

WEIBULL ANALYSIS OF THE TENSILE STRENGTH VARIATION WITH DIAMETER FOR JUTE FIBERS

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Abstract

The jute fiber is one of the strongest lignocellulosic fibers with applications ranging from simple items such as fabrics and ropes to engineering composites for automobile parts and building panels. Like other lignocellulosic fibers, the jute may have an inverse strength dependence with its diameter. In principle, thinner jute fiber could be comparatively stronger and consequently more effective as a composite reinforcement. Therefore, an attempt to correlate the jute fiber strength obtained in tensile test with its corresponding diameter, precisely measured by means of a profile projector, was carried out. A Weibull statistical analysis confirmed the inverse dependence between the jute fiber tensile strength and the corresponding fiber diameter. Scanning electron microscopy observation of the fracture of selected ruptured fiber revealed possible mechanisms that could justify the strength/diameter inverse dependence.

Introduction

In recent years a growing increase in the use of natural materials is taking place in engineering application motivated by worldwide events. These are the generalized pollution due to discard of non-degradable synthetic materials and climate change attributed to CO₂ emission during their production [1]. The need to replace petroleum-based energy systems, used in the production of synthetic materials, by other environmentally friendly alternatives is also a strong motivation in favor of natural materials [2]. Additionally, most natural materials are less expensive than their synthetic counterparts and provide societal advantages to low income communities or developing countries in which they are produced [3].

An important example is that of the natural fiber, mainly those lignocellulosic obtained from vegetable, that have been traditionally used in simple items such as baskets, ropes, clothes, carpets', roofing's, etc. These lignocellulosic fiber are currently being applied as reinforcement in composite materials [3,8] for automobile parts as well as building construction panels and furniture. In fact, there is nowadays a clear tendency towards the substitution of lignocellulosic fibers for glass fiber in polymer composites [3]. However, the poor adhesion to polymer matrix as well as the heterogeneous dimensions and non-uniform properties of the natural fibers are drawbacks to their use as composite reinforcement [3-8].

In practically all regions of our planet in which cellulose-based plants can grow, hundreds of different lignocellulosic fiber can be found. Among these, the jute fiber is one of the most

investigated an industrially used in composites owing to its high specific strength, impact resistance and relatively low cost [10]. A large number of works has been dedicated to the characteristic and properties of the jute fiber alone and its reinforced composites [11-15], just to mention a few of the most recent publications.

A relevant aspect on the investigated and industrially applied mechanical properties of jute composites is the fact that research works normally use short-cut fibers. This does not provide the highest potential as compared to continuous and aligned fibers [15]. Moreover, the possibility of a correlation between the strength and the diameter of the jute fibers has not yet been statistically investigated. Therefore, the present work attempts to correlate the jute fiber diameter with its tensile strength by means of precise profile projector measurements employing the Weibull analysis for the recorded data.

Experimental Procedure

The jute fibers investigated in this work were commercially supplied by the Brazilian firm SISALSUL. Figure 1 illustrates the typical jute plant and a bundle of fibers extracted from its stem.



Figure 1. (a) Typical jute plant; (b) bundle of fibers extracted from the stem.

The lot of as-received jute fibers displayed a noticeable variation in diameter. The distribution of fiber diameter has been recently presented [15]. Here, it is worth mentioning that a randomly selected group of 100 jute fibers presented diameters in a range of 0.04 to 0.18 mm with a mean value of 0.082 mm. Based on this range of diameters, seven 0.02 mm equally spaced intervals were considered. For each interval, about 20 fibers were selected through profile projector average measurements along the fiber length in five distinct locations.

All selected fibers were individually tensile tested in a model 5582 Instron machine at $25 \pm 2^\circ\text{C}$. Especial tensile grips and holding procedures were used to avoid both slippage and damage to the fiber. The tensile test strain rate was $4.2 \times 10^{-4}\text{s}^{-1}$. The values obtained for the tensile strength corresponding to each diameter interval were statistically interpreted using the computer program *Weibull Analysis*.

In order to complement this investigation on the diameter dependence of the tensile strength, the fractures of representative ruptured fibers were analyzed. Fracture samples for each corresponding diameter interval fibers, were attached with conducting carbon tape to a metallic support and then gold sputtered to be observed by scanning electron microscopy, (SEM), in a model SSX-550 Shimadzu equipment operating with secondary electrons at an accelerating voltage of 15kV.

Results and Discussion

The digital recorded data obtained from the Instron machine allowed to construct representative load vs. elongation curves for each diameter interval [15], such as those presented in Fig 2. In this figure it should be noticed that all curves show an elastic linear segment up to a maximum load in which a total rupture occurred. This indicates that the jute fiber act as brittle material without any plastic extension after the elastic regimen. Moreover, most curves presents evidence of serrations especially for the thinnest fiber with diameter smaller than 0.08 mm. These serrations have been suggested [16] to be associated with partial rupture of fibrils that compose a lignocellulosic fiber. It is worth mentioning that thinner fibers are composed of relatively lesser fibrils, which result in superior mechanical behavior. This fact will be further discussed in the present work.

Tensile results such as the ones exemplified in Fig 2 permitted the evaluation of the tensile strength for every fiber investigated. These values of strength were analyzed by the Weibull statistic method, in each of the seven diameter intervals [15]. Figure 3 shows the logarithmic graphs of the reliability vs. location parameter, also known as the Weibull graphs. In this figure the graphs are unimodal with just one straight fitting for all points in the same diameter interval. This indicates that every jute fiber related to each one of the seven intervals belongs to a group with same mechanical behavior.

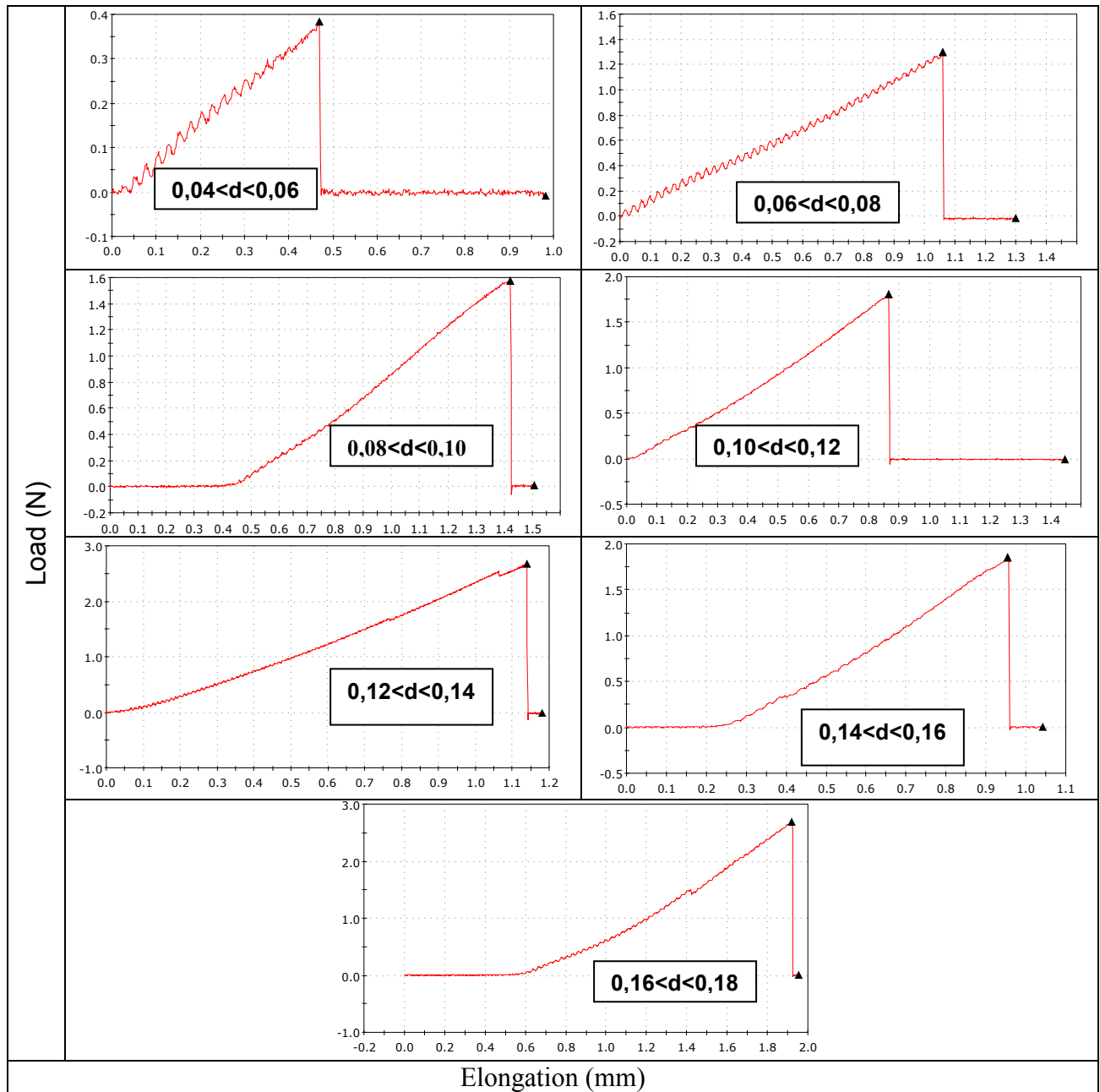


Figure 2. Typical tensile load vs. diameter of jute fibers for the distinct intervals

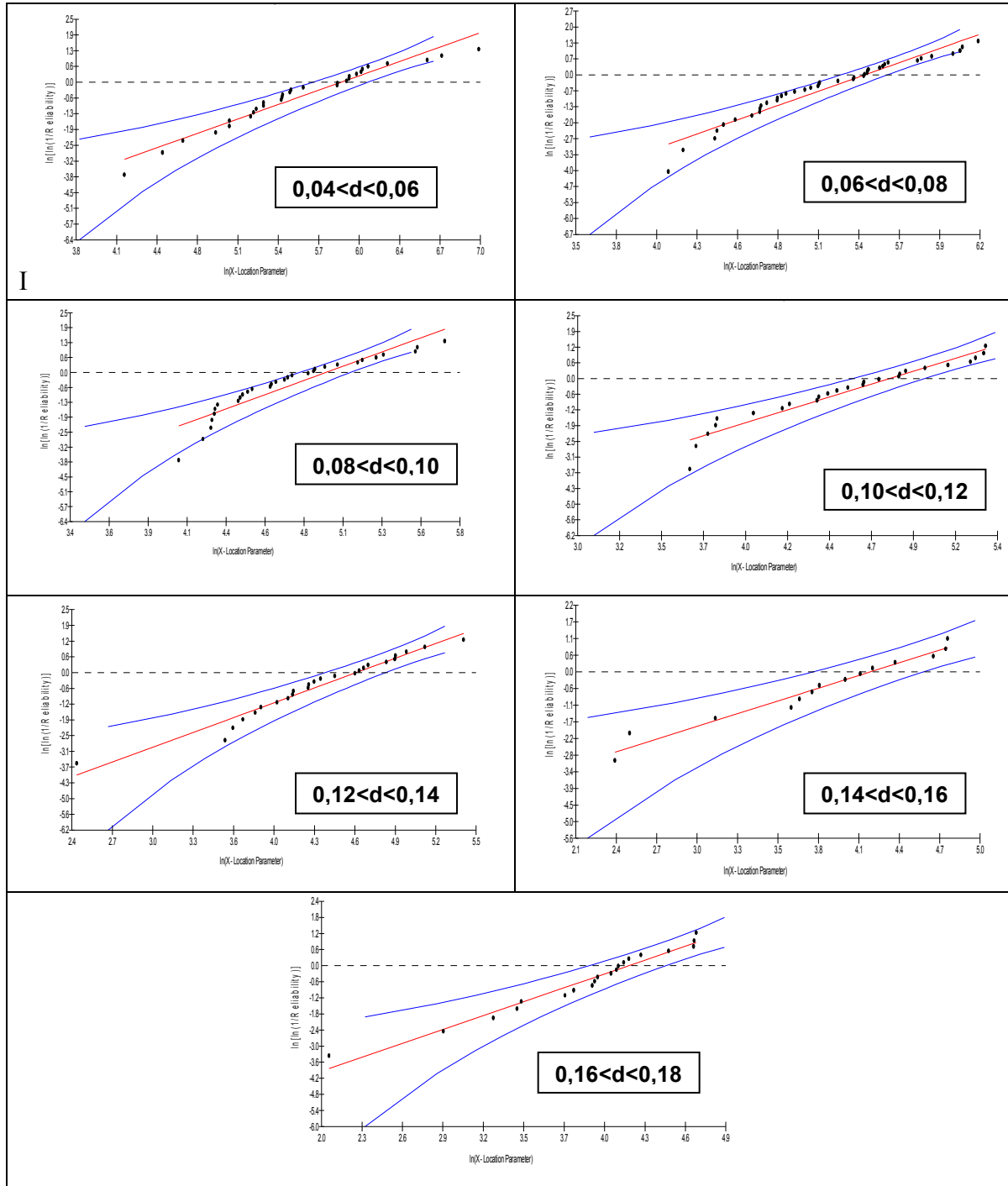


Figure 3. Weibull graphs for the different intervals.

Table 1 presents the values of the Weibull parameter associated with the statistical characteristic of each diameter interval. In this table, the parameter θ in the statistical analysis of this work represents the most characteristic tensile strength. The adjustment parameter R^2 indicates the precision degree of the statistical analysis.

Table 1. Weibull parameter σ_n the jute fiber strength in different diameter interval.

Diameter Interval (mm)	Weibull Modulus β	Characteristic Strength θ	Precision Adjustment R^2	Average Tensile Strength (MPa)	Statistical Deviation (MPa)
0.04-0.06	1.82	364.1	0.949	323.7	184.7
0.06-0.08	2.20	228.0	0.938	201.9	96.7
0.08-0.10	2.53	144.8	0.860	128.5	54.4
0.10-0.12	2.15	119.5	0.933	105.8	52.6
0.12-0.14	1.88	97.5	0.959	86.6	47.8
0.14-0.16	1.48	67,7	0.964	61.2	42.1
0.16-0.18	1.77	66.9	0.967	59.6	34.7

The variation of the characteristic tensile strength with the fiber diameter, i.e., the mean value of the interval, is shown in Fig 4. In this figure there is a clear tendency for θ to vary in an inverse way with respect to the fiber diameter (d). A physical consequence is that the thinner the fiber, the higher the characteristic tensile strength.

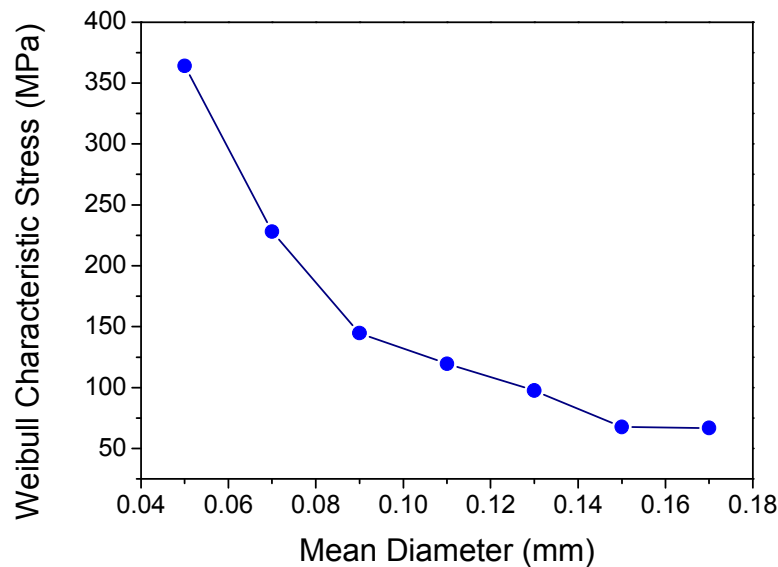


Figure 4. Variation of the characteristic stress with the mean diameter for each interval.

The corresponding values of R^2 in Table 1 statistically support the inverse correlation between θ and d . This correlation can be mathematically described as the following hyperbolic equation for jute fiber

$$\theta = 21/d - 76 \tag{1}$$

Another Weibull parameter of relevance is the average tensile strength, $\bar{\sigma}_m$. The interval of $\bar{\sigma}_m$ and its deviation encompasses the corresponding values of θ . In a normal distribution of tensile strength, within a given diameter interval, the values of σ_m , θ and the arithmetic average of the strength should coincide.

Figure 5 plots $\bar{\sigma}_m$ and deviations as a function of the diameter. In this figure, within the error bars, a hyperbolic inverse correlation can be adjusted between $\bar{\sigma}_m$ (MPa) and d (mm):

$$\bar{\sigma}_m = 20/d - 77 \quad (2)$$

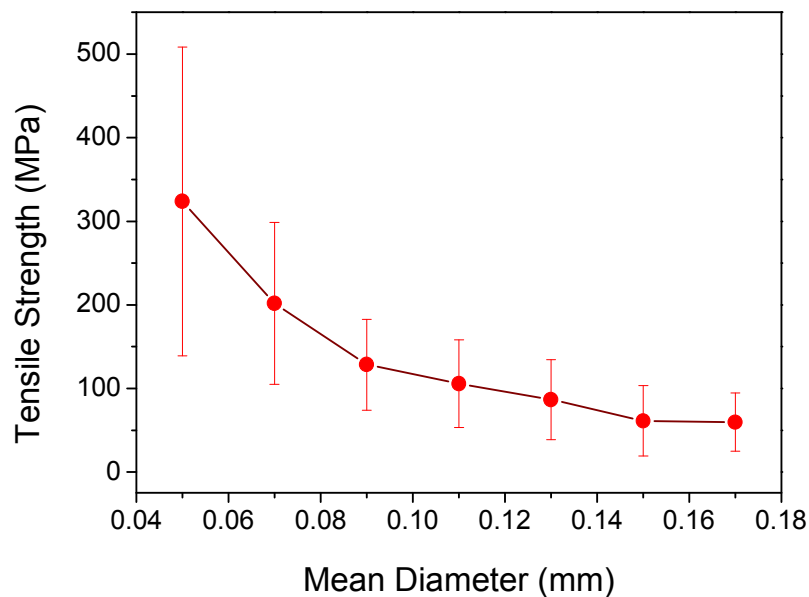


Figure 5. Variation of the average tensile strength with the mean diameter for each interval.

By comparing Eq (1) and (2), it can be seen that both have very similar mathematical coefficients. It is then suggested that a hyperbolic type of equation is indeed the best statistical correlation between the jute fiber tensile strength and its diameter. Hyperbolic correlations have recently been reported for curaua, sisal and ramie [17] as well as piassava fibers [18]. The reason for this behavior is apparently related to the mechanism of tensile fracture of lignocellulosic fibers.

Figure 6 shows SEM fractographs of the tip of tensile-ruptured jute fibers with different diameters. It can be seen in this figure that the thinner fiber with $d = 0.02$ mm, Fig 6 (a), displays a fracture associated with lesser fibrils. By contrast, the thicker fiber, with $d = 0.19$ mm, Fig 6 (b), shows a heterogeneous fracture comprising relatively more fibrils. As a consequence, there is a higher statistical chance that the thicker jute fiber would prematurely break at lower stress than the thinner one.

In fact, in two regular distribution of fibrils with comparable mechanical properties, associated with two fibers with different diameters, that with greater number (thicker fiber) has the probability of comprising stronger as well as weaker fibrils as compared to that with lesser (thinner fiber) number. Therefore, in a tensile test the first fibril (the weakest) in the thicker fiber, Fig 6 (b), should break at a stress level lower than that required for any fibril in the thin fiber, Fig 6 (a). Once a fibril is broken, it leaves a flaw in the fiber from which a crack may longitudinally propagate in between fibrils, see arrow in Fig 6 (b), and contribute to the earlier collapse of the fiber.

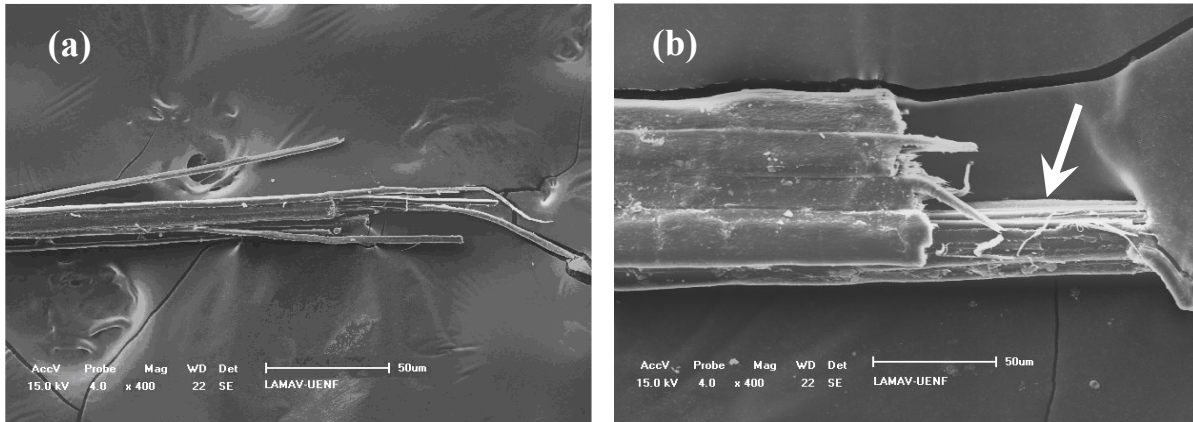


Figure 6. SEM fractographs with same magnification of tensile-ruptured jute fibers: (a) thinner, $d = 0.02$ mm and (b) thicker, $d = 0.19$ mm.

As a final remark, it is worth speculating that an inverse correlation between tensile strength and diameter, such as the hyperbolic in Eq (1) and (2) could in principle permit to select the thinnest jute fibers as probably the strongest alternative for reinforcing composites with improved properties.

Conclusions

- Like in other lignocellulosic fibers, a Weibull statistical analysis of the tensile strength of jute fibers, showed an inverse correlation with their diameters. This correlation adjusts well to a hyperbolic type of equation for both the Weibull average tensile strength and the characteristic strength.
- The fracture tip of the fibers revealed a mechanism of longitudinal crack propagation between fibrils before the final fiber break down. It is suggested that this mechanism would be associated with the premature rupture of a thicker fibers as compared to a thinner one with less fibrils and so explain the inverse correlation.

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