Industrial Crops & Products 113 (2018) 179–186

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Exploring the link between flexural behaviour of hemp and flax stems and fibre stiffness

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ARTICLE INFO

Keywords:
Plant fibre
Stem
Bending
Anatomy
Mechanical properties

ABSTRACT

Hemp (*Cannabis Sativa*) and flax (*Linum Usitatissimum* L) are the most commonly cultivated fibre plants in Europe. The use of their fibres covers a wide range of applications and requires a precise knowledge of their mechanical properties. The aim of this study is to investigate the contribution of fibres to the stiffness of flax and hemp dry stems subjected to bending during a simple three-point flexural test. The analysis is based on measuring the difference of bending stiffness between stems with fibres and stems without fibres after removal by manual peeling. Mechanical characterization shows that hemp and flax fibres contribute 54% and 71%, respectively, on average, to the flexural stiffness of a stem. Then, a microstructural analysis of stems is used to determine fibre distribution and geometry, which leads us to obtain longitudinal moduli of 33.9 ± 13.0 GPa and 55.8 ± 14.5 GPa for hemp and flax, respectively. These values are close to those obtained by tensile tests on elementary fibres (30.0 ± 13.3 GPa and 54.7 ± 13.2 GPa). These results encourage to propose the three-point bending test on stems as a standard test for the estimation of bast fibre stiffness.

1. Introduction

Ecological and environmental concerns have increased interest in the use of natural fibres from plants for the development of biocomposites. Hemp (*Cannabis Sativa*) and flax (*Linum Usitatissimum* L) fibres are ideal candidates to be used as substitutes for synthetic fibres as reinforcements in composite materials (Baley and Bourmaud, 2014; Beckermann and Pickering, 2008; Duval et al., 2011). In Europe, hemp and flax are the most commonly cultivated plants providing fibres with suitable environmental, mechanical and ecological properties. Interestingly, seeds and woody core also have specific markets, thus increasing the profitability of cultivation. This leads to a total area of cultivated land which can attain 140 000 ha per annum, on average, with 10% being attributed to hemp and 90% to flax (Karus and Vogt, 2004). Since these annual crops are favoured by a short life cycle, they are easily integrated into farmers' crop rotations.

Stems can be considered as hollow cylinders of variable length and diameter depending on growth conditions, variety and the stage of development of the plant (Bourmaud et al., 2016; Goudenhooft et al., 2017). In Europe, hemp plants in the field reach between 2 and 4 m in height with a stem diameter of about 5–30 mm decreasing from the base to the apex (Bouloc, 2006). In the case of flax, the plant height reaches around 1 m with a diameter of about 3 mm (Kulma et al., 2015). The flax stem is made up of several tissues arranged in the form of successive rings (Goudenhooft et al., 2017) affording protection, support, conduction and various metabolic functions.

1.1. Stem scale

From the centre to the periphery, the structure within the stem is as follows: pith, xylem, vascular cambium, phloem, fibres (used in textiles, and considered as support tissue), cortical parenchyma and epidermis. Hemp stems show a similar structure and contain primary fibres derived from primary growth along the length of the stem, but have the particularity of having a secondary fibre network, developed rather in the lower part of the plant (Snegireva et al., 2010).

1.2. Tissue scale

Two main tissues can be identified: fibres at the periphery of the stem, and wood at the centre of the stem. The woody core (also called shives in the case of flax) is a highly lignified alveolar structure made up of xylem and phloem (Beaugrand et al., 2014; Day et al., 2005). The xylem is responsible for the conduction of raw sap from the roots to the vegetative parts. This structure also plays the role of a supporting element (Deger et al., 2010). On the other hand, the phloem ensures the conduction of elaborated sap (Déjardin et al., 2010). Primary fibres are located between the epidermis and the vascular cambium, surrounding

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https://doi.org/10.1016/j.indcrop.2018.01.035
Received 7 June 2017; Received in revised form 12 January 2018; Accepted 14 January 2018

the woody core. The fibres are arranged in various size bundles influenced by plant growth or variety (Crônier et al., 2005; Goudenhooft et al., 2017). Owing to differences in the structure and composition of fibres, they do not all respond in the same way to mechanical stress. The resulting broad scattering of mechanical properties between various vegetal fibres leads to a variation in the stiffness and stability of plants, since fibres represent their main structural basis (Bourmaud et al., 2015).

The mechanical properties of elementary plant fibres have been investigated in many research studies (Charlet et al., 2010; Placet, 2009). It has been shown that, despite having a similar structure, flax fibres exhibit better mechanical properties than hemp fibres (Marrot et al., 2013). However, only little attention has been paid to the understanding of these differences in mechanical properties, which can possibly be explained by the biochemical composition of cell walls (Alix et al., 2008; Bourmaud et al., 2013).

Previous studies have focused on exploring the behaviour of stems. Different research teams have studied the lodging resistance of stems against external loads (Berry et al., 2007; Gibaud et al., 2015), while Niklas investigated the influence of sample geometry on the bending response of hollow stems (Niklas, 1997). Experimental studies have also been performed on stems from different plants to establish reliable methodologies for measurement of their bending stiffness (Robertson et al., 2015). These studies provide information to better understand the biomechanics of plants by determining their mechanical properties and their response to bending. However, to the best of the authors' knowledge, little information is available on the contribution of the different tissues to the bending stiffness of the stem.

This study aims to improve the understanding of the mechanical contribution of fibres within dry stems under flexural load, which is potentially linked to their mechanical performance. Firstly, the anatomy of stems is described in detail based on histological observations. Then, after defining optimal testing parameters, bending tests are carried out on stems with and without fibres. The flexural stiffness of the samples is studied taking into account both the contribution of the fibres and the xylem geometries. The last section compares the longitudinal modulus of fibres, estimated by bending tests, to the modulus measured by tensile tests on elementary fibres.

2. Materials and methods

2.1. Materials

Flax plants were provided by Terre De Lin, a flax cooperative based in Normandy (France). "Bolchoï", a variety selected in 2014, was chosen for the tests as it is an increasingly cultivated recent variety which leads to high fibre yields. Plants were all cultivated in France (Saint-Pierre le Viger, Normandy) in 2016. Conventional seeding densities and sowing conditions were used (Bert, 2013) and entire plants were pulled out at maturity (Goudenhooft et al., 2017). They were then dried following the conventional procedure for the industrial processing of flax but without being scutched.

Hemp stems (variety Fedora 17) were supplied by Fibres Recherches Développement (FRD, Troyes, France) and were grown by La Chanvrière (Bar-sur-Aube, France). The stems were mechanically harvested at the end of August 2016 before pre-harvesting the seeds. After cutting the stems in two, the lower halves, measuring approximately 1 m to 1.1 m (3 cm from the ground), were windrowed and stored. Sampling areas were randomly distributed in the field, allowing us to take into account the heterogeneity of the tested samples.

In addition, hemp and flax plants were grown under normal meteorological conditions, as described by Lefeuvre et al. (2014).

2.2. Anatomical analysis of the stems

Stem anatomy and fibre geometry were characterized using histological transverse sections. Flax and hemp stem sections were obtained after immersion of dry samples through a graded series of water-ethanol and Histoclear-ethanol solutions. Then, stems were embedded in paraffin and cut using a microtome. The sections obtained were observed under an optical microscope. To carry out different measurements of the tissue features present in the stem, the images were processed with Gimp ® and then analysed with ImageJ®.

2.3. Specific gravity measurements

The specific gravity of flax and hemp xylem was determined. The experiment was performed in duplicate on 1 cm sized samples extracted from hand-peeled stems of various diameter. Prior to measurement, the samples were weighted in air. They were then immersed in ethanol at 22 °C, using an ultrasonic bath for degassing during 30 min. Samples were then weighed in ethanol solution and the values were taken once stabilization of the mass. The specific gravity of a sample is expressed by:

$$Specific\ gravity = \left[\frac{w_{Air}.\,(\rho_{EtOH} - \rho_{Air})}{w_{Air} - w_{EtOH}}\right] + \rho_{Air} \tag{1}$$

Where w_{Air} is the weight of the sample in air, w_{EtOH} is the weight of the sample in ethanol, while ρ_{Air} (0.0012 g/cm^3) and ρ_{EtOH} (0.7876 g/cm^3) are the specific gravities at 22 °C of air and ethanol, respectively.

2.4. Three-point bending test

Three-point bending tests were carried out at controlled temperature (23 ± 1 °C) and relative humidity (50 ± 1%). Tests were performed using a universal MTS tensile testing machine equipped with a 50 N capacity load cell. The displacement rate was fixed at 0.1 mm/s. Prior to experiments, both load cell and cross head were calibrated. Flax and hemp samples were cut from the middle height of the stem, corresponding to a position where the fibres exhibit optimal mechanical properties (Charlet et al., 2007). The tests were first performed on dry flax and hemp stem samples with a limited maximum load of 5 N to preserve the elastic behaviour of the samples. Experiments were conducted on flax and hemp stems to study the test set-up conditions, thereby allowing pure bending stress to be applied. This analysis reveals the influence of the L/D ratio on the flexural stiffness of the stems, which varies from 17 to 87 for flax and from 9 to 44 for hemp, with L being the span length and D the stem diameter. The stems were then carefully hand peeled and similarly tested to determine the mechanical properties of the xylem samples.

By considering both the entire stem and the xylem as a uniform beam with a circular cross section, displacement y in the middle of the section is given by Eq. (2) for small displacements (Timoshenko, 1947):

$$y = \frac{F.\,L^3}{48.E.\,I_{stem}} \tag{2}$$

Where F is the applied force, L the span length, (EI) the bending stiffness, I_{stem} the quadratic momentum and E the bending modulus.

The stem or xylem apparent modulus is then obtained by applying the following formula

$$E = \frac{dF}{dy}.\,\frac{L^3}{48.I} \tag{3}$$

Where dF/dy is the slope on the linear part of the force-displacement curve.

The stem is assimilated to a composite tube of two layers: the fibre and the xylem layer. For each layer constructing the tube, the bending stiffness is obtained by multiplying the stiffness (E) to the quadratic momentum (I). Finally, the bending stiffness of the stem is obtained by adding the bending stiffness of each layer. Fig. 1 is a scheme illustrating the modelling of the entire stem with a circular cross section, the