KATHOLIEKE UNIVERSITEIT
LEUVEN

Composite
Materials
group

THE RELATION BETWEEN BAMBOO FIBRE MICROSTRUCTURE AND MECHANICAL PROPERTIES

9th World Bamboo Congress
Antwerp, Belgium
11th April 2012

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Promotors:
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Motivation

To understand the mechanical behaviour of bamboo fibres and bamboo fibre composites

How the morphology and microstructure of bamboo (*Guadua angustifolia*) fibres explain the mechanical performance of bamboo fibre and bamboo fibre composites?

Content

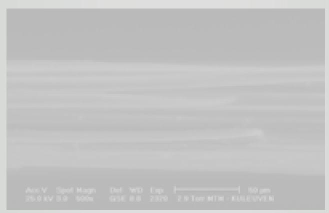
1.Macro-level

Bamboo Guadua angustifolia

- Natural fibres
- The bamboo culm
- Vascular bundles distribution

2. Meso-level

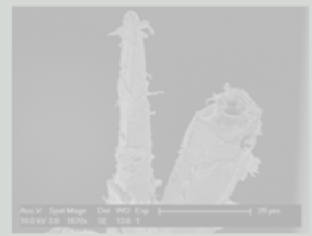
Bamboo technical fibres

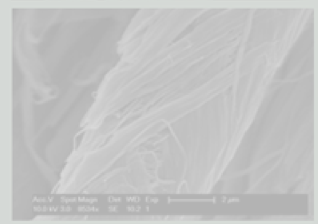


- Mechanical properties

3.Micro-level

Bamboo elementary fibres

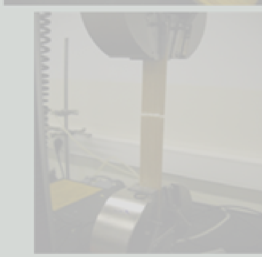




- Polylamellate structure
- Fibre dimensions
- Mechanical properties
- Microfibril angle

4. Composites

Bamboo fibre composites



- Tensile properties
- Mechanical properties
- Moisture sensitivity

Natural fibres

CLASSIFICATION OF PLANT FIBRES ACCORDING TO THEIR ORIGIN

PLANT FIBRES

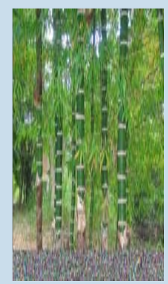
- Wood

- Stem

  - Flax
  - Jute
  - Hemp
  - Ramie
- Leaf

  - Sisal
  - Abaca
  - Pineapple
  - Fique
  - Henequen
- Seed

  - Cotton
  - Coconut
- Grass

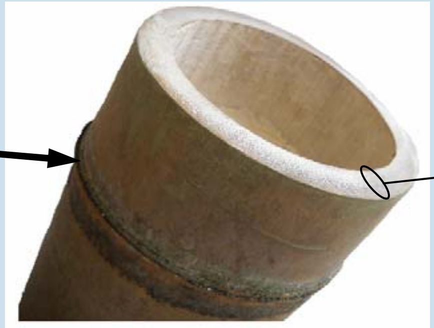


  - **Bamboo**
  - Rice

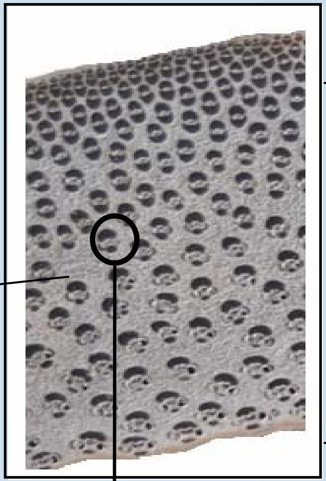
Adapted from Maiti, R., 1994

Bamboo fibres

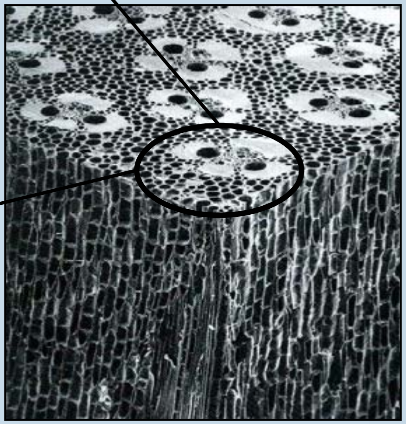
Bamboo culm



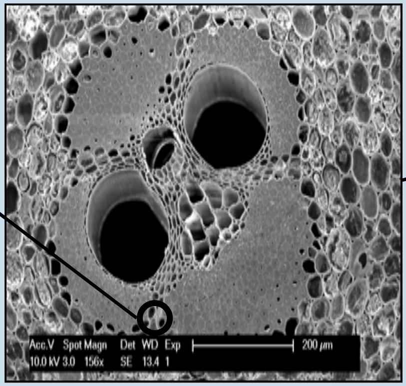
Cross section



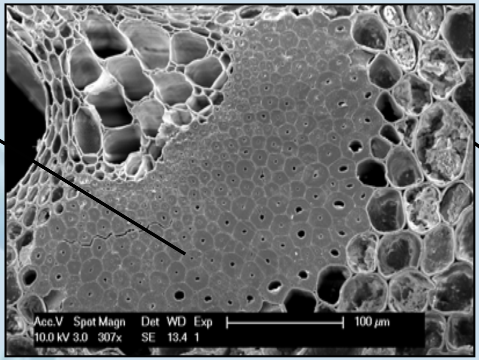
Fibres are distributed densely in the outer region of the wall and sparsely in the inner region



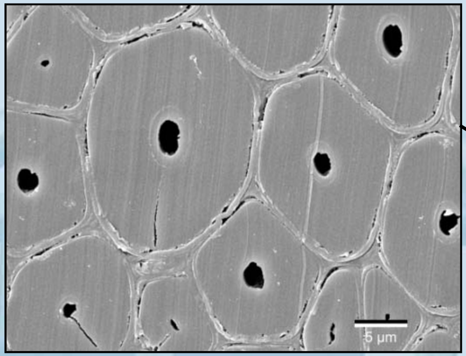
Bamboo wall
Liese, W., 1998



Vascular bundle

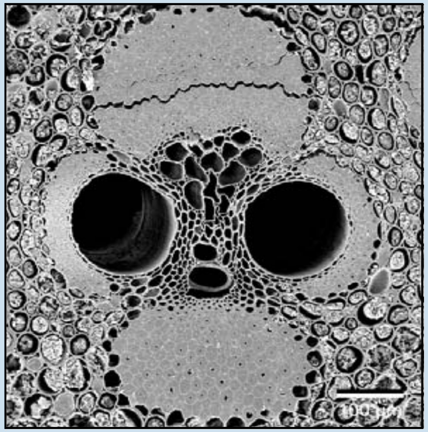


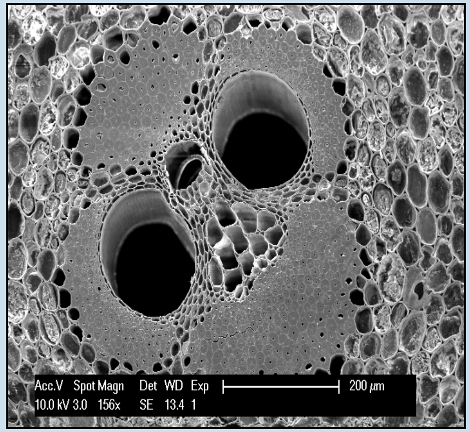
Technical fibre

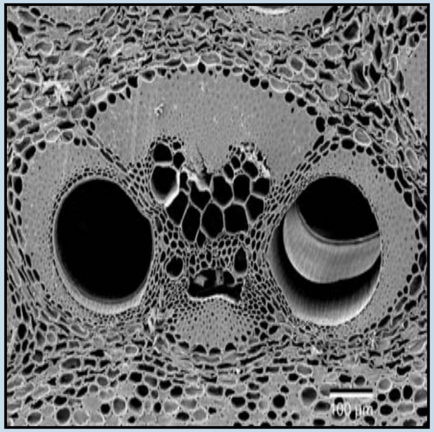


Elementary fibres

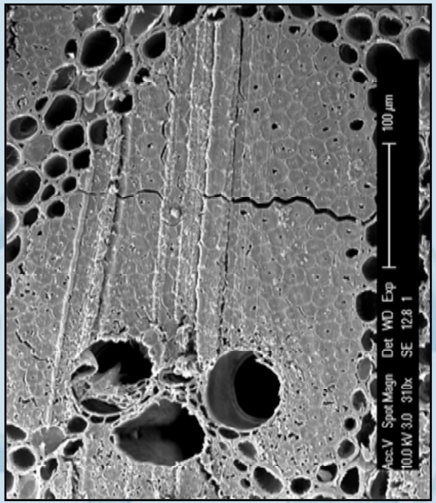
Morphology of the vascular bundles

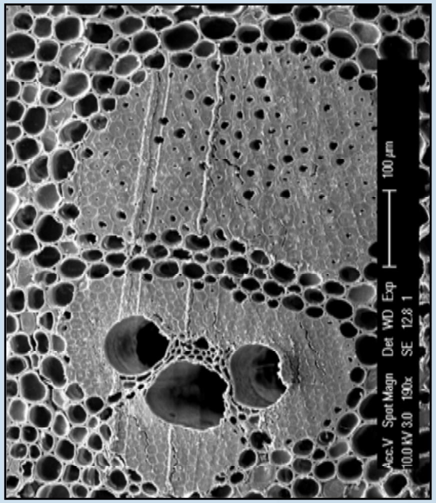


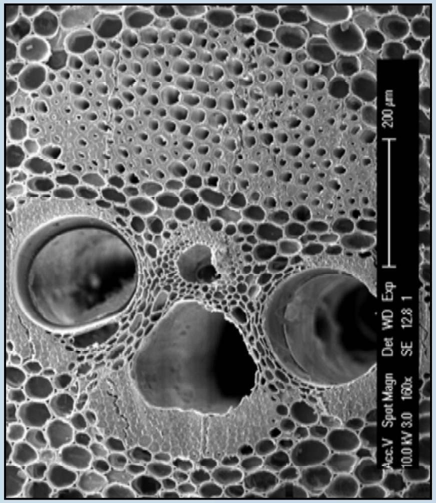




Guadua *angustifolia*







Dendrocalamus membranaseus

OUTER PART

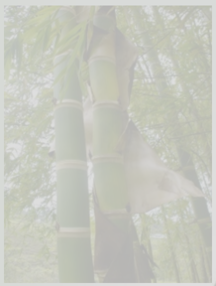
MIDDLE PART

INNER PART

Content

1.Macro-level

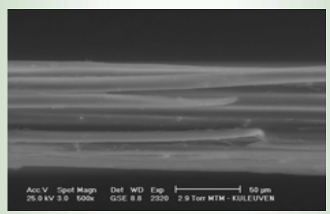
Bamboo Guadua angustifolia



- Natural fibres
- The bamboo culm
- Vascular bundles distribution

2. Meso-level

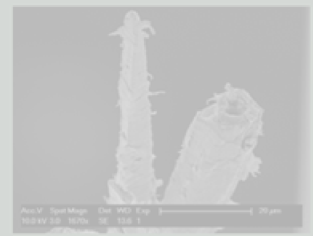
Bamboo technical fibres

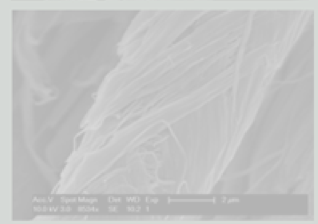


- Mechanical properties

3.Micro-level

Bamboo elementary fibres

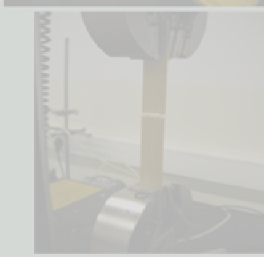




- Polylamellate structure
- Fibre dimensions
- Mechanical properties
- Microfibril angle

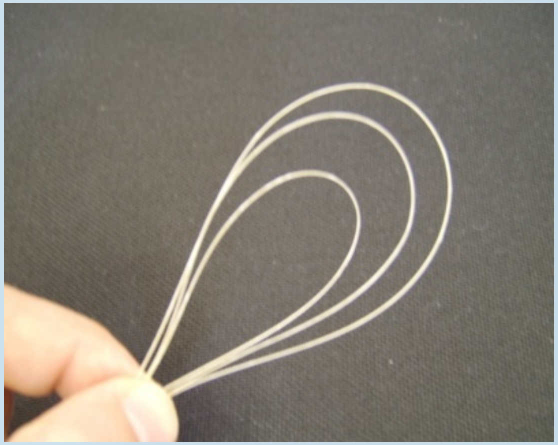
4. Composites

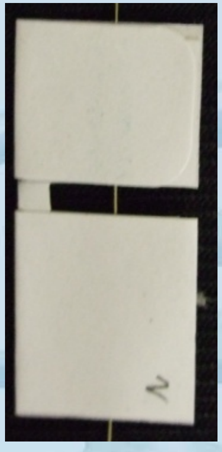
Bamboo fibre composites

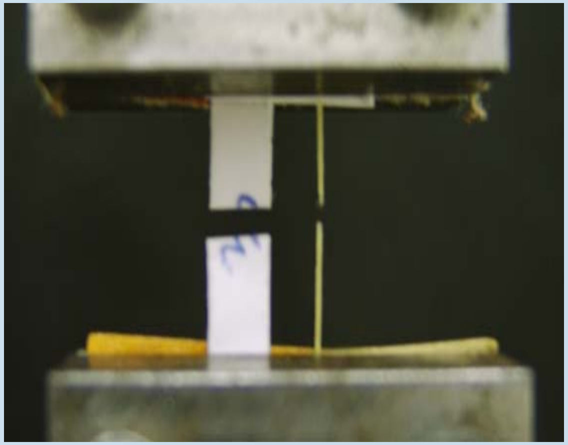


- Tensile properties
- Mechanical properties
- Moisture sensitivity

The mechanical properties of the technical fibre

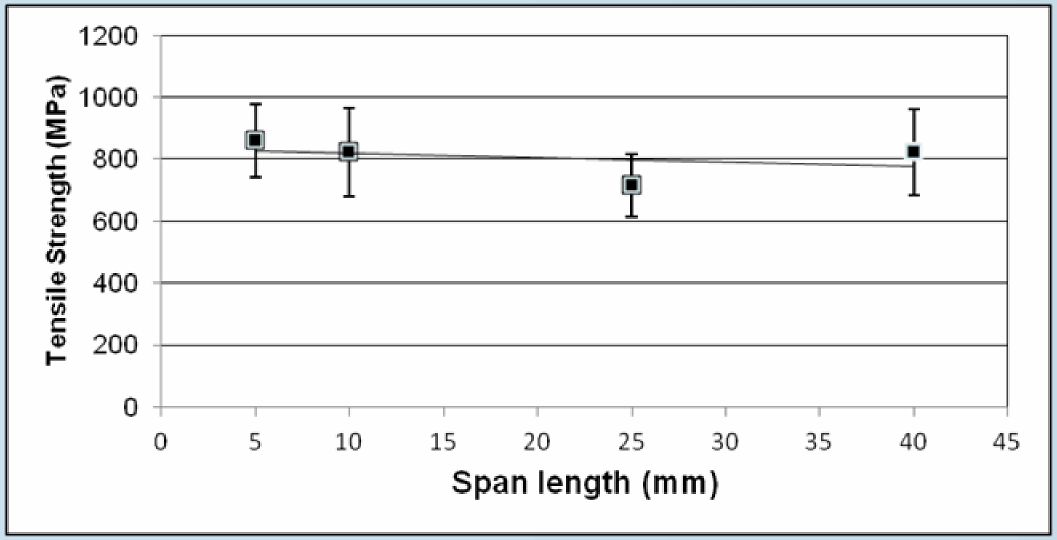




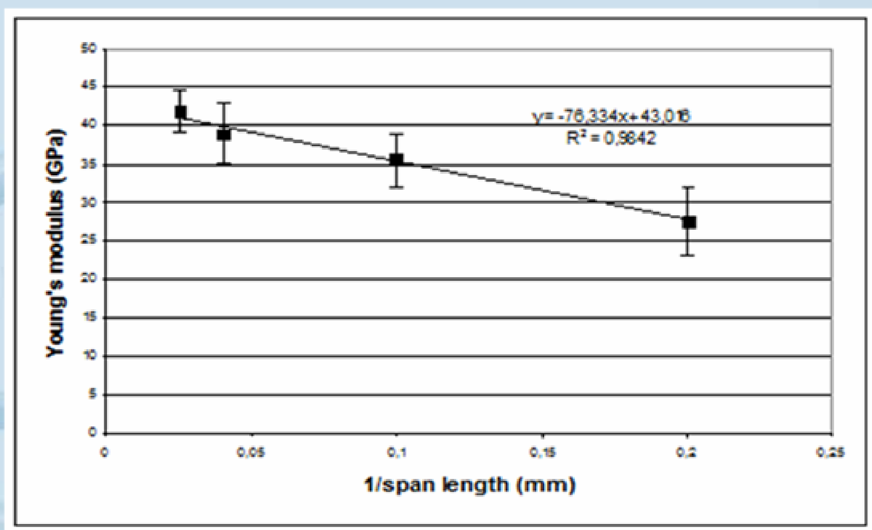


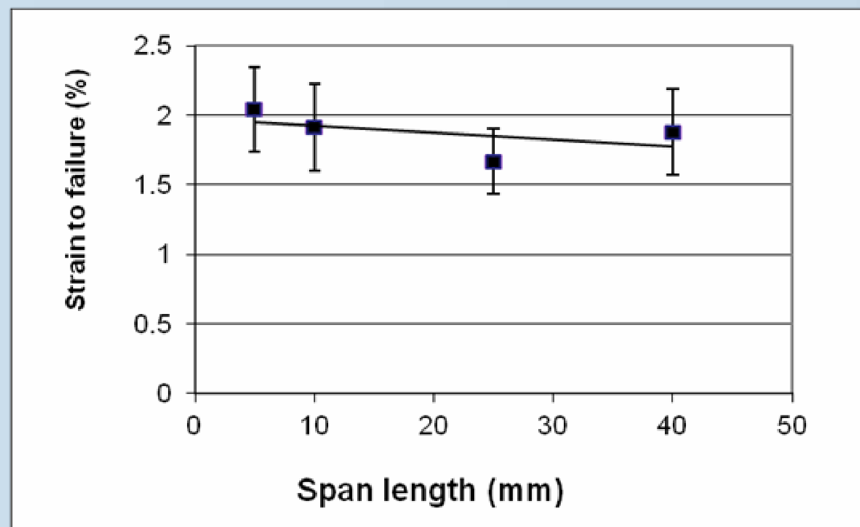
Before the tensile test every fibre is selected to avoid the presence of defects along the length. The use of a paper frame enhances the gripping and protects the fibre.

Mechanical properties

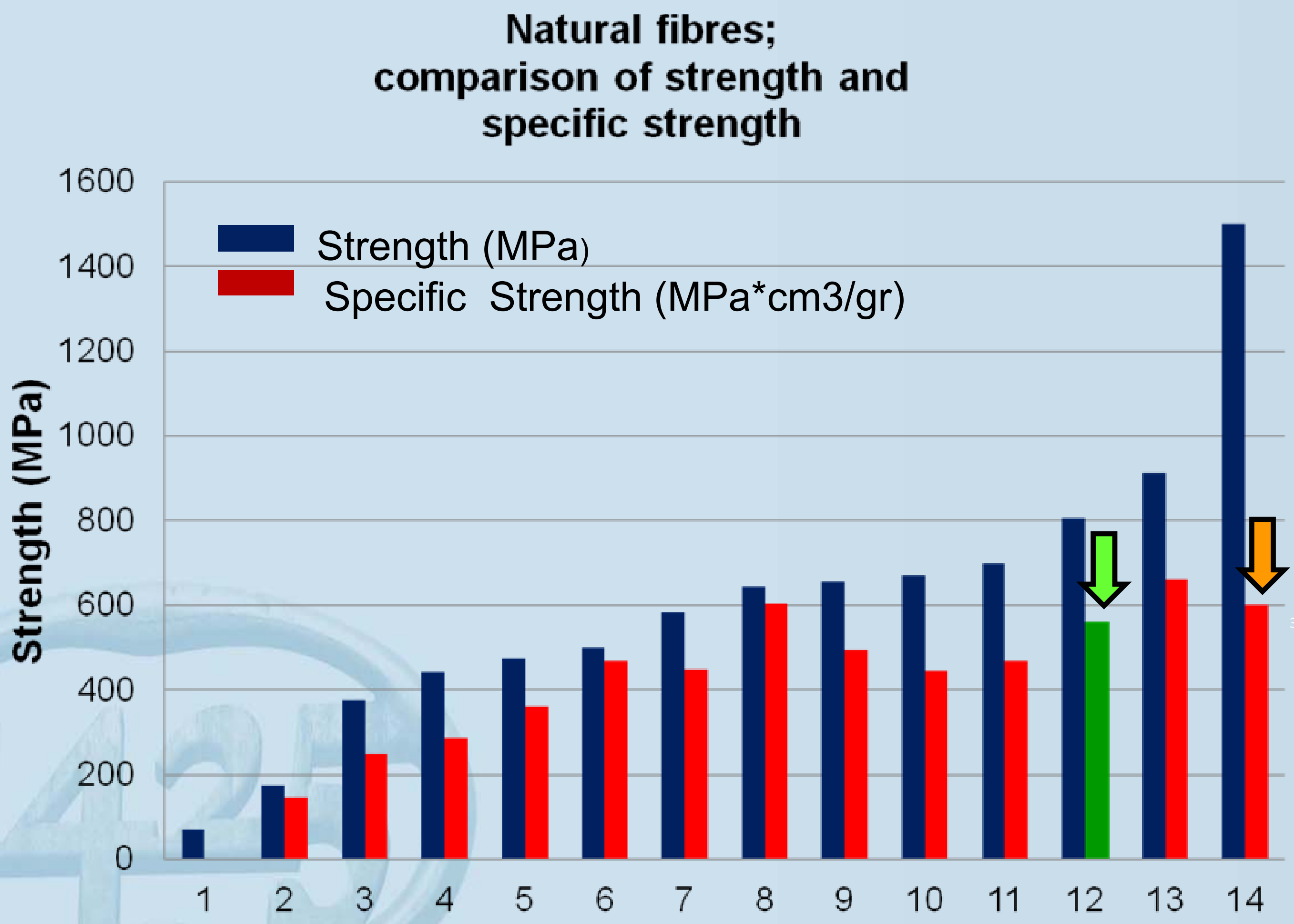


Mechanical properties of the technical fibres at different span lengths





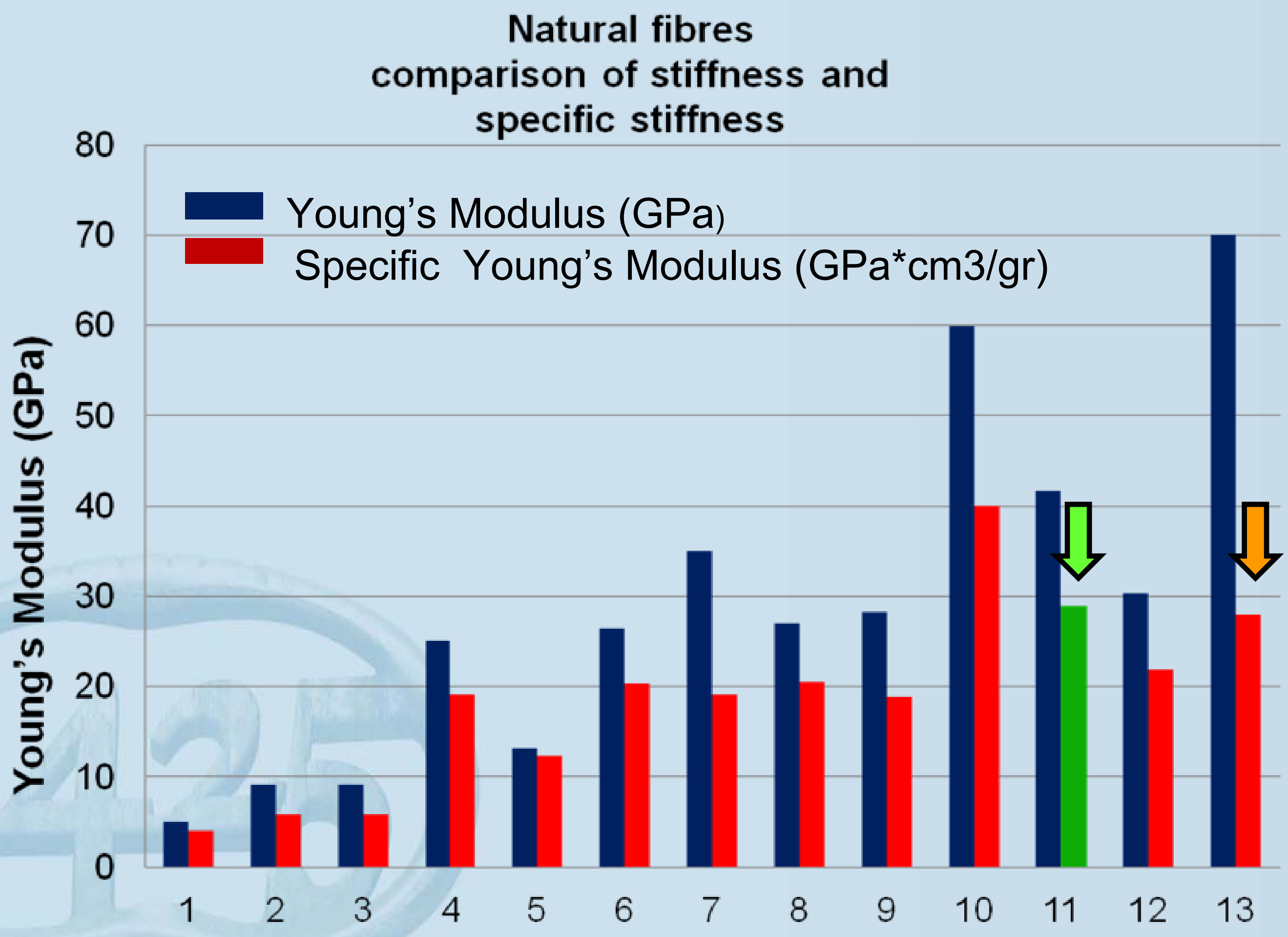
Comparison with other natural fibres



1. Bagasse
2. Coir
3. Sisal
4. Cotton
5. Kenaf
6. Henequen
7. Jute
8. Hemp
9. Pineapple
10. Ramie
11. Flax
12. Bamboo
13. Curauà
14. E-Glass

Composite materials group

Comparison with other natural fibres



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Bamboo Guadua angustifolia

•Natural fibres
•The bamboo culm
•Vascular bundles distribution

2. Meso-level

Bamboo technical fibres

• Mechanical properties

3.Micro-level

Bamboo elementary fibres

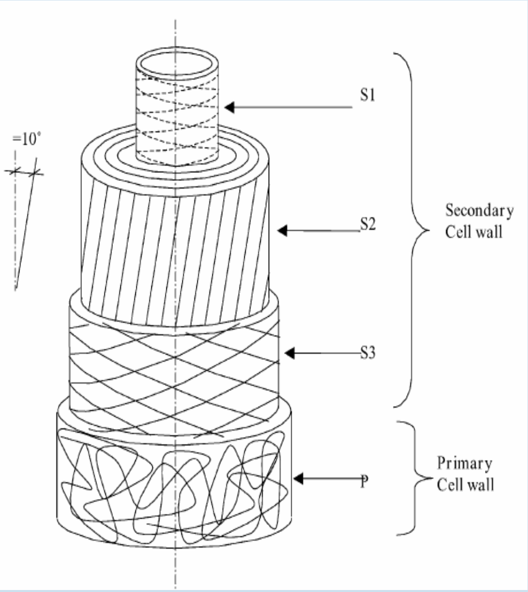
•Polylamellate structure
•Fibre dimensions
•Mechanical properties
•Microfibril angle

4. Composites

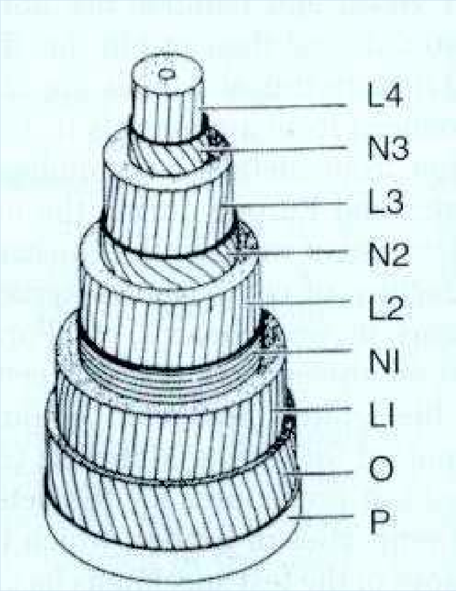
Bamboo fibre composites

•Tensile properties
•Mechanical properties
•Moisture sensitivity

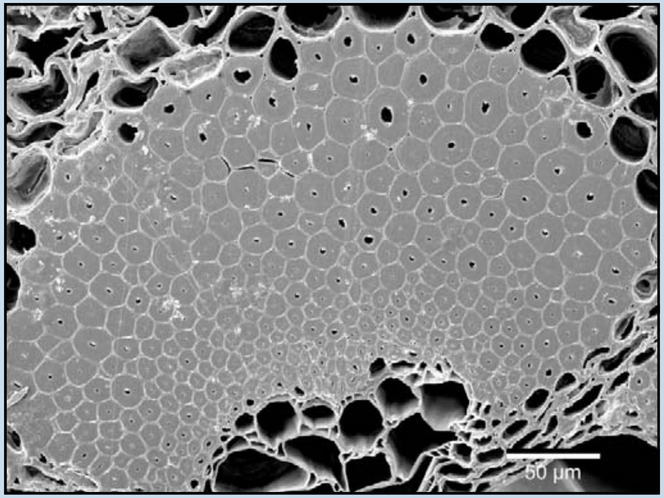
Polylamellate structure of elementary bamboo fibres

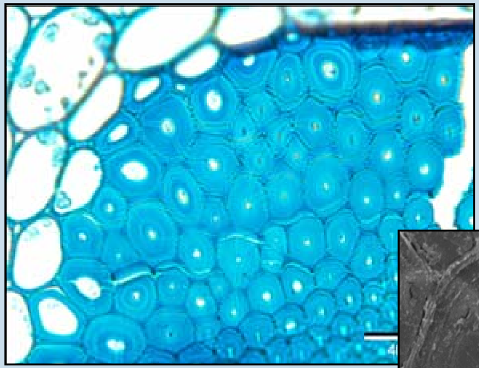


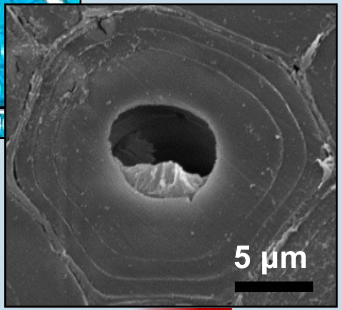
Flax fibre, *Baley C*. 2002



Bamboo fibre , *Liese W.* 1998



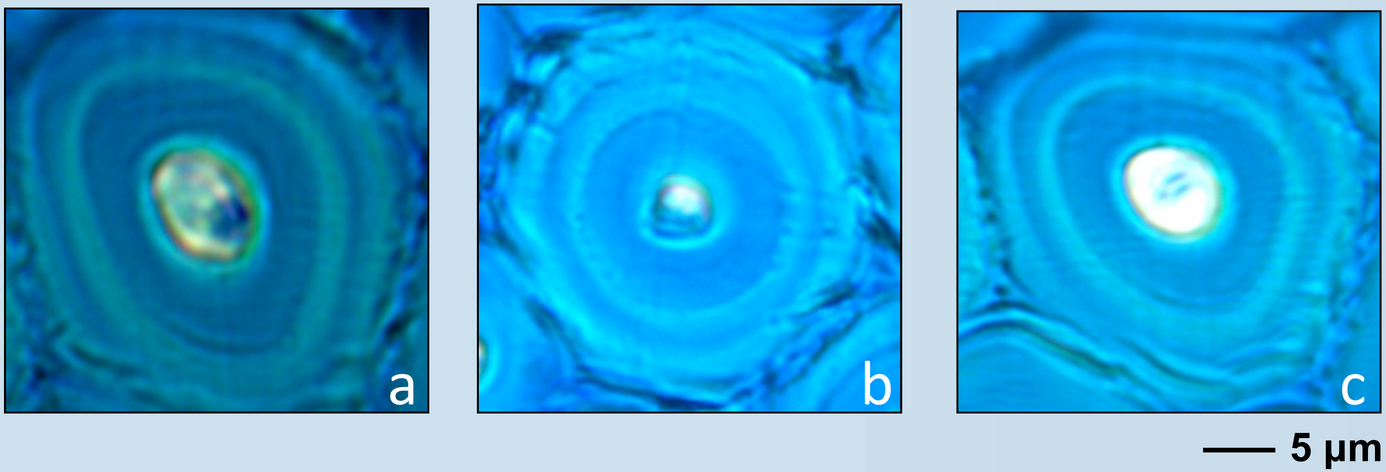




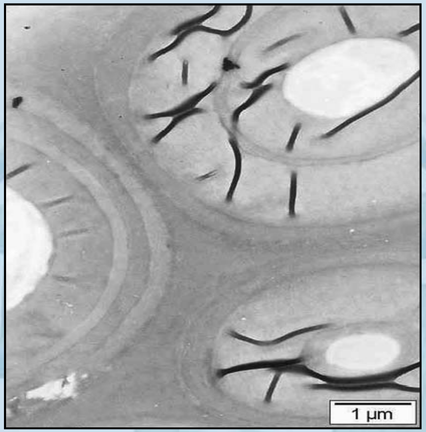
A majority of the fibres does not possess any obvious layering of their walls. However, thick-walled fibres with distinct layering occur especially in the peripheral region adjacent to the epidermis. Liese, W. 1998

The same statement was published by Gritsch, C. 2004, 2005 and Lybeer, B. 2006,

Polylamellate structure of elementary bamboo fibres

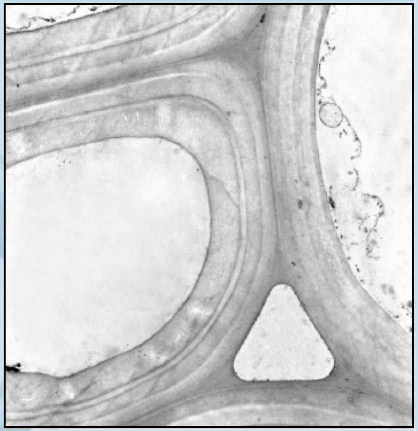


Light microscope images where transition (thin) layers are visible. Images a, b and c correspond to elementary fibres of the periphery of the fibre bundle.



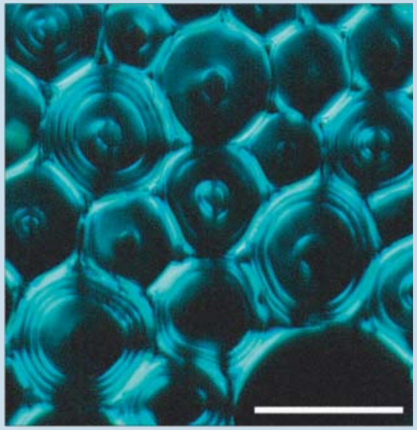
Lybeer, B. 2006

P. Viridiglaucescens



Sanchis, C. 2005

Dendrocalamus asper

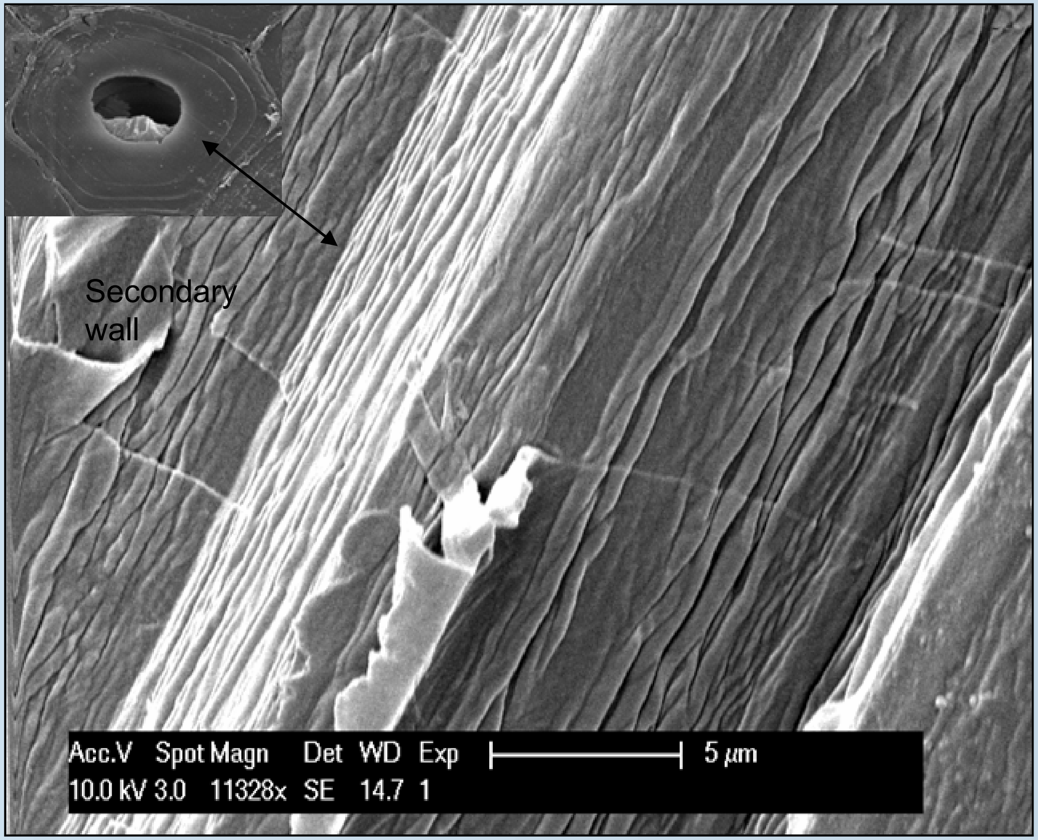


Sanchis, C. 2004

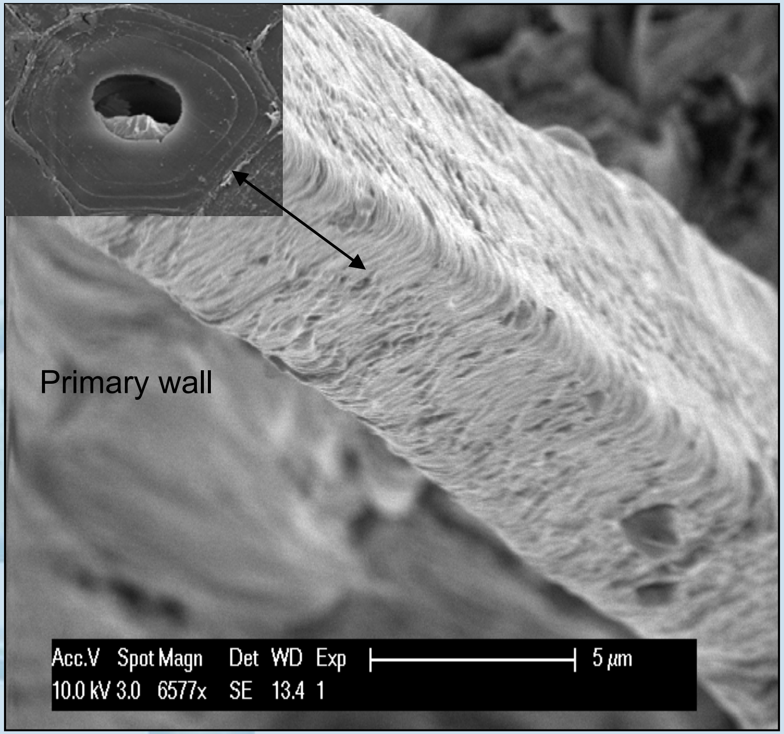
Dendrocalamus asper

Microfibril angle

In the **broad** lamellae the microfibrils are oriented at an angle of **2 – 5°.** The **narrow** lamellae shows mostly fibrils oriented horizontally at an angle of **85 – 90°**, which remains constant over the whole width of the wall. Liese, W. 1998

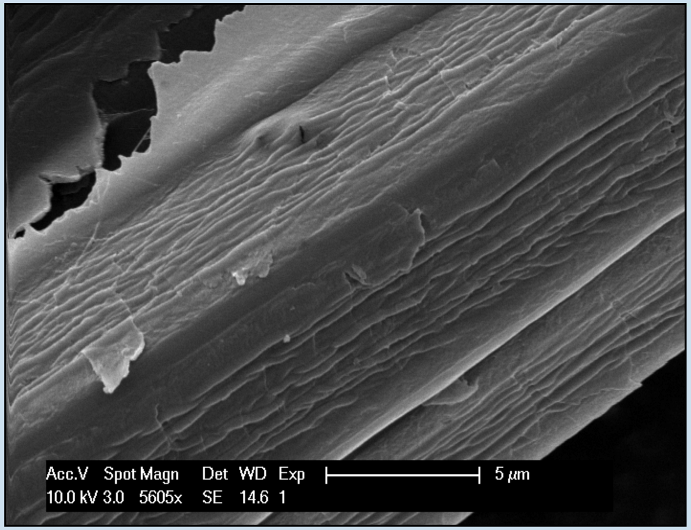


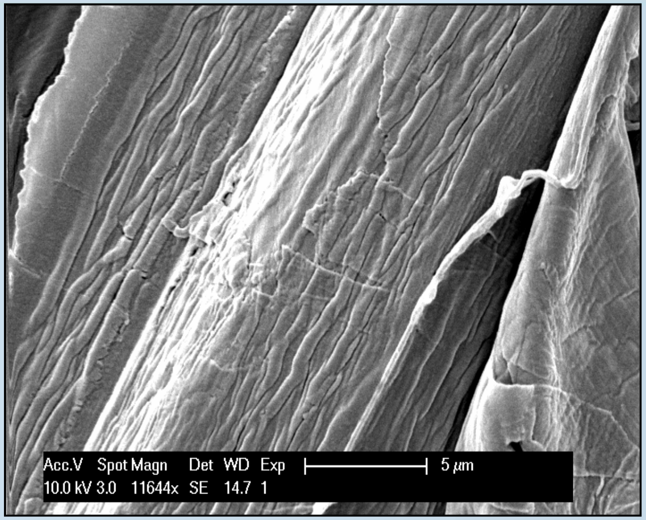
Secondary wall with microfibrils oriented at an angle of ~0°



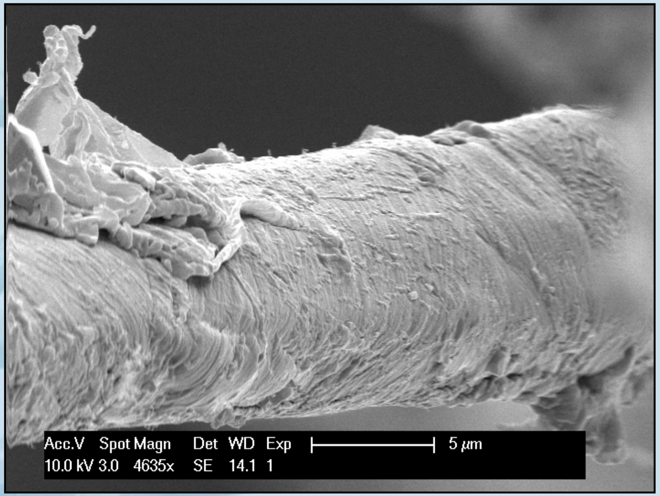
Primary layer with Microfibrils oriented at an angle of 90°

Microfibril angle

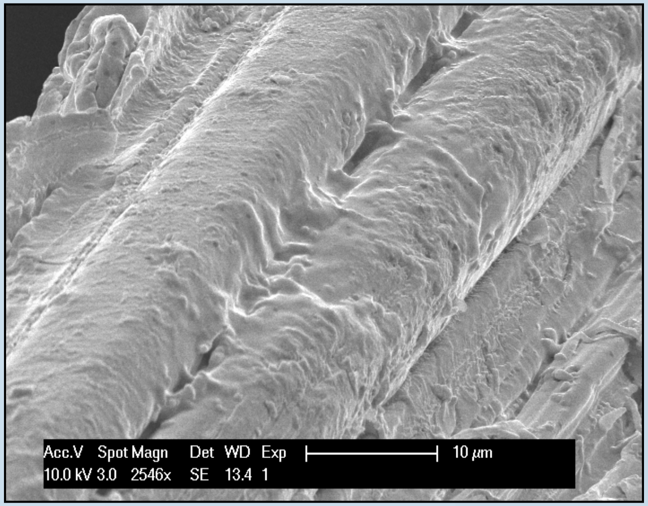




Fibres oriented at an angle of ~0°

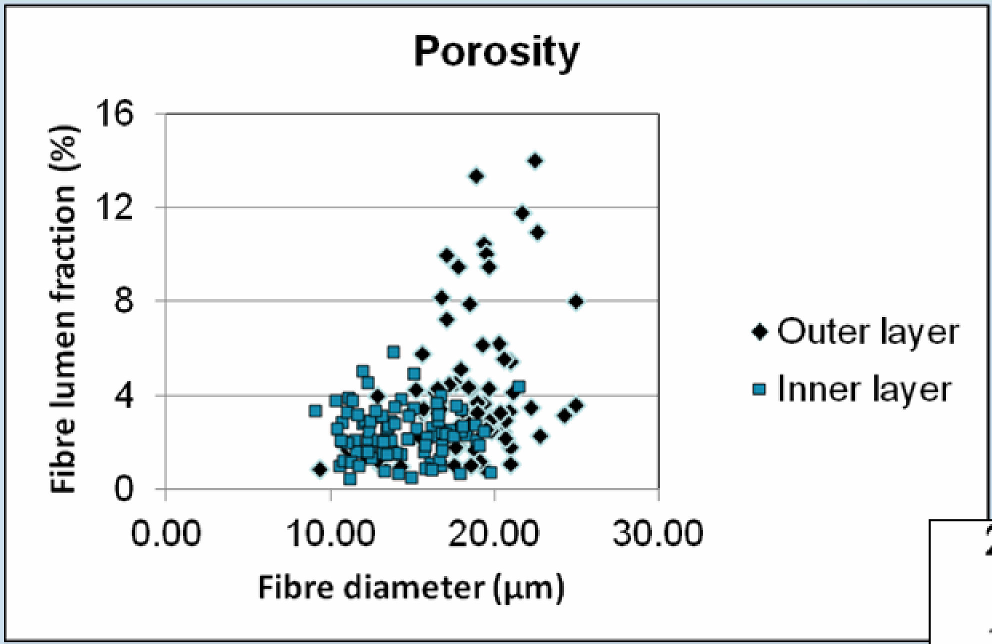


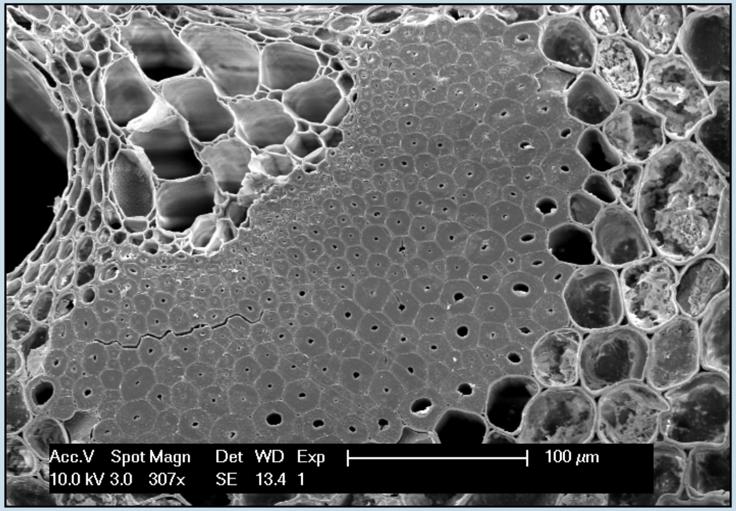
Fibres oriented at an angle of 90°

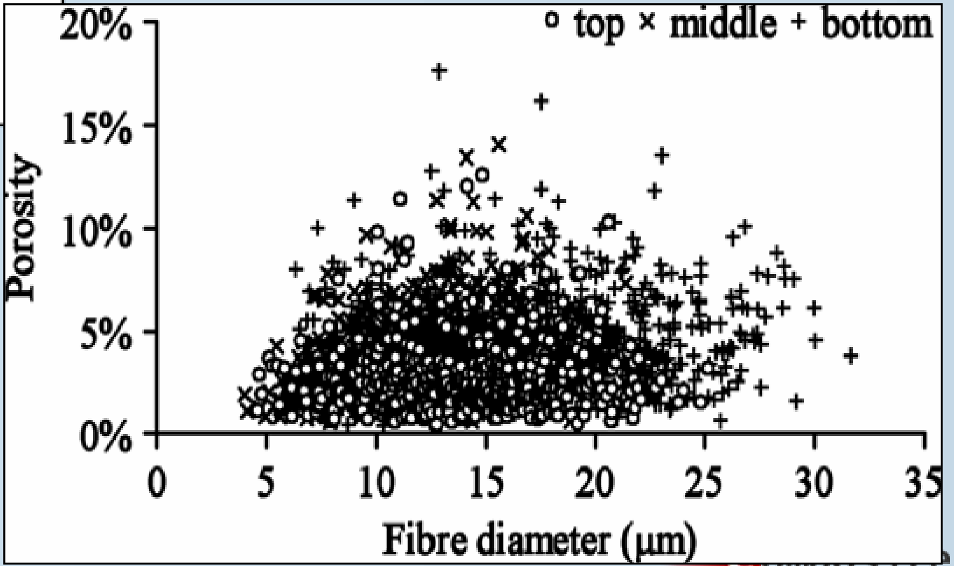


Fibre surface covered by lignin

Fibre porosity





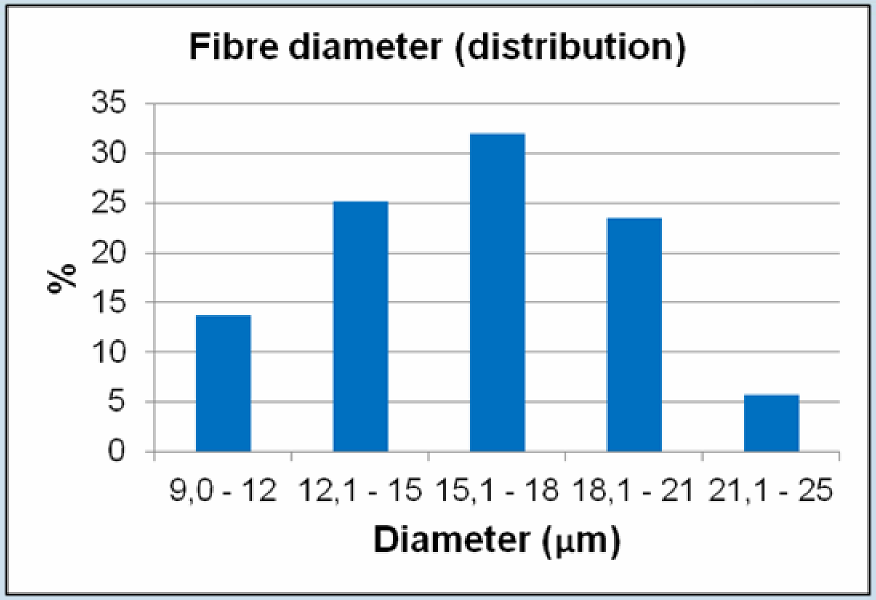


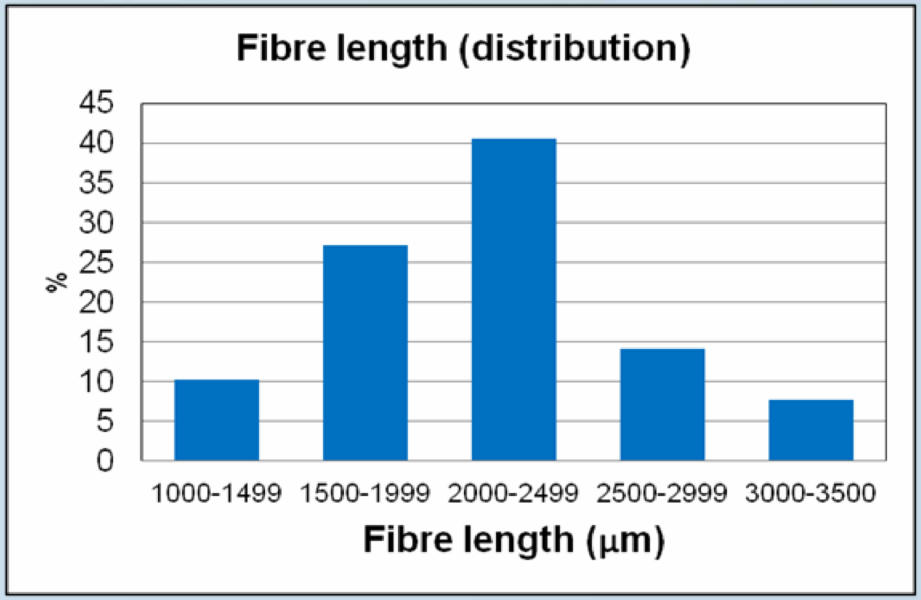
Flax fibres, Charlet K. 2007

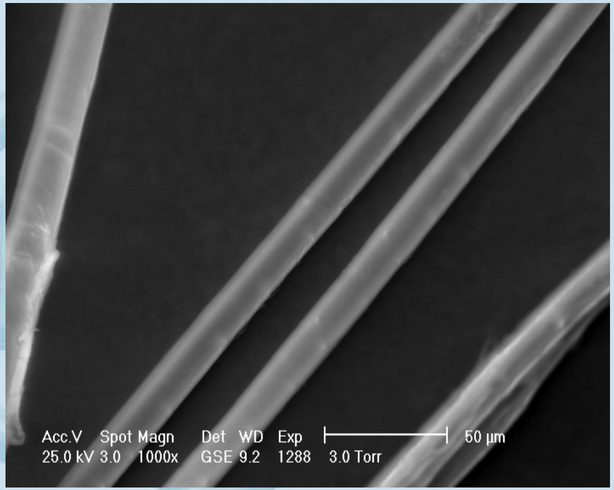
The 'fibre lumen fraction' (ratio of the lumen area to the fibre section) of bamboo fibres according to the position in the technical fibre remains around **4%**. The thickness of the lignin layer is 0.5 µm which represents **~7%** of the wall thickness.

composite materials group

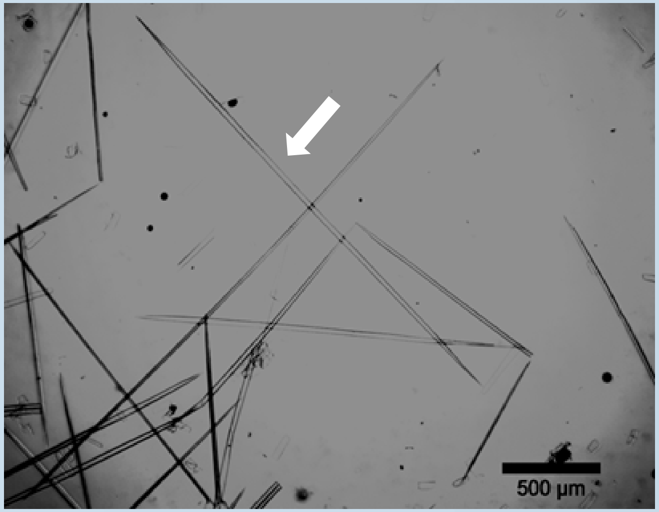
Fibre dimensions







The average elementary fibre diameter is **17 µm**



The average elementary fibre length is **2.1 mm**

Content

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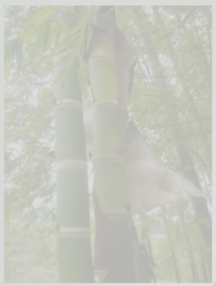

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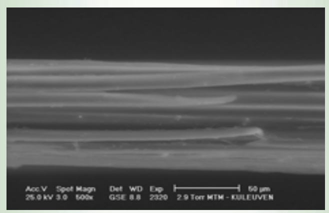


- Mechanical properties

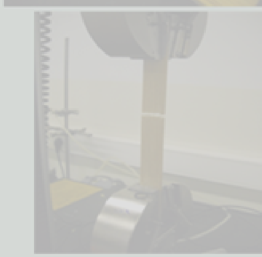
3.Micro-level

Bamboo elementary fibres

- Polylamellate structure
- Fibre dimensions
- Mechanical properties
- Microfibril angle

4. Composites

Bamboo fibre composites

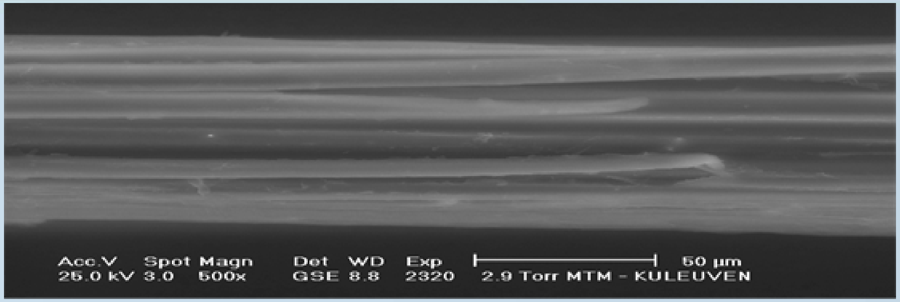


- Tensile properties
- Mechanical properties
- Moisture sensitivity

Mechanical properties

Estimation of the Young's Modulus of the elementary fibre

The fibre bundle is treated as a UD short fibre composite of lignin matrix reinforced with bamboo elementary fibres.



HALPIN-TSAI EQUATION

$$E_1 = E_M \left(\frac{1 + \xi \eta V_F}{1 - \eta V_F} \right)$$

?

$$\eta = \frac{(E_F / E_M) - 1}{(E_F / E_M) + \xi}$$

$$\xi = 2(l/d)10$$

Predicting the elastic modulus of natural fibre reinforced thermoplastics. Facca, A. et al 2006

SHEAR-LAG THEORY (COX'S EQUATION)

$$E_1 = E_F \left(1 - \frac{\tanh\left(\frac{\eta L}{2}\right)}{\frac{\eta L}{2}} \right) V_F + E_M V_M$$

$$\eta = \frac{1}{r} \left(\frac{2E_M}{E_F(1 + \upsilon_M) \ln\left(\frac{P_F}{V_F}\right)} \right)^{1/2}$$

?

Estimation of the Young's Modulus of the elementary fibre

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$$E_1 = E_F \left(1 - \frac{\tanh\left(\frac{\eta L}{2}\right)}{\frac{\eta L}{2}} \right) V_F + E_M V_M$$

$$\eta = \frac{1}{r} \left(\frac{2 E_M}{E_F (1 + \upsilon_M) \ln \left(\frac{P_F}{V_F} \right)} \right)^{1/2}$$

		Strength (MPa)	Young's modulus (GPa)
Gage length (mm)	5	860 ± 119	46 ± 1.2
	10	811 ± 136.5	43 ± 0.9
	25	778 ± 121.9	43 ± 1.4
	40	775 ± 103.3	42 ± 1.1

Estimation of the Young's Modulus of the elementary fibre

HALPIN-TSAI EQUATION

$$E_1 = E_M \left(\frac{1 + \xi \eta V_F}{1 - \eta V_F} \right)$$

$$\eta = \frac{(E_F / E_M) - 1}{(E_F / E_M) + \xi}$$

$\xi = 2(l/d)10$

SHEAR-LAG THEORY (COX'S EQUATION)

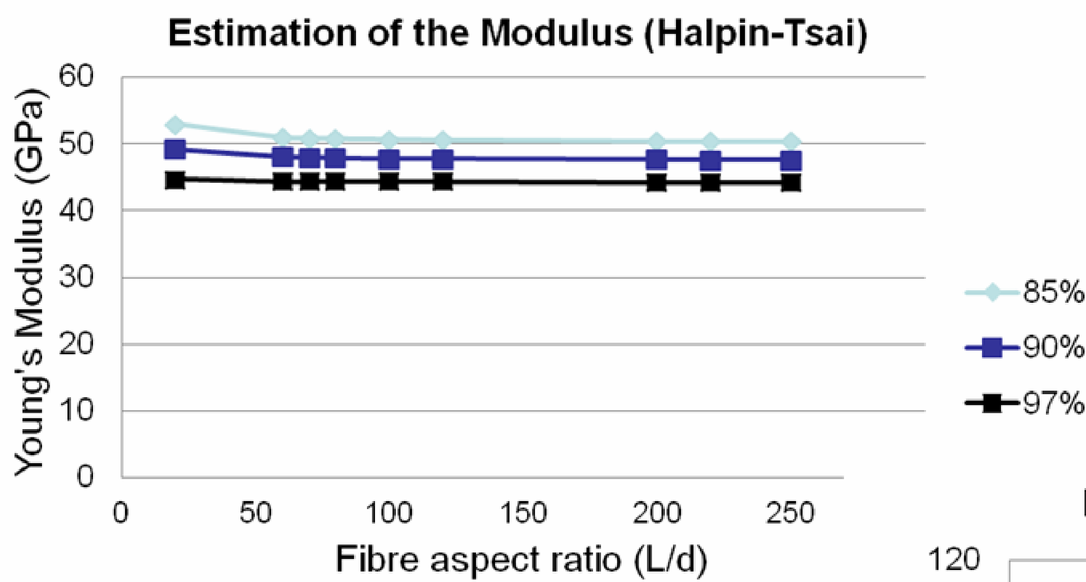
$$E_1 = E_F \left(1 - \frac{\tanh\left(\frac{\eta L}{2}\right)}{\frac{\eta L}{2}} \right) V_F + E_M V_M$$

$$\eta = \frac{1}{r} \left(\frac{2E_M}{E_F (1 + \upsilon_M) \ln\left(\frac{P_F}{V_F}\right)} \right)^{1/2}$$

From the microstructural analysis:

- Lumen percentage: 0,9 to 10%
- Fibre diameter: 10 to 25µm
- Fibre length: 1,1 to 3,4 mm
- Length to diameter ratio: 70 – 200

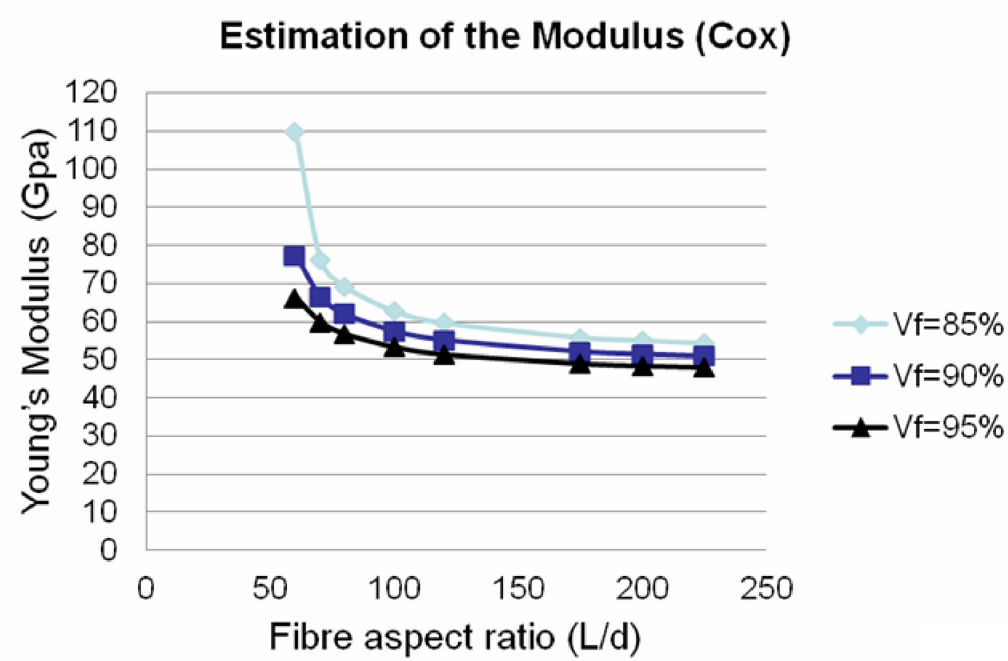
Estimation of the Young’s Modulus of the elementary fibre



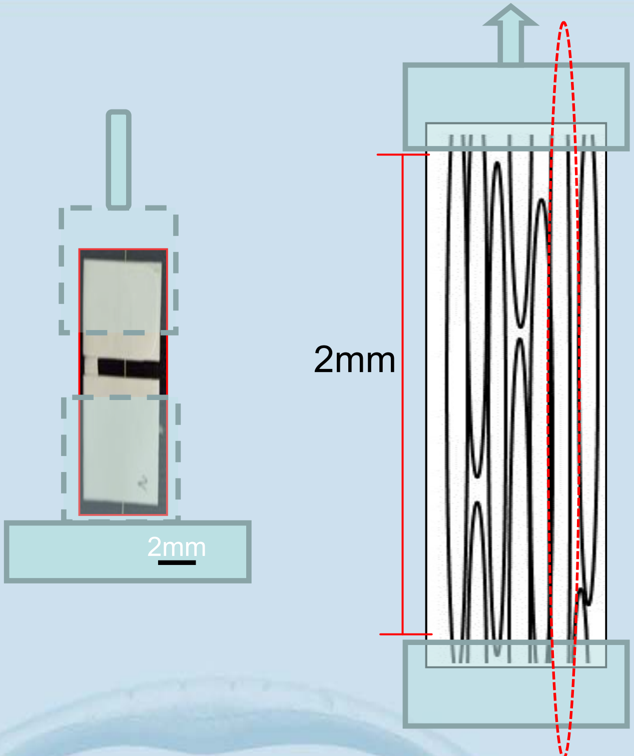
	Young’s Modulus (GPa)
Bamboo	50
Flax	60

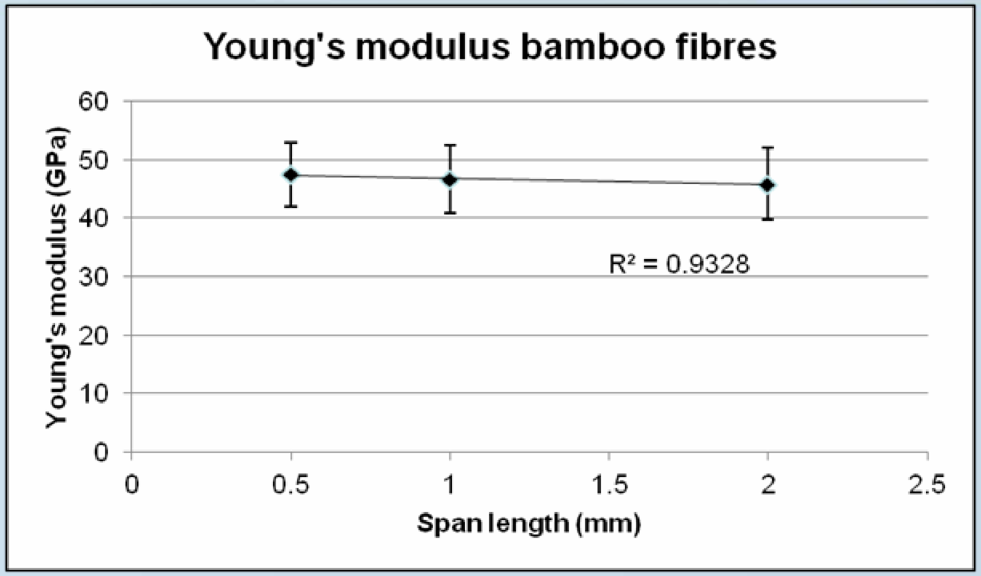
Charlet K et al 2009

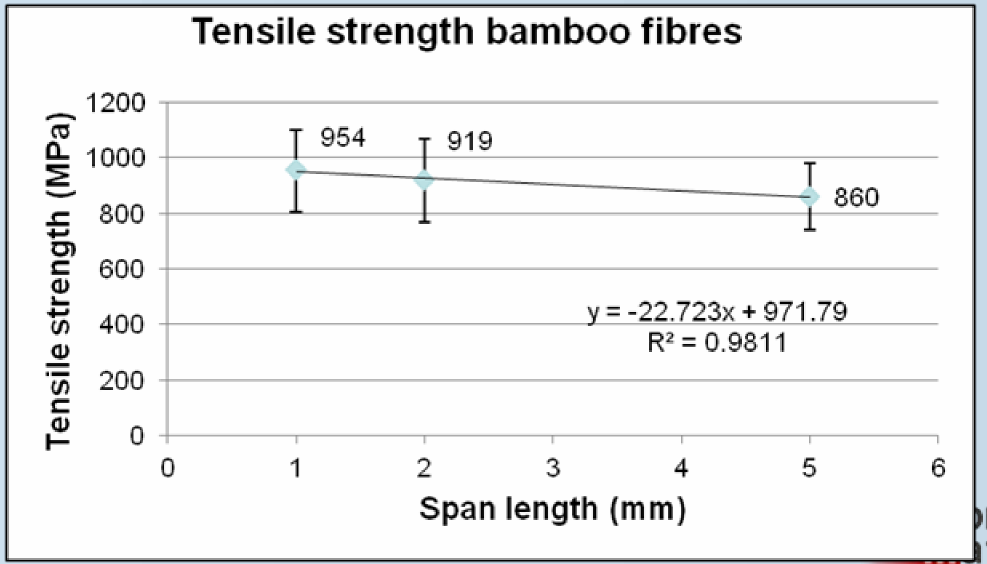
The estimated fibre modulus is about **~50** GPa with the two models. Graphs show the sensitivity of the models to high volume fractions.



Validation



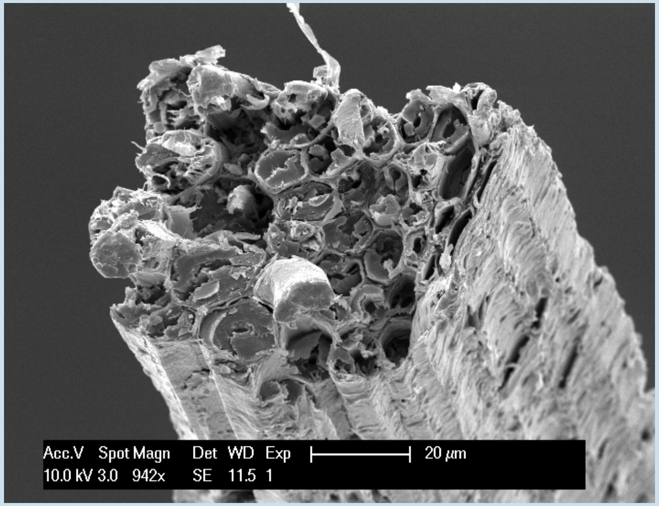




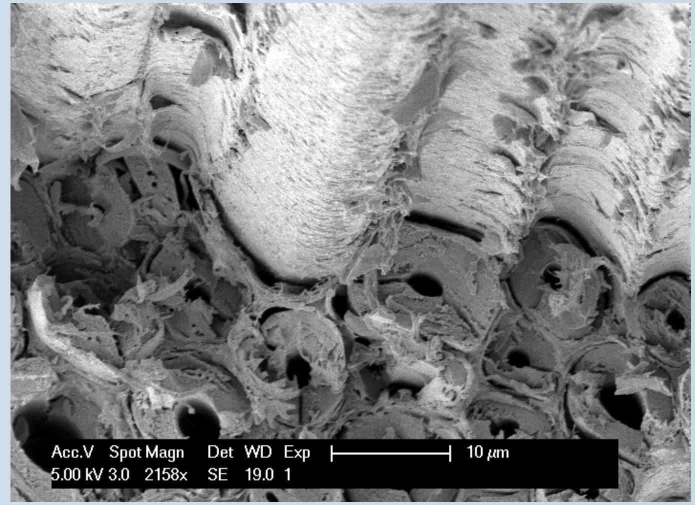
DMA set-up

Instron set-up

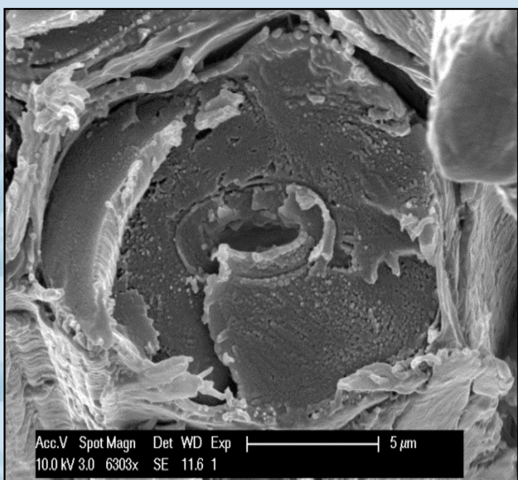
Fracture surfaces



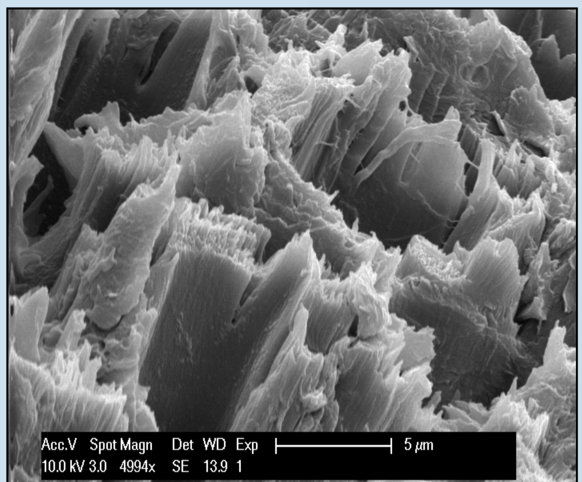
Clean failure all through the fibre surface

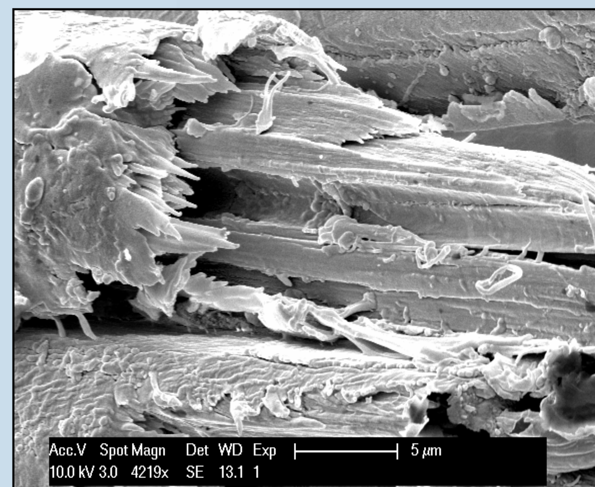


Failure in the primary layer



Elementary fibre wall





Microfibrils of the secondary wall

Content

1.Macro-level

Bamboo Guadua angustifolia

- Natural fibres
- The bamboo culm
- Vascular bundles distribution

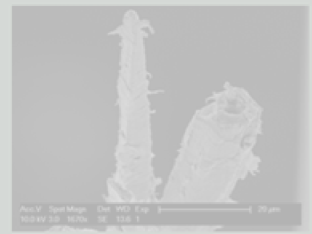
2. Meso-level

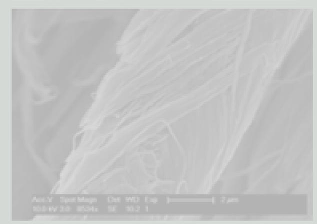
Bamboo technical fibres

- Mechanical properties

3.Micro-level

Bamboo elementary fibres

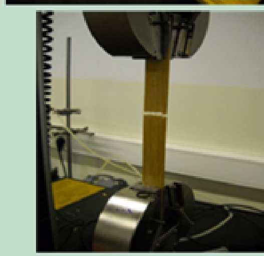




- Polylamellate structure
- Fibre dimensions
- Mechanical properties
- Microfibril angle

4. Composites

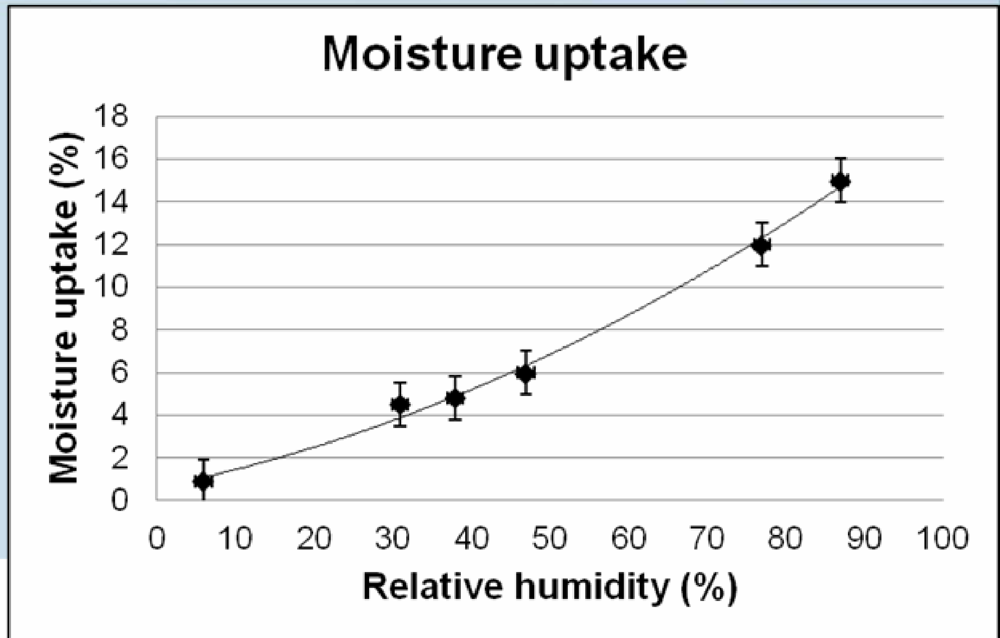
Bamboo fibre composites

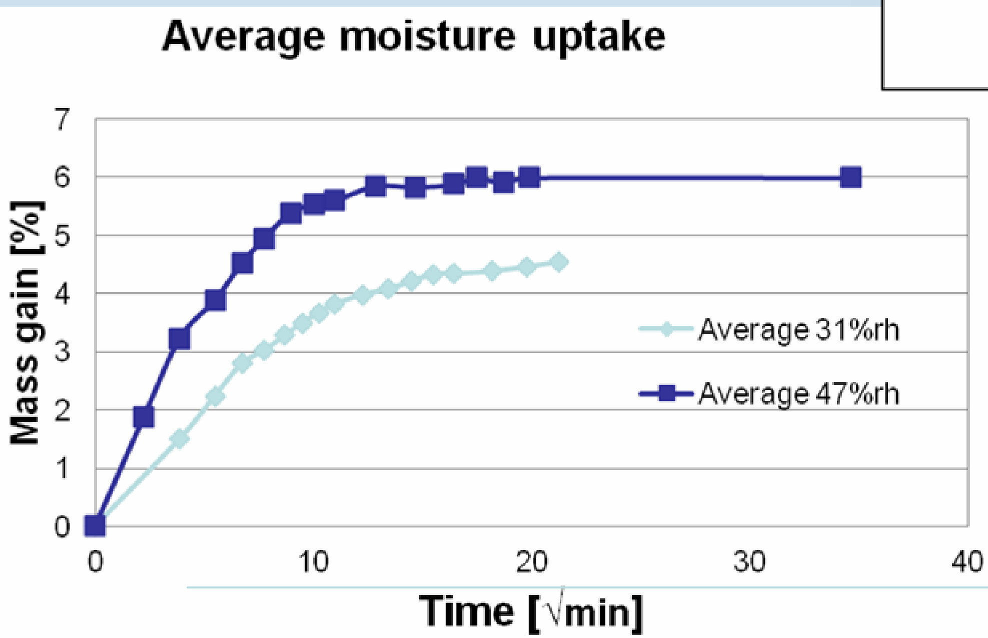


- Tensile properties
- Mechanical properties
- Moisture sensitivity

Moisture uptake

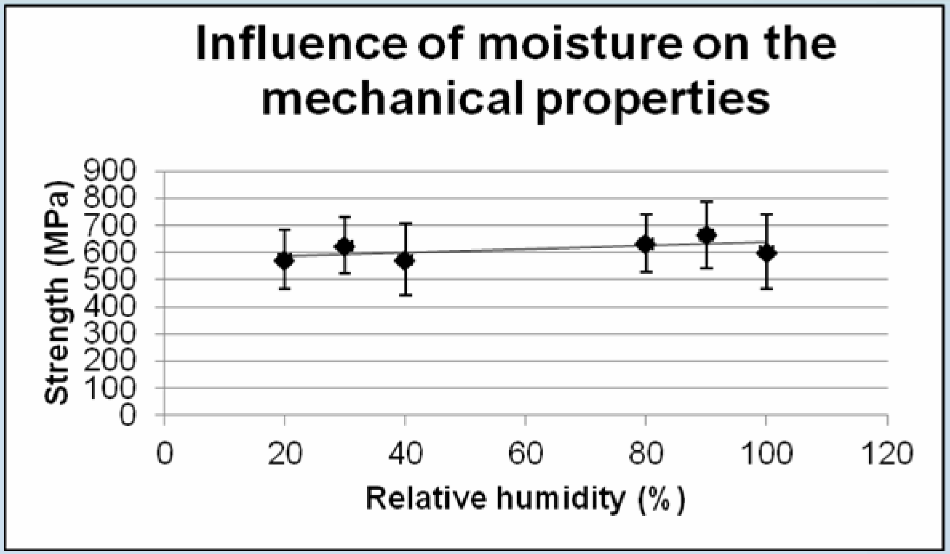
- Dried fibres
- Final moisture content material dependent
- Uptake rate↑ with moisture level↑

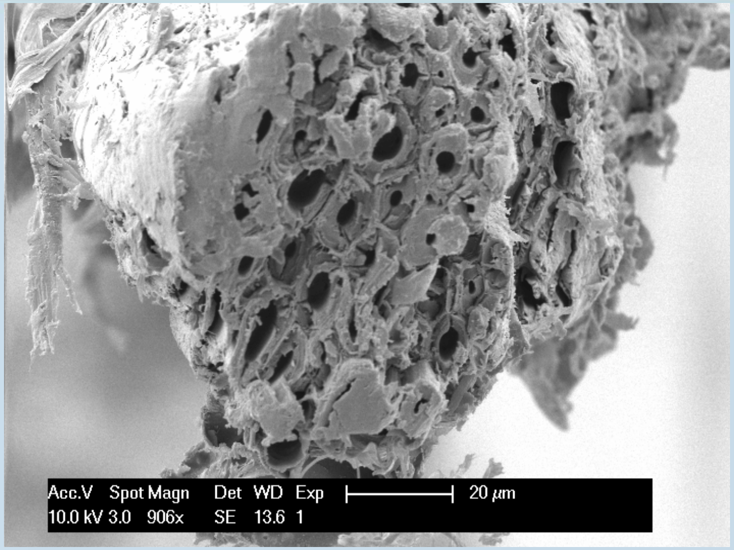




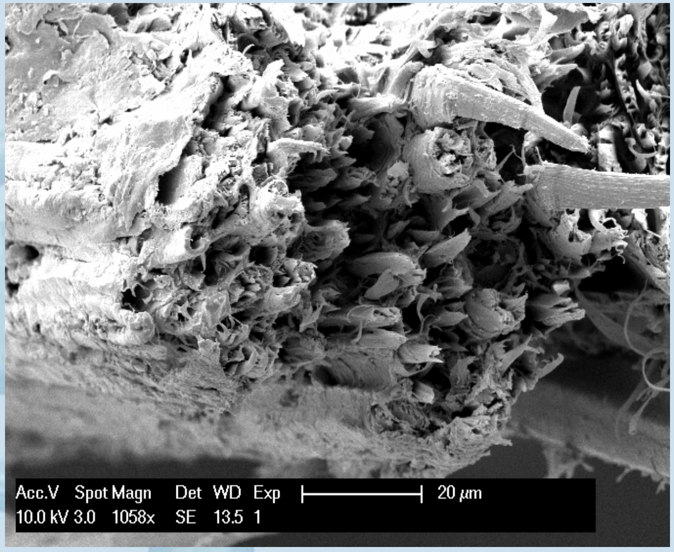
Submersion	41,2±7,2% (Moisture uptake)

Moisture sensitivity

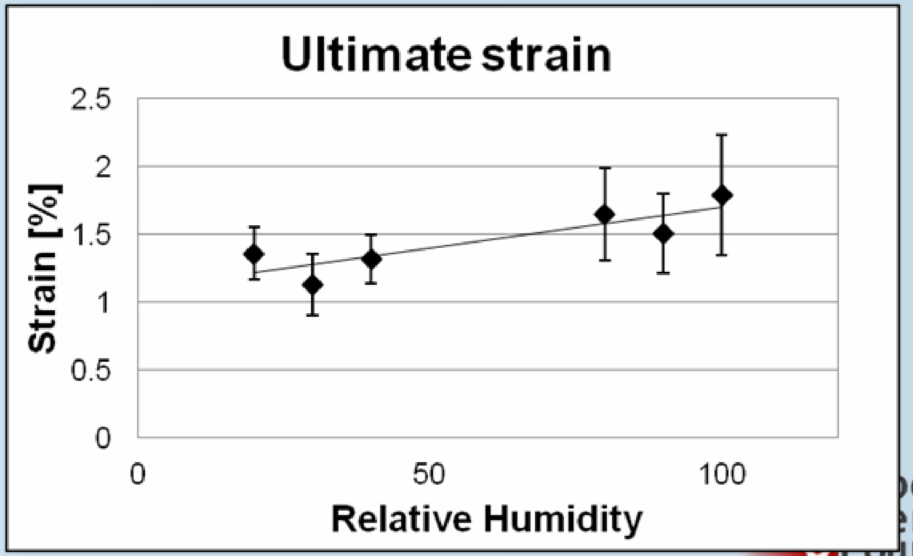




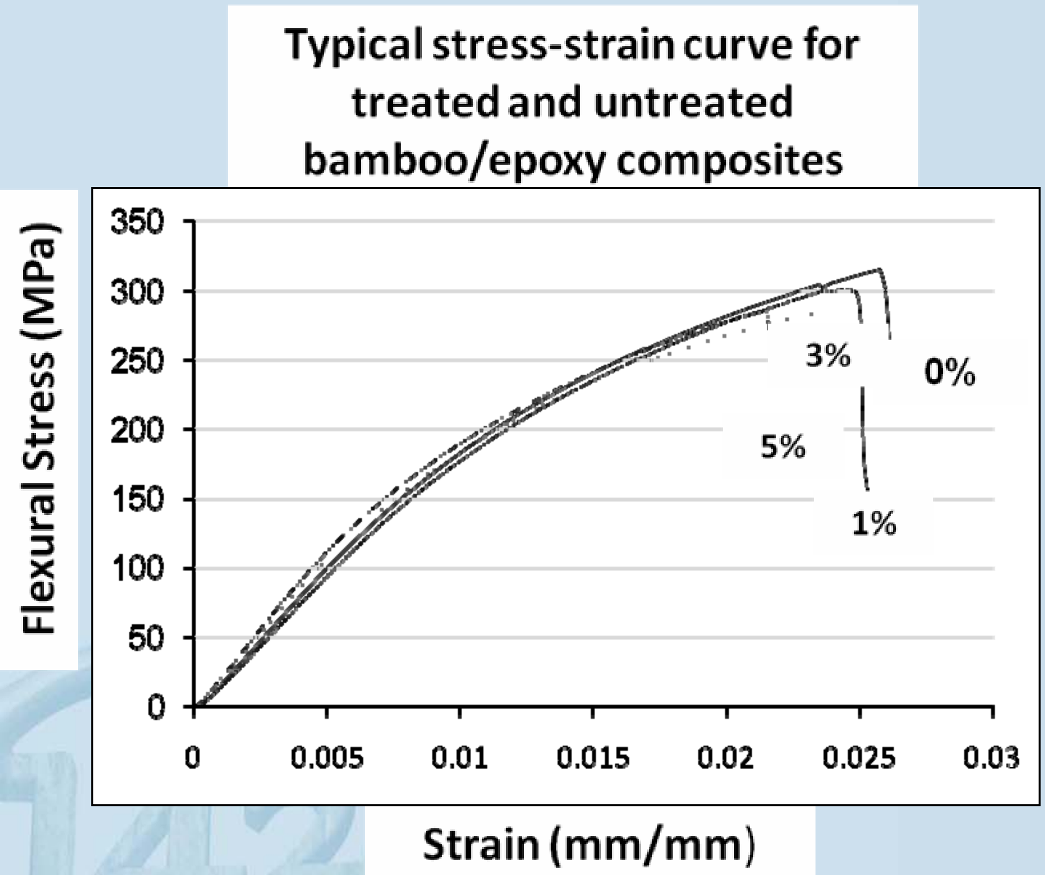
20%rh

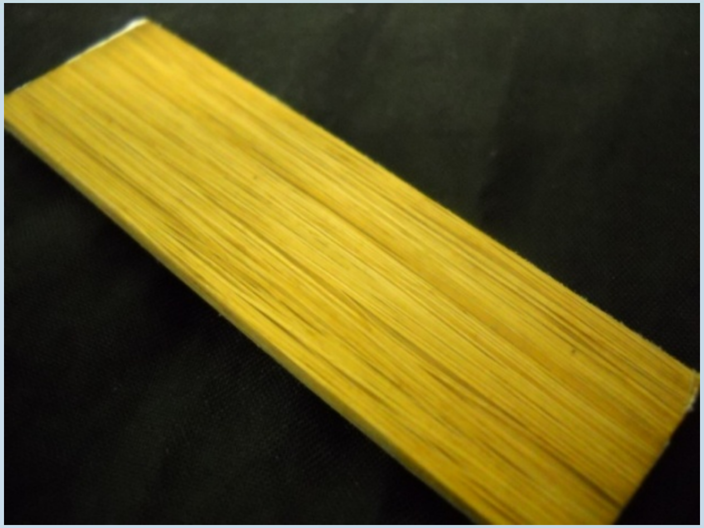


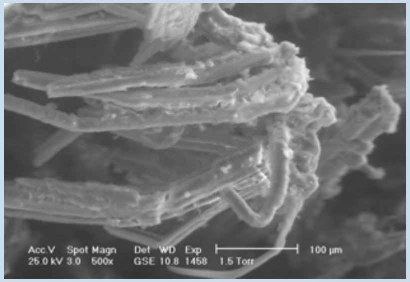
80%rh

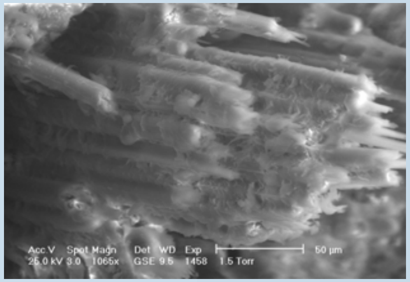


Bamboo fibre composites

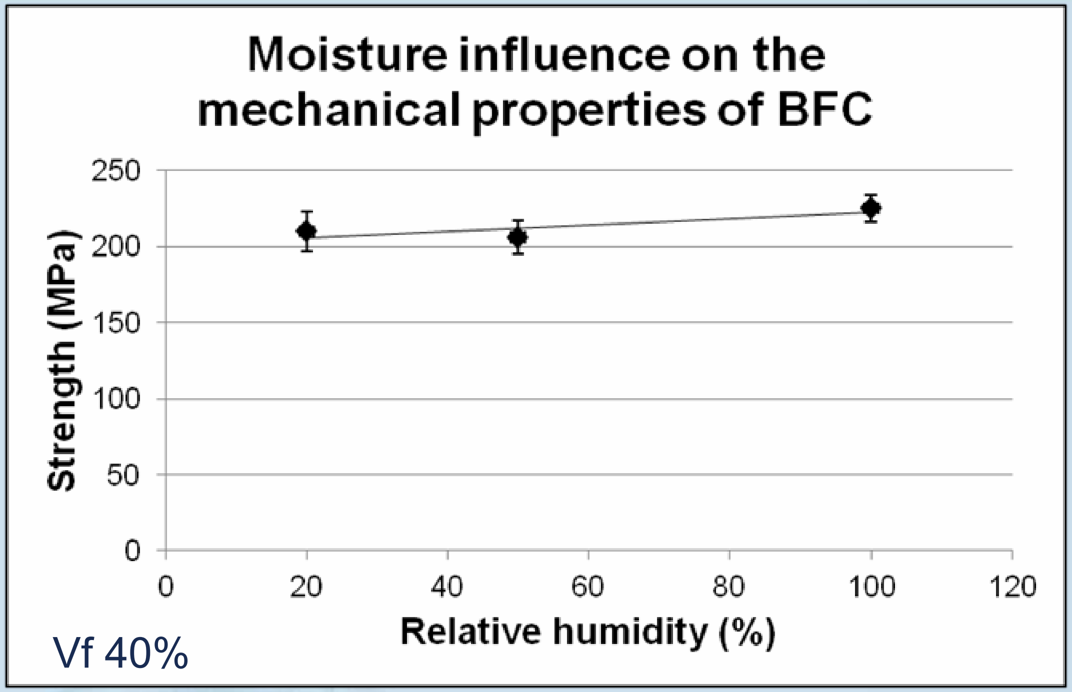






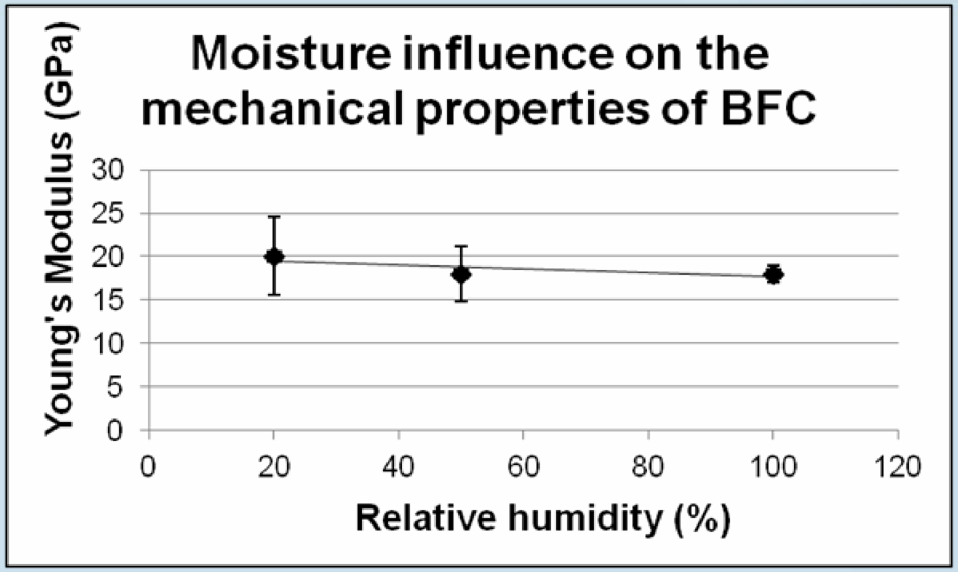


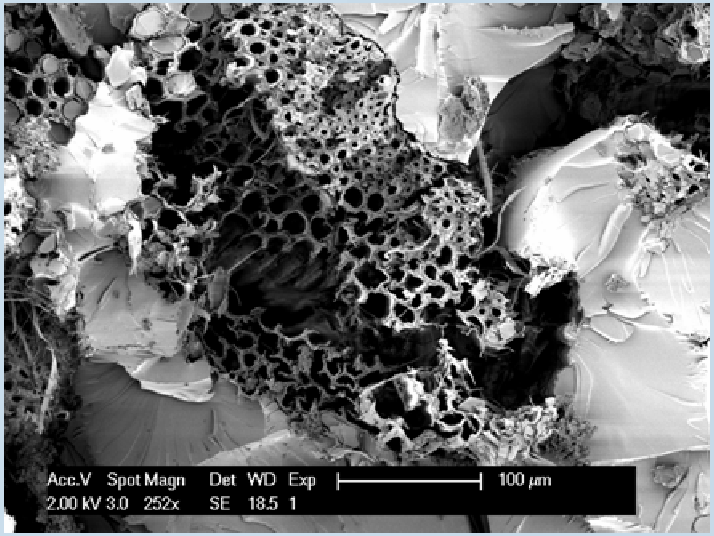
Moisture sensitivity of bamboo fibre composites



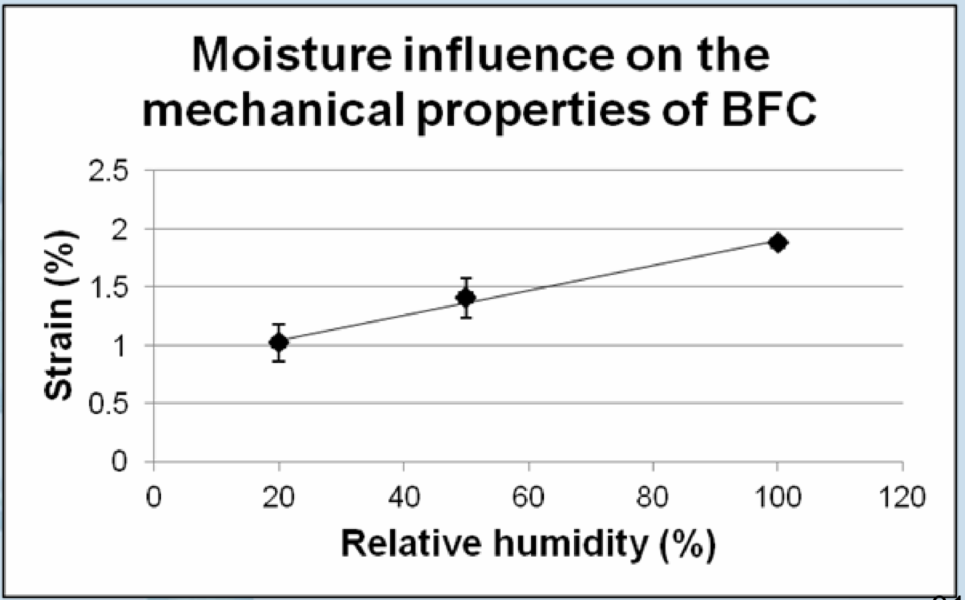
Vf 40%

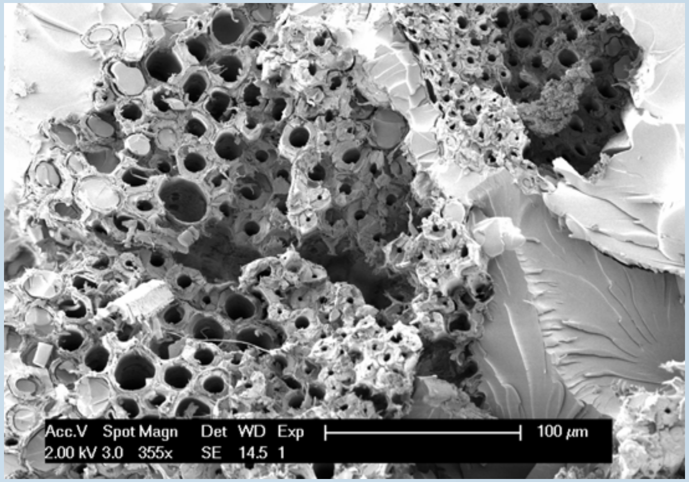
Moisture sensitivity of bamboo fibre composites





50%rh

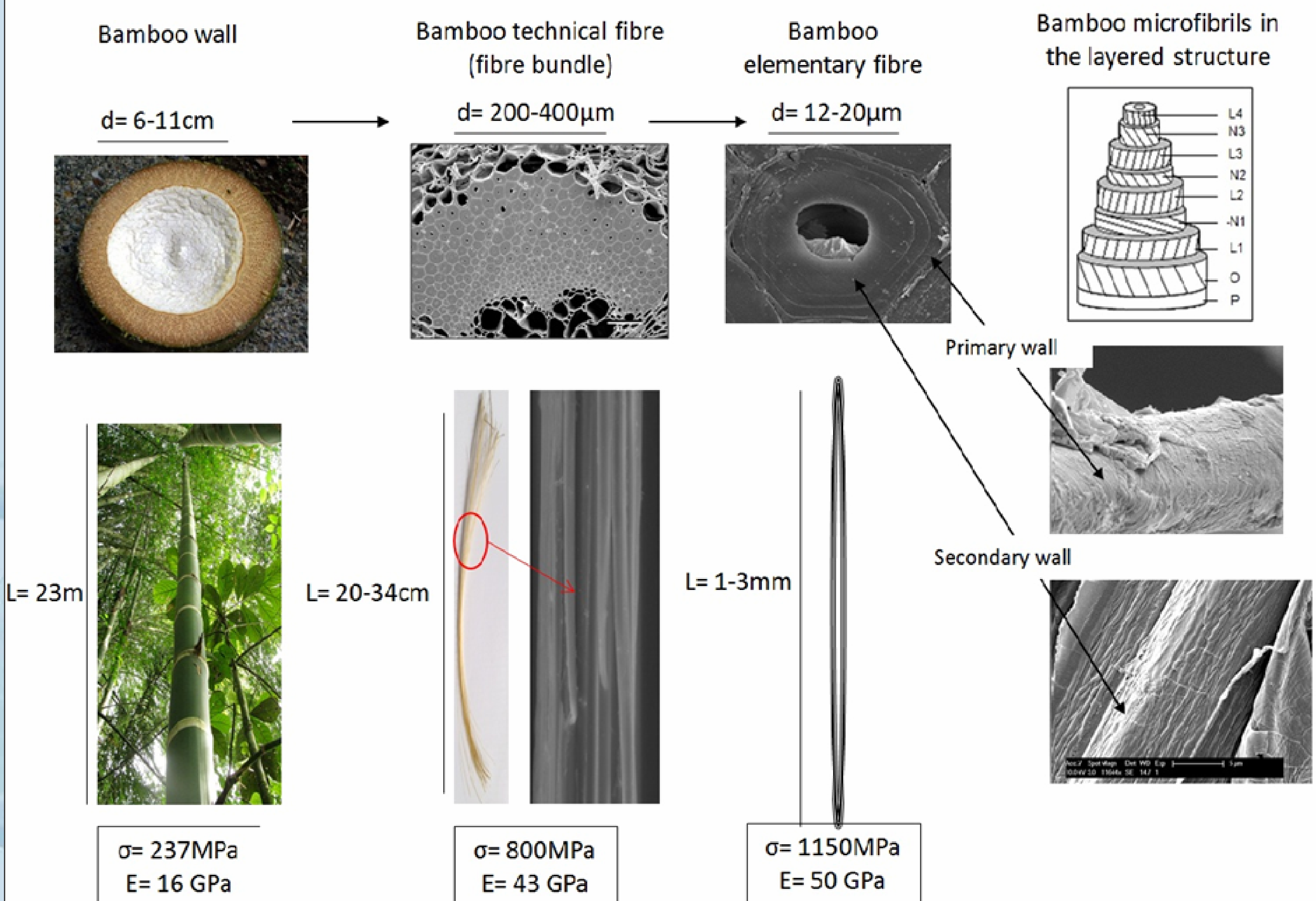




20%rh

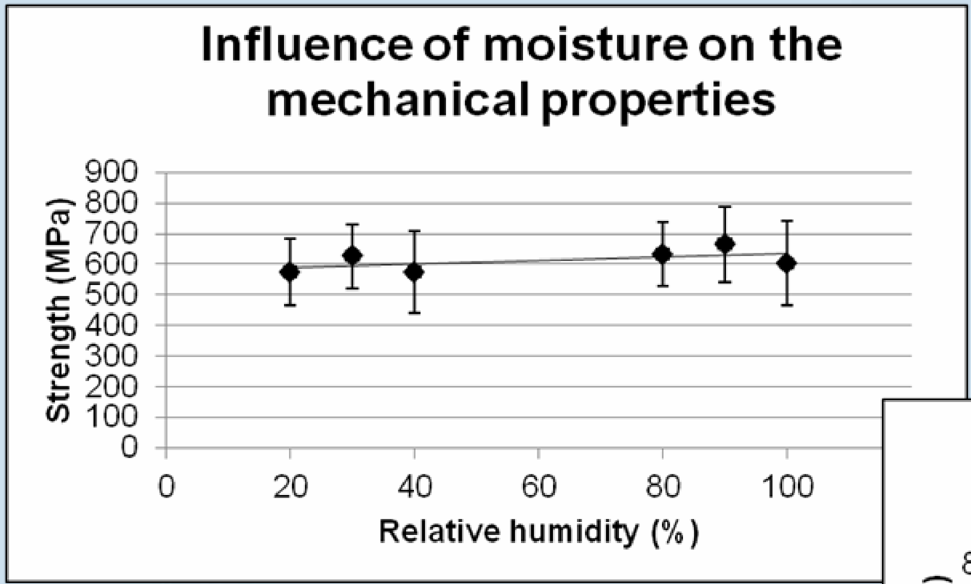
Composite materials group

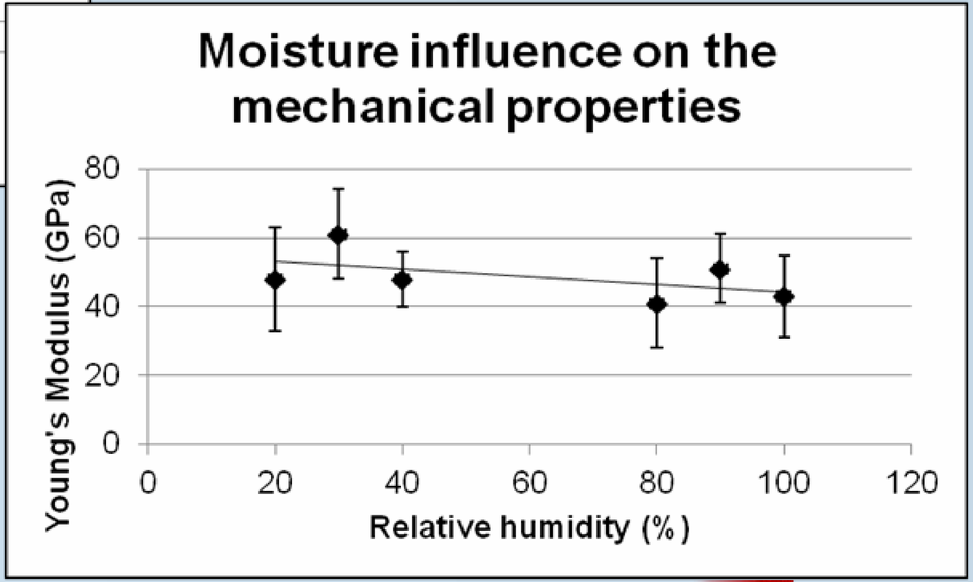
Morphological hierarchy in bamboo

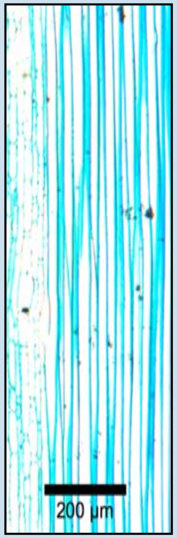


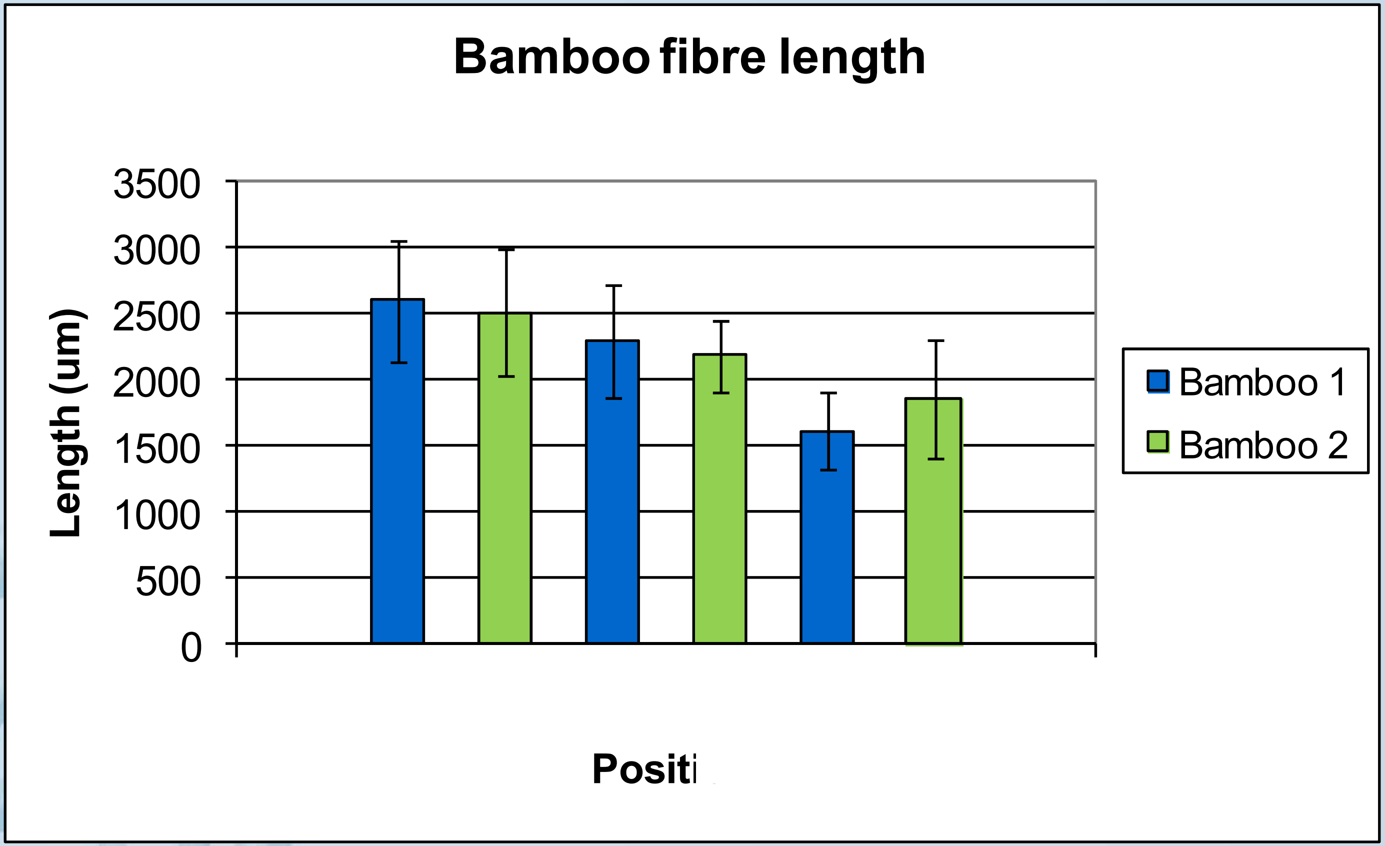
Thank you very much!

Influece of moisture on the mechanical properties of bamboo fibres





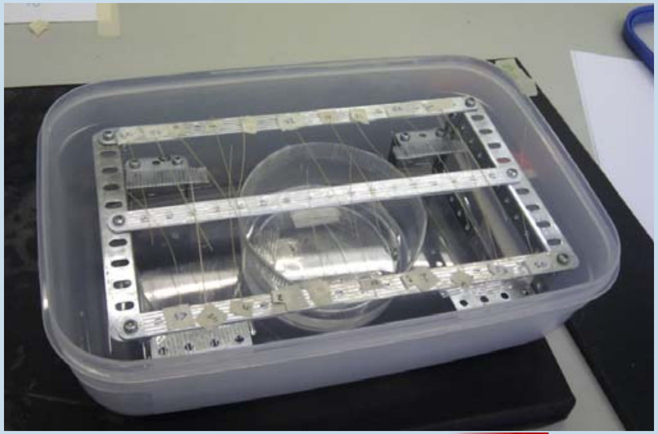

200 µm


Bamboo fibre length
3500
3000
2500
2000
1500
1000
500
0
Length (um)
Positi
Bamboo 1
Bamboo 2

Moisture implementation

- Use of saturated solution for high moisture level
- Use of dry salt for low moisture levels

Salt	Relative humidity (Experimental) [%]	Form
LiCl	20	Dry
CH_3COOK	30	Dry
$MgCl_2$	40	Dry
NaCl	70	Wet
KCl	90	Wet
K_2SO_4	100	Wet



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- ir. Suzanne Verheyden, MTM Department, K.U.Leuven
- Belgian Science Policy Office (BELSPO) for the financial support

For more information:

Test methods for bamboo fibres (Eduardo Trujillo)

Characterization of the interface in BFC (Carlos Fuentes)

http://www.mtm.kuleuven.be/Onderzoek/Composites/