Effect of the fibre morphology on the mechanical properties of hemp fibres: Digital imaging treatments coupled to 3D computational analysis

F. Ilczyszyn[1*], A. Cherouat[2], G. Montay[1]

[1]*Charles Delaunay Institute, Troyes University of Technology (UTT), LASMIS laboratory, 12 rue Marie Curie, BP 2060, 10010 Troyes, France*
[2]*Charles Delaunay Institute, Troyes University of Technology (UTT), GAMMA3 laboratory, 12 rue Marie Curie, BP 2060, 10010 Troyes, France*
**florent.ilczyszyn@utt.fr*

Keywords: natural fiber, tensile test, hemp, digital imaging

Abstract

The hemp fibres present specific fibre morphology and a complex non homogeneous cross section which changes in function of the location along the fibre length. Thus the mechanical properties of hemp fibres request a specific characterization method. In this study, firstly, a digital treatment method was developed allowing to consider different geometrical modelling methods: homogeneous or non-homogenous cross section, average global cross section, and cross section measured at the rupture location, including a 3D CAD model reconstruction of the fibre. In this paper, inverse optimization computation using the simplex algorithm, experimental tensile tests and 3D finite elements computational analysis were carried out in order to take into account the real fibre morphology and to determinate the engineering hemp fibre material properties. Different tensile tests for several fibre morphologies was achieved and discussed. The results showed a high impact of the hemp fibre morphology on their main mechanical properties (Young modulus, maximum stress and failure strain).

1 Introduction

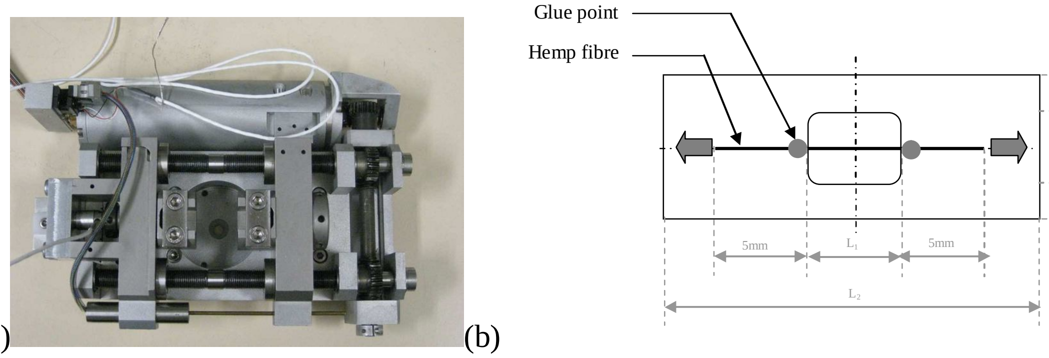
Fibres used as reinforcements into compounds based on polymer are mainly synthetic as glass or carbon fibres. This kind of fibres presents very high mechanical and morphological properties. However other fibres can replace them like natural fibres which present some interesting physical and mechanical properties [1-4]. In this study, hemp fibres extracted from the hemp stem was characterized. In order to use hemp fibres into a compound, it is necessary to determine the exactly mechanical properties of the reinforcement. Hemp fibres present a non-standard geometry after extraction. The majority of studies consider the cross section of fibres as circular, but this hypothesis lead to make some errors of different property values, especially the maximum stress and the Young modulus.

In this paper, a new method which allows to determine finely the fibre cross section using digital imaging treatment is used. Basing on the geometrical morphology data, different models were investigated to characterize the hemp fibre engineering properties. The models are based on the following consideration: (1) average homogenous circular cross section; (2) average homogenous polygonal cross section; non-homogenous cross section as circular (3) or polygonal (4) section at the failure location and (5) 3D geometric real model of fibre which takes into account the non circularity and the variation of the cross section along the fibre.

Digital imaging treatment and CAD reconstitution of fibre are used to compute the 3D fibre design. Optimization computation using Simplex algorithm coupled to finite element method (Abaqus) is used to characterize the mechanical engineering properties of the hemp fibre. Experimental and numerical tensile tests results considering the above different models will be presented and interpreted.

2 Materials and testing methods

The tensile tests described in this work can be applied to elementary fibers as well as bundles. The sampled tested are elementary fibers manually extracted from hemp stem was cultivated in Aube (France). The fibers are assembled with a paper support which is pierced in its middle by a rectangular hole showed in Fig.1b. For these tests, the length of hole L1 =10mm was used. Tow glue points at both ends of sample keep the fiber on the support. The lengths L2, L3 and L4 were fixed respectively to 60, 6 and 10mm, which allows to set up the support in the tension machine.



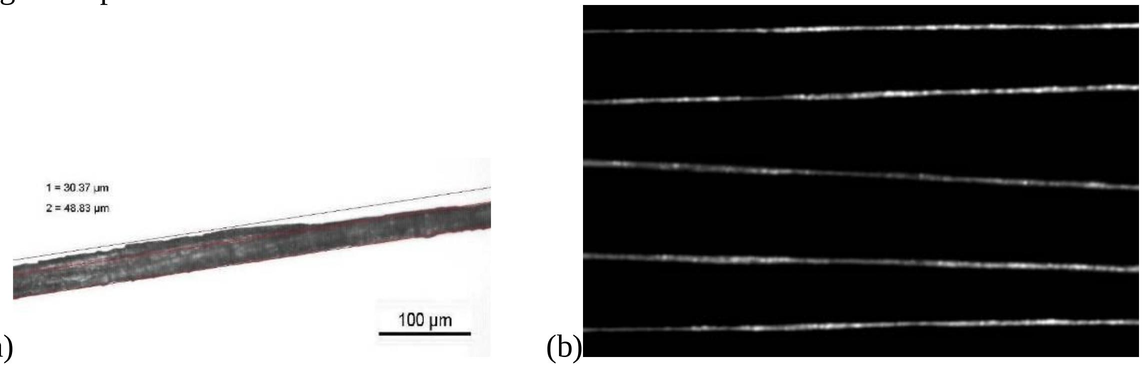
(a) (b)

Figures 1. Photo of the micro-tensile test machine (a) and scheme of support (b)

A micro-tensile test machine Kammrath & Weiss (Fig. 1a) was used to carry out uniaxial tensile tests of very small samples. The displacement speed of the machine was 1µm.s-1. The load cell capability is 50N with an uncertainty of 1/100N. With this kind of tensile test machine, the measure errors caused by the rigidity of the machine can be disregard.

3 Digital imaging treatment

Hemp fibres are a natural material and they present a non-standard geometry. The diameter is not constant along the fibre; consequently the fibre profile is not constant as showed by the Fig.2. Moreover the cross section is not circular, the diameter change in function of the angular aspect.



(a) (b)

Figure 2. Microscopy of hemp elementary fibre, a) part of an elementary fibre et b) microscopic pictures of hemp fibre for different orientations

Different methods are used to measure the diameter and to determine the cross section as the light diffraction method used by C.Romão [5], the scanning electron microscopy used by L.Y. Mwaikambo [6], the local measure method along the fibre for which the cross section is defined as being circular used by R. Schledjewski [7] and the local measure method which take into account the non circularity of the cross section used by S. Munawar [8]. These methods are rough and have tow disadvantages: (1) some methods are an average of local measures which couldn't detect all variations of the cross section profile and (2) others don't take into account the non-circularity of the cross section. Thus the mechanical properties, specifically the Young Modulus and the longitudinal stress, will be wrong. Firstly, the goal of this study was to develop a method to measure the real geometry of the fibre. Secondly, to take into account this measured profile to determinate the mechanical properties of a unitary fibre [9]. Thus a profile detection and cross section measure method of fibre was developed and investigated. This method consists in taking several pictures at different tested sample orientations. A total of 5 pictures (Fig 2b) were taken at 0°, 36°, 72°, 108° and 144° using a specific mounting showed in Figs 3 and 4.

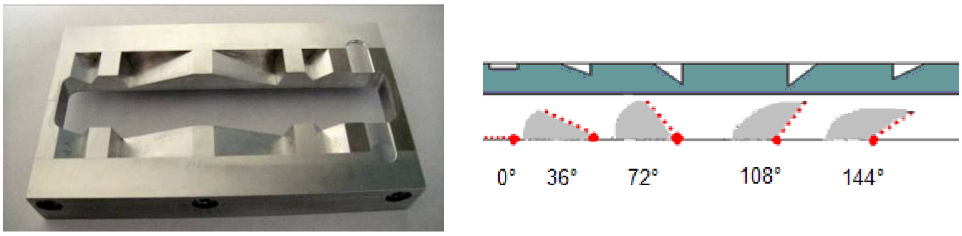


Figure 3. Photo and scheme of the mounting allowing to measure the cross section at different orientations

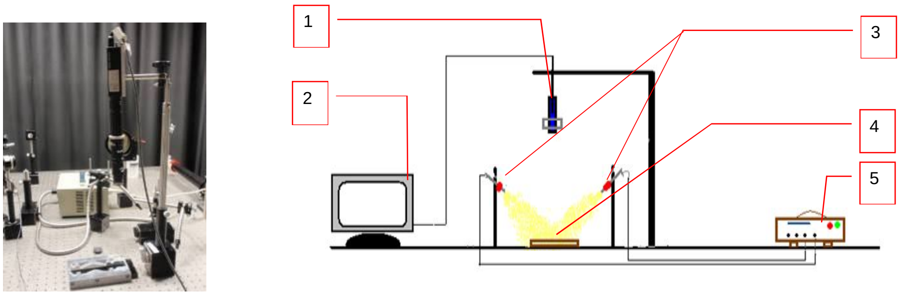


Figure 4. Photo and scheme of the system allowing to measure the cross section
1 : camera with an optical lens (×5), 2: computer, 3: white and cold light, 4 : mounting which allows to adjust the angular orientation, 5: Monitor to set the intensity of light

For the automatic treatment of the microscopic digital pictures, a program was developed using OpenCV libraries. For each fibre aspects, the program determines:

1. the coordinates of boundary profile points (Fig. 5)
2. the average diameters (D_i) (Fig.7)
3. the diameter (Di_c) at the failure location.

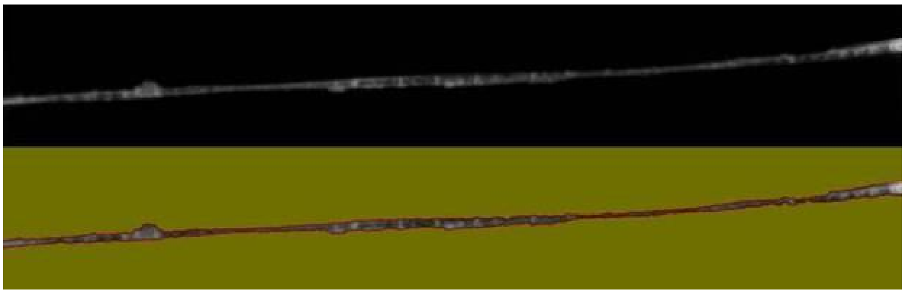


Figure 5. Photo of a fibre before and after the digital treatment

4 Geometrical section models

The geometric data of boundary profiles determined by a digital imaging treatment are used to reconstruct the 3D geometrical profile. As hemp fibre doesn't have a standard profile, it's necessary to determine the real geometry of each hemp sample tested. From the geometric data points, five different methods of fibre cross section modelling were investigated in order to characterize the mechanical tensile test properties of hemp fibres (Fig. 6).

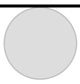
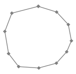
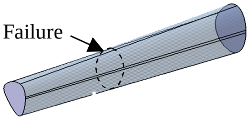
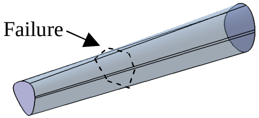
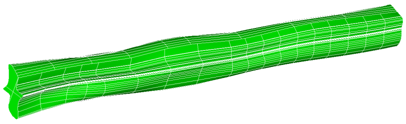
Average cross section	**Method 1** Circular and homogenous cross section along the fiber	 $\sigma = \dfrac{F}{S_{circular}}$
	Method 2 Polygonal and non-homogenous cross section along the fiber	 $\sigma = \dfrac{F}{S_{polygonal}}$
Cross section at the failure point	**Method 3** Circular cross section at the failure point	
	Method 4 Polygonal cross section at the failure point	
Realistic 3D model	**Method 5** Real non-homogenous cross section	

Figure 2. Différentes méthodes de modélisation de la fibre

For the method 1 and 3, the value of the cross section is the average diameter for each fiber orientations (Fig. 7). For the method 2 and 4, the value of the polygonal sections was calculated using finite elements discretization.

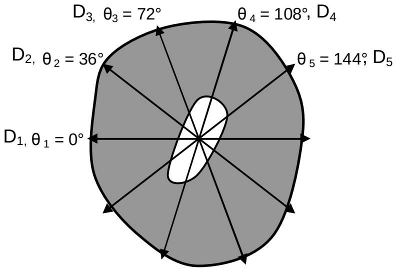


Figure 7. Boundary profile of the fibre cross section

For the method 5, the 3D CAD model of hemp fibre was generated using the CATIA-V5 software. The CAD model is reconstructed using ten section profiles spaced out of 1mm (Fig.8). The section profiles are obtained by imaging treatment showed previously.

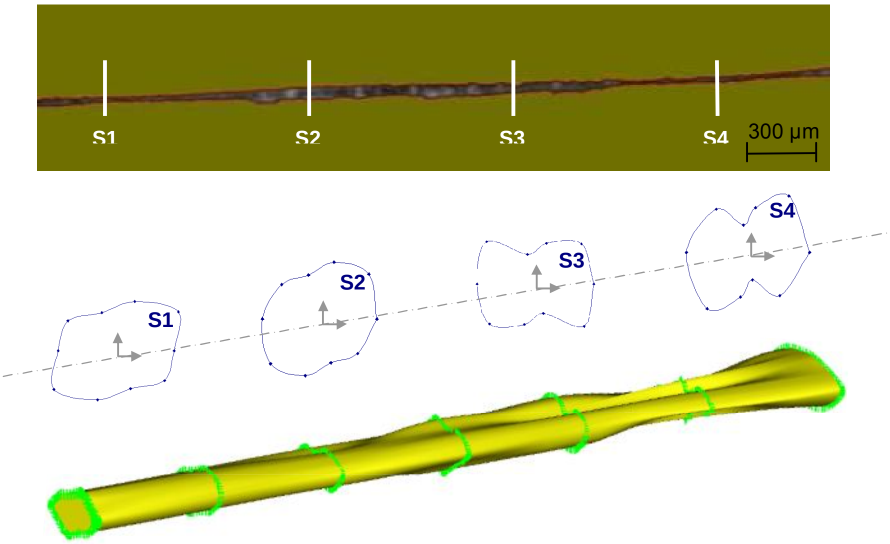


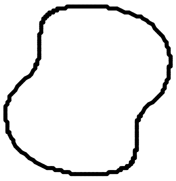
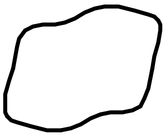
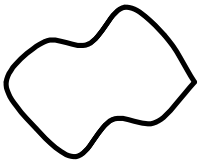
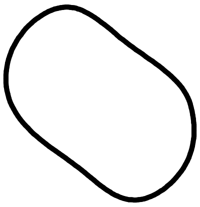
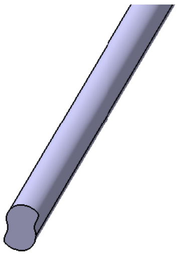
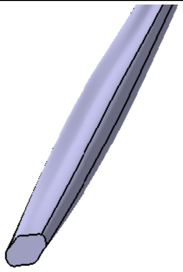
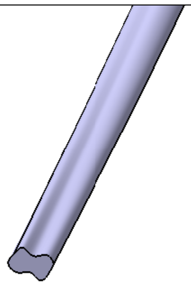
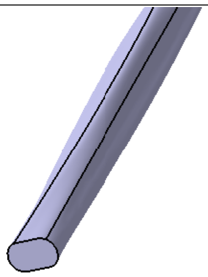
Figure 8. 3D CAD model of hemp fibre

An inverse optimization process using simplex algorithm and finite elements method (ABAQUS solver) is used to estimate the hemp fibre engineering material constants considering the 3D CAD fibre model. The mechanical behaviour of hemp fibres can be considered as quasi-linear from the beginning of the tensile solicitation until the failure state. The principle of inverse methods for material identification is to update iteratively the engineering constants in a finite element model of the tested specimens in such way that the computed forces match the measured forces. The engineering constants which minimize the output residual are considered as the optimized solution. The minimization of the output residual is fulfilled by an optimization process, which minimize a scalar function called ‘‘the objective function’’. In this study, the objective function is the sum of squared residual components.

5 Results and interpretations

A set of computer simulations and experimental tests was accomplished with each of five methods. The experiments use different cross section geometries of unitary hemp fibres. Each fibre presents different morphologies due to a natural state and several successive extraction steps. An example of different hemp fibre cross section profiles are presented in Table 1. The hemp fibre samples are an average diameter of 42µm with a deviation of ±10 µm. The hemp fibre tensile tests results (Table 2) show a high scattering of the engineering elastic property (Young’s modulus) and tensile strength (maximum strain and stress at the failure time). Considering the global circular model characterization (Method 1), the maximum longitudinal tensile stress is 170 ±75MPa, the strain at the failure time is 1.8 ±0.6% and the Young’s modulus is 9515 ±4218MPa. The maximum tensile load doesn’t rise above 0.3N and the longitudinal displacement varies from 121 to 247µm. In order to characterize the mechanical property of hemp fibres, the five cross section modelling methods presented above are used. The longitudinal strain will not change because it doesn’t depend of the cross section, whereas the tensile stress and the Young’s modulus is calculated from the cross section, thus they will be influenced by the modelling methods.

Table 1. Examples of hemp fibre sample sections and 3D models

	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**
Cross section profile at 0.02mm				
3D model				

The results showed in Figure 9 describe the tensile stress versus the strain for different cross section modelling. The maximum stress is about 170±75MPa for a circular cross section (Method 1) and 182 ±80MPa for the cross polygonal section (Method 2). The maximum stress of the cross circular and polygonal section methods (Methods 3 and 4) at the failure location is respectively 252±116MPa and 268±125MPa (Table 2). The results also show that the fibre failure and crack occur at a point where the section is smaller than the average global section. So there is a stress concentration phenomena located at the failure point which favours the crack of fibre.

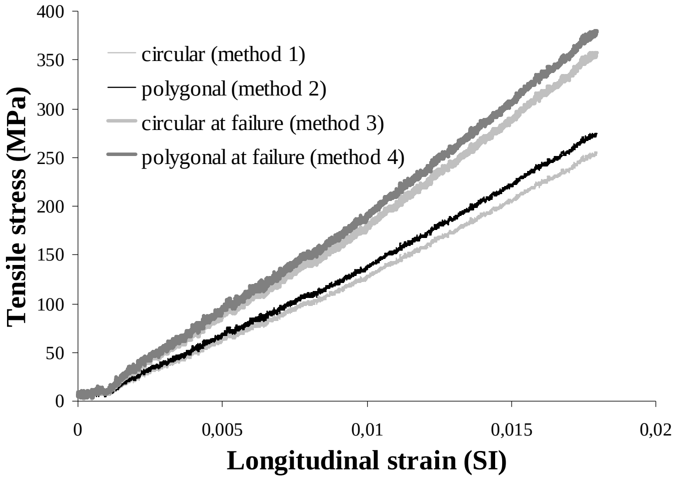


Figure 9. Tensile stress versus longitudinal strain using different methods

The results (Fig. 10) show a dispersion of 6.5% of the cross section value, the maximum stress and the Young's modulus. This error is due to a geometrical rough guess of the cross section. To represent the cross section by a polygon shape is more accurate than to consider it as circular. It allows to take into account the evolution of diameter in function of fibre aspect. The cross section value is 36.6% smaller than all over the fibre, the maximum stress is 4.8% higher and the Young's modulus is 55.8% higher at the failure location. So considering a homogenous section (circular or polygonal) along the fibre don't allow to take into account the real morphology of hemp fibre, and thus the stress concentration zone caused by a variation of the cross section at the failure point cant be detected. Thus it is necessary to take into account the real geometric morphology of fibres for the mechanical characterization of fibre engineering properties.

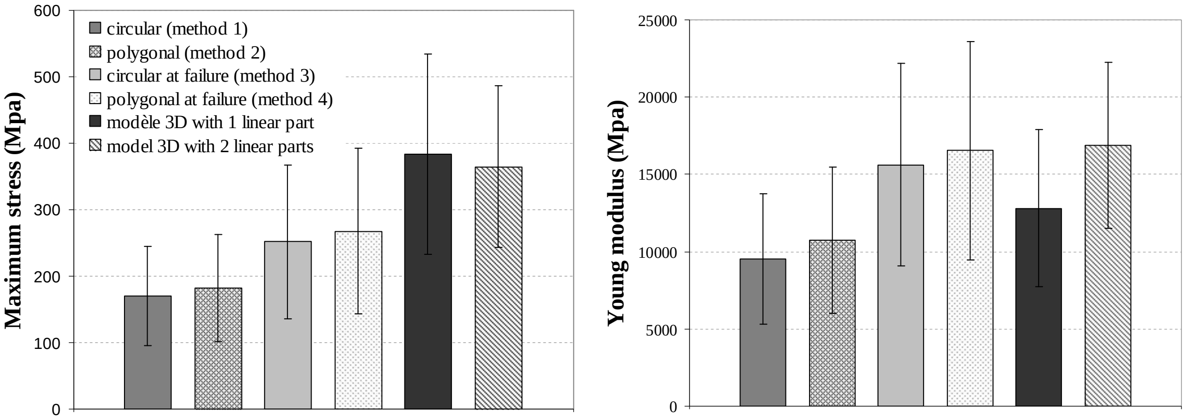


Figure 10. Maximum stress and Young's modulus

For 3D modelling method, the Young's modulus was determined using an optimization simplex method. Two cases were investigated in this study. In the first case, we consider the behaviour until the crack time as elastic linear (Method 5a) and in the second case as elastic non-linear (Method 5b). The maximum stress found using the Methods 5a and 5b, is respectively about 383±152MPa and 365 ±122MPa (Table 2). These methods give the highest values of the maximum stress. It shows that there are along the fibre, some sections which are smaller than the section at the failure point, thus in the fibre it can have some place where the rigidity is different; for example the location where the natural defect appears or where there are some residues from other materials composing the hemp fibre bundles. The value of the maximum stress is almost the same using a model with one linear part and with two linear parts. Modelling the mechanical behaviour of an unitary fibre with two linear parts model reduce the statistical deviation, thus the method 5b allow to determine with a better accuracy the maximum stress. At contrary, the non-linear model gives a value of the Young's modulus slightly superior to the value obtained with polygonal cross section at failure (Method 4). Considering a 3D modelling of fibre allow to reduce the deviation of the Young's modulus, from 7069MPa for the Method 4 to 5401MPa for the Method 5b. Thus to take into account the variation of the cross section along the fibre considering a non-homogeneous section allows to determine with more accuracy the mechanical properties.

Table 2. Mechanical properties of hemp unitary fibres considering different methods

	Cross section (mm²)		**Stress at failure (MPa)**		**Young's modulus (MPa)**	
	Average value	**deviation**	**Average value**	**deviation**	**Average value**	**deviation**
Method 1	1.464×10^{-3}	0.681×10^{-3}	170	75	9515	4218
Method 2	1.370×10^{-3}	0.642×10^{-3}	182	80	10749	4701
Method 3	0.925×10^{-3}	0.350×10^{-3}	252	116	15620	6538
Method 4	0.873×10^{-3}	0.334×10^{-3}	268	125	16544	7069
Method 5a	-	-	383	152	12808	5085
Method 5b	-	-	365	122	16879	5401

6 Conclusion

In this paper, a digital imaging method was developed allowing to get the real geometric profile of an unitary hemp fibre. With these geometrical data, different fibre modelling methods was investigated to characterize the mechanical properties of an unitary hemp fibres.

- Firstly, results determined by different characterization methods were presented. It shows a dispersion of 6.5% for the cross section value, the maximum stress and the Young's modulus. This error is due to a geometrical rough guess of the cross section.
- Secondly to represent the cross section by a polygon is more accurate than to consider it as circular. It allows to take into account the evolution of diameter in function of fibre orientation. Considering a local and polygonal cross section at the failure point allows to take into account the variation of the cross section along the fibre, and thus the stress concentration caused by a variation of the cross section at the failure location can be detected.
- Thistly to consider the real geometric morphology of fibres allows to calculate with more accuracy the Young's modulus and to determine the exact value of the maximum stress and strain considering the stress concentration into the fibre caused by the variation of the section along the fibre.

References

[1] Bodros E., Pillin I., et al. Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications?, *Composites Science and Technology,* **67(3-4)**, 462-470 (2007)

[2] Joshi S.V., Drazl L.TL., Mohanty A.K., Arora S. Are natural fiber composites environmentally superior to glass fiber reinforced composite, *Composites: Part A,* **35**, 371-376 (2004)

[3] Mohanty A.K., Missa M., Drazl L.T. Natural fibres, biopolymers and bio composites, (2005)

[4] Wambua P., Jan Ivens, Verpoest. I. Natural fibres: Can they replace glass in fibre reinforced plastics, *Composites Science and Technology,* **63**, 1259-1264 (2003)

[5] Romão C., Vieira P., Peito F., Marques A.T., Esteves J.L. Single filament mechanical characterisation of hemp fibres for reinforcing composite materials. *Molecular crystals and liquid crystals,* **Vol. 418**, 87-99 (2004)

[6] Mwaikanbo L.Y., Ansell M.P. Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials – I. hemp fibres. *J Master Sci 41,* 2483-2496 (2006)

[7] Schledjewski R., Medina L., Schlarb A.K. Mechanical and morphological characterization of selected natural fibres, *Advanced Composites Letters,* **Vol. 15 N°2** (2006)

[8] Munawar S.S., Umemura K., Kawai S. Characterization of the morphological, physical, and mechanical properties of seven nonwood plant fiber bundles, *The Japan Wood Research Society,* **53**, 108-113 (2007)

[9] Ilczyszyn F., Cherouat A., Montay G. *Caractérisation des propriétés mécaniques de fibres de chanvre* in Proceeding of *Matériaux 2010,* Nantes, France, (2010)