



Original article

The effect of fiber morphology on the tensile strength of natural fibers

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ABSTRACT

In the present work the morphology of natural fibers was correlated with their mechanical properties via image analysis. Jute, sisal, curaua, coir and piassava fibers were tested under direct tension in a universal testing machine and the cross-sectional areas of the fibers were calculated using images obtained in a scanning electron microscopy. For the jute fiber the tests were performed for several gage lengths in order to investigate its influence on the tensile strength and to compute the machine compliance. For sisal, jute and curaua fibers the amount of fiber-cells, the size of the cell walls and the real area of the fibers were measured and their correlation with the tensile strength addressed. The curaua fiber presented the highest mechanical performance with tensile strength and Young's modulus of 543 MPa and 63.7 GPa, respectively. Weibull statistical analysis was used to quantify the variability of fiber strength. The sisal fibers presented the highest Weibull modulus (3.70), whereas the curaua presented the lowest one ($m = 2.2$), which means that the sisal had the lowest variability and curaua the highest.

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1. Introduction

The use of natural fibers as reinforcement in cementitious and polymeric matrices has been extensively researched over the past 20 years. Materials with high performance can be obtained through the addition of synthetic fibers, such as glass

and carbon. In cases where the aim is to obtain light weight products, natural fibers can be used as reinforcement with success. These fibers can also be used as thermal and acoustic insulators. There are many studies in the literature looking for new applications with natural fibers for the manufacture of materials in which the resistance is not the most important requirement [1].

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The vegetable fibers present several advantages compared to synthetic fibers. They are biodegradable, lightweight, renewable, have good mechanical properties and are abundant. Furthermore, they are not abrasive to the processing equipment, have neutral emission of CO₂ and are an important source of income for the population living in rural areas [2,3]. Compared to glass fibers, the production of natural fibers causes less environmental impacts. This is because the cultivation of natural fibers depends primarily on solar energy and needs small amount of energy from fossil fuels in the production and extraction processes [4].

There are some disadvantages in using natural fibers as reinforcement in composite materials, such as: quality and production efficiency, which depend on the natural conditions; heterogeneity of their properties which may be associated with the production, extraction and processing conditions of the fibers, and the hydrophilic behavior which leads to water absorption in the composite systems [5].

Several authors have investigated the tensile behavior of natural fibers. There are large discrepancies among values reported for tensile strength and Young's modulus in the literature. As natural fibers generally present variable and irregular cross-sections, their measurement can lead to huge errors in the computation of stress. The gage length, strain rate, gripping, resolution of load cell and actuator precision can also play an important role in the final results. Finally, the methodology for measuring the modulus of elasticity is of great importance as the compliance of the machine should be taken into account.

Defoirdt et al. [1] investigated the tensile strength of coir (white and brown), bamboo and jute fibers. The fibers were tested in a mini tensile testing machine at a displacement rate of 0.1 mm/min, 1 mm/min and 5 mm/min for jute, bamboo and coir, respectively. The tests were performed in different gage lengths in order to evaluate the influence of the length on the tensile strength. The cross-section area was calculated by determining the weight and length of each fiber from the average density obtained through gas pycnometry. The coir fibers presented low mechanical strength (177 MPa – white coir), low modulus of elasticity (3.44 GPa) and high deformation capacity (37.85%), in other words, large capacity of energy absorption. This has been explained due to the low cellulose content (32–53%) and high microfibrillar angle (30–49°). The jute fibers have cellulose content in the range of 61–71.5% and microfibrillar angle of 8°, which makes the fiber resistant (353 MPa) with a high modulus of elasticity (26.25 GPa) and low capacity of deformation (3.05%).

Tomczak et al. [6] correlated the mechanical properties of curaua fiber with diameter, length and strain rate. Morphological characterization was performed using scanning electron microscopy (SEM). Fibers with different diameters (26–64 μm) and length of 20 mm were tested under tensile load at a displacement rate of 5 mm/min. The fibers with diameter of 46 μm were tested at different lengths (from 5 to 25 mm) at a displacement rate of 5 mm/min. Moreover, fibers of the same diameter (46 μm) and same length (20 mm) were submitted to different displacement rates (from 5 to 50 mm/min). The authors observed that the tensile strength and elastic modulus decreased from 310 to 131 MPa and from 96.1 to 30.0 GPa, respectively, while the strain capacity remained

constant (4.57%) as the diameter increased. With increasing lengths, the tensile strength decreased from 223 to 173 MPa and also the strain decreased from 10.2 to 3.74%, and the modulus of elasticity increased from 26.6 to 52.9 GPa. When there was an increase in strain rate, the values of tensile strength increased from 178 to 217 MPa, but the modulus and strain remained unchanged (mean values of 48.7 GPa and 4.57%, respectively).

D'Almeida et al. [7] reported results for mechanical testing, chemical composition and morphological aspects of the piassava fiber. The machine compliance was taken into account for measuring the fiber's modulus of elasticity. Fifteen tests were performed for gage lengths ranging from 15 to 150 mm at a displacement rate of 1 mm/min. The morphology was observed by SEM. The piassava fiber showed low values of tensile strength (133 ± 13.5 MPa) and elastic modulus (2.9 ± 1.2 GPa) compared to the sisal and jute, but the mechanical properties of piassava are comparable to coir fiber (tensile strength between 106 and 270 MPa, and elastic modulus between 3 and 6 GPa).

Silva et al. [8,9] evaluated the mechanical behavior of sisal fibers. Tensile tests were performed for gage lengths ranging from 10 to 40 mm at a displacement rate of 0.1 mm/min. The true elastic modulus was computed by taking into account the machine compliance. The authors also analyzed the fracture mode of the fiber in terms of microstructure and defects. The strain-to-failure decreased from approximately 5.2–2.6% when the gage length was increased from 10 to 40 mm. The tensile strength, on the other hand, was found to be independent of the gage length. Average tensile strength and modulus of elasticity were reported as 400 MPa and 19 GPa, respectively. The Weibull modulus decreased from 4.6 to 3.0 when the gage length was increased from 10 to 40 mm, respectively.

The present work presents a systematic study of the tensile behavior of the sisal, jute, curaua, coir and piassava fibers. Since the fiber cross-section is not perfectly circular and exhibits some variability, the cross-sectional areas for each fiber were measured using a SEM and an image analysis system. The different morphologies presented by the several studied fibers were correlated with their tensile behavior. The discussion is based on the amount of fiber-cells, the size of cell walls and the real area of fibers. Finally, the variability of the fibers was quantified using Weibull statistics, and a relationship between fiber microstructure and strength is discussed.

2. Materials and experimental procedure

Five vegetable fibers were investigated: sisal, curaua, piassava, jute and coir. These fibers were obtained from certain regions of Brazil.

The jute fiber came from the Amazon region. It is extracted from the stem of the plant *Corchorus capsularis* by a combination of processes which comprises the following steps: cutting, retting, shredding, drying, packing and classification.

The sisal fibers were obtained from farms located in the city of Valente, in the state of Bahia. The fibers were extracted from the leaf of the plant *Agave sisalana* by a mechanical process called decortication. In this process, the leaves are crushed

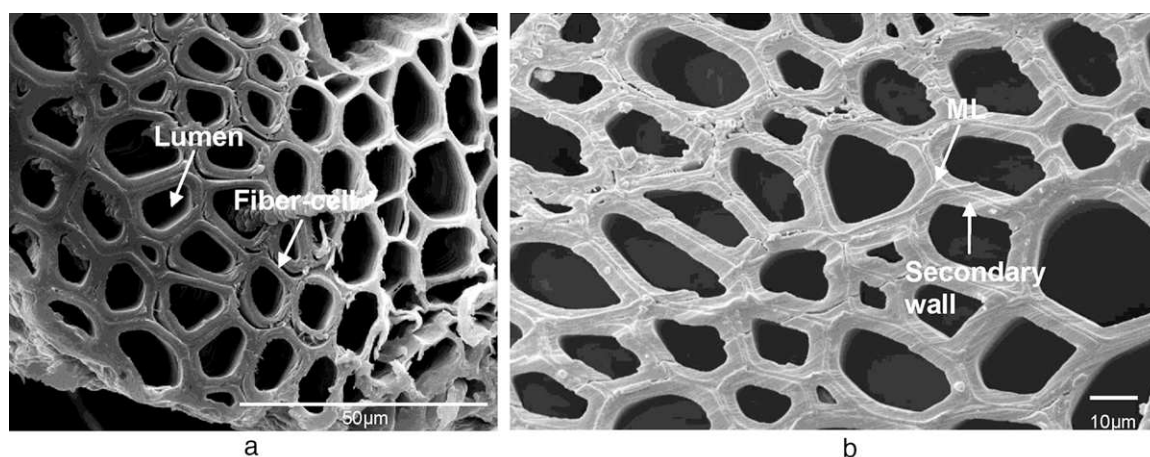


Fig. 1 – Sisal fiber microstructure showing (a) fiber-cells with lumen and middle lamellae and (b) detail of middle lamellae and cell-walls.

by a rotating wheel with blunt knives, where only the fibers prevail. Decorticated fibers were dried under the sun light. A suitable drying is essential since the quality of the fiber depends on the reduced moisture content. The dried fibers are combed by a machine and classified in several grades, largely on the basis on separation of leaves into groups of different sizes [8].

The curaua fibers were provided by the company Pematec, located in the city of Santarém, in the state of Pará. The fiber is produced in the Amazon region, and extracted from the leaf of the plant *Ananas erectifolius* by a process similar to the process used for sisal fiber.

The piassava fiber came from the region of Ilheus, in the state of Bahia. It was extracted from the stem of the leaves of the plant *Attalea funifera*, more specifically the petiole of the leaves. The stems are cut with knives, and then the fibers are washed, brushed and classified according to length. The fibers of the best commercial value are longer and more flexible, being exported to other countries, while the shorter and rigid fibers are used for the production of brooms.

The coir fibers were obtained from the city of Fortaleza, in the state of Ceará. The coir fiber is extracted from coir shell. The process of extracting the fiber is traditionally made by retting and decortication.

The vegetable fibers generally have a similar morphology. They are composed of many fiber-cells which are formed by primary, secondary and tertiary cell walls and lumens. Each fiber-cell is united by the middle lamellae (ML), which consists of lignin and hemicellulose, as shown in Fig. 1. The differences among the various fibers types are the number of fiber-cells, the cell walls size and the fiber cross-section area. Therefore each fiber presents different characteristics and mechanical behavior.

2.1. Tensile test

The fibers were tested as received. The preparation of the specimen was performed according to ASTM C1557 [10], as illustrated in Fig. 2. The tensile tests were performed in a universal testing machine Shimadzu, model AGX, as shown

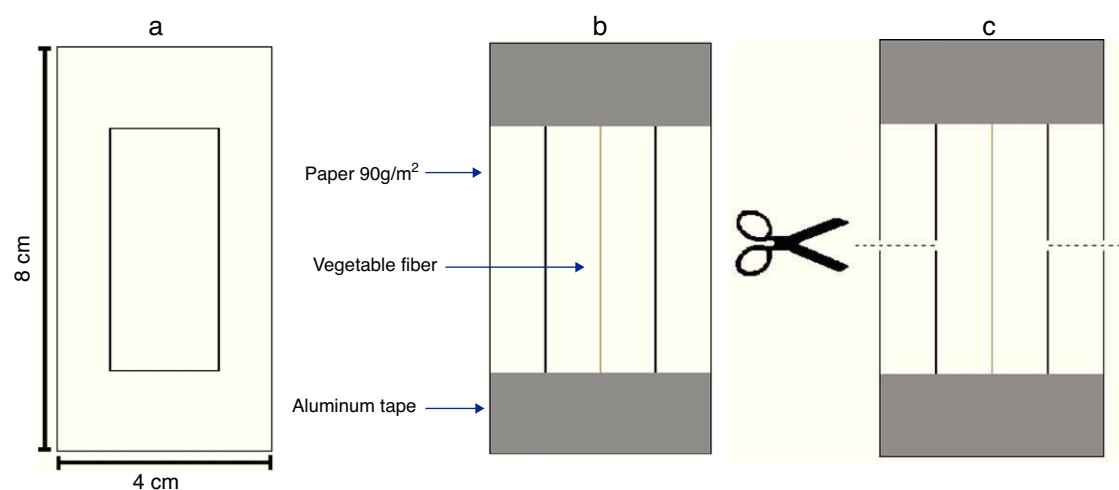


Fig. 2 – Preparation of specimen for the tensile test: (a) paper for fixing the fibers, (b) fibers fixed in the paper and (c) detail of the cutting of the paper before the test.

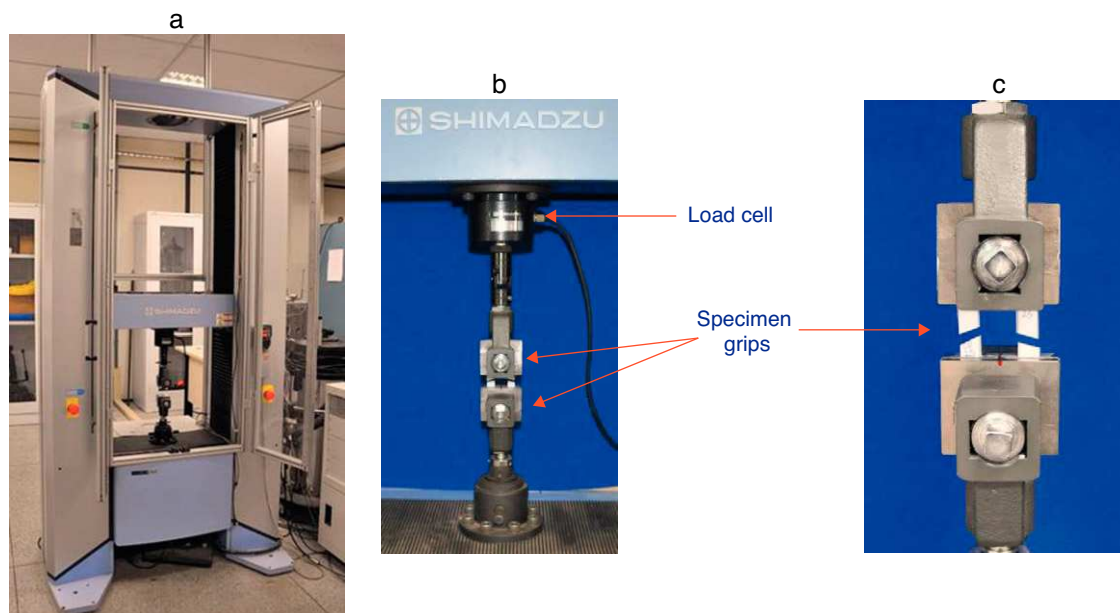


Fig. 3 – Setup of the tensile test according to ASTM C1557: (a) universal testing machine, (b) detail of clamps and (c) specimen.

in Fig. 3. The tests were carried out on specimens with 40 mm gage length using the displacement control at a rate of 0.2 mm/min (strain rate of 0.00008 s^{-1}). For each type of fiber 15 tests were performed. For the jute fibers, tests in gage lengths of 10, 20, 30, 50 and 60 mm with displacement control at a strain rate of 0.00008 s^{-1} were also performed to determine the machine compliance and to study the influence of gage length on the fiber tensile behavior.

The compliance of the loading and gripping system was determined by obtaining the force versus displacement behavior of the fiber at various gage lengths following the methodology used by Silva et al. [8] and Chawla et al. [11]. The total cross-head displacement during fiber testing, δ_t , can be expressed by:

$$\frac{\delta_t}{F} = \left[\frac{1}{EA} \right] \ell + c \quad (1)$$

where c is the machine compliance, F is the applied force, E is the Young's modulus of the fiber, and A is the cross-sectional area of the fiber. Thus, a plot of δ_t/F versus gage length, ℓ , will yield a straight line of slope $1/EA$ and intercept c , the compliance of the load train.

2.2. Microstructural analysis

The fiber's microstructure was investigated using a SEM FEI Quanta 400. The fibers were coated with approximately 20 nm of silver to become more conductive and suitable for SEM analysis. The SEM was operated using 25 kV of acceleration tension and 30 mm of working distance. The images obtained were processed using the software package ImageJ for measuring the cross-section of each fiber. A contour line was interactively drawn to delineate the fiber cross-section (Fig. 4) and then the area was measured.

3. Results and discussion

3.1. The gage length effect

Table 1 presents the tensile results of the jute fibers for the different gage lengths. A total of 15 fibers were randomly chosen from a given batch and tested. Young's modulus was calculated in the elastic portion of the stress-strain curve and then corrected for compliance by measuring force versus displacement, at various gage lengths, using Eq. (1) (Fig. 5). The gage length does not seem to influence the Young's modulus of the fiber. The variability in Young's modulus is probably related to the variability in microstructure of the jute fiber and possible damage during the extraction process, as

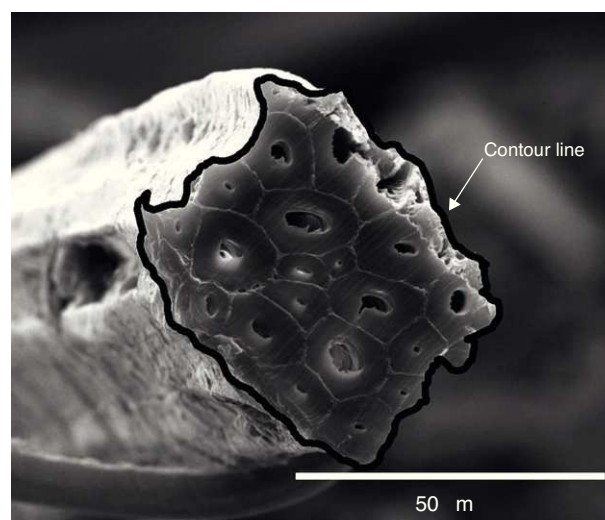


Fig. 4 – Area calculation using ImageJ.

Table 1 – Summary of average tensile test results and standard deviation of the jute fibers.

Gage length (mm)	Tensile strength (MPa)	Young's modulus corrected for compliance (GPa)	Strain-to-failure (%)	Weibull modulus	Area (mm ²)
10 mm	306 ± 130	38.5 ± 14.2	0.9 ± 0.3	1.59	0.003 ± 0.002
20 mm	314 ± 131	35.2 ± 15.1	0.9 ± 0.3	2.09	0.004 ± 0.003
30 mm	263 ± 65	37.7 ± 09.2	0.7 ± 0.2	3.78	0.003 ± 0.001
40 mm	249 ± 89	43.9 ± 12.3	0.6 ± 0.2	2.74	0.004 ± 0.001
50 mm	308 ± 130	48.4 ± 13.3	0.7 ± 0.2	2.27	0.003 ± 0.001
60 mm	258 ± 120	41.3 ± 12.9	0.6 ± 0.2	2.33	0.003 ± 0.001

previously reported by Silva et al. [8,9]. As observed for the Young's modulus, the tensile strength does not seem to be a function of the gage length. The obtained tensile strength varied for different gage lengths from 249 to 314 MPa with standard deviation ranging from 65 to 131 MPa. Strain-to-failure results seem to be higher for the 20 mm gage length and did not show significant variation for the lengths of 30 mm and higher. Similar behavior has been reported by Silva et al. [8,9] for sisal fibers which were related to the average size and distribution of flaws in the volume of the fiber.

3.2. Tensile behavior

The tensile behavior of all fibers is presented in Fig. 6 and the results are summarized in Table 2. Based on these results the fibers can be divided in two different groups: high (Fig. 6a) and low performance (Fig. 6b) natural fibers. Curaua, sisal and jute can be classified as high performance as they presented tensile strength above 249 MPa and Young's modulus higher than 19 GPa. Curaua for example presented Young's modulus of about 64 GPa which is comparable to that of glass fibers (70 GPa). The highest tensile strength has also been observed for curaua with 543 MPa. This value can be compared to that of polypropylene fibers,

which presents tensile strength ranging from 400 to 550 MPa [12]. Coir and piassava presented high strain-to-failure behavior with Young's modulus lower than 3.8 GPa and tensile strength below 131 MPa. It is interesting to notice that sisal, coir and piassava presented a non-linear region starting at stress levels of 100 MPa or below. This non-linear region, following the initial portion of the stress-strain curve has been hypothesized to be due to a collapse of the weak primary cell walls and delamination between fiber-cells [8]. This degradation mechanism should be more severe for coir and piassava as the loss of linearity is more pronounced for these fibers.

The natural fibers present similar morphology, but they differ from each other by factors such as the internal area of the lumens, the number of lumens, the number and size of fiber-cells, the thickness of the secondary cell-walls and the real cross-section (the total area minus the lumen area). Fig. 7 shows the microstructure of the studied fibers. Through analysis of cross-section characteristics of fibers, their individual tensile results can be correlated with their different morphologies.

Generally it can be seen that as the internal area of the lumens decrease and the secondary cell-wall thickness increases the fiber strength and Young's modulus increase (refer to Table 3). The studied curaua fiber consists of

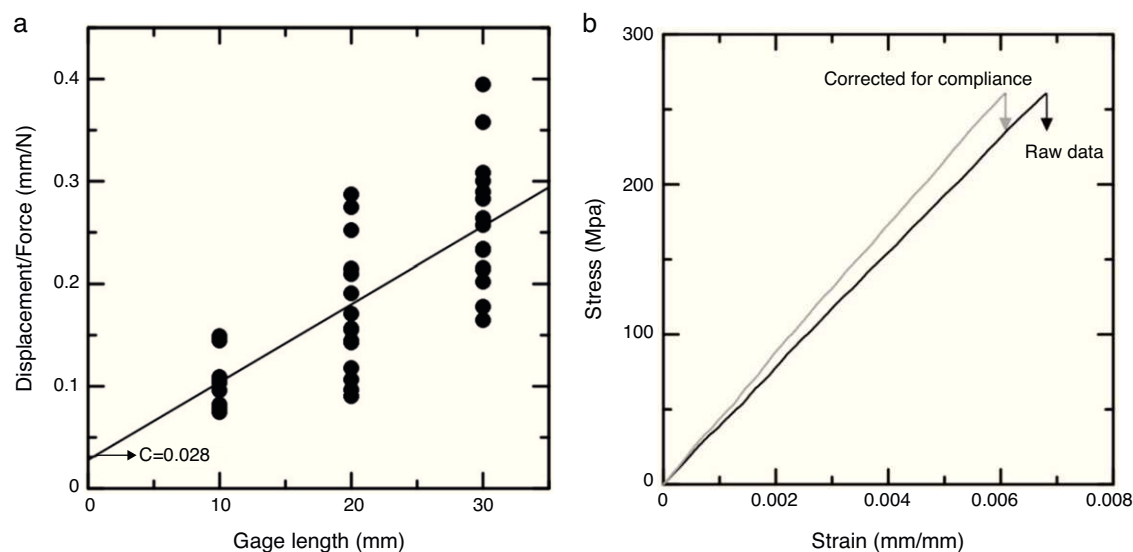


Fig. 5 – Determination of the machine compliance: (a) displacement/force versus gage length. The machine compliance, given by the intercept ($c=0.028$), was determined from this plot, (b) stress-strain behavior of a jute fiber tested at a 40 mm gage length, showing the “as measured” data and that corrected for compliance.

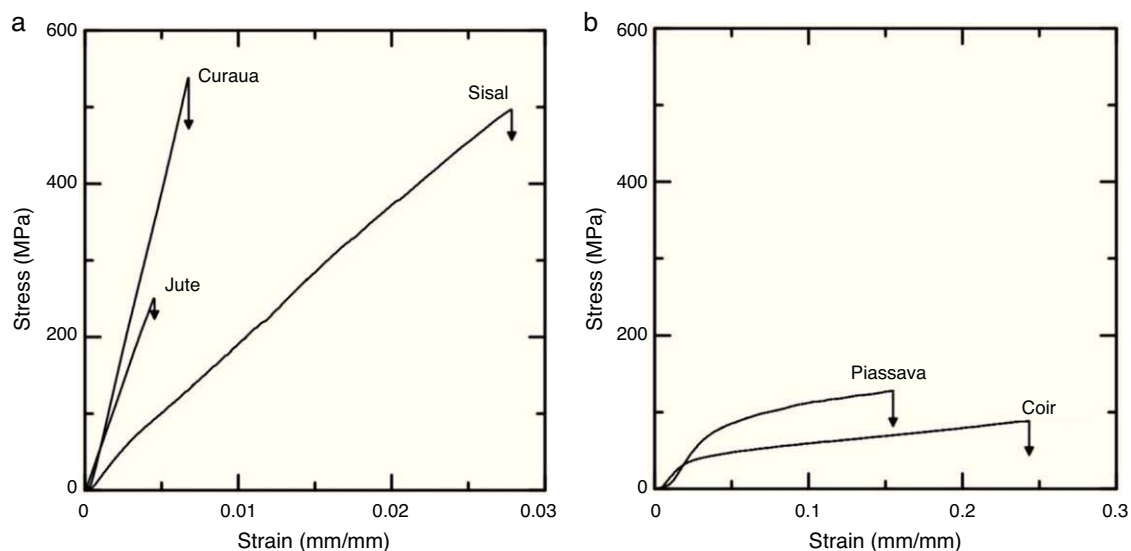


Fig. 6 - Typical curve stress versus strain of the fibers: (a) curaua, sisal and jute and (b) piassava and coir.

Table 2 - Summary of average values and standard deviation of the tensile properties of curaua, jute, coir, piassava and sisal fibers.

Fibers (40 mm)	Tensile strength (MPa)	Young's modulus corrected for compliance (GPa)	Strain-to-failure (%)	Weibull modulus	Area (mm ²)
Curaua	543 ± 260	63.7 ± 32.5	01.0 ± 0.2	2.22	0.004 ± 0.002
Jute	249 ± 89	43.9 ± 12.3	00.6 ± 0.2	2.74	0.004 ± 0.001
Coir	90 ± 35	02.6 ± 00.7	18.8 ± 9.1	2.74	0.052 ± 0.030
Piassava	131 ± 36	03.8 ± 00.9	11.4 ± 3.6	3.68	0.585 ± 0.279
Sisal	484 ± 135	19.5 ± 04.5	03.3 ± 1.6	3.70	0.023 ± 0.007

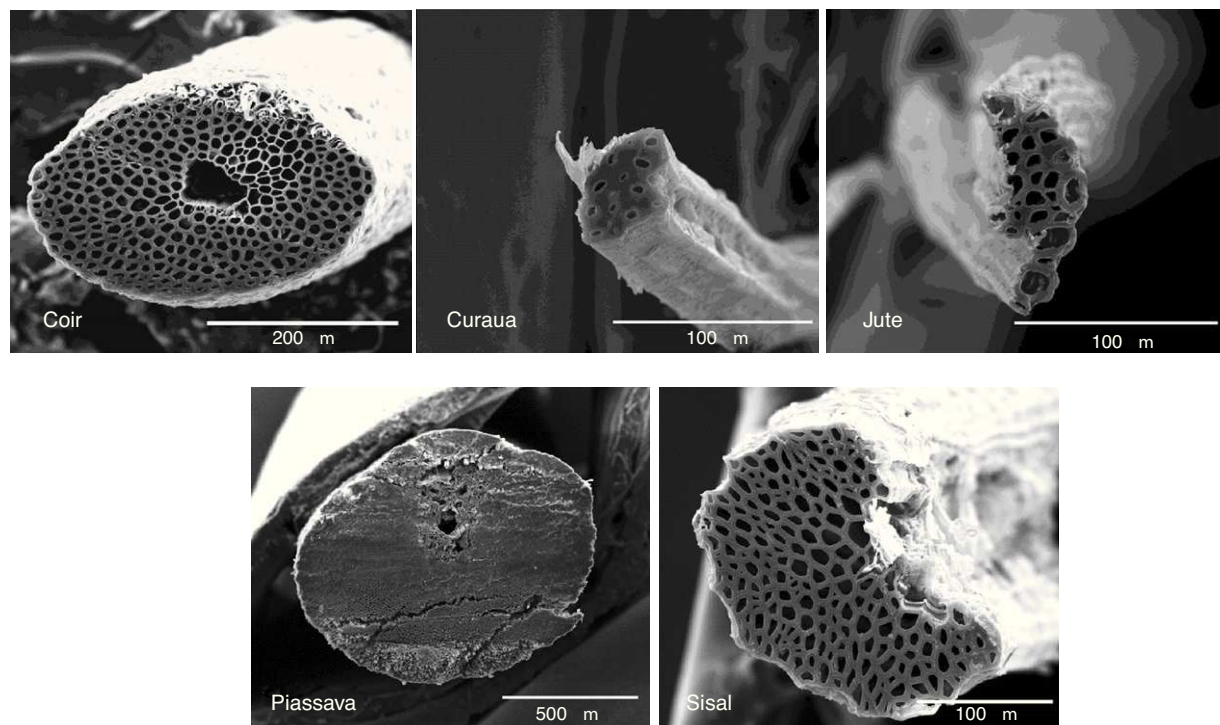


Fig. 7 - Micrographs of jute, coir, curaua, piassava and sisal fibers obtained by SEM analysis.

Table 3 – Measurement results for area and diameter of lumens, number and thickness of cell wall for curaua, jute and sisal.

Fibers	Lumens area (μm^2)	Cell wall thickness (μm)	Diameter of lumens (μm)	Number of fiber-cells	Real area (mm^2)	Total area (mm^2)
Curaua	162	3.5	4.0	12	0.003838	0.004
Jute	1014	2.5	6.7	26	0.002986	0.004
Sisal	5796	2.6	8.2	144	0.017203	0.023

few fiber-cells (12) and its cell walls are thicker ($3.5\ \mu\text{m}$) when compared with the other fibers. Sisal fibers presented the highest number of fiber cells (144), highest lumens area of $5796\ \mu\text{m}^2$, and cell wall thickness of $2.6\ \mu\text{m}$.

Fig. 8a shows a correlation of jute fiber total area and tensile strength for tests performed with the gage length of 40 mm. No influence of the area has been observed on the fiber tensile strength. The same comparison has been done for the several studied fibers with their total areas (Fig. 8b) and again no clear relationship could be established. When the analysis was carried out using the real cross-section area of the fibers the conclusion was the same. On the other hand, there are studies in the literature with curaua fibers [6] that relate the cross-sectional area of the fiber with the tensile strength indicating that smaller the area the higher the stress supported by the fiber.

Furthermore not only the morphology may influence the results of tensile tests, but also the chemical composition. The cellulose is the main component responsible for the resistance of the fiber. For example, the sisal fiber has cellulose content of approximately 73% [13] and jute 65% [14]. Therefore, the sisal may have higher resistance not only because of its morphological characteristics but also for its higher content of cellulose. Current studies are being carried out to explain the coupled effect of chemical and morphological composition on the fiber tensile behavior.

3.3. Weibull distribution applied to the mechanical performance

The application of Weibull distribution on the tensile strength of fibers is described by several authors [1,8,11,15]. In this study, the form presented by Silva et al. [8] was used. According to the Weibull analysis, the probability of survival of a fiber at a stress σ , is given by:

$$P(\sigma) = \exp \left[- \left(\frac{\sigma}{\sigma_0} \right)^m \right] \quad (2)$$

where σ is the fiber strength for a given probability of survival, and m is the Weibull modulus. σ_0 is defined as the characteristic strength, which corresponds to $P(\sigma) = 1/e = 0.37$. The higher the value of m the lower the variability in strength. Ranking of the fiber strengths is performed by using an estimator given by:

$$P(\sigma)_i = 1 - \frac{i}{N+1} \quad (3)$$

where $P(\sigma)_i$ is the probability of survival corresponding to the i th strength value and N is the total number of fibers tested. Substituting Eq. (3) into Eq. (2) yields:

$$\ln \ln \left[\frac{N+1}{N+1-i} \right] = m \ln \left(\frac{\sigma}{\sigma_0} \right) \quad (4)$$

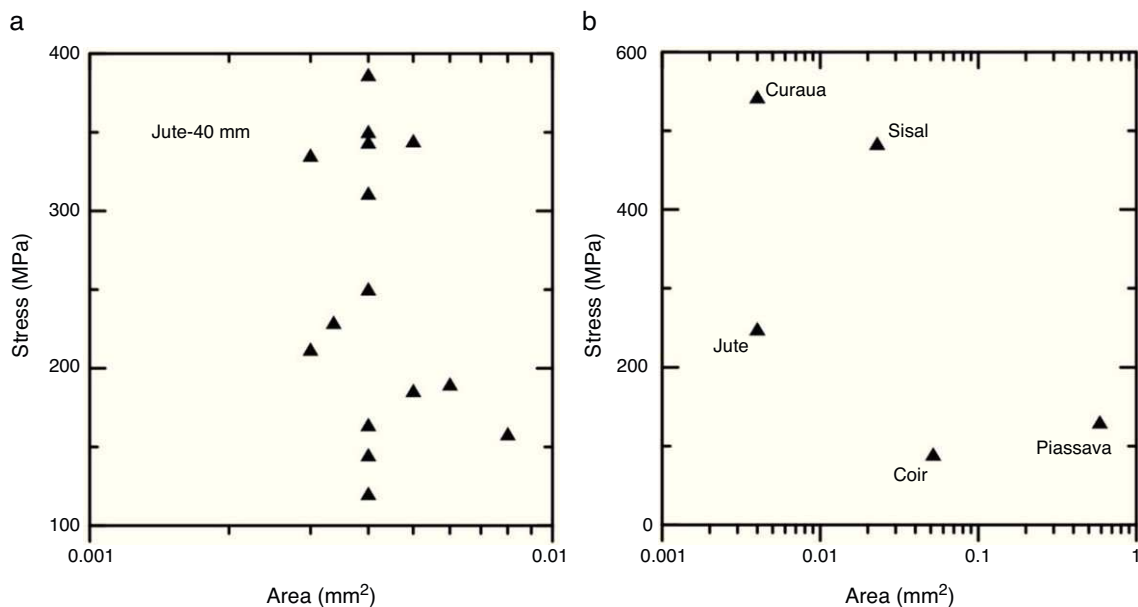


Fig. 8 – Influence of the total area in the tensile strength of: (a) jute fibers of 40 mm gage length and (b) all fibers studied.

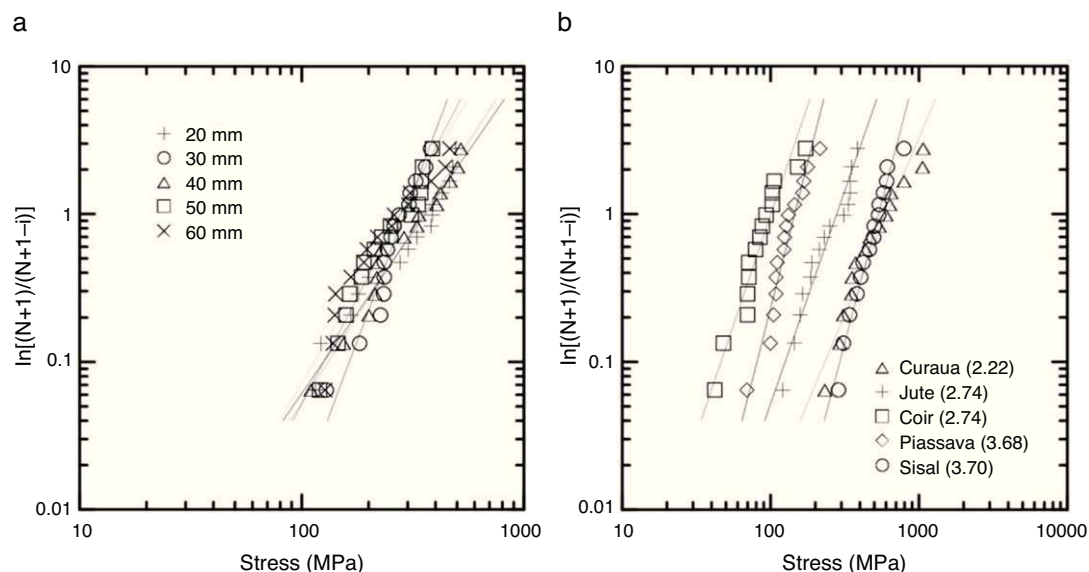


Fig. 9 – Weibull distribution of the (a) jute fiber tensile strength for different gage lengths and (b) comparative between fibers.

Thus, a plot of $\ln \ln((N+1)/(N+1-i))$ versus $\ln(\sigma/\sigma_0)$ yields a straight line with slope of m .

Fig. 9a shows the variation of the Weibull modulus m of jute fiber in various gage lengths, and Fig. 9b values of m for all fibers studied in this work. Table 1 reports the values of the computed Weibull modulus. The Weibull modulus is a measure of variability in fiber strength. A high value of m means low strength variability. Through Table 1 and Fig. 9a it can be observed that for different gage lengths of jute, there was a fluctuation in the values of m , which is not possible to realize the variation in strength values. A different behavior has been reported for sisal fibers when increasing the gage length resulted in a decrease in the Weibull modulus [8]. In the present work the Weibull modulus for the jute fiber ranged from 2.09 to 3.78. In the work of Silva et al. [8] the Weibull modulus decreased from 4.6 to 3.0 when the gage length was increased from 10 mm to 40 mm, respectively. This can be explained as the flaw sizes and distributions may differ from fiber to fiber. Regarding Fig. 9b, it can be seen that the sisal fibers presented the lowest variability ($m = 3.70$) whereas the curaua presented the highest variability ($m = 2.2$). As the number of defects controls the Weibull modulus, it is concluded that curaua, besides having the highest mechanical behavior, have a larger probability of failure when submitted to similar stress conditions.

4. Conclusions

The monotonic tensile behavior of jute, curaua, sisal, coir and piassava fibers has been investigated. Their mechanical properties have been correlated with their morphology and a Weibull statistical analysis has been addressed. The following conclusions can be drawn from this work:

- Mechanical tests of natural fibers are not trivial. Each fiber has a characteristic morphology. Therefore, the irregular

cross-section of the fibers should be considered in the analysis of the tensile tests.

- The gage length seems not to influence the tensile strength and Young's modulus of jute fibers. Strain-to-failure results seem to be higher for the 20 mm gage length and did not show significant variation for the lengths of 30 mm and higher.
- The tensile results for all fibers showed that they can be classified in two distinct groups. Curaua, sisal and jute belong to the high performance natural fibers whereas the coir and piassava represent those of the low performance. Curaua presented the highest Young's modulus and tensile strength of 63.7 GPa and 543 MPa, respectively.
- Sisal, coir and piassava presented a non-linear region starting at stress levels of 100 MPa or below which can be related to a degradation mechanism due to the collapse of the weak primary cell walls and delamination of fiber-cells.
- From the morphology analysis it can be seen that as the internal area of the lumens decrease and the secondary cell-wall thickness increases the fiber strength and Young's modulus increase.
- The sisal fibers presented the lowest variability ($m = 3.70$) whereas the curaua presented the highest one ($m = 2.2$). Thus, the curaua fiber has a larger probability of failure when submitted to similar tensile stresses.

Conflicts of interest

The authors declare no conflicts of interest.

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