LONG BAMBOO FIBRE COMPOSITES

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1 Introduction

Bamboo has been attracting considerable attention in recent years as a sustainable construction material. Also, bamboo textile fibres were developed based on re-generated bamboo. The extraction of good quality natural, technical fibres from the bamboo culm is still a challenge. This paper reports on the performance of high quality technical bamboo fibres, extracted by a mechanical extraction process from bamboo culms.

Bamboo fibres have potential as a sustainable alternative for glass fibres. Specific mechanical properties approach these of glass fibre. Giant bamboo species from the tropical regions, can grow at rates up to 20 cm/day and reach full height of approximately 20 m after just half a year. They then mature in a few years time, ready to be harvested. Thus they sequester about 60 tons of CO_2 per hectare per year, about 4 times the rate of a young mixed natural forest.

There are several important steps in the development of long bamboo fibre composites:

- Extraction and cleaning of the fibres
- Study of fibre morphology and fibre properties
- Preparation of preforms or prepregs
- Study of fibre surface chemistry and physical chemistry and compatibilisation (wetting/adhesion) with useful matrices
- Preparation of composites and determination of mechanical properties
- Study of specific (in-use) characteristics like moisture resistance

Research is conducted at KU Leuven into all of these subjects and is as such a good example of our approach in developing natural fibre composites.

2 Results and discussion

2.1 Fibre extraction

Extraction of undamaged long technical bamboo fibres, with a diameter of about 150 µm and a length equal to the internode length of about 25 cm, is a challenge. A proprietary, mechanical extraction process was developed at KU Leuven, resulting in a substantial fraction (about 15% of the culm weight) of long, largely undamaged fibres. The average modulus of these fibres (particularly of the species Guadua Angustifolia) is 43 GPa (± 2.5%) and the strength reaches 800 MPa (± 15%). The developed pilot machine includes a combing step to remove the superfluous parenchyma tissue.

Figure 1 compares the strength of the extracted fibres with values from other processes in literature.

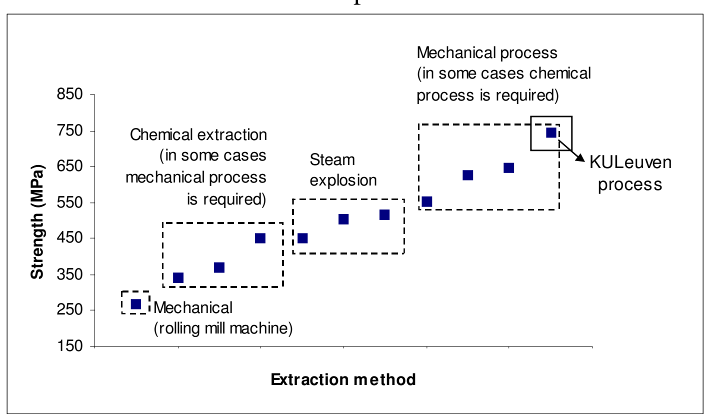

Fig. 1. Comparison of various extraction processes for technical bamboo fibre

Current research focuses a.o. on conducting fibre bundle tests to characterize the fibre properties, instead of performing single fibre tests. Both dry and impregnated bundles are considered. Also, for both bundle tests and single fibre tests, strain measurements are now performed by an optical method (strain mapping).

2.2 Study of fibre morphology

It is important to know the relation between fibre nano- and micro-structure and the mechanical properties of the fibres. Thus, the performance of fibres of different species, age, geographical location and location in the culm can be explained, allowing a better selection of the raw material or even in future breeding of better suited bamboo plants.
Figure 2 shows a detail of the primary wall of elementary bamboo fibres of the species Guadua Angustifolia. The 90 degree orientation of the nano-fibrils will provide some off-axis mechanical performance.

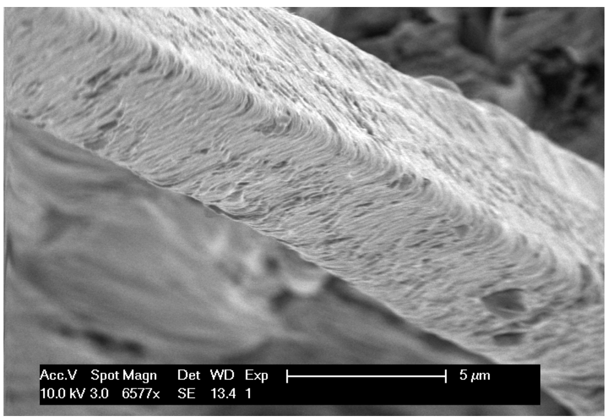

Fig.2. SEM image of primary layer of elementary bamboo fibre (Guadua Angustifolia); image from fracture surface

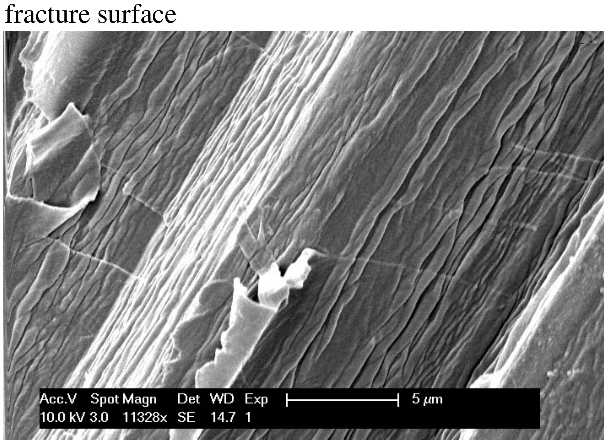

Fig.3. SEM image of secondary layer of elementary bamboo fibre (G. Angustifolia); after etching away the primary layer

Figure 3 shows a detail of the secondary wall, after the primary wall has been etched away. The orientation of the micro-fibrils is close to 0 degrees. As the secondary wall is the most important layer in an elementary bamboo fibre, this explains the high longitudinal stiffness and strength of bamboo fibres.
The properties will be somewhat reduced due to the visible 'wavy' pathways of the micro-fibrils. Off-axis mechanical properties of the fibres still need to be characterized.

2.3 Preforming and prepregging

Long bamboo fibres have a length equal to the internode length of about 25 cm. Thus, the material would be very suitable to prepare fibre mats, but to exploit the highest possible mechanical properties it is necessary to prepare uni-directional material (with close to zero twist or textile crimp). Therefore, further processing effort is directed towards preparing uni-directional prepregs, both with thermoset and thermoplastic matrices. The challenge is to obtain a good pattern of overlapping fibre ends and to produce this in a continuous process, preferably in-line with the extraction process. Spinning the fibres is almost impossible because of their high bending stiffness.
Figure 4 shows an example of uni-directional thermoplastic prepreg tape, prepared at lab-scale. Further processing development is underway.

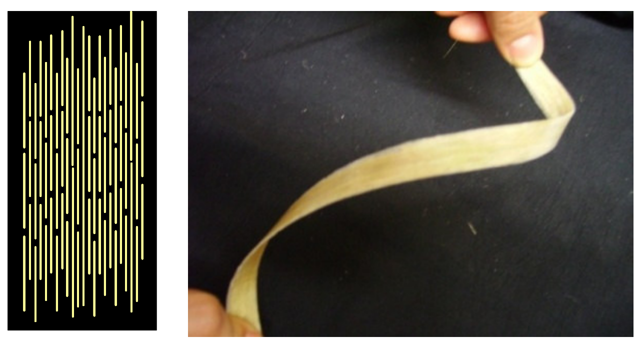

Fig.4 Example of uni-directional bamboo fibre polypropylene tape, prepared at lab-scale

2.4 Interface studies

An important piece of research concerns the chemical and physical-chemical characterization of both the extracted bamboo fibre surface and various useful matrices, with the aim to achieve good wetting and interfacial adhesion in the composite.

Based on this analysis, fibre treatments or matrix modifications are proposed. Chemical surface analysis is mainly conducted by XPS; physical-chemical characterization entails particularly determination of surface energy components. For this, dynamic contact angle measurements are done (with a single fibre tensiometer) in various known test fluids and a.o. the molecular kinetic theory is used to determine static contact angles. With these static contact angles, surface energy component theories can be employed to determine the hydrophobic and polar components of the surface energies [2].
A new development is to determine true equilibrium contact angles, which are actually required in surface energy component analysis. For smooth materials this may be accomplished by measuring both advancing and receding contact angles, but on relatively rough natural fibre surfaces it proves almost impossible to measure the receding angle. Therefore, a new procedure has been developed, in which ultrasound is used during a static experiment on the tensiometer. It proves possible to obtain contact angles in between advancing and receding values, as would be expected.
Three-component surface energy analysis (acid-base theory) indicates that the bamboo fibre surface has a rather basic character, with a substantial basic (γ^-) surface energy component. This means that good compatibility may be expected with somewhat acidic polymer matrices. This is currently verified.
After matching fibre and matrix and preparation of the composite, the adhesion is verified by micro-mechanical testing and/or evaluation of the transverse 3-point bending strength on unidirectional composite samples.
For thermoplastic matrices it may be expected that physical adhesion mechanisms are very important or even dominant in the overall adhesion value, unless chemically reactive substances like maleated polymer matrices are employed.
Indeed, a decent correlation is found between work of physical adhesion or interfacial surface energy with transverse 3 point bending strength results for various treatments on bamboo fibre and PP and PVDF thermoplastic matrices (figure 5 and 6).
An important conclusion is that, after mechanical extraction and cleaning, the surface of the technical bamboo fibres is largely covered by lignin. This was determined by XPS analysis, see figure 7.

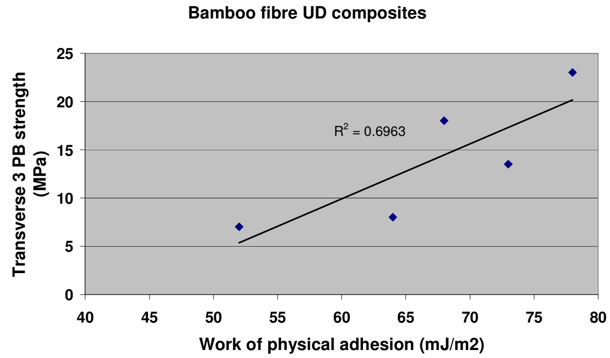

Fig.5. Transverse 3 point bending strength as a function of work of physical adhesion in bamboo fibre UD composites, with various surface treatments and PP and PVDF polymer matrices

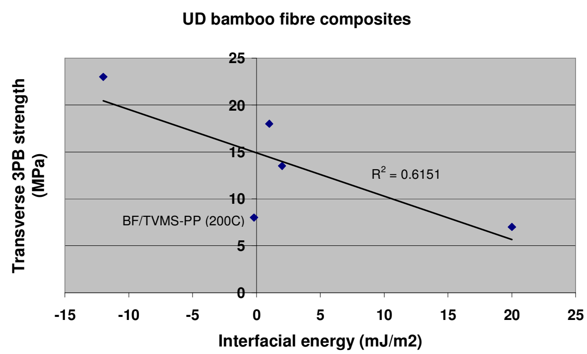

Fig.6. Transverse 3 point bending strength as a function of interfacial surface energy in bamboo fibre UD composites (same materials as in figure 5)

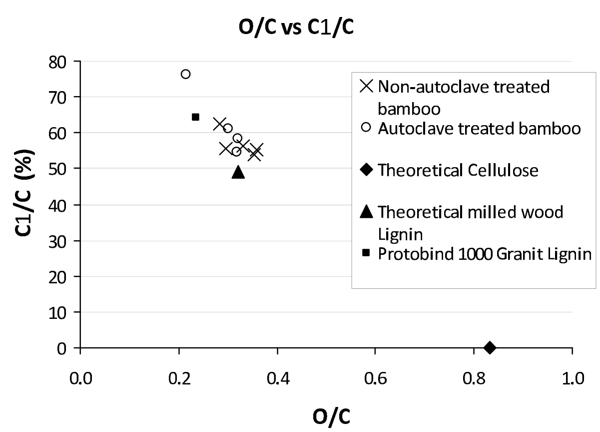

Fig.7. C1/C ratios versus O/C ratios for chemical groups at the surface of bamboo fibres, autoclave treated bamboo fibres, lignin from Granit, as determined by XPS; and theoretical values for cellulose and lignin according to Shchukarev [3]

In common epoxy resin, the adhesion of untreated technical bamboo fibre is quite good. A transverse bending strength of 33MPa (± 5%) was found.

2.5 Composite performance

Uni-directional composites were prepared with common epoxy resin, PP, maleic anhydride modified PP (MAPP) and PVDF. Mechanical evaluations have predominantly been done by longitudinal (and transverse) flexural testing. Currently, further systems are prepared with various fibre treatments and selected matrices, based on the interface studies mentioned above.

In epoxy, the good wetting and adhesion is reflected in a 95% transfer of fibre longitudinal modulus into composite longitudinal bending modulus and a 80% transfer of longitudinal strength. Based on a fibre modulus of 43 GPa, a composite flexural modulus of 21 GPa (± 4%) at 48% fibre volume fraction is reached. Composite longitudinal bending strength reaches 310 MPa (± 4%) at V_f = 48%, for a fibre strength of 800 MPa [1].

Both PP and MAPP have a similar and less good adhesion to our technical bamboo fibres. Transverse 3 point bending strengths reach values between 16 and 20 MPa depending on composite consolidation temperature. The longitudinal flexural modulus reaches 19.3 GPa for PP and 16.4 GPa for MAPP respectively, compared to a theoretical modulus of close to 20 GPa (V_f = 45%), indicating that the wetting in case of PP must be quite good. Strength values are less good, respectively 190 MPa for PP and 170 MPa for MAPP, compared to a theoretical strength of 360 MPa, indicating that improvements in adhesion are desirable (although low plastic yield strength of the polymers may also play a role).

The latest results with PVDF matrix show a relatively good adhesion (transverse 3 point bending strength 23 MPa) and longitudinal strength values above 200 MPa at a fibre volume fraction of 45%, reflecting the improved adhesion.

2.6 Moisture and temperature resistance

This is a new line of research to verify the effect of environmental and processing conditions on selected bamboo fibre composites and the fibres on their own. In general there are two routes to improve moisture resistance, hydrophobing the fibres or improving fibre-matrix adhesion, or a combination of both.

First results show that bamboo fibre has a diffusion coefficient and equilibrium moisture content, which are smaller than literature values for flax and sisal fibre. The moisture uptake curve from fully dry condition is shown in figure 8.

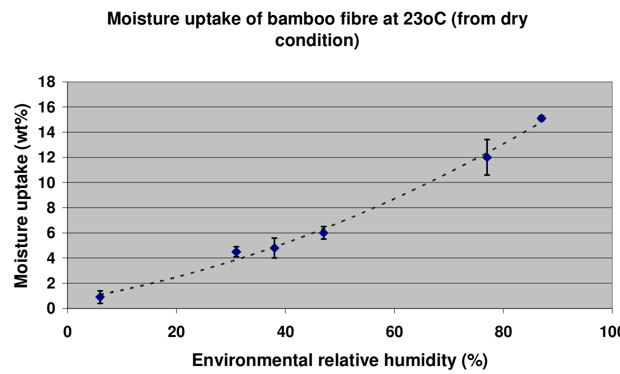

Fig.8. Moisture uptake curve (wt%) of bamboo fibre at different levels of environmental relative humidity

Humidity has a plasticizing effect on the fibres with an increase in strain to failure, but hardly an effect on fibre strength. In bamboo epoxy composites, the effect of humidity is again an increase in strain to failure, but also a small increase in longitudinal UD composite strength.

3 Concluding remarks

Bamboo fibres show promising properties in composites, which may allow them to be a good, bio-based replacement for glass fibres. In epoxy, specific (equivalent) tensile modulus and strength values are reached comparable to glass fibre (specific means normalized to density); the specific bending stiffness is higher than for glass fibre.

Acknowledgements

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