Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 7 (24): 3951-3957, 2007
ISSN 1812-5654

Mechanical Behavior of Agave *Americana* L. Fibres: Correlation Between Fine Structure and Mechanical Properties

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Abstract: In this study, results of a mechanical behavior study of fibres extracted from the agave *Americana* L. plant, the most abundant variety in Tunisia, are presented. These results deal with the principal and mechanical characteristics of these fibres which are the elongation at break, the elasticity modulus and the rupture facture. These results permitted to situate these fibres, compared to the other textile fibres, as materials that can be used in technical applications such as reinforcing composites or geotextile. In order to understand the mechanical properties of these fibres, a correlation study between the properties already cited and the fine structure was done. The obtained results showed that the mechanical properties of agave *Americana* L. fibres are closely related to the individual fibers deformations and to the natural matrix (lignin and gums) that links these elementary fibres.

Key words: Agave *Americana* L., mechanical behavior, fine structure

INTRODUCTION

The agave *Americana* L. is a monocotyledon plant, which belong to the Amaryllidaceae class (Guendo, 1998). This plant originates from Central America and Mexico. It was introduced to Europe and Africa by the Spanish. Than, it grew naturally, especially in the arid climates, in the Mediterranean countries, India and Pakistan (Lewin and Pearce, 1985). Agave is composed of a rhizome that gives a dense flower of great rigid leaves that contain stings. The length of these leaves varies from 1 to 1.5 m (Herbert, 1954).

The leaves of these plants contain textile fibres that belong to the class of hard fibres. These fibres can be extracted either mechanically by scratching and beating using special machines called raspadors, or by splitting up the natural matrix of the leaves in sea water. After extraction, we obtain technical fibres composed of elementary ones which average length is 1 to 7.5 mm and average diameter is 24 μm (Lewin and Pearce, 1985).

Many varieties of agave grow in Tunisia, but the most abundant one is agave *Americana* L. which fibres were used by the local peoples to make ropes for marine and agriculture activities (Cuendo, 1954). Nowadays, this plant isn't used for its fibres. A study has been carried out since 1998 in a cooperation project between the ISET-Ksar Hellal (Tunisia) and the ENSIT-Mulhouse (France) to explore this source of raw material by studying its textile potential.

Studies carried out by Msahli *et al.* (2005, 2006) and Chaabouni *et al.* (2004, 2006) show that mechanical behavior of technical fibre is related to its fine structure. Indeed, technical fibre is a composite material in which the reinforcement is composed of elementary fibres and the matrix is composed of gums and wax. So, to understand the mechanical behavior of this composite structure, we must study elementary fibre and the interface elementary fibre/matrix.

Results of the mechanical behavior study of the agave *Americana* L. fibres, carried out on 2005 in laboratories of Textile Research Unit of ISET Ksar Hellal (Tunisia) and in Laboratory of Textile Physics and Mechanics in ENSIT of Mulhouse (France), are presented in this study.

MATERIALS AND METHODS

Extraction of technical fibres: Agave fibers can be extracted from leaves either mechanically by combined action of crushing and beating using machines called raspadors, or by retting of the leaves' vegetable parenchyma in seawater and cleaning by hand or a

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decorticator. Crushing and beating actions risk to decrease resistance of fibers. Furthermore, ecological problems caused by rejects and the long period of time for extraction in seawater let us not to recommend the use of these two methods. For this reasons, some tests for extracting chemically the fibers were achieved by many researchers.

In our case, the used fibers are appropriated from several leaves of different agave *Americana* L. plants growing in the region of Monastir (Tunisia). They are extracted by hydrolysis method consisting in retting agave leaves at high temperature in Mathis autoclave. This method consists in cutting a part of agave leave, immersing it in distilled water and then increasing the temperature. The method is optimized and the best results are obtained with treatment temperature of 120°C and treatment duration of 90 min. At the end of the treatment, the fibres are separated from the matrix by a calendaring treatment and then the individual fibres are rinsed with water (Chaabouni *et al*., 2006).

Extraction of ultimate fibres: Technical agave fibers occur, after their extraction, in bundles constituted of several individual fibers held together by waxy and sticky substances. The individual fibres are extracted, in this work, with the help of an alkali solution of 3.8% of NaOH at 130°C for 360 min in a classical Mathis autoclave. Such a treatment attacks the lignin and dissociates the bonds between individual fibres, so that well separated individual fibres can be obtained (Chaabouni *et al*., 2006).

Evaluation of physical and mechanical properties: The obtained technical fibers are controlled in order to evaluate their main physical and mechanical properties according to specific standards. In fact, the measurement of linear density of technical agave fibers was achieved by the gravimetric method according to the American standard ASTM D 1577-79. Results are used to calculate the average equivalent diameter of a hypothetical fiber having the same linear density and a circular section. Apparent diameter was measured using a projection microscope according to the American standard ASTM D 2130-85. Concerning the density, it was measured at 21°C using the gradient column technique.

The tensile tests of these technical fibers were carried out using Shirley dynamometer, Micron 250, with constant strain rate with a rupture duration of 20±3 sec (NFG 07-002) and a specimen length of 25 mm (ASTM D 3217-79).

All tests are conducted under standard conditions: 20±2°C and 65±2% R.H. according to the standard ASTM D 1776-85.

RESULTS AND DISCUSSION

The morphological and physical characteristics of technical fibres of agave *Americana* L. are:

- Density: 1.36
- Average count: 24 tex
- Average diameter calculated by assimilating the fibre to a cylinder: 150 μm
- Average apparent diameter: 263 μm

Compared to other textile fibres of the same class (hard vegetable fibres), agave fibres have interesting morphological and physical properties, especially its structure and its weight.

Agave *Americana* L. fibre structure: After extraction, Agave fibres occur as technical fibre composed of elementary ones held together by gums and wax (such as lignin, pectin, hemicelluloses ...). SEM examination of technical fibre (Fig. 1 and 2) confirms this composite structure.

SEM photos of technical and elementary fibres (Fig. 2-4) show also that the elementary fibres that

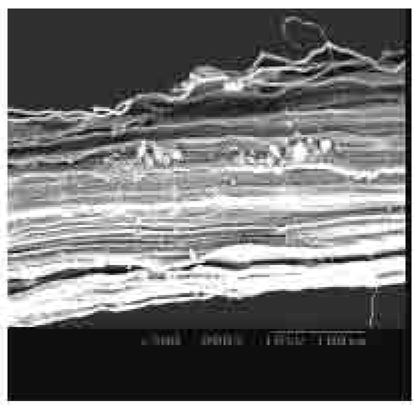


Fig. 1: Agave technical fibre

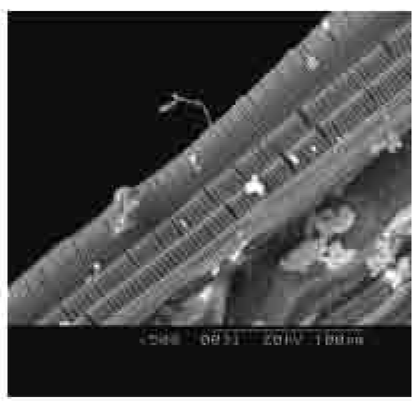


Fig. 2: SEM photos of surface view of agave technical fibre showing helical structure of elementary fibres

Fig. 3: SEM Photos of agave elementary fibres

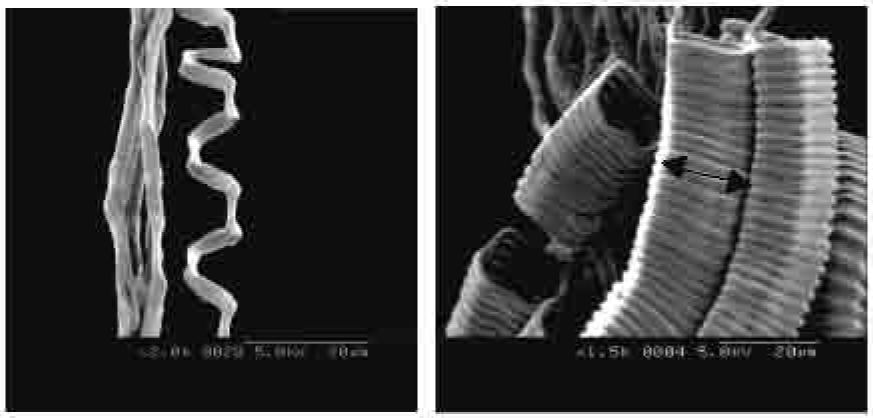


Fig. 4: SEM photos showing characteristic parameters of agave elementary fibres

compose the technical one, appears as a helical structure of square shape spires. These fibers can be characterized by two parameters: the average length of a spiral side which is about 10.1 μm and the average diameter which is equal to 3.1 μm. The average diameter is very small compared to other natural fibres such as flax (which diameter varies between 10 and 30 μm) (Satta *et al*., 1986), sisal (about 24 μm) and alfa (about 6 to 22 μm). This particular structure will be used to explain the mechanical behavior of the technical fibers.

Mechanical behavior of agave *Americana* L. fibres: Mechanical properties of textile fibres are probably the most important properties because, first of all, they characterize the mechanical behavior of the fibres in the different fabrication processes, second, they characterizes the product obtained from these fibres. The most important parameters studied in a tensile mechanical test are the rupture stress, the rupture strain, the work facture and the initial modulus. These parameters can be considered to characterize the mechanical behaviors of the fibre.

Results of the mechanical properties measurement are presented in Table 1.

Compared to other textile fibres (McGoven, 1990), agave *Americana* L. fibres present a high tenacity, a weak initial modulus, relatively high rupture energy and a very high rupture strain, which is around 50% (knowing that the elongation at rupture of natural vegetable fibres is around 5%). Table 2 presents this comparison between agave and the other textile fibres.

Stress strain curves obtained on 50 fibres tested by tensile test and a diagram of one single tested fibre are presented, respectively on Fig. 5 and 6.

Figure 5 shows that the stress strain curves forms obtained on different fibres by simple tensile test are relatively similar. This form is similar also to the stress strain curve obtained by the same test on viscose fibre and considered by Morton as a model of mechanical behavior of textile fibres (Morton and Hearle, 1975).

The relative disposition of the different diagrams confirms the high dispersion shown also by the great variation coefficient of all mechanical properties. This dispersion shows the particular structure of agave fibre.

Table 1: Experimental results of tensile test (average values obtained on 50 fibres)

	Load (N)	Tenacity (cN/tex)	Stress (MPa)	Strain (%)	Initial modulus (cN/tex)	Work facture (J)
Value min	3.80	15.556	211.70	29.36	20.11	0.023
Value max	10.05	41.078	558.14	62.36	145.49	0.076
Average value	6.9	28.3	384.6	49.6	61.0	0.046
CV%	22.9	22.9	22.9	12.5	55.6	30.14
Confidence interval (95%)	0.45	1.84	0.25	1.763	9.65	0.004

Table 2: Comparison of mechanical properties between textile fibres

Fibres	Tenacity (cN/tex)	Strain (%)	Initial modulus (N/tex)	Work facture (mN/tex)
Agave *Americana* L.	15-41	29-62	0.2-1.45	7.7-25.4
Sisal	36-45	2-3	25-26	-
Henequen	20-24	3.5-5	-	-
Flax	23-24	2.7-3.3	18	8
Jute	26-51	1.2-1.9	17.2	2.7
Coton	26-44	3-10	5	10.7
Wool (Botany 645)	11	42.5	2.3	30.9
Glass fibres -E	75	2.5	29.4	9.8
PET (HT)	56	7	13.2	22

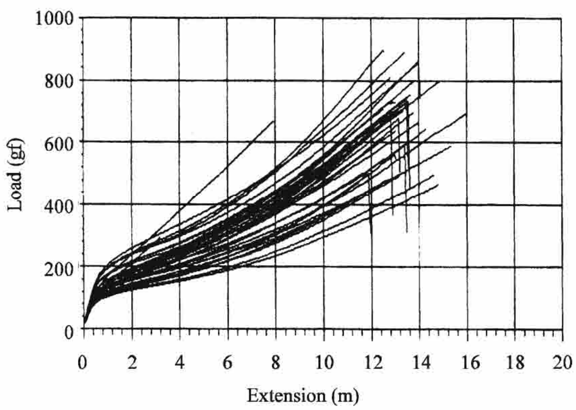


Fig. 5: Stress stain curves of tested fibres

Indeed, the number of elementary fibres that compose the technical one isn't, necessary, the same in every point in the technical fibre.

The stress strain curve of Fig. 6 is characterized by three different zones that present particular behavior:

- A first linear zone (zone 1) where the stress strain curve is linear. This zone is characterized by a small elongation and a total immediate elastic recuperation,
- A second zone (zone 2) characterized by a great deformation corresponding to a small increase of stress. In this zone of viscoelastic deformation, the recuperation is total, but it is not immediate,
- A third zone (zone 3) characterized by a plastic deformation of great slope that causes the rupture of the fibre.

In the purpose to explain this particular behavior of agave *Americana* L. fibres, a study of rupture mechanism was carried out. Indeed, the high elongation of these

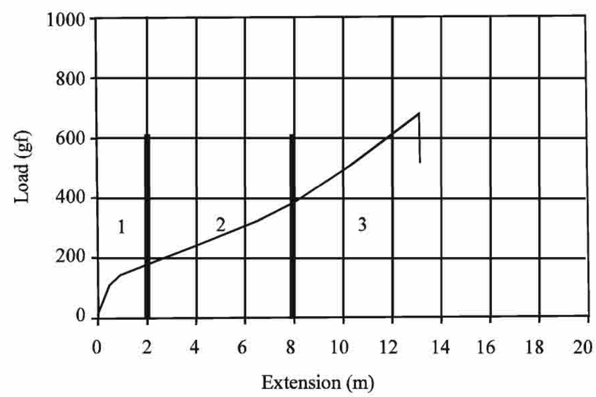
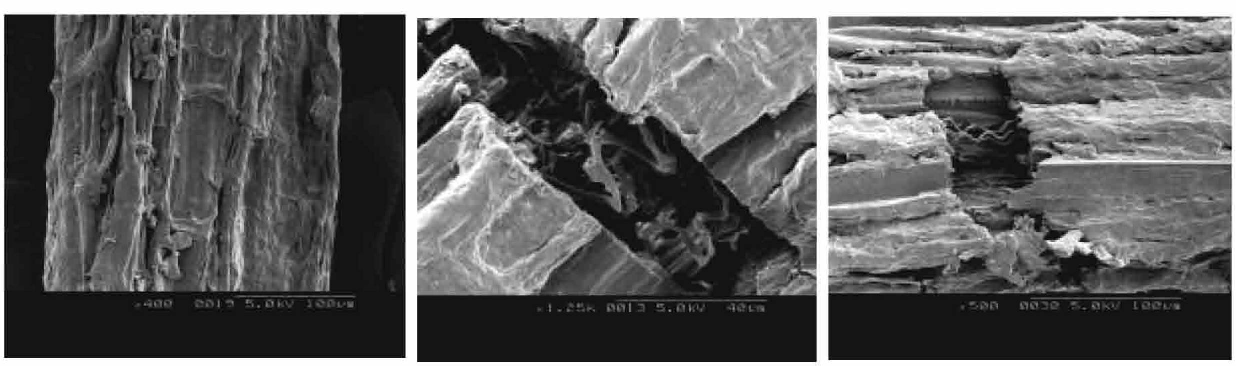


Fig. 6: Stress stain curves of one single fibre



a: Small deformations

b: Medium deformations

c: High deformations

Fig. 7: SEM photos of a technical fibres of agave *Americana* L. deformed at different degrees

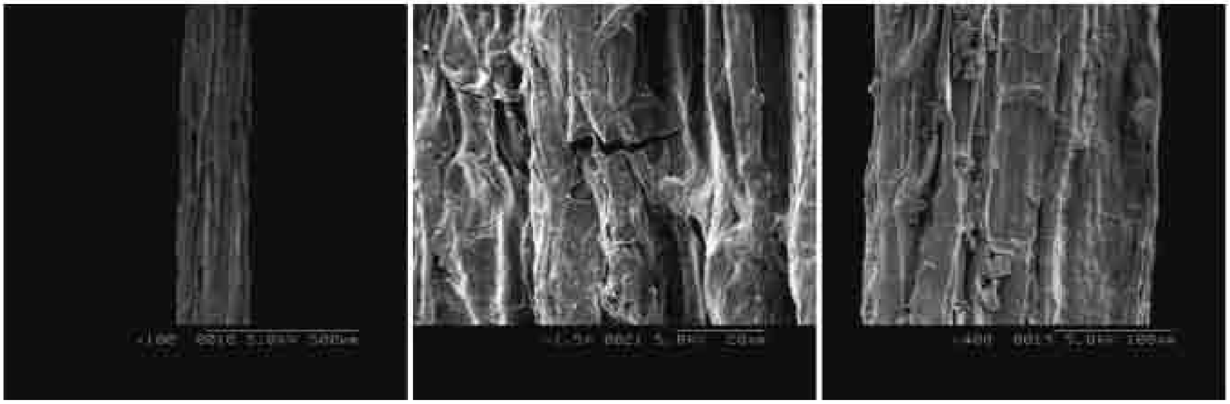


Fig. 8: SEM photos of a technical fibres of agave *Americana* L. deformed at 2%

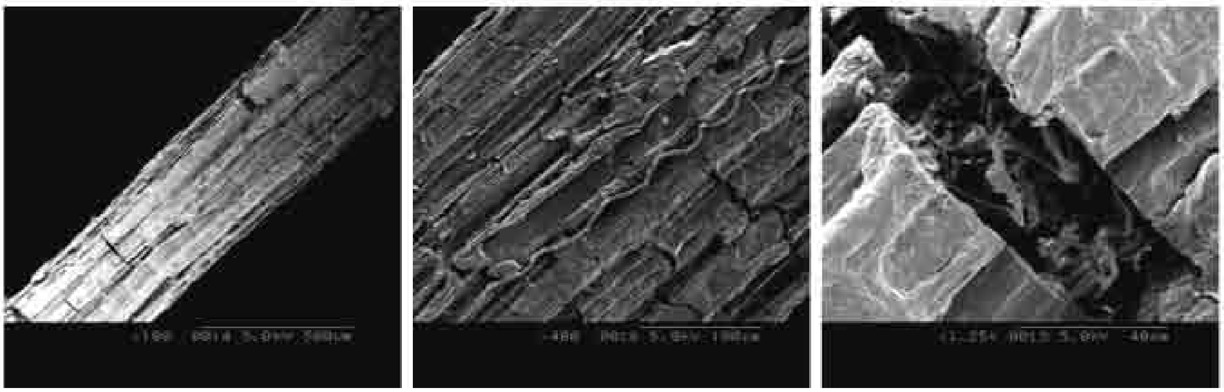


Fig. 9: SEM photos of a technical fibres of agave *Americana* L. deformed at 10%

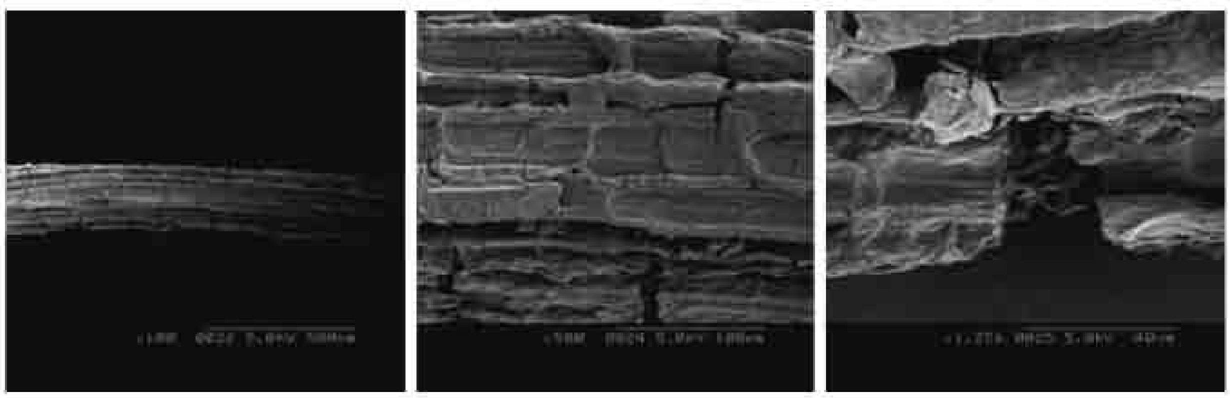


Fig. 10: SEM photos of a technical fibres of agave *Americana* L. deformed at 20%

fibres is due to the relationship between fibres and lignin. SEM photos presented in Fig. 7-11 show that the fibre is more or less cracked depending on the elongation and this phenomena generates the deformation of the elementary fibres.

At small deformations (zone 1, corresponding to elastic behaviors), the lignin endure the stress without passing it to the elementary fibres (Fig. 8). At medium deformations (zone 2, corresponding to viscoelastic deformation), the elementary fibres begin to switch on (Fig. 9 and 10) without being really deformed. The spring form of the elementary fibres makes the technical one very extensible. At high deformation (zone 3, corresponding to plastic deformation), elementary fibres begin to be deformed until the rupture (Fig. 11 and 12).

We can conclude that the mechanical behavior of technical fibre of agave *Americana* L. is highly related to its fine structure. Indeed, at small and medium

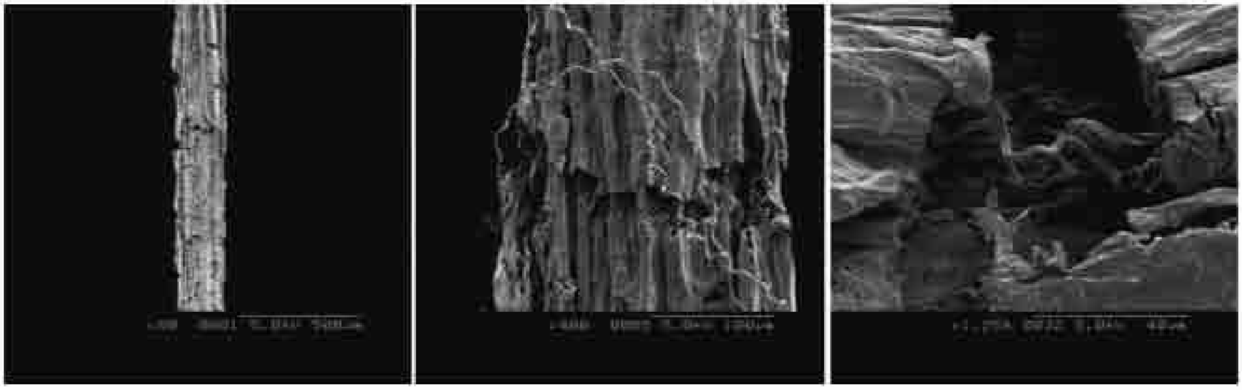


Fig. 11: SEM photos of a technical fibres of agave *Americana* L. deformed at 28%

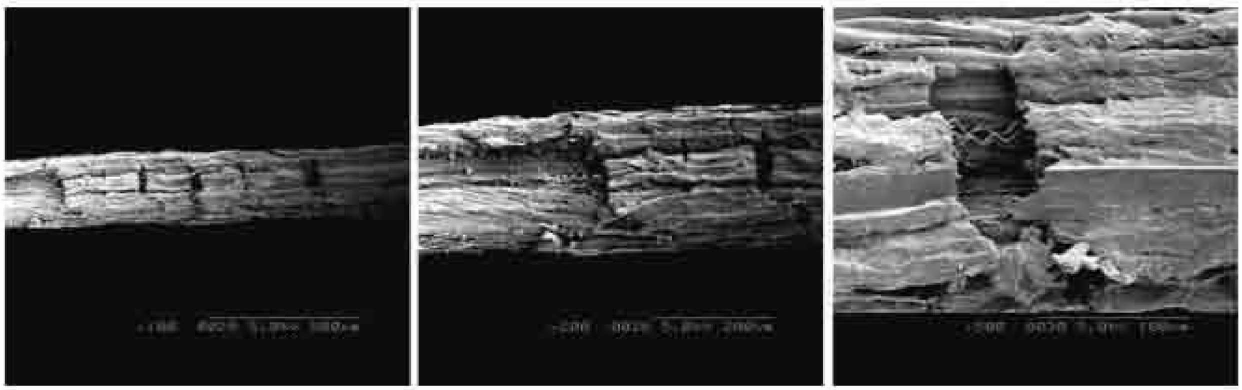


Fig. 12: SEM photos of a technical fibres of agave *Americana* L. deformed until rupture

deformations, physical and mechanical properties of technical fibre are related to physical and mechanical properties of wax and gum matters that link elementary fibres. At high deformations, that characterize this particular fibre, physical and mechanical properties are related to the properties of elementary fibres which can be elongated to more than 400%. In the rupture zone, the resistance of elementary fibres, their number, their dispersion and their adhesion to the natural matrix explain the behavior of technical fibre.

CONCLUSIONS

The characterization of an industrial sample of fibres extracted from the most abundant variety of agave in Tunisia, agave *Americana* L., permitted us to find relatively high mechanical properties compared to other textile fibres. Indeed, the tenacity of agave technical fibres is about 29 cN/tex. This value is relatively high compared to the specific resistance of other fibres belonging to the same class. The low density of agave *Americana* L., which is 1.36, is an important characteristic. Indeed, in some technical applications (composite materials for example), the ratio resistance/density is an important parameter. The elongation at rupture of agave *Americana* L. fibres is very high compared to other vegetable fibres. This characteristic is explained by the particular fine structure that changes in the course of the tensile test.

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