CONCEPTION OF AN INSTRUMENTED TORSION PENDULUM FOR MEASURING THE SHEAR MODULUS OF FIBRES

1- Validating the method for both synthetic and natural fibers

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A. INTRODUCTION

The use of synthetic or natural fibers as reinforcements requires a thorough knowledge of their mechanical properties. Among these properties, the Young's modulus *E* reflects the resistance of a material stressed in tension or compression whereas the Coulomb's modulus *G* is involved in the characterization of deformations caused by the shear stresses (twisting, etc.). If the material is isotropic (invariance of physical properties depending on the direction), *G* can be calculated from *E* and the Poisson's ratio.

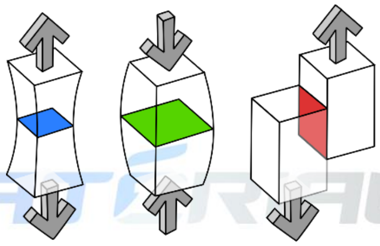

Figure 1: Stress modes (tension, compression and shear).

Currently, the Young's modulus of natural fibers is measured through tensile tests on monofilaments. However, these fibers have an anisotropic structure, which means that their Coulomb's modulus cannot be determined from the data derived from tensile tests.

The development of a characterization method based on the torsion pendulum will allow measurement of the shear strength of vegetable fibers. The main difficulty of this study lies in the very nature of these fibers which, unlike synthetic fibers, have characteristics that may vary depending on the variety, the place of culture, the year of production, etc.

B. METHOD

1) Description (Figure 2)

A filament is fixed between two semi-cylindrical aluminum jaws. They have a low mass calculated in such a way that there is a very low and negligible tensile stress on the fiber.

After completing the bonding, the "filament + jaw" system is suspended below the motor axis by the upper jaw. Computer-controlled pneumatic clamps block the suspended mass (i.e. the lower jaw) when it is completely motionless. A twist angle is applied through the motor generating a stress in the fiber. After release of the stress, the lower jaw oscillates freely in the air until full damping.

To measure the amplitude and the damping of the oscillation, the pendulum is equipped with a HD camera placed under the lower jaw. Software developed by Matériau Ingénierie calculates the angle of the lower jaw in motion according to the initial position.

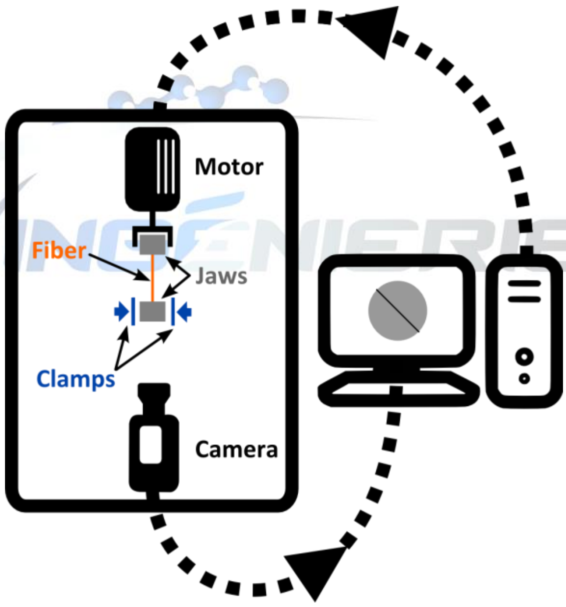

Figure 2: Schematic diagram of the torsion pendulum developed by Matériau Ingénierie.

2) Rotation direction

Vegetal fibers are composed of plant cells bonded together by a layer of lignin (see *Figure 3*). It is removed during harvesting and subsequent processing steps. This leaves only the plant cells which have the form of monofilaments whose internal structure is composed of:

- the lumen, an empty area in the heart of the plant cell (ranging from 1 to 6% for a mature fiber);
- the three secondary walls, consist of cellulose crystals arranged helically (those of the wall S2 are oriented at an angle said Micro-Fibrillar Angle or MFA);
- & the primary wall, made of amorphous cellulose.

The microfibrillar orientation is different for the different types of cellulosic fibers. This is a factor of major influence on the mechanical properties of the fibers. For example, the MFA is 41-45° for coir, 10° for flax and 20° for sisal. Furthermore the orientation of microfibrils, the strength and the stiffness of fibers will depend on their constitution, the rate of cellulose, the degree of crystallinity and the degree of polymerization. Furthermore, the maturity of fibers and the part of the plant from which the fibers are are important [1].

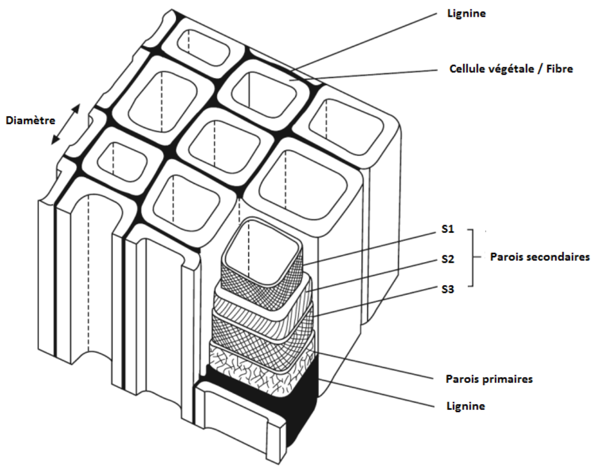

Figure 3: Structure of vegetal cellulosic fibers.

Given the major influence of the MFA comparative tests in clockwise and anticlockwise direction have been made.

3) Materials

Tests were carried out on three types of synthetics fibers:

- Glass fibers (5 batches) ;
- Ex-PAN carbon fibers (2 batches)
- Copper fibers (1 batch).

Tests were then conducted on natural fibers. Four vegetal species have been identified:

- hemp fibers (1 batch) ;
- coco fibers (1 batch);
- kenaf fibers (1 batch) ;
- flax fibers (8 batches), which comes in two forms:
  - ✓ the tow, obtained after the heckling;
  - ✓ the roving (fiber sliver easy to weave), obtained after a processing step.

C. RESULTS

1) Synthetic fibers

Results obtained for synthetic fibers are given in *Table 1*. Values of the column "References" are theoretical values calculated from the Young's modulus and Poisson's ratio long been known (for isotropic fibers) or data found in the literature (for carbon fibers).

Table 1: Torsion modulus of synthetic fibers.

Name	G (GPa)	s.d. (GPa)	References
E-CR Glass	29,8	0,1	30-36
H Glass	29,1	0,2	33
S Glass	26,3	0,3	35,1
AR Glass	25,5	0,0	30
R Glass	25,6	-	35,5
Copper	45,3	0,0	44,7
Carbon H1	21,8	0,4	17-28
Carbon H2	22	2,0	17-28

The torsional modulus obtained for copper fibers matches the data from the literature [2].

Similarly, the values obtained for ex-PAN carbon fibers are in the range of values obtained by different authors [3-9].

For glass fibers, differences appear compared to the theoretical values, except for the fiberglass E-CR. These differences are probably due to the diameters values used in the calculations. For synthetic fibers (other than copper), we used the theoretical diameter values provided by manufacturers [10]. The presence of sizing can induce a slight difference between this value and the actual value generating a significant error on the calculation of the module. Systematically measuring of diameters will help improve the results accuracy.

2) Natural fibers

Results obtained from natural fibers are given in *Table 2*. At first, we did not consider the rotation direction.

<u>**Comparison of vegetal species:**</u> The modulus of the kenaf fiber is the lowest (0.33 GPa) due to a low rate of cellulose and a small MFA.

Moduli of flax (0.82 to 1 GPa) and hemp fibers (1.03 GPa) are almost identical, these two fiber types having similar structures. Cellulose rate and MFA are within the same ranges of values (*Table 2*). This similarity finds himself by analyzing the Young's modulus values of the literature.

Coconut fiber has the highest modulus (2.81 GPa). This result is due to its deeply different structure: its cellulose rate is low (43-46%) but the MFA is important (39 -49°).

<u>Note:</u> Standard deviations are higher than for synthetic fibers. This dispersion of results may be related to the heterogeneity of natural fibers.

Table 2: Torsion modulus of natural fibers & structural and morphological data [11-14].

Name	G (GPa)	s.d. (GPa)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	MFA (°)	E (GPa)
Flax D1$_f$	0,84	0,32	60-81	14-21	2-5	1-4	5-10	50-70
Flax D2$_f$	0,83	0,28						
Flax D3$_f$	0,82	0,3						
Flax D1$_r$	0,43	0,06						
Flax D2$_r$	0,68	0,12						
Flax D3$_r$	0,6	0,21						
Flax F1$_f$	0,89	0,37						
Flax C1$_f$	1	0,43						
Hemp F1$_f$	1,03	0,19	70-92	18-22	3-5	1	6	30-60
Coco C1	2,81	0,71	43-46	0-25	45-46	3-4	39-49	6
Kenaf C1	0,33	0,18	44-87	22	15-19	2	7-8	22-60

Comparison tow/roving : The only difference between fibers from tow batches D1$_f$, D2$_f$ and D3$_f$ and those from roving batches D1$_r$, D2$_r$ and D3$_r$ is the additional processing step undergone by the latest. This step degrades the fibers by mechanical action. Logically we note a decrease of Coulomb's modulus from 0.83 GPa to 0.57 GPa (on average). Unlike the standard deviations tend to decrease (from 0.3 to 0.13 GPa) which could indicate an homogenization of fibers performance.

Influence of the rotation direction: Some natural fibers were solicited by applying rotations clockwise and counterclockwise. Here the aim is to check if the direction of rotation influences the modulus measurement (*Table 3*).

Table 3: Torsion modulus based on the rotation direction.

Name	G_{min} (GPa)	s.d. (GPa)	G_{max} (GPa)	s.d. (GPa)
Flax D1$_r$	0,5	0,07	0,55	0,08
Flax F1$_f$	0,74	0,13	1,08	0,25
Flax C1$_f$	0,92	0,28	1,06	0,31

Tow batches F1$_f$ and C1$_F$ show modulus differences depending on the direction of load, ranging from 0.18 to 0.34 GPa. The roving batch D1$_R$ exhibits only minimal difference (0.05 GPa) smaller than the standard deviation It is currently difficult to conclude. Additional tests are expected.

D. CONCLUSIONS

This first series of tests has shown our instrumented pendulum allows an accurate measure of fibers Coulomb's modulus. Based on of these results, structure/properties relationships have been proposed for natural fibers.

Further tests are planned to refine the results, particularly those concerning the relationship between the MFA and the direction of rotation. Other types of fibers will be tested (kevlar, nylon, cellulose, etc.) in order to validate the performance of our instrument on a lager panel of materials.

The next step in the development of this pendulum is ongoing and involves integrating an accurate measuring system of fiber diameter by laser diffraction in the unit. This measure will be performed automatically before testing (on a fiber undergoing the tensile stress imposed by the lower jaw).

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