ASSESSMENT OF THE PROPERTIES OF BAMBOO FIBRE AND BAMBOO FIBRE COMPOSITES

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ABSTRACT

In this study the microstructure of the fibre is liked with the mechanical behaviour of the fibre. The tensile properties for single bamboo (G. angustifolia) fibres were set at different span lengths after machine compliance correction, showing that the specific E- Modulus and the specific strength can compete with glass fibre. Strength values of around 800 MPa were obtained by using a novel green mechanical extraction process. Untreated unidirectional bamboo/epoxy composites show good flexural strength. For UD bamboo fibre thermoplastic PP composites, flexural tests with two fibre orientations were performed. The material performance was reasonable, but further work is necessary to improve the performance of the material.

INTRODUCTION

Natural fibres are becoming a real alternative for the transport sector thanks to their green nature, low density, and in some cases better specific mechanical properties (normalized to material density) than glass fibres. Thermal conductivity of natural fibres is low; therefore they make a good thermal barrier. Low cost, inexhaustible supply and good environmental performance, make natural fibres possible substitutes to synthetic reinforcing fibre materials, especially for polymer matrix composites. Bamboo fibres represent one of the most attractive natural fibres because of their availability and excellent mechanical properties.

Nevertheless, only few efforts have been carried out globally to extract long bamboo fibres from the culm particularly because of difficulties in extracting long high quality, undamaged fibres. Only in recent years there has been an increasing interest to study scientifically the potential of bamboo fibre as reinforcing material for polymer matrix composites [1-5].

In this paper, long bamboo (*Guadua angustifolia* Kunth) fibres are studied to be used as reinforcement in both continuous thermoset and thermoplastic composite materials.

2 Materials and 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 fibers were extracted from the bamboo culms giving a maximum technical fiber length between 20 and 35 cm and a diameter between 90 and 250 μm.

2.1 Single fibres

2.1.1 Microscopic observations

SEM observations were made on transverse sections of the culm in order to investigate the distribution of the vascular bundles as well as the microstructure of the fiber wall. Samples ($1cm^3$) were cut using a sledge microtome (Reichert, Vienna, Austria) in order to preserve all the surface features and to avoid impurities that can appear after grinding or polishing techniques. After treating with a bleaching agent, the samples where rinsed and dehydrated in an ethanol series (50, 75 and finally 96%), followed by gold-coating and observed using a scanning electron microscope (SEM), Philips XL 30 FEG.

2.1.2 Microfibril angle

The angle of the microfibrils in the primary and secondary wall layer of bamboo elementary fibers was determined based on a new technique developed by Wang [6].

2.1.3 Single fibre test:

The cross sectional area of each individual fibre was determined using both the apparent density (1.4 g/cm^3) and the weight as well as the length of the fibre. The single fibre tensile test was carried out under standard environmental conditions (21 ± 2 °C and 50 ±2 %RH), in a mini-Instron 5943 universal tensile testing machine using rubber-faced clamp grips with 10x30 mm grip faces and a 1kN load cell.

Single fibres at different span lengths (5, 10, 30 and 40 mm) were tested in order to evaluate the influence of the gauge length. The crosshead speed was set at 0.85 mm/min. The fibres were pneumatically clamped using a pressure of 5 bar, using rubber clamps specially designed for single fibres, avoiding the use of a paper frame and reducing manipulation during the test. The load was registered during the complete test. At least 35 successful tests were performed for each span length, excluding fibres that broke near the edge of the clamps. The Weibull parameters for individual bamboo fibres were also determined following the methodology described in [7].

For the determination of the Young's modulus, the procedure described in [8, 9] was followed. For that, experiments are performed on a range of test spans, to allow determining an extrapolated E-modulus at infinite span length. In this way the effect of slippage in the clamps can be filtered out. Also, by determining the system compliance, strain values can be corrected for slippage.

2.2 Bamboo fibre composites

2.2.1 Bamboo fibre-polypropylene composites

Thermoplastic composites were prepared by compression moulding of stacks (7 layers) of bamboo prepregs , each of them consisting of untreated fibres and two different thermoplastic films (Polypropylene and Maleic Anhydride grafted Polypropylene (MAPP)). To obtain good impregnation, the temperature used was about 25 degrees C higher than the melting temperature of the polymer and a pressure of 15 bars was used. In all cases, the natural fibres and prepregs were dried overnight at 65°C to prevent problems due to moisture. Fibre volume fraction was set at 45% by weight measurements. Flexural strength and Young's modulus for UD composites with longitudinal disposition of the fibres were evaluated by 3 point bending tests on a universal testing machine (Instron 4426) based on ASTM D790M. Interface strength was determined from transverse bending strength according to the mentioned standard.

2.2.2 Bamboo fibre-epoxy composites

Vacuum resin infusion (VARI) technique was used to manufacture the UD bamboo fibre – epoxy composites and the impregnated UD fibre bundles. This technique allowed to keep the alignment of the fibres and also provided a good surface quality in both sides of the composite. The fibre UD preforms were placed into a multicavity mould with their corresponding upper moulds to produce the samples, the fibres were carefully aligned and evenly spreaded by hand in order to have an homogeneous thin layer of fibres, see Figure 1. A fibre volume fraction of 40% was aimed and recalculated by weight measurements after manufacturing.

Figure 1. a) Bamboo UD preforms ready be used and b) positioning the preforms in the mould.

3. Results and discussion

3.1 Bamboo fibre microstructure

The vascular bundle, one of the main anatomic constituents of the bamboo plants is shown in Figure 2a. The technical fibers (bean-shaped) attached to the conductive supporting tissue are the mechanical support of the bamboo culm; they consist of many elementary fibers connected by lignin called middle lamellae (see Figure 2b).

The elementary bamboo fibers exhibit a hexagonal or pentagonal shape; the small hole in the centre of each elementary fiber is called lumen. Each elementary bamboo fiber wall possesses a unique multilayer configuration called polylamellate structure (Figure 3a), where every layer is reinforced with cellulose microfibrils at different angles. This structure determines the mechanical properties of the technical fibers and contributes to the strength and modulus of the bamboo culm.

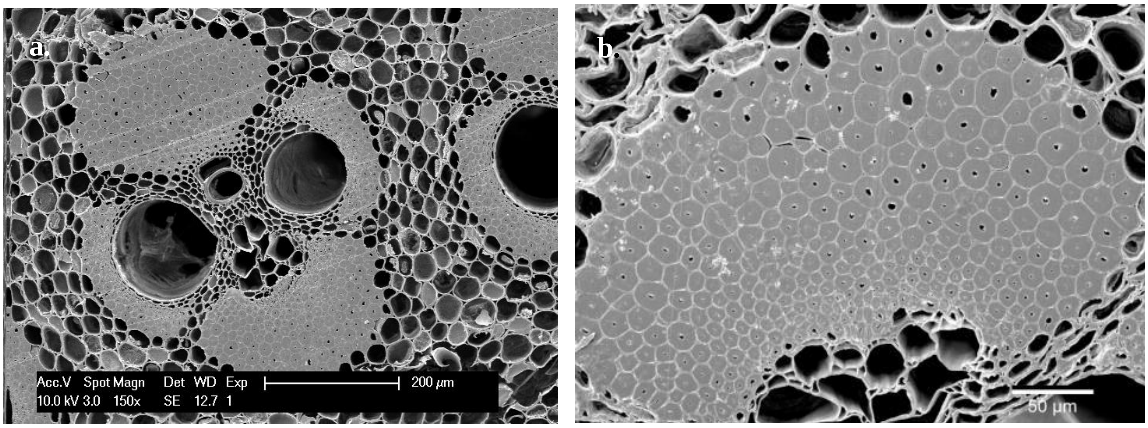

Figure 2. a) Cross sectional are of the bamboo culm observing a) vascular bundle, b) fiber bundle; upon fibre extraction the bundle splits up in a few technical fibres, each consisting of several elementary fibres.

Figure 3b shows a detail of the secondary wall of an elementary fiber, after chemical treatment where the primary wall has been etched away. The orientation of the micro-fibrils is close to 0 degrees in agreement with Liese [10]. In agreement with other researches [10-12], the polylamellate structure or multilayering of the elementary fibers for *Guadua angustifolia* is more visible in the periphery of the fiber bundle where the elementary fiber wall has in general 2 to 4 layers (Figure 3a).

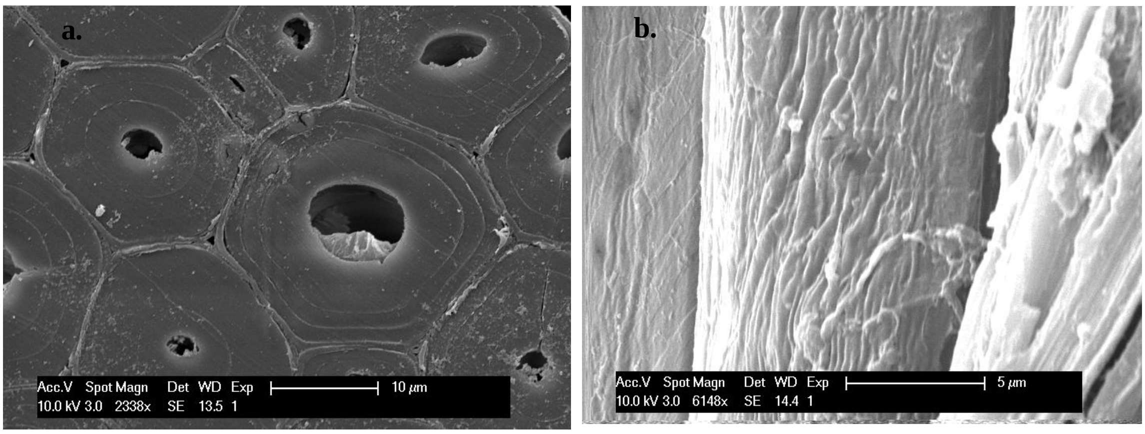

Figure 3. a) Polylamellate structure of elementary bamboo fibers, b) microfibrils of the secondary wall.

3.2 Single fibre properties

A summary of Weibull modulus, m, and the characteristic strength (σ_o) for single bamboo fibres after tensile testing are shown in Table 1.

Table 1. Weibull modulus (m) and the characteristic strength (σ_o), for failure stress of bamboo (G. angustifolia) single fibres after tensile test.

Gauge length (mm)	**No. of observations**	**Characteristic strength (σ_o) (MPa)**	**Weibull shape parameter (m)**
5	40	833±101	9.9
10	40	836±119	8.3
35	40	778±122	7.5
40	35	772±113	8.1
All fibres	155	804±115	8.2

For single fibres, the characteristic strength as observed at different span lengths remains rather constant; nevertheless a slight decrease is observed when the gauge length increases. This can be explained by the fact that the average flaw size is independent of the gauge length, but the number of defects increases with the length. An Analysis of Variance (ANOVA) indicates that there is not a significantly strength difference between these four single fibre groups (four different span lengths); indicating not only that this property, but also the shape parameter does not appear to be a function of the gauge length. The tensile strength has a small variation as a function of the span length and remains at about 800 MPa. The Young's Modulus is on average 43 GPa. In terms of specific properties, normalized to the density, they can be compared with glass fibers [13, 14].

Weibull modulus (m) values between 10 and 8 and characteristic strength values of approximately 800 MPa were obtained by single fibre test. When the four groups of fibres are re-grouped by fibre diameter (4 groups of defined diameter range) and not by gauge length as done before, again the ANOVA analysis shows no statistical difference for the strength values. As stated by [15], the calculated "m" and σ_o should be independent of the tested fibre length. A variation of the Weibull parameters with length or diameter of the fibres is one of the main concerns when this statistical distribution is applied to natural fibres. Significant variations in properties are often related to the harshness of the extraction process and the amount of defects that are introduced when the fibres are damaged, lowering their mechanical properties. In this case, the newly developed extraction process [13] shows to be gentle with the fibres.

3.3 Thermoplastic composites

For unidirectional bamboo fibre thermoplastic composites loaded in the longitudinal direction of the fibres, it was found that for both Polypropylene and MAPP the consolidation temperature has a clear effect on the final behaviour of the composite. There is no clear difference in maximum strength between PP and MAPP, as all samples are roughly situated on one line as a function of processing temperature. In both cases, not only a shift to the left part of the spectrum when the temperature is raised by 10 degrees is observed, but also there is a reduction in strain at maximum stress. Both combined result in a modulus increase (see Figure 4). Young's modulus for PP composites goes from 15.6 to 19.3 GPa and for MAPP composites from 11.8 to 16.4 GPa, improving 24 and 39% respectively, again for the same increase in temperature.

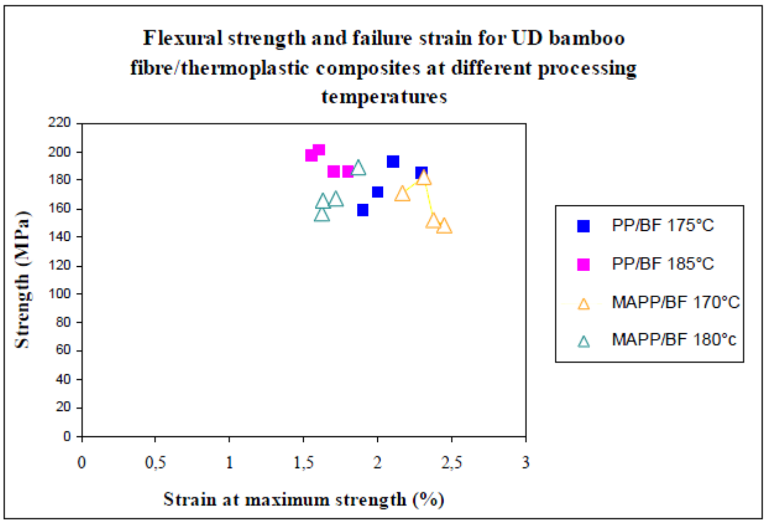

Figure 4. Strength and failure strain results of bamboo fibre thermoplastic composites

This increase can be explained because the higher the temperature, the lower the viscosity of the polymer, so it will flow around the fibres more easily. Young's modulus is particularly indicative of the quality of impregnation. Theoretically, at 45% fibre volume fraction, one would expect a longitudinal modulus of about 20 GPa. Thus, it can be hypothesised that for PP at 185°C (20° above the melting temperature), the wetting is probably quite good. The theoretical longitudinal strength is about 360 MPa. Whereas, for epoxy resins these strength values have been approached, for PP and MAPP the strength remains relatively low, indicating that probably significant improvements in interfacial bond strength are still possible and desirable. From transverse properties (Table 2), it is clear that even with an improvement in wetting (see above); the interface remains relatively weak, since the transverse strength values are lower than the strength values of the pure polymers.

Table 2. Results for transverse flexural strength of bamboo fibre/thermoplastic composites

Transverse flexural strength BFC (MPa)	Consolidation temperature			
	165 °C	**170°C**	**175°C**	**180°C**
Polypropylene matrix	17 ± 1.8	20 ± 0.5	18 ± 2.2	17 ± 1
MAPP matrix	16 ± 1.4	19 ± 0.8	18 ± 0.8	20 ± 0.3

There is also very little difference between the results with PP and MAPP. There are indications that the surface of our bamboo fibres is covered with lignin [16, 17], which is apparently not highly compatible with either PP or MAPP.

3.3 Thermoset composites

The results reveal that the experimental values for longitudinal tensile stiffness (~17 GPa) and strength (~222 MPa) reached respectively 92% and 79% of theoretical values. This points out that a strong fibre-matrix interface is present between fibres and matrix and that the resin impregnates the fibres very well.

A visual inspection of the samples after failure indicates in general, a brittle fracture with a crack mostly propagating in one plane (Figure 5a). The fracture failure were also examined under SEM, see Figure 5b, showing good resin impregnation and a rather clear fracture of the sample with low presence of fibre pull out and good dispersion of the fibres where the initial layer wise configuration of the composite is not visible in the final material.

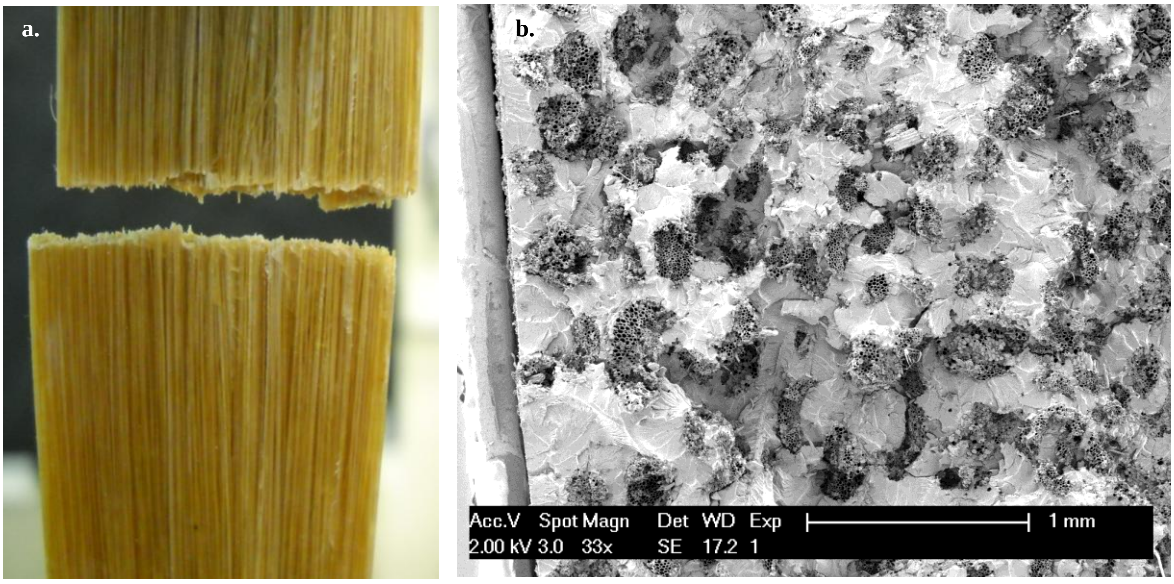

Figure 5. SEM- observations of the fracture plane of the UD continuous fibre composites after tensile testing.

In general high strength is found for the unidirectional continuous samples. It seems that the reason for this good behaviour is the gentle and careful mechanical extraction process of the fibres that not only conserves the intrinsic good characteristics, but also rough fibre surface fibres, as reported by [13]. This irregular surface could help to establish a better mechanical interlock with the thermoset matrix. In addition, it seems that there is a good bonding of the epoxy with the chemical groups present on the fibre surface, giving as a result that the fibres do not have the necessity of a chemical treatment in order to have good properties.

4. CONCLUSIONS

Microstructural observations reveal that the cellulose microfibrils of the elementary fibers have predominantly 0 degree orientation, combined with a thin outer primary wall layer of the elementary fibres with 90 degree orientation.

The currently studied bamboo fibres showed to follow a Weibull distribution for the strength in single fibre testing. Also, there was no correlation between the maximum stress and the fibre diameter. Single fibre properties show that the specific Young's modulus can compete with glass fibre and the specific strength is only 10% lower. These good properties are the result of a novel mechanical extraction process that preserves the intrinsic properties of the fibre. Unidirectional continuous fibre composites with PP and epoxy matrices evaluated in this paper chapter show a good potential for this material, although, more research is needed.

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