Physical and hygroscopic characterization of fibers extracted from the Baobab trunk for their use as reinforcement in a building material

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Abstract - Vegetable fibrous material is, today, increasingly used as a reinforcing element in structural or insulating composite materials. This use requires, first of all, control of the physical, hygroscopic and even thermal properties of vegetal fibers. In this context, the work presented focused on the experimental characterization of long fibers extracted from the baobab tree trunk (Adansonia Digitata L.). This study consisted in determining the density of the raw fibers and those having undergone various treatments as well as measuring their water absorption rates and moisture content.

The obtained results have shown that the raw fibers have high water absorption and moisture content, in the order of 265.25% and 7.5%, respectively and the carried out treatments lead to the reduction of these hygroscopic properties. In addition, the measured densities are low.

These results allow us to consider the use of these fibers in the manufacture of lightweight concretes.

Keywords: Fibers, density, water absorption, moisture content.

I. Introduction

In some countries, such as Senegal, high population growth leads to high and increasing energy consumption, especially in the summer period in services and households.

The building sector is one of the most energy-intensive sectors thanks to the need for thermal comfort using air conditioning units.

The climatic environment of a building, being strongly linked to the properties of building materials, it is necessary to develop new composite materials called eco-materials or bio-sourced materials that can be directly used in construction or for the thermal insulation of buildings. This would significantly reduce energy consumption in the building sector.

These eco-materials are mainly manufactured from biodegradable renewable resources, preferably of vegetable origin. This vegetable resource, due to its availability and the good quality of its physical, thermal, hygroscopic and acoustic properties, is commonly used in the manufacture of eco-concretes for the construction of comfortable, low-energy consumers and biodegradable homes.

In this sense, we propose, within the framework of this paper, an experimental characterization of the physical and hygroscopic properties of vegetal fibers extracted from the trunk of Baobab tree, scientifically called "**Adansonia Digitata. L**" **(Fig 1)**.

The valorization of vegetable resources for the manufacture of materials used in the building construction sector has prompted many scientific researchers to focus on the physical characterization of bio-sourced composite reinforcement materials, extracted from plants or herbs in the form of fibers, aggregates or leaflets.

Manohar et al. [1] studied the physical properties of fibrous material extracted from coconuts**, date palms** and **sugar cane** stalks**.** Their study focused on density determination.

The results of measuring the average density of these three types of fibers are 686 kg/m3 for sugarcane, 755kg/m^3 for coconut and 797kg/m^3 for date palm.

These results allowed the authors to conclude that the three types of fibers studied have low densities compared to those found in the literature.

As well, **Harbaoui et al. [2]** characterized vegetal aggregates from the **esparto plant** (Stippa Tenacissima)**.** The authors focused their study on the determination of the physical properties of aggregates.

The obtained results showed that Alfa aggregates have a low water absorption coefficient of around 56% and the apparent and absolute densities are 99.4 kg/m^3 and 1309.5 kg/m^3 respectively, with a porosity of around 92% of the aggregates.

They have concluded that these Alfa's aggregates can be included in the range of alternative materials to conventional fibers for the manufacture of ecological concretes.

In his PhD thesis, **Richard Ntenga [3]** carried out the physical characterization of two types of plant fibers: fibers from the **Sisal** plant and fibers from the aerial roots of **the *Rhectohyllum camerunese (R.C.)*** plant. In this work, the author measured the density and porosity of the fibers.

The results of this measurement show that the densities of Sisal and Rhectohyllum camerunese *(*R.C.) raw fibers are 1352 kg/m^3 and 947 kg/m^3 respectively. The porosity of C.R. fibers is around 28%.

Houda Saad [4] worked on the determination of the physical and hygroscopic properties of three types of vegetal fibers: stem fibers of **Alfa grass**, fibers of **Rush's grass** and **date palm leaflets**.

The density measurements carried out for each type of fibers are such that of the Rush stem is the least dense with a density of 454 kg/m^3 followed by palm leaflets with a density of 710 kg/m3 and the Alfa's stem with a density of 890 kg/m^3.

The moisture content of these materials is 10.22% for Rush's fibers, 8.33% for palm leaflet fibers and 7.28% for Alfa's fibers.

Aizi Djamel Eddine and Kaid Harche Meriem [5] studied the mechanical and physical behaviour of fibers extracted from the stem of **the Ratama Monosperma L. plant**.

In order to do this, the authors highlighted the different methods of extracting the fibers from the stem, among which soda solution one with a concentration of 14% by mass, which gave the more flexible fibers.

The results of their measurements showed that these fibers have a Young's modulus of 13.3 GPa, an absolute density of 1.3 g/cm^3 and a low water absorption coefficient of 53% compared to that of hemp, Jute or sisal fibers.
Alleged et al. [6] were interested in measuring the dimensions and density of **raw Posidonia fibers**. (posidonia oceanica)
Microscopic observations allowed the authors to show that these fibers are short and have a thickness of 32 to 106 µm, a width of 165 to 214 µm and a length of 2450 to 11585 µm. In addition, the measurement of the density of the raw fibers gave a value of 1.49 g/cm^3 and according to the authors, this density value is well within the range of light materials of vegetal origin.
Ouédraogo et al. [7] carried out the physical and hygroscopic characterization of the fibers extracted from the stem of the **kenaf plant of the** Hibiscus altissima variety.
Their measurement results show that the diameter and density of the fibers are around 0.14 mm and 1.05 g/cm^3 respectively. Moreover, the hygroscopic study has led to a value of 4.56% of the moisture content and 230% of the water absorption rate of the kenaf fibers.
According to the authors, kenaf fibers have lower moisture content than sisal fibers but the absorption rate is of the same order of magnitude as sisal and is higher than that of coconut and flax fibers. **[8]**
Djoudi et al. [9] focused their study of hygro-physical properties on a part of the date palm: the palm. The palm represents the long stem carrying the palm leaflets.
The characterization concerned two palm by-products: **the petiole (palm base)** and **the rachis (palm tip)**.
The authors determined the densities and moisture content of the wood and fibers of these two palm by-products. The measurement results gave values of 0.19 g/cm^3 and 0.66 g/cm^3 for the densities of petiole wood and spine wood respectively, while the same values are 0.61 g/cm^3 for the fibers extracted from petiole wood and 0.81 g/cm^3 for those from spine wood.
The measured moisture content is 70% for petiole wood and 50% for spine wood.
Based on the analysis of their results, the authors concluded that the hygrophysical properties of the two palm by-products depend on the area of extraction and also the properties of those materials are close to those of the fibers used in the reinforcement of composites.
To improve the physical, mechanical and hygroscopic properties of these vegetable materials, some researchers have carried out treatment (chemical or thermal or thermochemical) to modify the surface and internal structure of the fibers.
In this sense, **Sellami Asma [10]** was interested in the characterization of physical properties such as apparent and absolute densities, water absorption rate and moisture content from the raw fibers of the Diss grass and treated by boiling for 4 hours.
The measured apparent densities of the raw and boiled Diss fibers are 50.3 kg/m^3 and 37.5 kg/m^3 respectively. The absolute density is 1250 kg/m^3 for raw Diss fibers and 1400 kg/m^3 for boiled Diss fibers.
The water absorption rate of these fibers is around 100%. However, the moisture content, of the order of 4.3%, is considered relatively low compared to that of other types of vegetal fibers. The author concluded that these Diss fibers have physical characteristics very close to those of materials often used as reinforcements in bio-sourced composites.
The study of the effect of boiling heat treatment of **coconut** fibers and **Diss grass** fibers was carried out by **Asasutjanit et al. [11] and Merzoud et al [12],** respectively, for the development of fibers-cement composite materials. Both studies have shown that heat treatment reduces the water absorption rates and moisture content of the fibers and therefore leads to a strengthening of the mechanical properties of the composites.
Achour Abderraouf [13] worked on the morphological and hygroscopic properties of two types of fibers: fibers from **Diss grass** and those from the **Doum plant.**
The author has carried out his work on raw fibers and those treated with a soda solution (N_aOH) with a concentration of 5% by mass in a thermal bath at a temperature of about 160°C. The results of scanning electron microscope observations have shown that the treated Diss and Doum fibers have clean and rough areas, whereas in the raw state, their surfaces contain amorphous and viscous materials such as waxes, lignin, pectin and impurities.
The author also showed the effectiveness of the treatment by measuring the absorption rate of fibers immersed in water for 24 hours. It measures an absorption rate of 96% of treated Diss fibers and 160% of treated Doum fibers, while these values are 112% and 171% respectively for Diss and Doum raw fibers. The author concludes that chemical treatment combined with heat treatment better improves the hygroscopic properties of vegetal fibers.
Werchefani et al. [14] used three treatments to modify the chemical composition of Alfa grass fibers: salt water retting technique, hot water treatment and soda solution (NaOH) treatment followed by enzymatic treatment with a xylanase solution.
By studying the moisture content and the chemical composition of the treated fibers samples, the authors showed that the moisture content of the fibers and the quantities of lignin, hemicellulose and pectin decreased considerably and that it was the soda treatment followed by the enzyme treatment that led to these better results.
According to the authors, significant removal of non-cellulosic components such as lignin, hemicellulose and pectin would lead to a decrease in fibers moisture content.
At the end of this bibliographical review, we noted, to our knowledge, that no study of characterization of the Baobab trunk fibers was carried out, reason why, we proposed to study the physical and hygroscopic properties of these fibers in order to use them as reinforcements in a biodegradable composite material.

II. Materials and Methods

2-1- Baobab tree trunk fibers (Adansonia digitata L.).

The baobab is a large tree of the botanical family of malvaceae found in tropical Africa, especially in semi-humid and semi-arid regions.
Almost all parts of this tree are exploited either for food (fruit and leaves) or for traditional medicine (leaves, bark) and even for rope.
The base of the tree trunk is a part that is renewed annually and consists of a spongy mass and smooth bark. This part can be attacked, up to 2 m high and around its

entire circumference, by man, who extracts long fibers from it which are used to make ropes and weave mats.
The fibers were extracted by cutting the bark from the top of the trunk, which, when pulled longitudinally, detaches to the bottom of the trunk. The fibers are then mechanically separated from the bark, washed and then dried at room temperature for two weeks until the mass has stabilized. We cut them into lengths of about 1cm.

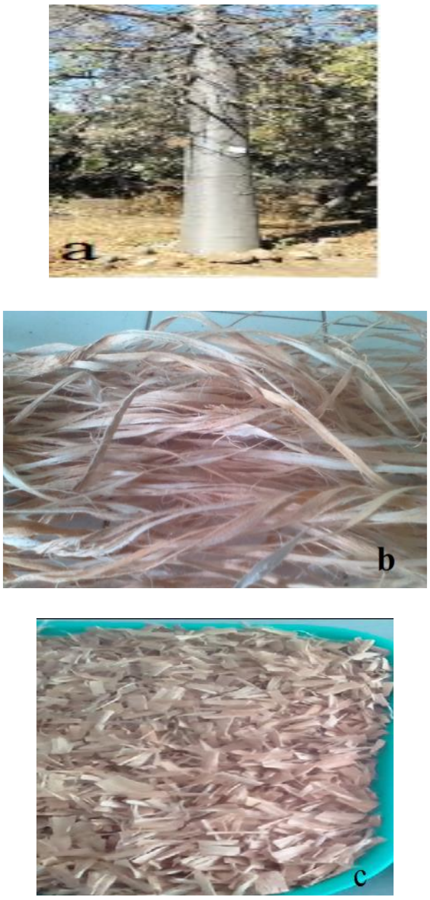

Fig 1: a) Baobab trunk b) fibers extracted from the trunk c) fibers cut out

2-2- Fibers treatment methods

Fibers surface modification was carried out using three treatment methods listed in the literature to evaluate the effects of each treatment on the physical properties of the fibrers.

2-2-1- **Heat treatment**

This treatment consists of boiling fibers in water for at least four hours. The fibers are then rinsed abundantly with distilled water to remove organic substances (waxes, peptides, impurities) and dried for 72 hours at room temperature. **[MER 12] [ASMA 10].**

2-2-2- Alkaline treatment

The fibers are dried before being immersed in a sodium hydroxide solution with a concentration of 5% by mass of caustic soda (NaOH) at room temperature for six hours (6 hours). Then they are washed thoroughly with distilled water and soaked again in a 1% sulfuric acid solution for 2 hours to remove the excess soda absorbed on their areas.
Finally, the fibers are washed with distilled water until cleaned water is obtained and then dried at room temperature for 72 hours.

2-2-3- Thermochemical treatment of fibers

Thermochemical treatment is the combination of heat treatment and sodium hydroxide solution treatment. The principle consists of boiling the fibers and then immersing them in a sodium hydroxide solution with a concentration of 5% by mass.
The fibers are then rinsed with a 1% concentration of sulfuric acid solution and washed clean with distilled water. **[10], [15]. Fig 2** shows aspects of the four types of fibers studied.

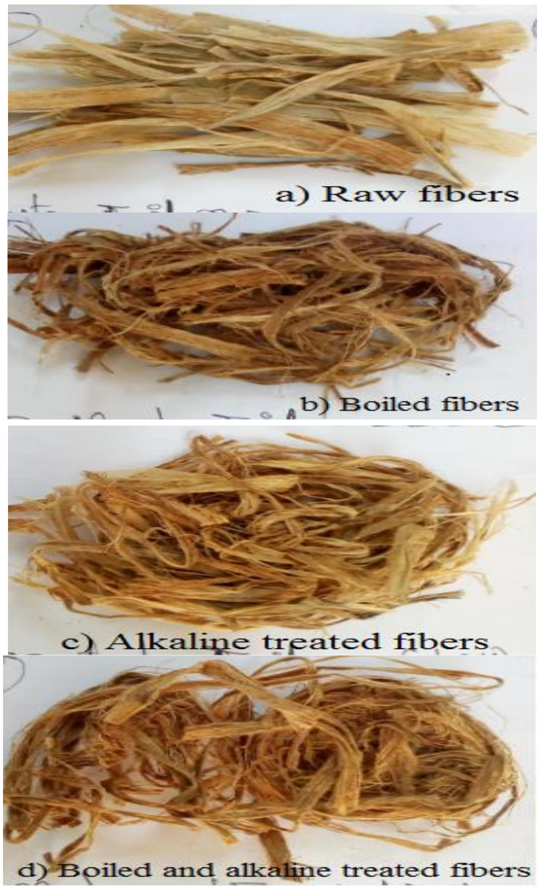

Fig 2: Appearance of fibers: **a)** Raw fibers, **b)** Boiled fibers **c)** Alkaline treated fibers **d)** Boiled and alkaline treated fibers

2-3- Measurement of the water absorption rate.

To carry out this measurement, the Baobab trunk fibers, cut into lengths of 1 cm, then dried and weighed, were introduced into a volume of distilled water at room temperature and the measurements are carried out at different time intervals (5mn, 10mn, 1h, 5h then 24h) before reaching their saturation in water.
Before each weighing, they are removed from the water and lightly wiped to remove excess water from the surface and then weighed using a Mettler Toledo scale, accurate to 0.01g. The operation is repeated until two successive very similar measurements are obtained ($\Delta m \leq 0{,}01$ g). Thus, the rate of water absorption is given by the formula:

$$\omega(\%) = \frac{m_h - m_0}{m_0} \times 100 \qquad (1)$$

m_h : the wet sample of the mass ; m_o: the dry sample of the mass

2-4- Measurement of the moisture content.

The water content, characterizing the amount of water present in the pores of the fibers in their natural state, is determined by steaming the fibers at constant temperature. The fibers were initially weighed with a 10^{-2} g precision scale and then placed in an oven at 100°C for 24 hours. The drying operation is stopped when the last two measurements are very close together ($\Delta m \leq 0{,}01$ g). The moisture content is calculated by the formula:

$$H(\%) = \frac{m_0 - m_s}{m_0} \times 100 \qquad (2)$$

m_s : The dry sample of the mass

2-5- **Measurement of apparent density**.

Apparent density is the ratio of the mass of a material to its apparent volume. The mass of the material is determined by weighing using a 10^{-2} g precision scale.
The volume of the fibrous material is determined by a graduated container of well-known volume and filled with fibers without compression.

The density is calculated by the expression:

$$\rho = \frac{m}{V} \qquad (3)$$

m: the sample mass ;

V: The sample volume

2-6- Absolute density measurement.

The absolute density is determined by the water pycnometer method.
The measurement principle consists of the following steps **[3], [15]**:

- Fill the pycnometer, beforehand tared, with distilled water and weigh the mass of water (m_o)
- Empty and introduce the batch of material into the pycnometer and weigh the mass of the batch (m_1).
- Complete the filling of the pycnometer with water and then weigh the mass of the whole **(m_2).**
- Determine the mass of water **($m_3 = m_2 - m_1$).**

Fig 3: Pycnometer method

Two tests were carried out for each type of Baobab trunk fibers and the formula giving the absolute density is as follows

$$\rho_a = \frac{m_1}{m_0 - m_3} \times \rho_{water} \qquad (4)$$

III. Results and discussion

3-1- The coefficient of water absorption.

The evolution of the fibers absorption rate as a function of immersion time is shown in **Fig 3**. We can see that the water absorption rate of untreated fibers increases rapidly as the immersion time increases and then becomes almost constant beyond 150 minutes.
The same behavior is observed for treated fibers.
Indeed, previous studies **[4]** attest that this high water absorption of cellulosic materials is relatively due to the hydrophilic character of vegetal fibers which contain, within their structures, capillary pores capable of retaining large quantities of water and hydroxyl groups that bind water molecules by hydrogen bonds.
The absorption rate is of major importance because it allows determining the quantity of water that can be absorbed, the maximum immersion time to reach saturation and to evaluate the optimal mixing radio (water/matrix) which is a very useful parameter in the manufacture of a composite material.
The measured absorption rates of the different types of fibers are 265.25%, 236.87%, 230.62% and 226.08% for raw fibers, boiled fibers, alkaline treated fibers and boiled and alkaline treated fibers respectively.

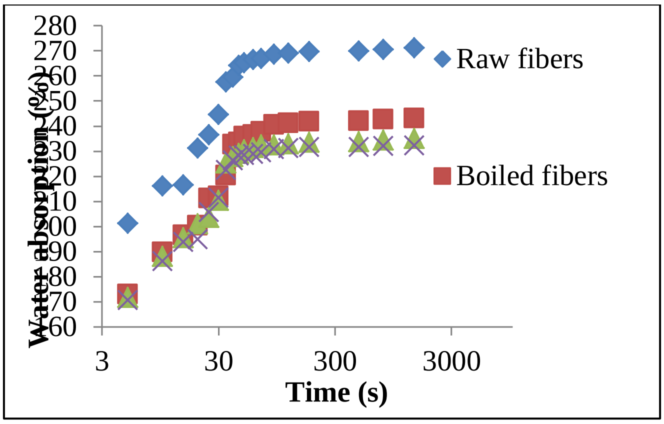

Fig 4: Water absorption rate of Baobab trunk fibers.

We note that all treatments result in a decrease in the water absorption rate of the fibers. However, the double treatment of the fibers leads to a greater decrease in the absorption rate compared to the heat treatment.

This result can be explained by the fact that heat treatment only contributes to the removal of waxes, oils and impurities on the fibers areas and therefore does not affect the internal structure of the fibers. **[12], [14].**

On the other hand, soda treatment and thermochemical treatment not only clean the surface of the fibers from these impurities, but also cause a degradation of non-cellulosic extractable matter such as waxes, lignin, hemicellulose and thus making the surface of the fibers rougher, and the internal structure less hydrophilic. **[13], [14]**

This extraction of these molecules, which strongly contribute to the retention of water in the fibers, leads to a decrease in the water absorption rate of fibers.

This measurement shows that the absorption coefficient of raw baobab fibers is higher than the coefficients of raw Diss fibers (100%) **[10],** raw Rush fibers (144%), raw date palm leaflets (168%) **[16]** and lower than that of hemp particles, which is 300% **[16].**

Moreover, treated baobab fibers with soda have a higher coefficient than treated Doum fibers (160%) **[13]** and lower than that of fibers from the Alfa plant treated with soda (460%). **[15]**

It can therefore be concluded that the fibers of the Baobab trunk have a relatively high water absorption capacity compared to most of the fibers already studied.

3-2- Fibers moisture content

The water contents of the different types of baobab fibers are shown in **figure 5**.

From fig 5, we have seen that the moisture content of untreated fibers decreases for every three treatments performed. The moisture content of untreated fibers is about 7.5% while the moisture content of boiled fibers, fibers treated with sodium hydroxide (N_aOH) solution and fibers boiled and then treated with soda decreased by 1.1%, 2% and 2.7% respectively.

This presence of water in the internal structure of the fibers is explained by the significant existence of hydroxyl groups, the main constituents of lignin, hemicelluloses and pectin.

In fact, the fibers areas contains a large number of hydroxide groups which, through Van Der Wall interactions (dipole-dipole bonds), bind water in the vapor state and then, through the process of vapor diffusion and capillary condensation, water is formed in the pores of the fibers **[18]**. The removal of these hydrophilic and water-soluble components by fibers treatment leads to a decrease in the capacity of the fibers to retain water.

This physical data allows us to know the maximum amount of water contained in the baobab trunk fiber under atmospheric conditions.

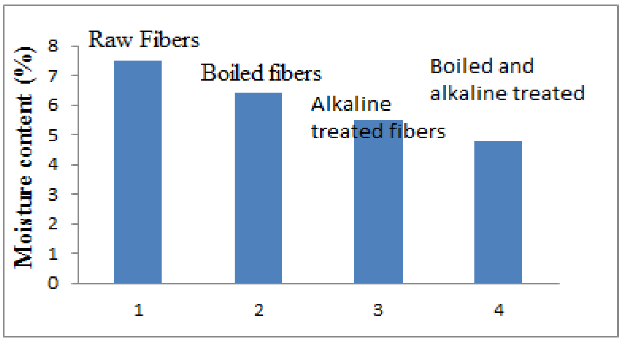

Fig 5: Moisture content of the fibers

The results of this study show that the moisture content of raw baobab fibers is, on the one hand, higher than that of Diss raw fibers, whose rate is **6.3% [10]** and Alfa raw fibers, whose rate is 7.28% **[4]** and, on the other hand, lower than that of Rush raw fibers, date palm leaflets **[4]** and Flax raw fibers **[17],** which are 10.22%, 8.33% and 7.6% respectively.

This study allowed us to evaluate the hygroscopic properties of baobab fibers and to find that all three treatments more or less improve the water absorption rate and moisture content of the fibers.

3-3- Density of the fibers.

Due to their porous structure, vegetal particles are generally low-density materials.

However, this property is strongly related to the distribution of pores in the vegetal particle.

Apparent density is the ratio of the mass of the sample to its apparent volume, while Absolute density is the ratio of the mass of the particle to its actual volume minus the pore volume.

In this study, apparent and absolute densities of raw and treated fibers were measured and the results are reported in **Table 1.**

From **Tables 1,** we note that the absolute densities of all fibers types are higher than apparent densities. This is justified by an overestimation of the apparent volume of the material due to the fact that the pore volumes and void spaces between the fibers are taken into account.

We also note an increase in the apparent and absolute densities of the fibers when they undergo various types of treatment, in particular those treated with a sodium hydroxide solution whose apparent and absolute density are relatively high compared to those of raw fibers.

Indeed, data from the bibliography **[19]** have shown that the majority components of cellulosic fibers such as cellulose, hemicellulose and lignin have densities of 1.63, 1.52 and 1.33 respectively in the stem of the Alfa plant, confirming that cellulose is the densest of these components. Therefore, the increase in the density of the treated fibers, also observed for Alfa fibers by **Dallel et al [15]**, is justified by the fact that the soda treatment eliminates good proportions of lignin, pectin and hemicellulose and thus leads to a majority presence of cellulose, which is the densest. This majority presence of cellulose in the treated fibers explains an increase in density

Table 1: Density of fibers**.**

Types of fibers	raw Fibers	Boiled fibers	Alkaline treated fibers	Boiled and alkaline treated
Apparent density (kg/m^3)	178.3	205.0	225.0	220.0
Absolute density (kg/m^3)	350.0	621.9	788.6	774.5

A simple comparison with other vegetable particles such as hemp and sunflower fibers **[18],** esparto fibers [**2**], shows that apparent density of baobab raw fibers is significantly higher than that of hemp **(**164,5 kg/m^3), sunflower fibers (20 kg/m^3), esparto fibers (99.4 kg/m^3), while it is lower than the apparent densities of kenaf fibers [7], palm wood fibers **[9]** and pineapple fibers **[22],** which are 1050 kg/m^3, 610 kg/m^3 and (210 kg/m^3) respectively.
Moreover, the result of measuring absolute density of baobab raw fibers is close to that of raw fibers of esparto grass (890 kg/m^3), rush grass (454 kg/m^3) and date palm leaflets (710 kg/m^3) **[4],** but it is much lower than that of kenaf fibers **[7]** and posidonia fibers **[6]** with densities of 1050 kg/m3 and 1490 kg/m^3 respectively.
However, the density measurement results for this study showed that treatment of the fibers with sodium hydroxide (N_aOH) solution contributes much more to the extraction of the non-cellulosic components and makes the fibers denser.
Results of physical characterization conducted on other types of fibers and reported in the literature are shown in Table 3

Table 3: Some data on the absolute densities from different treated fibers.

Type of treatment	Alkaline treated fiber	Alkaline treated fibers	treated thru 100°C (NaOH)	Boiled fibers
Materials	Baobab	Lin **[20]**	Alfa **[15]**	DISS **[21]**
Raw fibers density (kg/m^3)	350	1540	1430	890
Density of treated fibers (kg/m^3)	789	1620	1510	850

Nevertheless, there is a disparity in the density values of plant fibers which is related to the type and internal structure of these cellulosic materials.
At the end of this physical characterization, we can see that the raw fibers of the baobab trunk have physical and hygroscopic properties more or less high compared to those of other types of plant fibers studied.

IV. Conclusion

The objective of this work was to characterize new types of fibers extracted from the trunk of baobab (***Adansonia digitata. L***). The study was conducted on raw fibers and fibers that had undergone the three treatments described above.

The results of this experimental work showed that the water absorption coefficient of this vegetable matter is of the order of 265.25% for raw fibers. On the other hand, this coefficient decreased by 28.38%, 34.63%, and 39.17% respectively for heat treatment, alkaline treatment, and thermochemical treatment.

The apparent and absolute densities of the raw fibers are respectively equal to 178.3 kg /m^3 and 350 kg/m^3, with a porosity of 49%.
In addition, fibers treated with a soda solution of 5% concentration have higher apparent and absolute densities.

The analysis of these results allowed us to observe that all three treatments bring an improvement in the physical and hygroscopic properties of the fibers.
However, the alkaline treatment has a much greater influence on densities while the thermochemical treatment improves hygroscopic properties better.
These treatments therefore lead to a change in the chemical and morphological composition of the fibers surface. This could facilitate their incorporation into a mineral matrix.
It would also be important to conduct a characterization study of the properties of a composite based on a cement matrix reinforced by the fibers of the baobab trunk for their use in social housing.

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