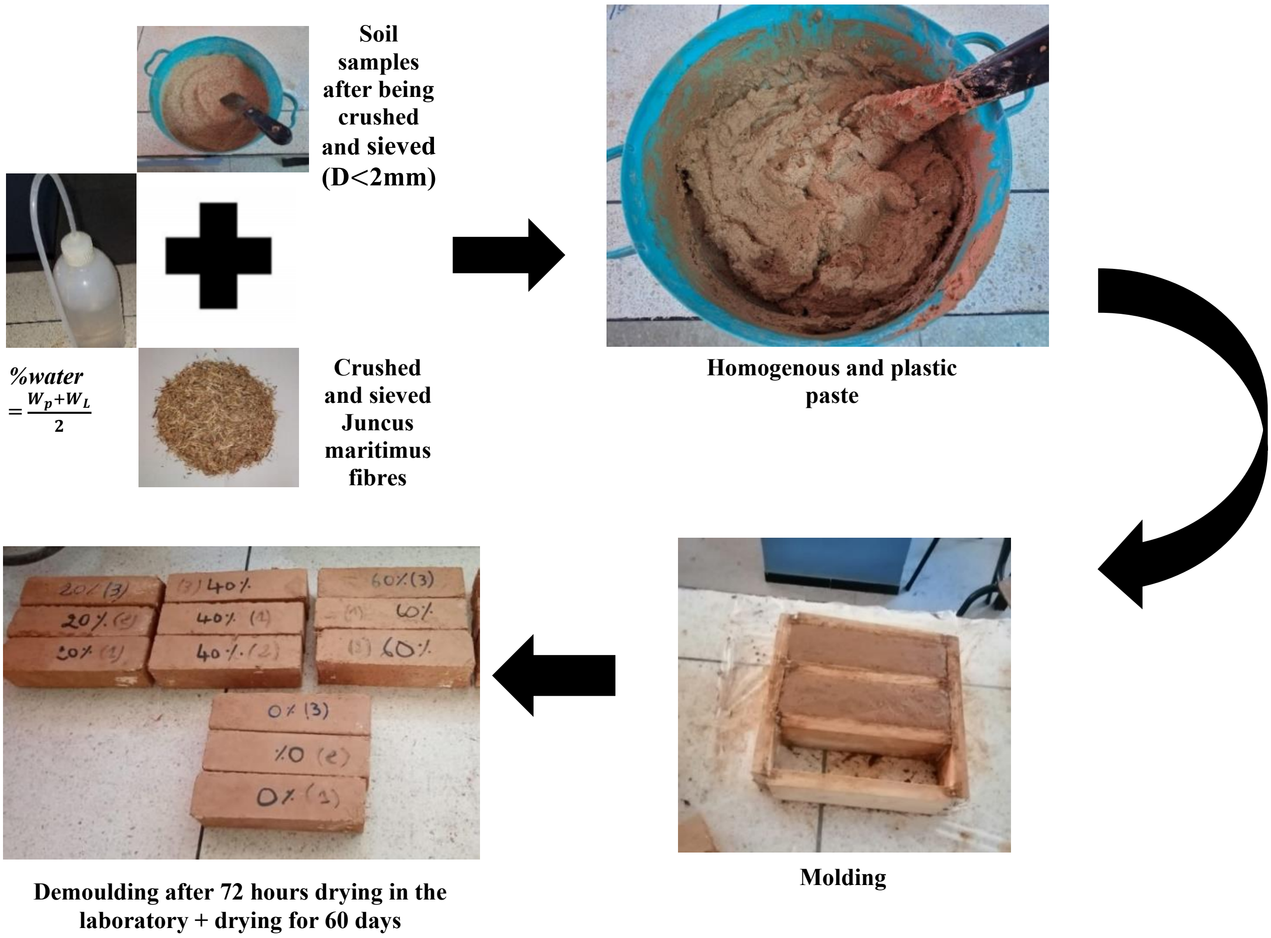


Figure 7. Adobe production

Table 6. Different formulations used

Samples Mix	Percentage by Volume of Soil (%)	Percentage by Volume of Fibre (%)	Water (g)
JMA0	100	0	Eq. (3)
JMA20		20	
JMA40		40	
JMA60		60	

Three samples were prepared for each percentage of fibre used in the thermal and mechanical tests. Before carrying out the thermophysical and mechanical tests on the samples, they were first dried in an oven at a temperature of 50°C until they had a constant mass. The main stages in the manufacture of adobe are shown in Figure 7.

3.2 Thermophysical and mechanical characterisation of adobes

The apparent density of the composites is determined by the quotient of the mass of the samples, taken after oven drying at 50°C ± 5°C to a constant mass, divided by the volume, which has been determined from the actual dimensions of each prototype.

The Controls Automax5 machine, utilizing Microdata Autodriver software, was employed to measure the flexural and compressive strengths of the produced specimens. In compliance with the NF EN 196-1 standard [48], 4×4×16 cm^3 prisms were used for the three-point bending test, and 4×4×8 cm^3 prisms, obtained after the bending test, were subsequently used for the compressive strength test (Figure 8). The tests are effected on three specimens for each composition.

Figure 8. Mechanical test on (4×4×16 cm^3) prisms of adobe bricks

The TPS 1500 hot disc method was used to determine the thermal properties of the specimens (10×10×2.5 cm^3) in accordance with the study [49]. The principle of the experiment is based essentially on a probe in the form of a disc consisting of a double spiral nickel electrical resistor 10 µm thick, protected by a rigid plastic material. This disc is linked to a system for recording the rise in resistance as a function of time R(t), creating a rise in temperature through electrical heating. Before starting the test, an essential step is to prepare the samples to be characterised, ensuring that the surfaces are flat and uniform. To ensure this uniformity, the faces of the samples were carefully polished with fine abrasive paper to remove any irregularities. This preparation avoids air gaps between the sample and the sensor, ensuring optimum thermal contact. The probe is then placed in the middle of two samples, in accordance with the principle of the semi-infinite medium (Figure 9).

The durability of the samples produced was studied by determining the capillary water absorption coefficient in accordance with standard [50]. Prismatic half-test specimens measuring 4×4×8 cm^3 were used to carry out this test according to the normative specifications, which are obtained by breaking the 4×4×16 cm^3 prisms in two, which have an age of 60 days under laboratory conditions.

Figure 9. Thermal test on (10×10×2,5 cm^3) prisms of adobe bricks

4. RESULTS AND DISCUSSION

4.1 Apparent density

Figure 10 shows the variations in the mean values of the apparent density of composite materials as a function of different Juncus maritimus fibre contents, and their errors are determined by the difference between the maximum and average value of each composition. The value of the dry apparent density of adobe without additive found is 1946,354 kg/m^3, this value is included in the range of 1540 kg/m^3 to 1950 kg/m^3 of the apparent density of adobe as established in the literature [51]. From this figure, there was a significant decrease in the apparent density of the 60% volume content of the additive of Juncus maritimus fibres (1402,832 kg/m^3), which corresponds to a reduction rate of 27.92% compared to the reference material without additive (1946,354 kg/m^3). This reduction is due to the low density of Juncus maritimus fibres, which is low compared to the density of the soil composition. On the other hand, this reduction was due to the porous nature of Juncus maritimus fibres and their water absorption capacity (250%), which leads to the creation of pores in the adobes after drying. The same trends in apparent density have been observed in previous and recent research studies [9, 52, 53].

The variation in the apparent density of the adobes incorporated by the plant fibres differs from one study to another. It depends essentially on the quantity of water used for the composites compared with the reference sample; the greater the difference in water, the greater the porosity created by the coating of the fibres in the composite after drying, and consequently a large reduction in the apparent density of the samples. In this sense, El-Yahyaoui et al. [54] incorporated clay bricks with different mass percentages (0%, 1%, 5%, 7%, 10%, and 12%) of saw palmetto fibres, and using 25% water for all composites, they obtained a reduction in apparent density of 20% for the sample reinforced with 12% fibres compared with the reference sample. Omrani et al. [25] developed a material consisting of 60% clay and 40% sand and replaced the sand with volume percentages of (0%, 5%, 10%, and 20%) Juncus acutus fibres. They used 90% water for the 20% volume percentage and 30% water for the sample without reinforcement, resulting in a 42% decrease in the apparent density of the composite materials for the sample containing 20% fibres compared with the reference sample. In this context, new research studying the thermal and mechanical behaviour of adobes incorporated with plant fibres has used a fixed quantity of water for all compositions, to ensure consistent workability across the composites. This value for the quantity of water is calculated using the following equation: W (%) = $(W_L+W_P)/2$, where WP and WL are the plasticity and liquidity limits respectively.

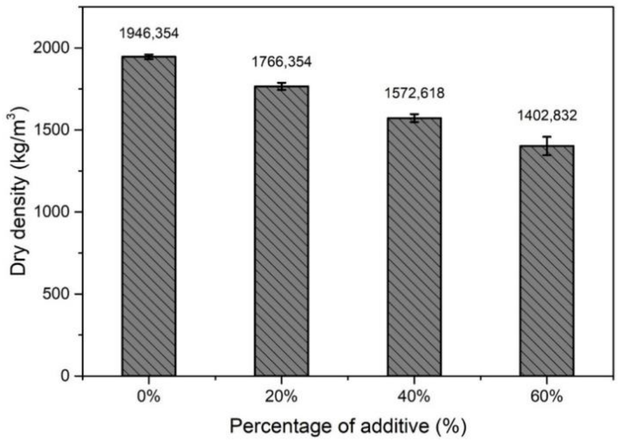


Figure 10. Bulk density of composites for different volume percentages of additive

4.2 Thermal properties

Figure 11 shows the dry thermal conductivity of the composites as a function of the different volume contents of additives. A decrease in thermal conductivity can be observed when fibre additives levels are increased, varying from 0,97 W/m. K for the sample without reinforcement to 0,494 W/m. K for the composite with a 60% volume additive content, which corresponds to a thermal insulation gain of 49.07%. This reduction in thermal conductivity is mainly due to the low conductivity of Juncus maritimus fibres, as found in the present study (0,0916W/m. K) (Table 5) and in that carried out by Saghrouni et al. [30] which obtained a value of 0,09 W/m. K. Scientific research shows that fibres have insulating properties [55, 56]. This reduction is also due to the increase in pores in the clay matrix created by the Juncus maritimus fibres, which are filled mainly by air, which is considered an insulating material, as it has a conductivity of 0,026 W/m. K, it is recognised that porous materials promote thermal insulation in buildings [23, 57]. The same finding was reported by El-Yahyaoui et al. [54] in their study on earth blocks containing Doum fibres. However, our formulations achieved a maximum reduction rate of 60% by volume (49.07%), which exceeds the 28.75% reduction reported by the author for earth bricks containing 7% by weight of Doum fibres. Similar results were observed by Mellaikhafi et al. [26], who obtained a 48% reduction in thermal conductivity by adding 6% by mass of pinnate leaf fibres to clay bricks. It is evident from these results that a less conductive composite material can be produced from materials with low conductivity. Previous studies show that the type of addition and the properties of the aggregates have a considerable impact on the variation in thermal conductivity [58, 59]. In short, the addition of Juncus maritimus fibres reduces the thermal conductivity of adobes, enabling it to better regulate temperature variations. In fact, lower thermal conductivity means greater thermal resistance. Figure 12 shows the relationship between the thermal conductivity of different composites and their dry density.

When density decreases, thermal conductivity decreases, and this variation is identical to that found in the literature [6, 9, 25, 26]. Their work has shown that the variation in the thermal performance of composites differs essentially depending on the proportions of the aggregates used, and the type of addition of these aggregates, as well as the thermal properties of the aggregates used, the density and porosity, and the quantity of water used [55, 56].

The evolution of diffusivity as a function of the percentage of Juncus maritimus fibre additive added to the adobe is shown in Figure 11. Thermal diffusivity characterises the rate at which heat is transmitted by conduction through the body. From Figure 13, we can see that the thermal diffusivity of the adobes decreases as the additive content increases, which corresponds to a reduction rate of 39.26% for a percentage of 60% of additive compared to the reference sample. This reduction is due to the low diffusivity of Juncus maritimus fibres (Table 5) compared to that of the soil, so the addition of these fibres allows the heat front to take time to penetrate the thickness of the composite.

Thermal effusivity is the rate at which the surface temperature of a material heats up (feels cold or hot to the touch). Specific heat capacity Cp of construction materials is essential for assessing the thermal comfort of buildings.

$$C_p = \frac{\lambda}{a.\rho} \quad (4)$$

$$E = \sqrt{\lambda \rho C_p} \quad (5)$$

The results show that the addition of 60% Juncus maritimus fibres resulted in an estimated 16.34% improvement in thermal storage capacity compared with clay bricks without additives, corresponding to a thermal capacity value of 693.881 J/kg.K, taking into account that the thermal capacity of clay bricks without additives equals 596.419 J/kg.K. Furthermore, Charai et al. [7], Laborel-Préneron et al. [60] and Serebe et al. [61] also observed an increase in specific heat capacity. These results confirm the effectiveness of Juncus maritimus fibres in the manufacture of lightweight adobes, providing good thermal insulation and increased thermal inertia. Figure 14 shows that thermal effusivity decreases as the quantity of Juncus maritimus fibres in the clay matrix increases, with a rate of decrease of 34.65%. As several previous studies have shown, thermal diffusivity, thermal conductivity and effusivity evolve in the same way, making this result predictable [7, 9, 61, 62]. However, the thermal inertia linked to the adsorption of the material is reduced when the thermal effusivity decreases. Thermal effusivity indicates a material's capacity to absorb heat. A material with a high thermal effusivity can absorb a large amount of heat without its surface temperature rising significantly. However, materials that have low thermal effusivity tend to heat up rapidly as the environmental temperature increases. In summary, reinforcing adobes with Juncus maritimus fibres improves thermal insulation and helps to regulate internal temperatures by reducing and retarding heat transfer through the adobes. Thus limiting the risk of overheating in indoor spaces during periods of high temperatures. Nevertheless, a reduction in thermal effusivity could reduce the effectiveness of adobes in absorbing and releasing heat. Consequently, adobes with a high fibre content may not be the best choice for interior cladding in hot climates.

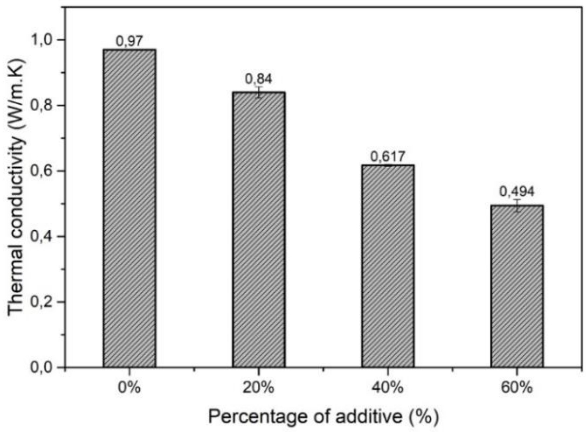


Figure 11. Thermal conductivity of dry composites at different volume contents of fibre additives

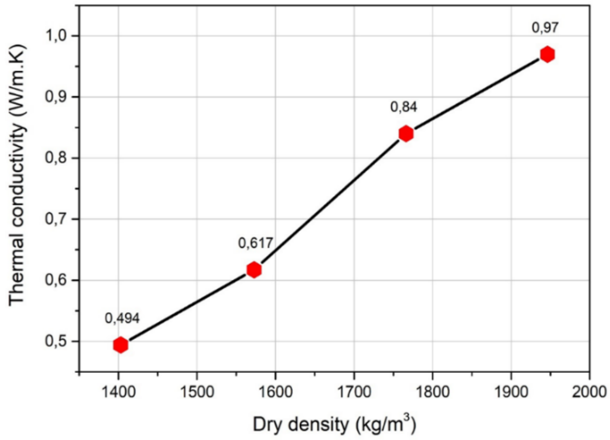


Figure 12. Variation of thermal conductivity with dry density across different composites

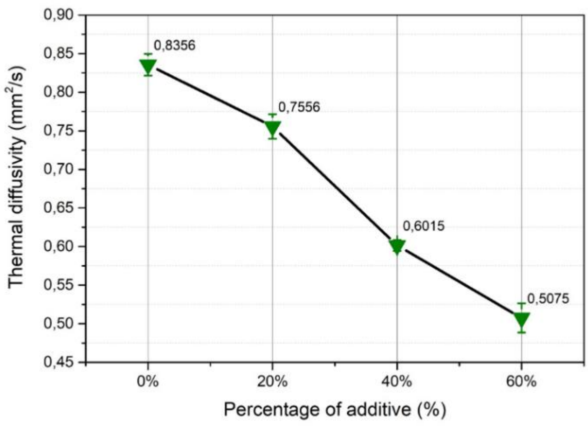


Figure 13. Variation in thermal diffusivity as a function of the percentage of additives

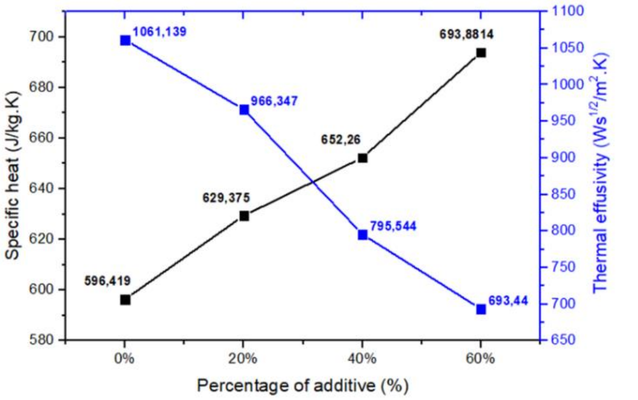


Figure 14. Thermal effusivity and heat capacity of adobes

4.3 Mechanical properties

The results of the flexural and compressive test are shown in Figure 15. A decrease in flexural and compressive strength was observed when Juncus maritimus fibres were increased in the clay matrix with a reduction rate of 63.46% and 73.86% respectively. These results are in concordance with those of other authors who have studied the effect of adding Pennisetum setaceum and date palm fibers on the thermophysical and mechanical properties of clay bricks [7, 9]. According to the literature [25, 63], increasing the percentage of fibres added to adobe increases the porosity of the samples, which has a negative impact on compressive and flexural strength. These depend mainly on the proportions of fibres used in the clay matrix and, consequently, on the creation of air voids within the matrix. The addition of fibres is the primary factor contributing to the reduction in compressive and flexural strength, and the relationship between the presence of fibres in the clay matrix and the reduction in compressive and flexural strength can be explained by the adhesion defects of the faces of the fibres in contact with the clay matrix. This is confirmed by the smooth appearance of the outer surfaces of the fibres, as illustrated in Figure 5(c) of scanning electron microscope observations showing the outer surface of Juncus maritimus fibres. Also, the clay incorporated by the fibres, through adopting a random mixing method, provides a less homogeneous distribution of the matrix components, and the sample under compressive and flexural loads results in cracks in the areas adjacent to the fibres, therefore the failure of these elements at a lower load than the load applied to the sample without fibres. These findings are consistent with the results reported by Saghrouni et al. [31] who used Juncus maritimus fibres as a replacement for cement and sand mixes with percentages of 0% to 10% by mass and noted that the compressive and flexural strength of the composites decreases as the fibre content of the cement composite increases. Similarly, Khoudja et al. [9] obtained a drop in compressive and flexural strength of 80% of raw earth bricks for a content of 10% by mass of date palm waste aggregates compared to the sample without reinforcement. Typha fibres were treated by Limami et al. [64], and they found that the compressive strength of mud bricks decreases as the quantity of fibres in the matrix increases, with a reduction rate of 40.42% for a typha fibre content of 20% by mass compared with the reference sample.

However, there are also studies which show that the mechanical strengths of construction materials can be improved by the incorporation of natural fibres, when these are used at lower percentages or in an optimised manner. For example, the study by Serebe et al. [61] showed that kenaf fibres at percentages ranging from 0% to 0.8%, and fibre lengths from 2 cm to 3 cm, led to an increase in mechanical strength at a fibre percentage of 0.6% and a fibre length of 3 cm, compared with control samples. Other studies have also shown that the application of chemical treatments to natural fibres improves the cohesion between the fibres and the cement matrix, thereby increasing the strength of the material [31].

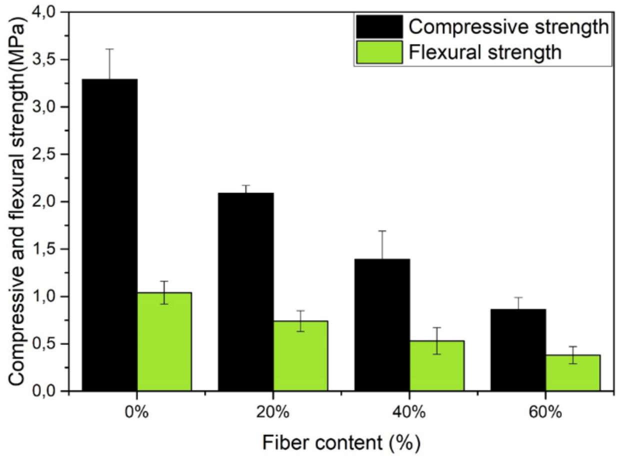


Figure 15. Compressive and flexural strength of different composites at 60 days

4.4 Microstructure of composites

Figure 16 shows the scanning electron microscopy analysis of the fracture surface of the adobes after the bending test in order to highlight the impact of the incorporation of Juncus maritimus fibres on the thermophysical and mechanical behaviour of the adobes. The secondary electron images of the adobe without additive (a) and the composite with 40% Juncus maritimus fibres (b,c) are presented in Figure 16. The SEM analysis carried out on the unreinforced adobe sample shows a homogeneous structure and the presence of the various aggregates making up the soil. This clay structure ensures that the material is optimally compacted. Figures 16(b,c) show that the matrix is heterogeneous and that the fibres added to the clay matrix are not completely coated by the clay paste. Air pores are visible between the fibres and the clay paste, which can be explained by the hydrophilic nature of the fibres and their capacity to absorb water (250%). This leads to swelling of the fibres during sample production and, consequently, to their detachment from the clay matrix once the composites have dried. Porosity is also influenced by the quantity of water used when mixing the clay with varying percentages of additives, the greater this quantity the greater the pores in the matrix. These observations explain the results obtained for mechanical properties (Figure 15). The increase in pores in the adobes with the addition of the fibres, as observed by SEM, also justifies the lightness of the adobes obtained and the improvement in thermal properties. This behaviour of composites incorporated with plant fibres has been observed by several researchers [9, 25, 32, 31].

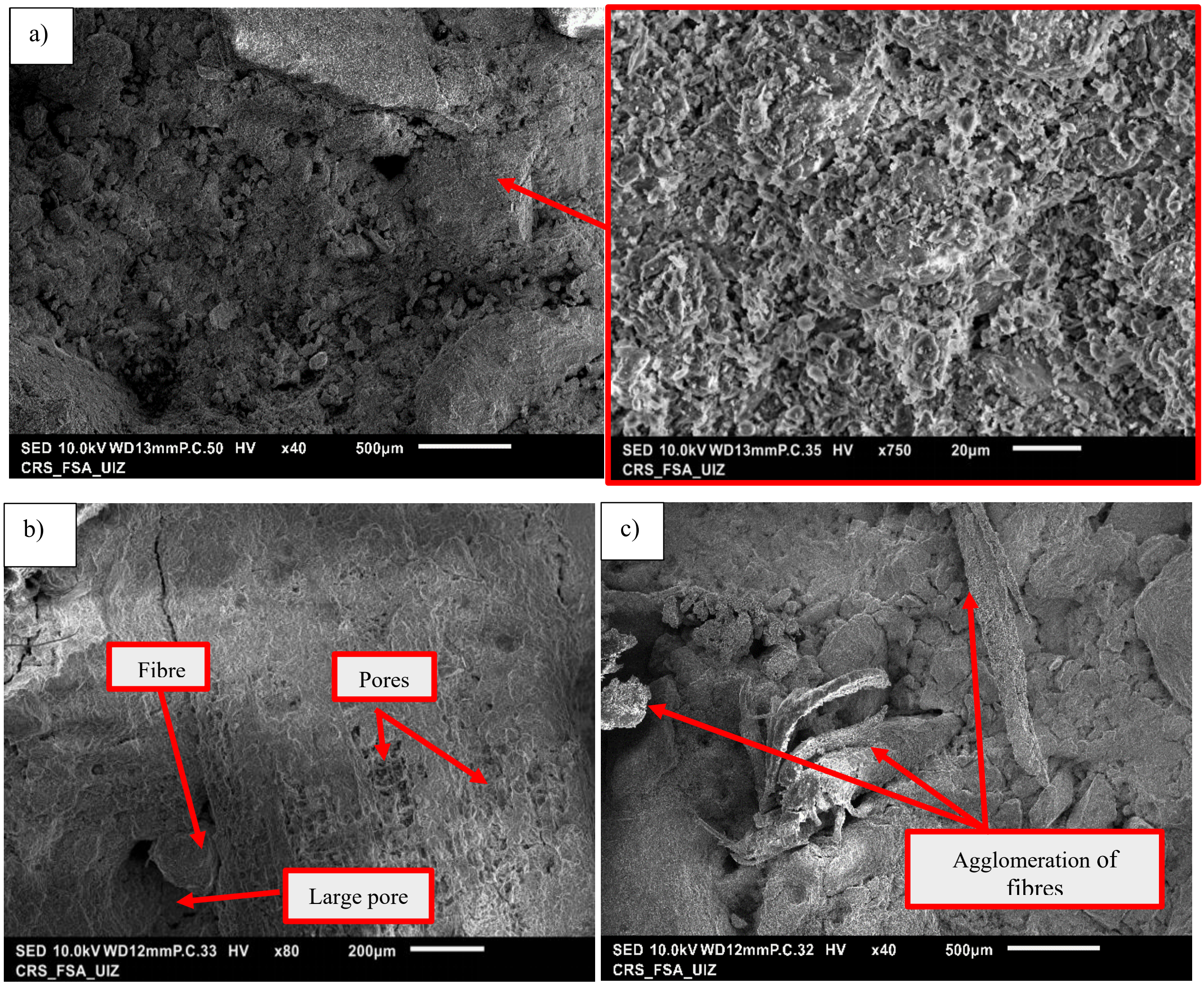


Figure 16. SEM secondary electron images of the fracture faces a): reference sample, b,c): composite material with 40% juncus maritimus fibres

4.5 Absorption of water by capillary action

The study of the water behaviour of composites reinforced with plant fibres is necessary if they are to be acceptable in building construction since fibres have a tendency to absorb water [9, 65, 66] and their effects on the absorption of water by capillary action in composite materials have been little studied. According to Figure 17, the capillary absorption coefficient is reduced with increasing Juncus maritimus fibre content, registering a value of 2.15 $Kg/m^2.min^{0.5}$ for the reference sample and a reduction rate of 37.2% for the composite incorporated with a fibre content of 60% (1.35 $Kg/m^2.min^{0.5}$). The presence of Juncus maritimus fibres limits the infiltration of water into the clay matrix. These results are due to the congestion of Juncus maritimus fibres on the clay matrix when the quantity of fibres increases and, therefore, a discontinuity in the flow of water in the adobe. In addition, this reduction in the capillarity coefficient of adobes with the addition of fibres may also be due to the large amount of cellulose contained in Juncus maritimus fibres, cellulose is a biopolymer that can improve the water resistance of raw earth. This new additive of Juncus maritimus fibres gives adobes the ability to reduce water absorption by capillary, which makes it interesting for building materials with regard to capillary rise in the part in contact with the ground (pathology of earthen constructions due to humidity). This finding aligns with the results reported by Ouedraogo et al. [6], who noted a decrease in water absorption from a content of 0.4% to 1% by mass of fanio straw fibres in the adobe. Similarly, Babé et al. [10] found a lower value for the coefficient of water absorption by capillarity for a millet fibre proportion of 2% by mass. More recently, Charai et al [7] concluded after testing the water absorption of adobes incorporated by Pennisetum setaceum fibres that the latter increased the resistance of adobes to water capillarity.

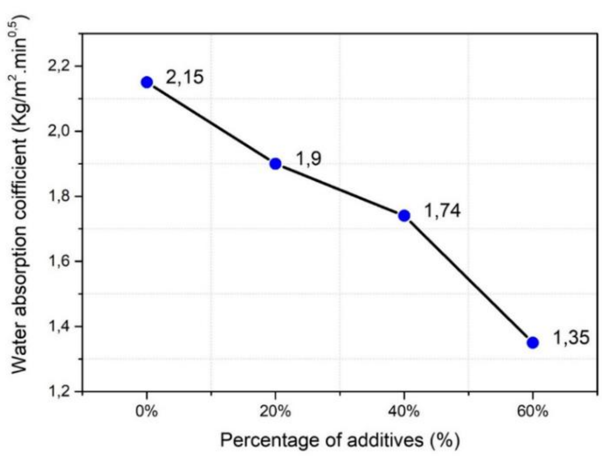


Figure 17. Evolution of capillary water absorption in composites

5. CONCLUSION

This study is mainly based on the characterisation of Juncus maritimus fibres and their use as an additive in the clay matrix in order to study their effect on the thermophysical, mechanical and durability properties of adobes manufactured with clay from Tafraout in percentages of 0%, 20%, 40% and 60% by volume. The conclusions of the results obtained are as follows:

- The dry density of the adobes decreases as the fibre content increases. It is reduced to 27.92% when 60% of the fibres are added. This behaviour can be explained by the low density of the fibres compared to that of the soil, and to their porous structures.
- Thermal properties such as thermal conductivity, thermal diffusivity and effusivity decreased with increasing additives. By adding 60% of Juncus maritimus fibres, thermal insulation performance improved by around 49,07% for thermal conductivity, 39,26% for thermal diffusivity and 34.65% for thermal effusivity. In addition, the reinforcement of adobes by fibres increases their specific heat. As a result, the incorporation of Juncus maritimus fibres improves thermal insulation and promotes better regulation of indoor temperature. This helps to limit overheating of interior spaces during hot periods.
- The flexural and compressive strengths of the adobes were affected by the addition of Juncus maritimus fibres. These two parameters were respectively reduced by 63.46% and 73.86% for 60% of the fibres, which are acceptable values for the construction of load-bearing walls, as permitted by certain standards.
- Secondary electron images of the fractured faces of the adobes show the existence of pores that increase with increasing the fibre ratio. they are due to the high capacity of the fibres to absorb water, which contributes to the creation of pores after drying, and to the smooth faces of the fibres, which cause poor adhesion with the clay paste.
- Juncus maritimus fibres help to minimise capillarity coefficients due to their high cellulose content, which can improve the water resistance of adobes, and to the congestion of the fibres, which acts as a barrier against rising capillary water. Adding 60% of the fibres reduces this coefficient by 37.2% compared to clay alone.

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