MICROSTRUCTURAL ANALYSIS AND MECHANICAL BEHAVIOUR OF BAMBOO FIBRES

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Abstract

Bamboo fibres are an attractive alternative to reinforce polymers in the new era of green composite materials. A new mechanical process has been developed to extract long bamboo fibres from the Colombian species Guadua angustifolia. The mechanical properties of technical fibres have been studied, the tensile strength and Young's Modulus are around 800 MPa and 43 GPa respectively.

To fully explore these excellent mechanical properties and to make an adequate use of this new material as reinforcement, it is indispensable to have a complete understanding of fibre behaviour as a function of the microstructure. Observations have provided us with a vast knowledge of the complex microstructure of this fibre from the macro down to the micro scale level, where different features like the distribution of the elementary fibres within the fibre bundle, dimensions and the layering pattern of the elementary fibres and the main microfibril angles could be measured.

1 Introduction

In recent years there has been an increasing interest in the use of natural fibres as reinforcement material for composite applications. This is to be expected as with a growing awareness of the need to preserve energy and resources there is also an increasing awareness for the necessity for environmentally friendly alternatives. Within the different types of natural fibres, Colombian bamboo (Guadua *angustifolia*) is especially promising. Taking its lightness into account, specific properties close to those of glass fibre can be reached [1].

Natural fibres like bamboo also require much less energy for cultivation and extraction than is used for the synthesis of glass and particularly carbon fibre, which gives them a very favourable carbon footprint. Added to that, their suitable mechanical properties, large availability and low cost make them a real alternative in the market of composite materials.

When discussing natural fibres, different hierarchical levels should be considered. On the micro level, the elementary fibres are composed of cellulose microfibrils embedded in a hemicellulose/lignin matrix. At the meso level, a technical fibre or fibre bundle is a group of elementary fibres that are glued together by an amorphous material called middle lamellae. The technical fibres are generally obtained after an extraction process and can be used as such to reinforce polymers. Their composition and structure is completely adapted to their function in the plant [2,3].

In natural fibres, the cell wall structure of the elementary fibre is the most important feature since its constitution determines all mechanical properties. In other words, the structure of the fibre bundle and the layering structure and thickness of the cell wall are of special interest. Some plant fibres like bamboo, flax, kenaf and oil palm among others have been studied and characterized by using special microscopic techniques [4-6]. The knowledge of the technical fibre structure gives us the understanding of the mechanical behaviour, e.g. the technical fibre modulus is strongly affected by the distribution of the microfibrils in the cell wall structure. This information is important to establish a correct use of the technical fibre as reinforcement in composite materials.

However, natural fibres are very susceptible to their environment. The mechanical properties are not only greatly influenced by the growing cycle and moment of harvest, but also by the conditions they are used in such as the presence of humidity. Due to the hydrophilic nature of the chemical constituents of a natural fibre, a constant tendency to absorb moisture is present.

Because of this, it is also necessary to study the influence of these factors on the mechanical behaviour. Depending on the type of natural fibre a decreasing (flax) or stable tensile strength (kenaf, sisal, jute, flax, coir, abaca) is measured [7] with increasing humidity level. No conclusive results are found for the stiffness and ultimate strain of natural fibres. The effect was studied for flax [8]. Drying of natural fibres introduces micro-cracks, leading to a decrease in strength. Fibres will shrink/swell depending on their desorption/absorption of water. Both processes cause dimensional change and introduce defects in the fibre.

Among the well-known natural fibres, bamboo has one of the most favourable combinations of low density and high mechanical properties, that is, it has high specific stiffness and strength [9]. Bamboo fibre bundles are distributed densely in the outer region of the culm wall and sparsely in the inner region, and also concentrated in the upper part of the culm compared with the base. Elementary fibres in such a bundle consist of thick and thin layers with different cellulose microfibrillar orientation. In the thick layers, the microfibrils are oriented at a small angle to the fibre axis, whereas the thin ones show mostly a more transverse orientation. This structure does not exist in the cell walls of fibres of normal wood and leads to an extremely high tensile strength of the culm [10, 11]. This is the reason why the fibres, the structural part of the culm, are often called ‘natural glass fibres’ [12,13]. The elementary fibre length and fibre diameter for this species are on average 1.6mm and 11 µm, respectively, and they constitute about 40–50wt% of the total bamboo plant tissue and between 60 and 70wt% of the total culm tissue [14].

In this paper, characteristics of bamboo technical fibres from the species Guadua *angustifolia* at the meso and micro level, are studied with special emphasis on the technical fibre, together with the characterization of mechanical properties from single technical fibre tensile tests and the subsequent study of the effect of moisture on the mechanical properties.

2 Materials and testing methods

The bamboo culms (species *Guadua angustifolia* Kunth) were extracted from a typical bamboo plantation in Colombia, specifically from the Coffee Region at the National Research Center for Guadua where the environmental conditions are: 1.240 meters above sea level, a temperature of 25°C and relative humidity of 80%. Bamboo technical fibres were extracted from the bamboo culms giving a maximum technical fibre length between 20 and 35 cm and a diameter between 90 and 250 µm.

2.1 Microscopic observations

For the scanning electron microscope, small blocks (± 5 mm thick) were cut and attached to stubs using electron-conductive carbon paste. The samples were sputter coated with gold. Observations were carried out at the Laboratory of Plant Systematics (K.U. Leuven) with a Jeol JSM 6360 SEM (Jeol Ltd., Tokyo, Japan).

2.2 Sample preparation and tensile test for single technical fibres

The technical fibres are selected before the tensile test and the area is determined based on the density as described in [1]. The selected technical fibres were glued in between two paper frames to assure a good gripping and straight direction in the test clamps. The opening of the paper frame determines the gauge length; for this experiment it was set at 2, 5, 10, 25 and 40 mm: at least 30 successful tests were performed for each span length. The tensile test was performed on a mini tensile testing machine developed in the Department of Metallurgy and Materials Engineering at K.U. Leuven, and the fibre strain was measured according to [15].

2.3 Implementation of humidity conditions

Humidity tests demand stable humidity conditions at a wide range of humidity levels. Different techniques are available that meet these requirements: desiccators, environmental chambers, saturated salt solutions, dry salts a.o. Due to its versatility but especially portability it was opted to use a combination of saturated and dry salts. When in equilibrium, a material and the environment have an equal water activity (aw) level. There is a natural tendency to maintain this equilibrium. Modification of the water activity of the environment will induce an equal change in the water activity of the fibre.

A saturated salt solution in a small closed chamber will change the relative humidity (rh). The advantage of this technique is the low sensitivity to humidity variations. This is especially so when excess solution is used. Saturated salt solutions can easily be used for humidity levels between 50-100%rh. At lower levels however, there are problems with dehydration of the atmosphere; 'dry' salts can be used instead. Measurement of the environmental humidity was done with an industrial temperature and humidity transmitter of the type HygroFlex from Rotronic.

2.4 Water uptake

The water uptake test gives information about the maximum amount of water that technical fibres can take up. The amount of moisture the technical fibre has absorbed is defined as (eq.1):

$$M = (M_{eq} - M_{dry})/M_{dry} \qquad \text{(eq.1)}$$

With M: the equilibrium moisture content or water concentration
M_{dry}: the dry material weight[g]
M_{eq}: the material weight when in equilibrium with the environment [g]

3 Results and discussion

3.1 Guadua angustifolia technical fibre

The technical fibres (bean-shaped) attached to the conductive supporting tissue are the mechanical support of the bamboo culm; they consist of many elementary fibres connected by lignin called middle lamellae (Fig.1 a and b).

The elementary fibres represent the main structural component of the vascular bundles in the bamboo wall; they exhibit a hexagonal or pentagonal shape; the small hole in the centre of each elementary fibre is called lumen (Fig.1c). As mentioned before, each elementary bamboo fibre wall possesses a unique multilayer configuration called polylamellate structure (Fig.1d) where every layer is reinforced with cellulose microfibrils at different angles. This structure determines the mechanical properties of the technical fibres and contributes to the strength and modulus of the bamboo culm. Figure1d shows the microfibrils present in *G. angustifolia* elementary fibres.

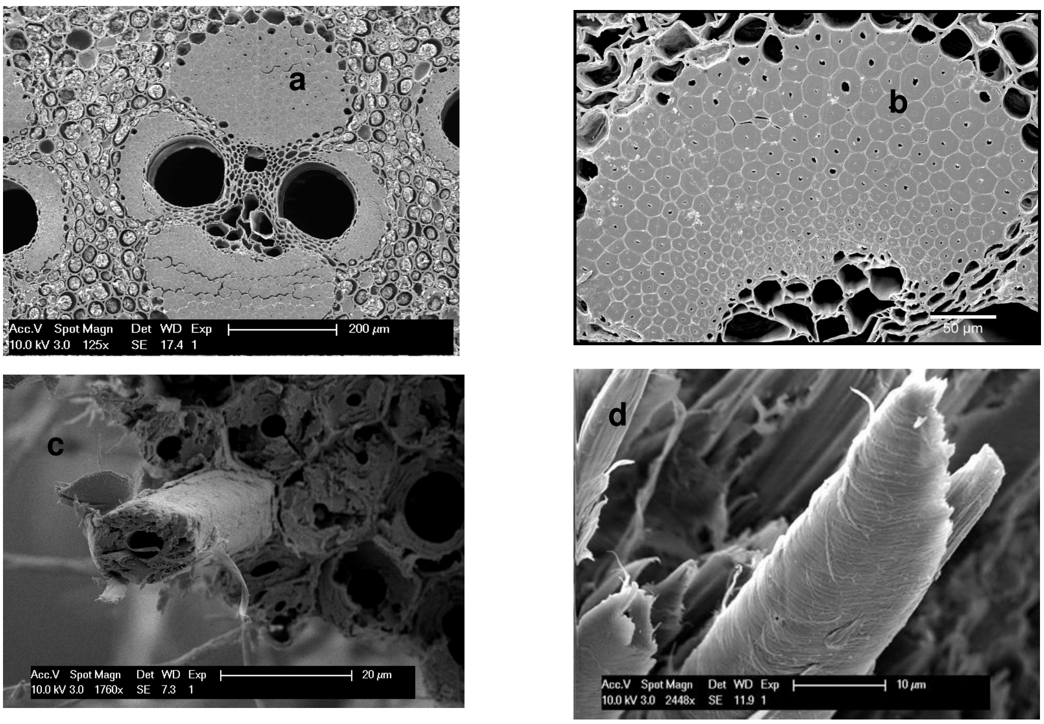
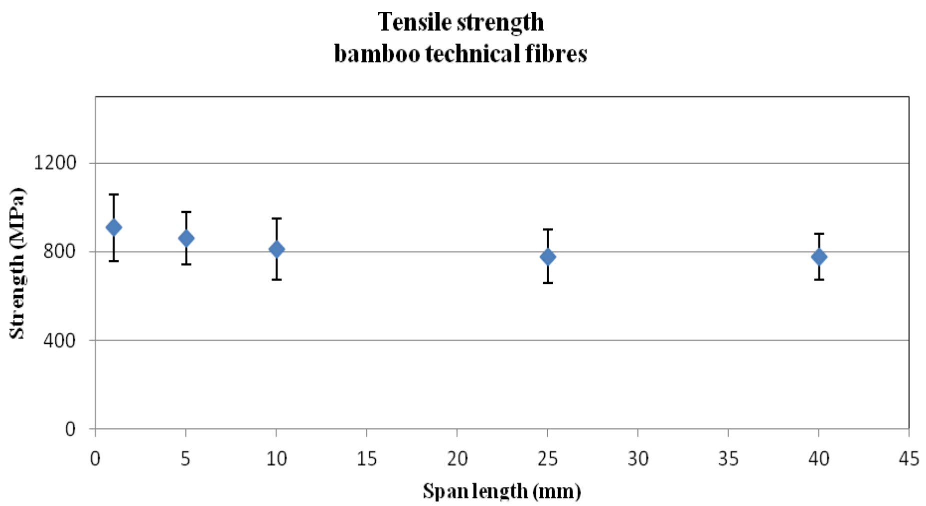


Figure 1. a) vascular bundle, b) fibre bundle, c) elementary fibre, d) cellulose microfibrils

3.2 Bamboo technical fibre mechanical properties

The values for tensile strength and stiffness for untreated bamboo technical fibres at different span lengths are shown in Figure 2a and b. The modulus and strength normalised to density (specific material properties) are similar to the values for glass fibre.



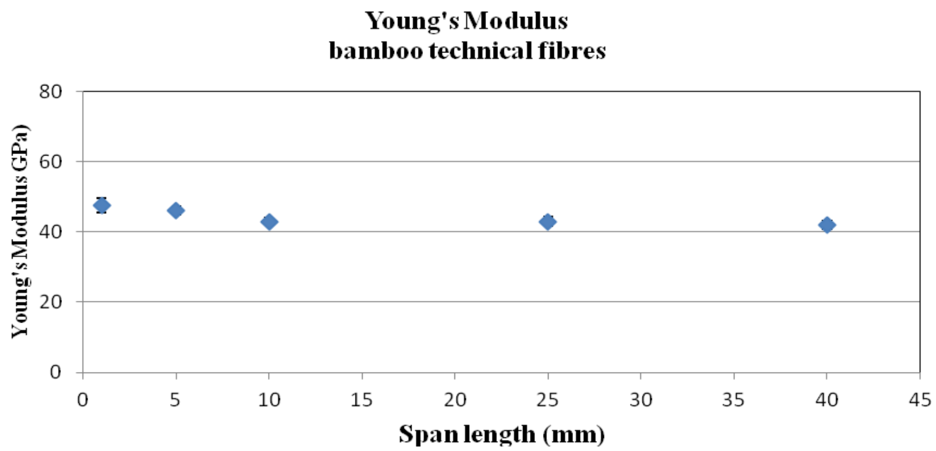


Figure 2. Tensile properties of bamboo technical fibres, a) tensile strength, b)Young's Modulus (after correction for machine compliance)

3.3 Moisture sensitivity of bamboo technical fibres

The moisture uptake rate depends on the relative humidity of the environment. As the concentration gradient is higher with increasing environmental relative humidity level, this was to be expected based on Fick's first law. Figure 3 shows the complete moisture uptake of the technical fibres with time. It is important to note that the rate at which equilibrium is reached decreases with decreasing relative humidity. A consequence of this is that samples at lower relative humidity levels will need longer periods for complete acclimatization. The material reaches it equilibrium moisture content when the water activity in the sample equals the water activity value of the environment.

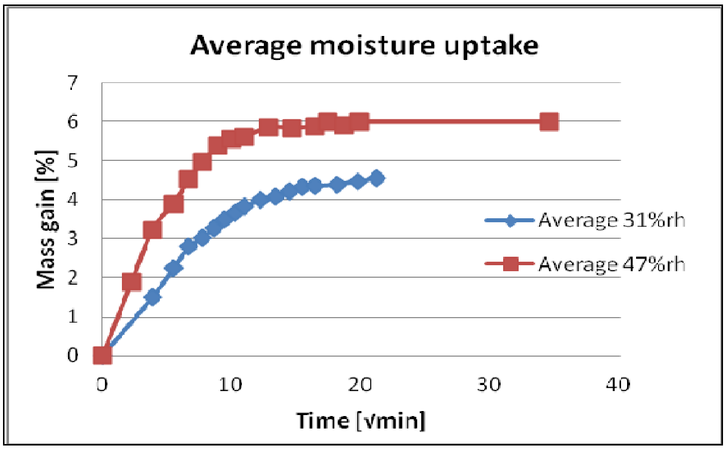


Figure 3. Moisture uptake in function of time of single bamboo technical fibres

3.4 Influence of moisture on the mechanical properties

Figure 4 shows that there is a slight increase in tensile strength with increasing humidity level. This tendency was expected as at low humidity level the technical fibres are prone to micro cracking. On the other hand at higher humidity levels the technical fibres swell slightly closing micro cracks and making the technical fibres less susceptible to a critical defect.

An increase in strain to failure with increasing humidity is caused by plasticization. When the technical fibre absorbs water mostly the interface between elementary fibres is influenced. The elementary fibres become less tightly bonded, resulting in a global plasticizing effect.

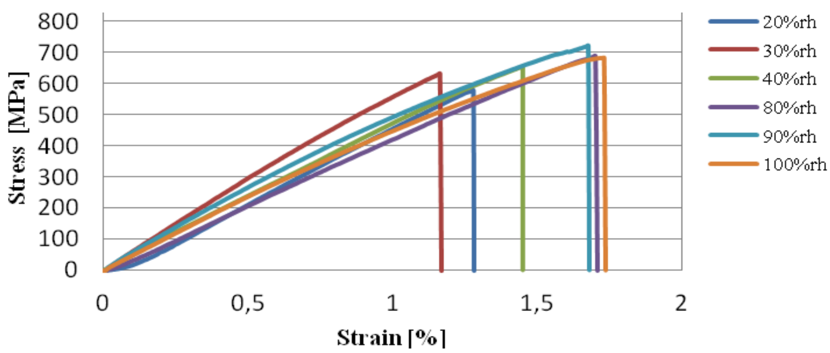


Figure 4. Typical stress-strain curves of climatized bamboo technical fibres

4 Conclusions

A novel mechanical extraction process produces long bamboo technical fibres with excellent mechanical properties with surface characteristics that benefit the performance of the material as reinforcement. The technical fibres are influenced by humidity. It was shown that an increase in moisture level induces an increase in ultimate strain, this due to plasticization of the technical fibres.

In general, the results of this study suggest that there is a good potential for long bamboo technical fibres as reinforcing material for polymeric matrices and that the material could be appropriate to be used for commercial applications, where the fulfilment of environmental regulations and weight reduction are important aspects.

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