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EVALUATION OF MECHANICAL PROPERTIES OF JUTE YARNS BY TWO- AND THREE-PARAMETERS WEIBULL METHOD

PROCENA MEHANIČKIH SVOJSTAVA PREDIVA KONOPLJE PRIMENOM DVO- I TRO-PARAMETARSKOG VEJBULOVOM METODA

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- jute
- Weibull distribution

Ključne reči
- prirodna vlakna
- kudelja
- Vejbul raspodela

Abstract

This paper deals with chemical, physical and mechanical characterization using different techniques of tests such as: FTIR, XRD analysis and static tensile tests of jute fibre yarns. The analysis of experimental results obtained in static tensile shows that tensile strength and Young's modulus vary depending on the increase in the number of tested samples. Therefore a statistical analysis is performed using Weibull method with two and three parameters.

Izvod

Prikazana je hemijska, fizička i mehanička karakterizacija prediva konoplje korišćenjem različitih tehnika, kao što su: FTIR, XRD analiza i statičko ispitivanje na zatezanje. Analiza eksperimentalnih rezultata, dobijenih ispitivanjem na zatezanje, pokazala je da modul elastičnosti i zatezna čvrstoća zavise od broja uzoraka. Stoga je primenjena statistička analiza korišćenjem dvo- i tro-parametarske Vejbulove metode.

INTRODUCTION

The fibres used as reinforcement in composite materials with polymeric matrix are mainly synthetic fibres like glass, Kevlar or carbon fibres. These fibres present very good mechanical properties but harmful disadvantages on the environment. However, other fibres can be used like natural fibres which present interesting mechanical, physical and chemical properties as well as economic and environmental advantages (low cost) because of their biodegradability (eco-friendly), /1, 2/.

The market of natural fibres (hemp, flax, cotton, jute, ramie, etc.) is in full expansion with many industrial outlets. Among these incipient markets, the integration of vegetable fibres in composite materials, such as the sisal /3, 4/, the flax /5/, the jute /6, 7/, hemp /9/, the esparto /10/, and other natural fibres /11-13/. Today in the world the production of natural fibres reaches a few tens of thousands of tons (with a growth from 10% to 15% a year), compared with the 2 million tons of synthetic fibres – mainly glass fibres – which reinforce the traditional composites /14, 15/.

The research on the characterization of natural fibres has expanded these last few years; many studies are interested in characterization of the technical fibres and few of them on yarns fibres characterization. Fibre yarns are often used in rope that contains many fibres linked together. The vegetable fibres usually used are those resulting from the plants and have good mechanical properties. For the natural fibres of jute, the properties change considerably according to their structure, indeed, the natural fibres are composed of several cells forming crystalline micro-fibrils (cellulose) connected together by amorphous lignin and hemicelluloses as layer, these walls of cells differ in their composition (relation between cellulose, lignin, and hemicelluloses are the most important components) and in the orientation (angle in spiral) the micro-fibrils from cellulose by which the characteristic structural parameters change from one natural fibre to another, /16/. The composites reinforced by natural jute fibres present good strength properties in tension, with interesting properties in bending, although it can present some problems of hardness, /17/.

Natural jute fibre has been the object of several scientific studies. These studies are spread out over a multitude of fields starting with the production of the plant until its use via the spinning mill, the choice of the micro-fibrillary angle, the mode of weaving and the treatments of the fibre. In the field of the production of jute, several studies related to: analysis of the nature and genetic variability on the output of fibres as well as the identification of the physiological and biochemical aspects in the short run on the species of harvests, /18/. Khöler et al. /19/ show that the genetic variability of jute fibre is related even to the nature of jute.

One of the main problems in the manufacturing of jute fabric resides in the optimization of yarn to use. Indeed, the optimization of the opening process fibre is important for improving the mechanical properties of the fibres, /20/. The behaviour of jute fibre is controlled by two parameters: the reorientation according to the loading axis of fibrillates and the slip of these latter ones according to the others, /19/.

Hearle et al. /21/ show that the micro-fibrillary angle characterizing the jute is influenced by the percentage of cellulose in the jute (61% to 71%). Broutman et al. /22/ works show that this micro-fibrillary angle, generally about 8°, influences the mechanical behaviour of the jute, indeed, the more the micro-fibrillary angle is weak, the rigidity and the resistance of the fibre are higher, however, the adverse phenomenon is observed for elongation.

This work is focused on the evaluation of the mechanical properties of yarns jute fibres by the use of the Weibull statistical method with 2 and 3 parameters. Furthermore, a characterization by *Fourier transform infrared spectroscopy* (FTIR) and *X-ray diffraction* (XRD) is also carried out and analysed. The choice of jute fibre is well justified due to the fact that jute plant takes about 120 days to become ripe and its output is of approximately two tons of dry fibres per hectare /14, 15/. Moreover, this fibre is one of the cheapest vegetal fibres, totally biodegradable and which can be also recycled.

EXPERIMENTAL TECHNIQUES

Jute plants are shrubs from 2 to 4 m height, with rigid and fibrous stem approximately 2 cm in diameter, only ramified in the upper part. The leaves, lengthily petiolate, with triangular limb make 10 to 15 cm length on 5 cm width. This plant is cultivated in tropical areas for its fibres; it is an annual culture which takes approximately 120 days to become ripe, /14/. Its output is of approximately two tons of dry fibre per hectare. This natural fibre with silky aspect is called 'gold fibre' because of its reflections. The jute fibre is long, soft and brilliant; its length varies from 1 to 4 meters and its diameter from 17 to 20 µm. In this study, the jute yarns are provided by the factory of ropes from natural fibres (Béjaia, Algeria).

The jute yarns have a diameter which varies between 600 and 1200 µm. The diameter of yarns is measured (Fig. 1) before the mechanical tests by using an ZEISS optical microscope equipped with a Moticam 2500 digital camera controlled by MoticImages plus V2.0 processing image software. The measure is taken along the yarn of 50 mm length in 9 different places per sample.

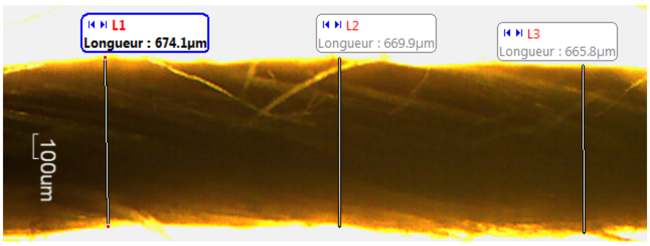

Figure 1. Optical microscopy image of longitudinal jute yarn.

Infrared spectrometry analysis (FTIR)

The infrared technique of spectrometry makes it possible to have information on the molecular structure of a compound given by detecting the presence of functional groupings in this compound. The jute fibre is analysed using a Perkin Elmer Spectrum 65FT-IR type spectrometer (Laboratory LGP2 Grenoble, France) with its own quantitative analysis software. The sample of the jute fibre is prepared in form of solid pastille with KBr (1:99) and has been measured on this device with IR rays of 125 nm with acquisitions in an interval between 500 and 4000 cm^{-1}.

The X-ray diffractometer used is a model X' Pert Pro PANalytical (CMTC Laboratory Grenoble, France). The experiment has been carried out under a vacuum using an X-ray PANalytical X' PERT generator, with a tension of 40 kV and an intensity of 40 mA. The sample to be analysed is put in a circular steel mould in the form of powder. The diffracted intensity of CuKα radiation (wavelength of 0.1542 nm) is recorded between 2θ equal to 10° and 40°.

The mechanical properties (stress and strain at failure and Young modulus) of jute yarns are given according to the standard ASTM D578 using a 50 mm of gauge length (GL). Because of the variability of natural fibres, 320 samples using a universal tensile testing machine of type ZWICK Z005, with a capacity load cell of 5 kN. Tensile tests are carried out at room temperature (23°C) and hygroscopy of approximately 55%, with a rate of 2 mm/min. The obtained results are treated by Minitab version 16 software.

RESULTS AND DISCUSSION

Figure 2 shows the Fourier transformed infrared spectrum of jute fibre with the principal infrared bands corresponding to the vibrations of various groupings. A broad band of 3392 cm^{-1} is observed which is due mainly to the OH groupings existing in the jute fibre structure. The peaks of 2905 and 2142 cm^{-1} correspond to vibrations of CH aliphatic chains. We also notice the presence of peaks at 1732 cm^{-1}, 1654 cm^{-1}, 1372 cm^{-1}, 1250 cm^{-1}, and 1036 cm^{-1}, which indicate the existence of the C═O stretching vibration of carboxylic acid, CH_3 asymmetric stretch, CH symmetric stretching, and aromatic and C─O simple connections, respectively.

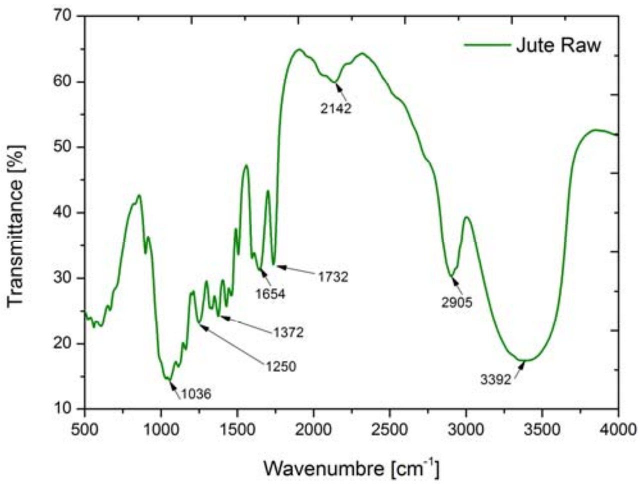

Figure2. FTIR spectra of jute fibre.

Table 1 presents the various observed peaks compared with those from literature. The studies of Roy et al. /6/ and those of Saha et al. /23/ on jute fibre show rather close peaks. Indeed, it is shown by Amroune et al. /13/ that the fibres extracted from date palm fruit branches present spectra similar to those found in this work.

In the same way, the study conducted by Fiore et al. /24/ on natural fibres (Arundo donax L.) shows that, the peak at 3400 cm^{-1} is a little bit higher than that found in the present study.

X-ray diffraction has been used to study the changes of physical structures of fibres according to the index of crystallinity (Cry). Segal et al. /25/ developed an empirical method to estimate the degree of crystallinity, Eq.(1), which is the main factor contributing to the increased resistance of the fibre.

$$CrI\% = \frac{I_{002} - I_m}{I_{002}} \quad (1)$$

where I_{002} is the maximum intensity of XRD peak at 2θ = 22.7° which consists of both contributions of amorphous and crystalline fractions; I_m is the small peak intensity height at 2θ = 18.9° and is attributed to the amorphous fraction.

The curve of X-rays diffraction of the jute fibre is represented in Fig. 3. It has the shape similar to those reported in literature.

The obtained crystallinity (Cry) rate of the jute fibre calculated by using Eq.(1) and shown in Table 2, is equal to 65.23% which is very close to 66% found by Moriana et al. /26/. However, the rate of crystallinity in this work remains higher than those reported by Roy et al. /6/, Saha et al. /23/ and Indran et al. /27/ which are 50.4%, 58.90% and 59.60%, respectively. Amroune et al. /28/ demonstrated that fibres extracted from the date palm fruit branches present a crystallinity rate equal to 42.76% which is lower than for the jute fibre.

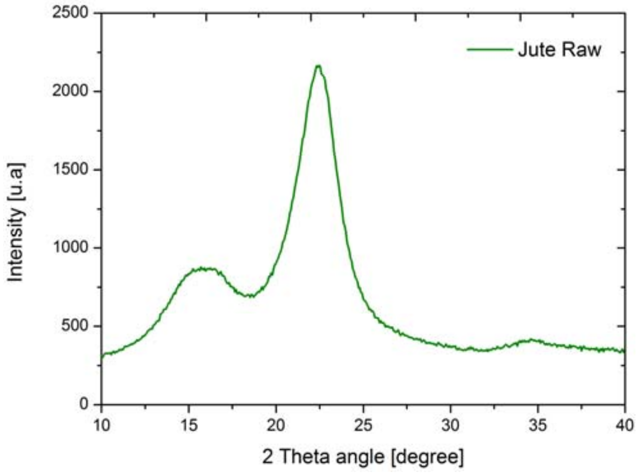

Figure 3. X-ray diffraction of jute fibre.

Tensile strength of jute yarn

In order to optimize the 320 tests carried out in this work on yarn jute, they are organised in 16 sets of 20 samples. Figure 4a shows stress/strain curves of 20 tensile tests on jute yarn, where an important dispersion of results is noticed. This dispersion is a characteristic of natural fibres; thus a statistical study is needed. In the typical stress-strain curve presented in Fig. 4b, the stress varies linearly, then quasi-linearly with an increase of strain until it reaches its highest value, then it decreases suddenly to about 45% of its maximal value. This decrease is due to partial failure of the jute yarn corresponding to the failure of dozens of weak fibres in the yarn, and then several drops in stress are recorded until final rupture, thus forming a stepwise behaviour.

Table 1. Main bands attributions observed on the FTIR spectrum of jute fibre.

This work	Ref. (6)	Ref. (23)	Ref. (13)	Ref. (24)	Possible attributions
3392	3200	3300	3343	3400	O-H Hydrogen bonded of OH stretching in cellulose
2905	2920	2910	2918	2923	C-H Stretching of cellulose
2142	-	-	-	1730	C-H Stretching of cellulose
1732	1738	1739	-	-	C=O Stretching vibration of carboxylic acid
1654	1452	1464	1536	1506	CH_3 Asymmetric stretch
1372	1374	1376	-	1372	CH symmetric stretching and aromatic
1250	1249	1249	-	1245	C-O Acetyl in pectin or hemicelluloses
1036	1035	1049	1031	1035	C-O Acetyl in pectin or hemicelluloses
3392	3200	3300	3343	3400	O-H Hydrogen bonded of OH stretching in cellulose

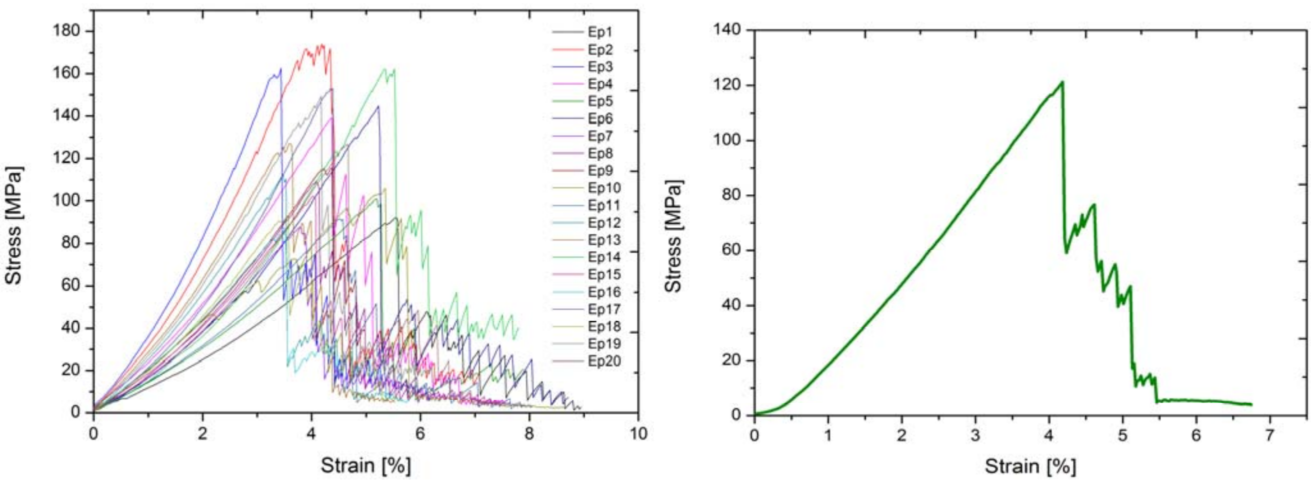

Figure 4. (a) Stress/strain curves of twenty tests on jute yarn, and (b) Typical stress-strain curve on jute fibres yarn.

Table 2. Crystallinity index (%) of jute fibre.

Sample	Intensity at 2θ = 18.9°	Intensity at 2θ = 22.7°	Crystallinity Index (*CrI*)
This work	722.3	2077.9	65.23%
Ref. (26)	-	-	66%
Ref. (23)	561	1365	58.90%
Ref. (6)	232.7	469.2	50.40%
Ref. (27)	238	590	59.60%
Ref. (28)	-	-	42.18%

The variations of average values of mechanical properties in terms of the increase of the number of samples tested are summarised in Table 3. The analysis of the obtained results has allowed finding average values of stress, strain and Young modulus, respectively equal to 21.94 MPa, 4.34% and 21.29 GPa for a number of 20 samples tested. For 40 samples tested, the average values of stress, strain and Young modulus have decreased and are equal to: 113.35 MPa, 4.42%, and 19.48 GPa, respectively. By increasing the number of samples tested by series of 40, from 80 to 320 tests, the mechanical properties (stress and Young modulus) increase and become constant from 200 tests. However, the variation of strain at failure is not significant.

Table 3. Mechanical properties variation of average values of fibre yarns in terms of the increase of tested samples.

Number	Stress σ (MPa)	Strain ε (%)	Modulus E (GPa)
20	121.94±28.07	4.34±0.71	21.29±6.22
40	113.35±27.47	4.42±0.89	19.48±7.13
80	119.25±32.88	4.34±0.77	21.76±10.05
120	123.47±32.70	4.31±0.79	23.38±10.25
160	124.04±30.98	4.23±0.78	24.65±10.34
200	123.43±30.89	4.21±0.75	24.84±10.22
240	125.69±32.96	4.19±0.73	25.40±10.53
280	126.61±32.47	4.18±0.71	25.16±10.05
320	126.44±32.09	4.18±0.70	25.02±9.81

Experimental results are characterized by a large dispersion; therefore a statistical analysis is needed. For this, the two- and three-parameters Weibull statistical distribution is used in Minitab 16 in order to estimate the average values of mechanical characteristics in terms of the number of tested samples. The stress σ can be represented by the two-parameters Weibull distribution law as follows /29, 30/:

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right], \quad \sigma > 0,\ \sigma_0 > 0,\ m > 0 \qquad (2)$$

where m is a dimensionless shape parameter related directly to the dispersion of data; σ_0 is a location parameter representing an average of σ; and $P(\sigma)$ is the fibre failure probability in terms of the σ parameter. When the threshold setting is applied in the distribution theory, the three parameters Weibull law is obtained as follows:

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m\right], \quad \sigma > \sigma_u > \sigma_0 > 0,\ m > 0 \qquad (3)$$

where σ_u is the threshold parameter (highest stress).

The value $P(\sigma)$ is evaluated by a metric estimator (value of an average rank), /31/:

$$P(\sigma)_i = \frac{i - 0.3}{n + 0.4} \qquad (4)$$

where i is the rank of i-th data point, and n is the number of points.

The parameters m and σ_0 are obtained from the plot of the straight line of Weibull linear model from Eqs.(2) and (3), after processes in terms of $\ln(\sigma)$ as follows:

$$\ln\left[-\ln(1-P)\right] = m\ln\sigma - m\ln\sigma_0 \qquad (5)$$

$$\ln\left[-\ln(1-P)\right] = m\ln(\sigma - \sigma_u) - m\ln\sigma_0 \qquad (6)$$

Figure 5 shows the two- and three-parameters Weibull distribution of mechanical properties derived from experimental results. We notice that the experimental values are close to the Weibull line. The Weibull distribution with two parameters for a number of 20 tested samples is used to estimate the stress and Young's modulus and the values found are σ_0 = 130.89 MPa and E_0 = 23.08 GPa with Weibull modules m_σ = 5.89 and m_E = 4.77. The results are close to experimental results σ = 121.94 MPa and E = 21.29 GPa. But for the three parameters Weibull the values obtained are far from experimental results, which are σ_0 = 38.2 MPa and E_0 = 9.91 GPa, with Weibull modulus m_σ = 1.07 and m_E = 1.48.

It is important to notice that the increase of the number of tests has an influence on the mechanical properties, especially the stress and Young's modulus, found experimentally or estimated by the method of Weibull. By varying the number of tested samples from 20 to 320, the mechanical properties decrease for 40 tests, then they increase with increasing the number of tested samples, and they become constant from 200 samples. While Thomason /31/ found that 80 tests are sufficient to have stability in the results of mechanical properties in the case of glass fibres, the values of various parameters obtained are shown in Table 4.

Table 4. Two- and three-parameters Weibull distribution of the jute fibre yarns in terms of increasing samples tested numbers.

Number	Two parameters Weibull						Three parameters Weibull					
	m	σ_0	m	E_0	m	ε_0	m	σ_0	m	E_0	m	ε_0
20	5.89	130,89	4,77	23.08	8.12	4.59	1.07	38.20	1.48	9.91	1.30	1.17
40	5.62	121.95	3.55	21.47	6.42	4.74	1.61	48.30	2.21	15.61	5.97	4.47
80	5.29	128.53	3.18	23.82	7.73	4.60	1.91	60.90	1.80	16.53	3.90	2.62
120	5.10	133.65	3.15	25.68	7.26	4.59	2.06	70.37	1.87	18.39	3.79	2.73
160	5.32	134.09	3.21	27.11	7.15	4.51	2.20	71.62	1.99	19.97	3.44	2.54
200	5.44	133.18	3.25	27.34	7.37	4.47	2.21	69.86	2.00	20.16	3.40	2.43
240	5.19	135.93	3.19	28.02	7.58	4.44	2.10	72.00	2.01	21.13	3.39	2.35
280	5.27	136.84	3.33	27.72	7.81	4.44	2.17	73.18	2.13	20.93	3.51	2.35
320	5.31	136.61	3.39	27.56	7.76	4.43	2.17	72.50	2.15	20.73	3.95	2.58

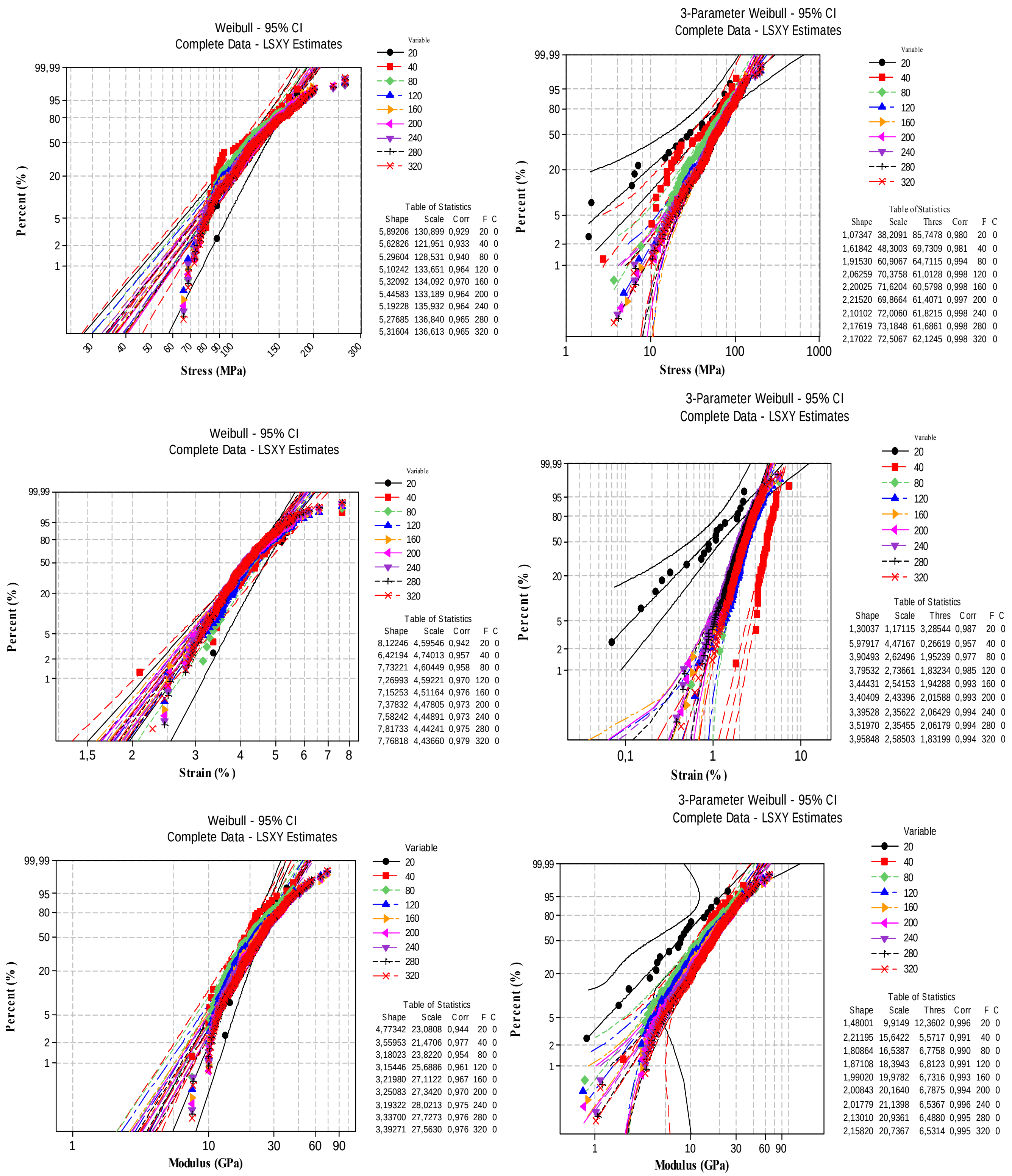

Figure 6. Two- and three-parameters Weibull distribution of the mechanical properties of jute fibre yarns.

CONCLUSION

This work shows the influence of the number of tested samples in static tension on the mechanical properties such as stress and strain at failure and Young's modulus. Furthermore, jute fibres have been characterized by both chemical and physical techniques XRD and FTIR. The chemical and physical characterization of different observed peaks show good agreement compared to those reported in literature.

Experimental results obtained from untreated jute fibre yarn, loaded in static tension for measured length (GL) of 50 mm are analysed using two- and three-parameters Weibull distribution. The analysis of the experimental results and those given by the Weibull distribution shows that:

- The studied jute yarns show a high dispersion in mechanical properties which increase with increasing the number of samples where they become constant from 200 samples tested;
- The two-parameter Weibull gave results close to those obtained experimentally, while those obtained by the three-parameter Weibull are far from the experimental ones.

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