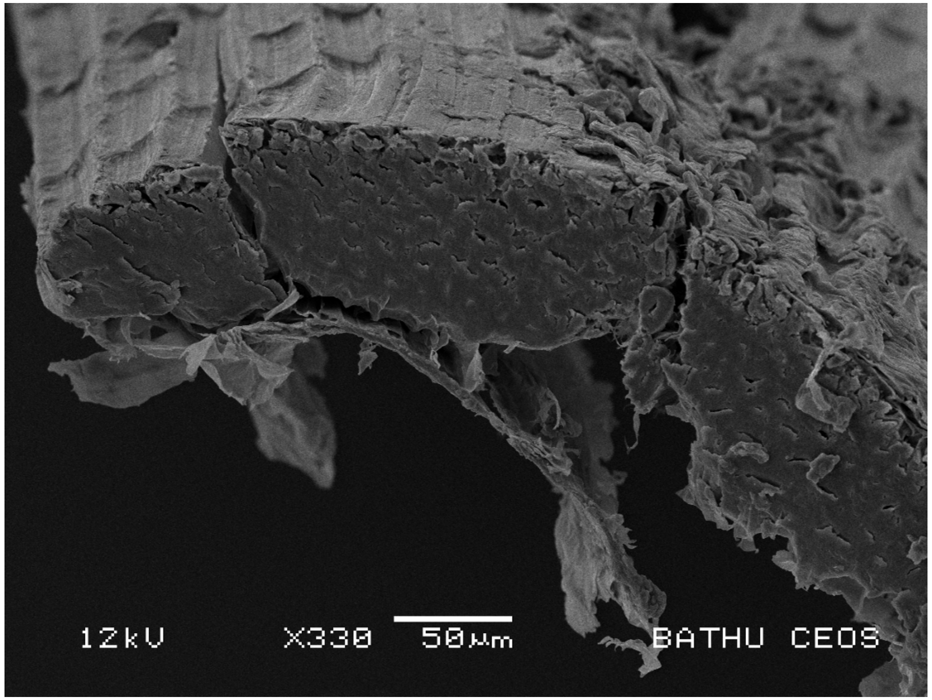
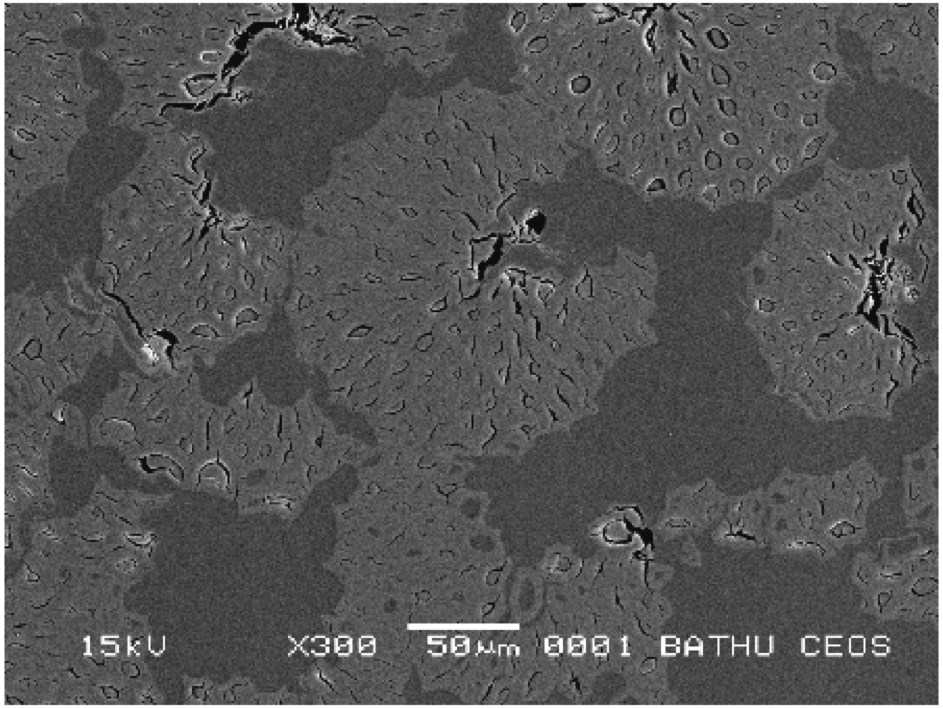
Natural fibre composites & their role in engineering

Martin Ansell, Reader in Materials

Department of Mechanical Engineering, University of Bath





Biocomposite materials for construction - BRE - Friday 23rd September 2011

UNIVERSITY OF BATH

HEMP-REINFORCED PLASTIC CAR

Photo: Hemmings.com

HENRY FORD'S SOYBEAN SUIT

"After twelve years of research, the Ford Motor Company has completed an experimental automobile with a plastic body. Although its design takes advantage of the properties of plastics, the streamline car does not differ greatly in appearance from its steel counterpart. The only steel in the hand-made body is found in the tubular welded frame on which are mounted 14 plastic panels, 3/16 inch thick. Composed of a mixture of farm crops and synthetic chemicals, the plastic is reported to withstand a blow 10 times as great as steel without denting. Even the windows and windshield are of plastic. The total weight of the plastic car is about 2,000 pounds, compared with 3,000 pounds for a steel automobile of the same size."

December 1941 issue of Popular Mechanics.

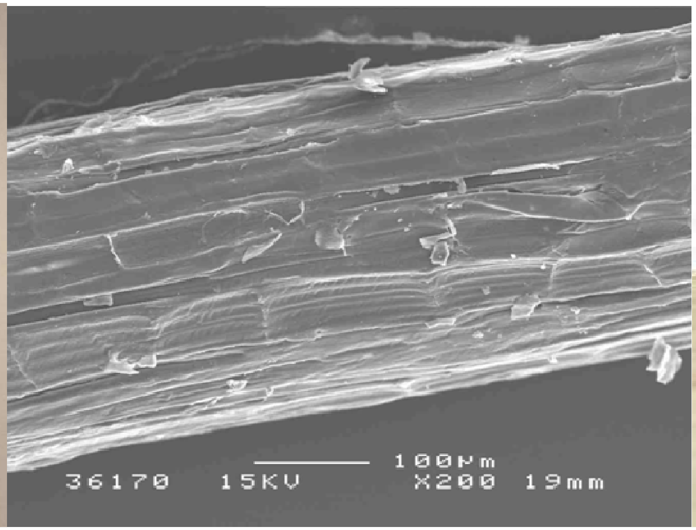
LOTUS ECO ELISE

- Hemp composite rear wing, front clamshell, roof
- Solar panels in roof
- Wool trim and hemp composite seat components
- Water-based paint

UNIVERSITY OF BATH

PRESENTATION SUMMARY

- INTRODUCTION: Fibre properties and fibre eco-profile.
- FIBRES AND INTERFACES: Fibre strength, fibre-matrix shear strength
- JOINTS: In-line joints, densification, L-shaped moment resisting joints.
- THERMOPLASTIC MATRIX COMPOSITES: PLA-sisal composites.
- AUTOMOTIVE CASE STUDY: Toyota Autobody.
- THE FUTURE: Automotive, aerospace?



PRODUCTION OF PLANT FIBRES

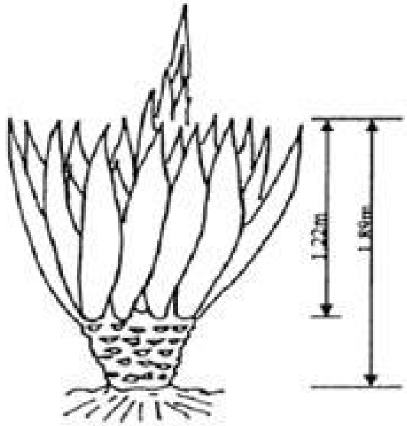
Plant fibre	Botanical name	Plant family	Fibre type	Production (10^3 tonnes)
Cotton	*Gossypium spp.*	Malvaceae	Seed	19,010
Kapok	*Eriodendron anfractuosum*	Bombacaceae	Seed	123
Bagasse	*Saccharum officinarum* L.	Gramineae		
Bamboo	*Gigantochloa scortechinii* *Dendrocalamus apus*	Linaceae	Bast	10,000
Flax	*Linum usitatissimum*	Linaceae	Bast	830
Hemp	*Cannabis sativa* L.	Cannabaceae	Bast	214
Jute	*Corchorus capsularis*	Tiliaceae	Bast	2,938
Kenaf	*Hibiscus cannabinus*	Malvaceae	Bast	970
Ramie	*Boehmeria nivea* Gaud	Urticaceae	Bast	100
Abaca	*Musa textilis*	Musaceae	Leaf	91
Banana	*Musa ulugurensis* Warb.	Musaceae	Leaf	200
Phormium	*Phormium tenax*	Agavaceae	Leaf	-
Pineapple	*Ananas cosmosus* Merr.	Bromliaceae	Leaf	-
Sisal	*Agave sisalana*	Agavaceae	Leaf	319
Coir	*Cocos nucifera* L.	Arecaceae	Fruit	315

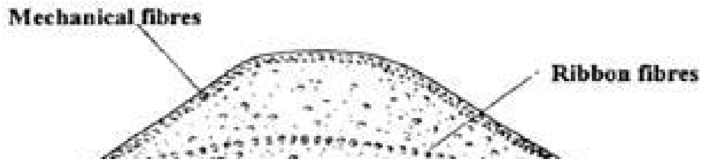
UNIVERSITY OF BATH

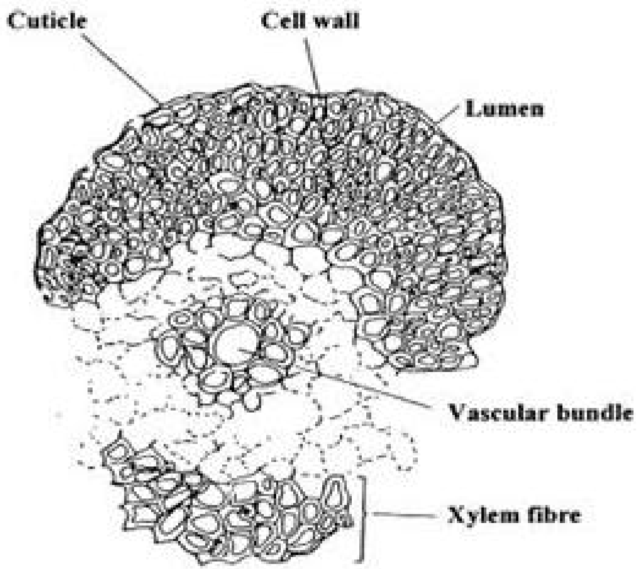
SISAL PLANT (*Agave sisalana*)

BEFORE CROPPING

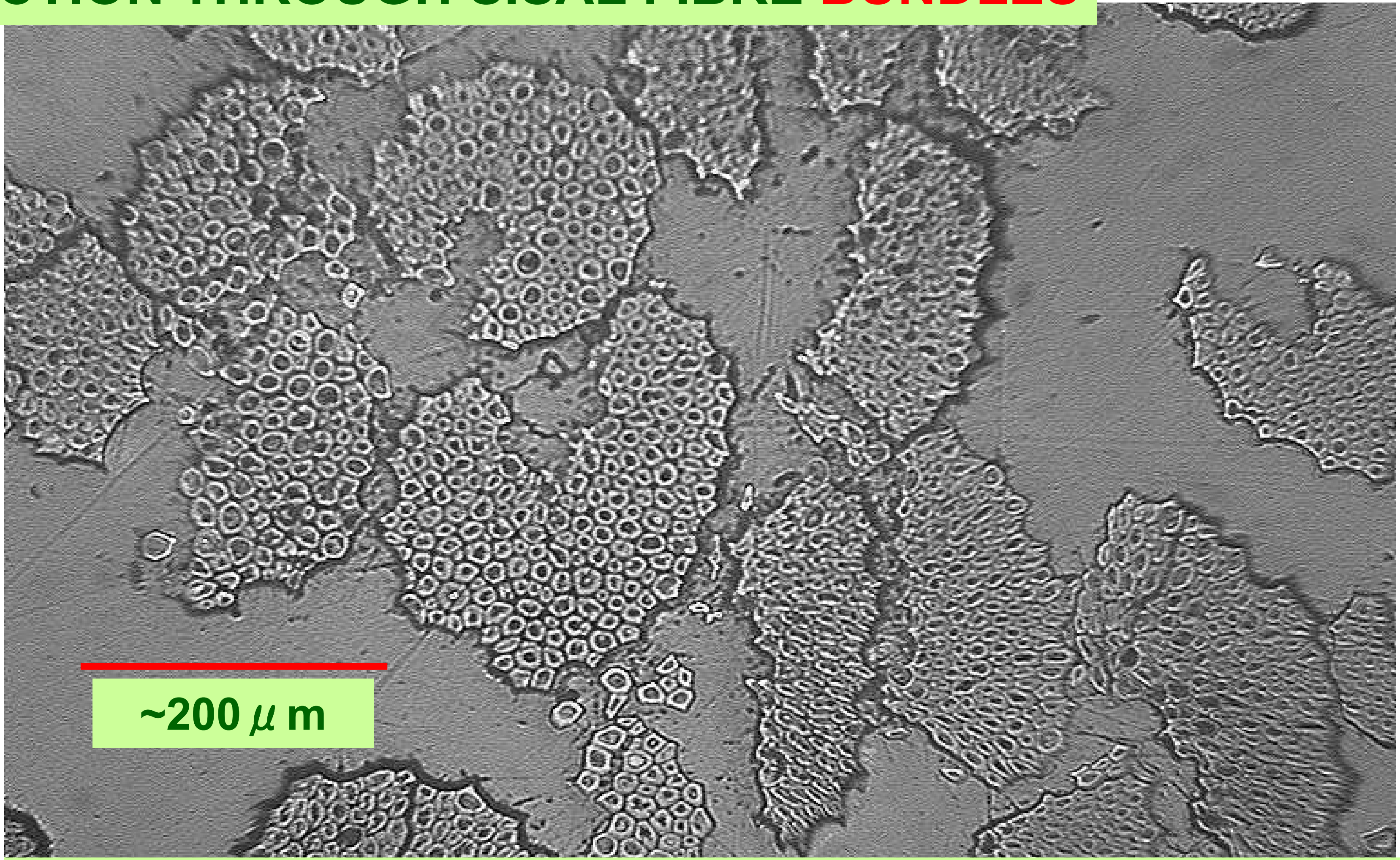
AFTER CROPPING







SECTION THROUGH SISAL FIBRE BUNDLES



- Variability in number of ultimate cells in each bundle
- Variability in shape of bundles, much larger than synthetic fibres
- Lumen size is variable but often small

UNIVERSITY OF BATH

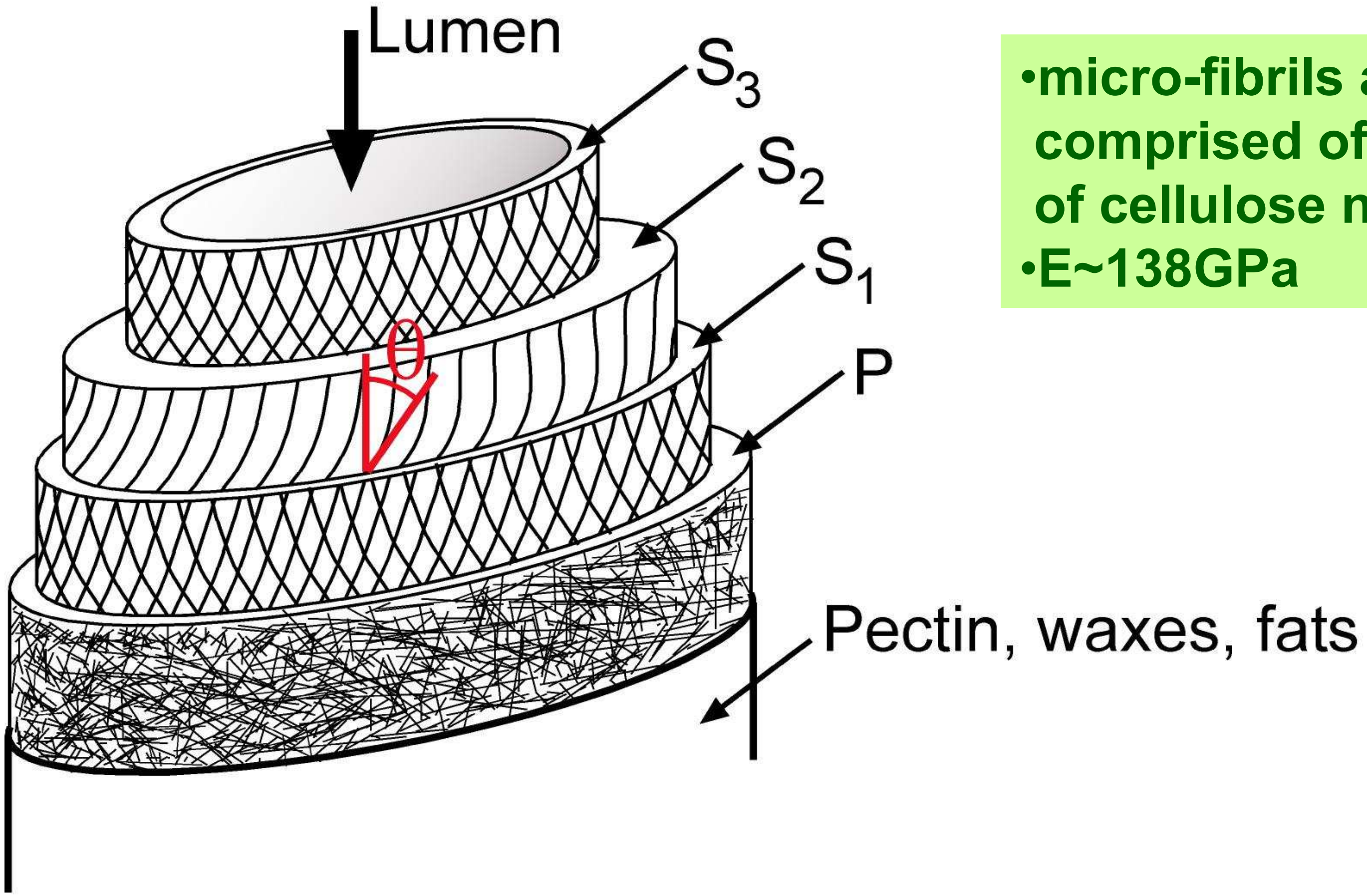
CHEMICAL COMPOSITION OF PLANT FIBRES

Plant fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)
Cotton[s]	82-96	2-6.4	0-5	<1-7
Kapok[s]	13	-	-	-
Flax[b]	60-81	14-20.6	2.2-5	1-4
Hemp[b]	70-92	18-22	3-5	1
Jute[b]	51-84	12-20	5-13	0.2
Kenaf[b]	44-87	22	15-19	2
Ramie[b]	68-76	13-15	0.6-1	2
Banana[l]	60-65	6-19	5-12	3-5
Pineapple[l]	70-82	16-19	5-12	2-3
Sisal[l]	43-78	10-24	4-12	0.8-2
Coir[f]	43-46	0.25	45-46	3-4
Oil palm EFB[f]	43-63	28-33	17-19	1

[s]seed, [b]bast, [l]leaf and [f]fruit fibres

Ansell, M. P. and Mwaikambo, L.Y. (2009), “The structure of cotton and other plant fibres”, chapter in “Handbook of textile fibre structure, Volume 2: Natural, regenerated, inorganic and specialist fibres”, Eds. S.J. Eichhorn, J.W.S. Hearle, M. Jaffe and T. Kikutani, Woodhead Publishing, ISBN 978-1-84569-730-3.

STRUCTURE OF ULTIMATE NATURAL FIBRE SHOWING CELL WALL LAYERS



- micro-fibrils are comprised of bunches of cellulose nano-fibres
- E~138GPa

- The micro-fibril angle θ has a major influence on the fibre stiffness
- The S_2 layer is the thickest
- The hollow lumen is responsible for the low fibre bundle density

PHYSICAL PROPERTIES OF FIBRES

Plant fibre	Length of ultimates, l (mm)	Diameter of ultimates, d (μm)	Aspect ratio, l/d	Microfibril angle, θ (º)	Density (kg.m^{-3})	Moisture content (eq.) (%)
Cotton[s]	20-64	11.5-17	2752	20-30	1550	8.5
Kapok[s]	8-32	15-35	724	-	311-384	10.9
Bamboo[b]	2.7	10-40	9259	-	1500	-
Flax[b]	27-36	17.8-21.6	1258	5	1400-1500	12
Hemp[b]	8.3-14	17-23	549	6.2	1400-1500	12
Jute[b]	1.9-3.2	15.9-20.7	157	8.1	1300-1500	12
Kenaf[b]	2-61	17.7-21.9	119	-	1220-1400	17
Ramie[b]	60-250	28.1-35	4639	-	1550	8.5
Abaca[l]	4.6-5.2	17-21.4	257	-	1500	14
Banana[l]	2-3.8	-	-	11-12	1300-1350	-
Pineapple[l]	-	20-80	-	6-14	1440-1560	-
Sisal[l]	1.8-3.1	18.3-23.7	115	10-22	1300-1500	11
Coir[f]	0.9-1.2	16.2-19.5	64	39-49	1150-1250	13

[s]seed, [b]bast, [l]leaf and [f]fruit fibres

UNIVERSITY OF BATH

MECHANICAL PROPERTIES OF PLANT FIBRES

Plant fibre	Tensile strength (MPa)	Specific strength (MPa)	Young's modulus (GPa)	Specific modulus (GPa)	Failure strain (%)
Cotton[s]	300-700	194-452	6-10	4-6.5	6-8
Kapok[s]	93.3	300	4	12.9	1.2
Bamboo[b]	575	383	27	18	-
Flax[b]	500-900	345-620	50-70	34-48	1.3-3.3
Hemp[b]	310-750	210-510	30-60	20-41	2-4
Jute[b]	200-450	140-320	20-55	14-39	2-3
Kenaf[b]	295-1191	-	22-60	-	-
Ramie[b]	915	590	23	15	3.7
Abaca[l]	12	-	41	-	3.4
Banana[l]	529-914	392-677	27-32	20-24	1-3
Pineapple[l]	413-1627	287-1130	60-82	42-57	0-1.6
Sisal[l]	80-840	55-580	9-22	6-15	2-14
Coir[f]	106-175	92-152	6	5.2	15-40

[s]seed, [b]bast, [l]leaf and [f]fruit fibres

UNIVERSITY OF BATH

DATABASES FOR MATERIALS, CARBON AND ENERGY

Inventory of Carbon and Energy (ICE)

Prof. Geoff Hammond and Craig Jones, SERT, Dept. of Mechanical Engineering

- Database for primary energy consumed and carbon released during resource extraction, transportation, manufacturing and fabrication of building materials.
- Inventory confined within the boundaries of Cradle-to-Gate (factory gate) or Cradle-to-Site (site of use) to separate it from operational impacts.
- Available for download as a pdf file at: http://www.bath.ac.uk/mech-eng/sert/embodied/

CES EduPack – Granta Design

- Interactive materials database
- Resource for teaching materials and process-related courses
- Includes materials science and engineering, mechanical engineering, eco design and sustainability, architecture and the built environment, etc etc
- http://www.grantadesign.com/education/
- Available campus-wide via BUCS web page (software, secure downloads) at: https://isecure.bath.ac.uk/securedownloads/Repository.aspx?id=CES+EduPack

SERT
Sustainable Energy Research Team

UNIVERSITY OF BATH

Granta for Education
CES 2010 EDUPACK

CES EduPack - Campus wide licence – software available at: http://www.bath.ac.uk/bucs/tools/software/index.html

Sisal

General properties

Designation

Sisal fiber is derived from an agave, *Agave sisalana*. Sisal is valued for cordage use because of its strength, durability, ability to stretch, affinity for certain dyestuffs, and resistance to deterioration in saltwater.

Density		1.4e3	-	1.45e3	kg/m^3
Price		0.422	-	0.492	GBP/kg

Composition overview

Composition (summary)

Cellulose 70 wt% and lignin 12 wt %.

Mechanical properties

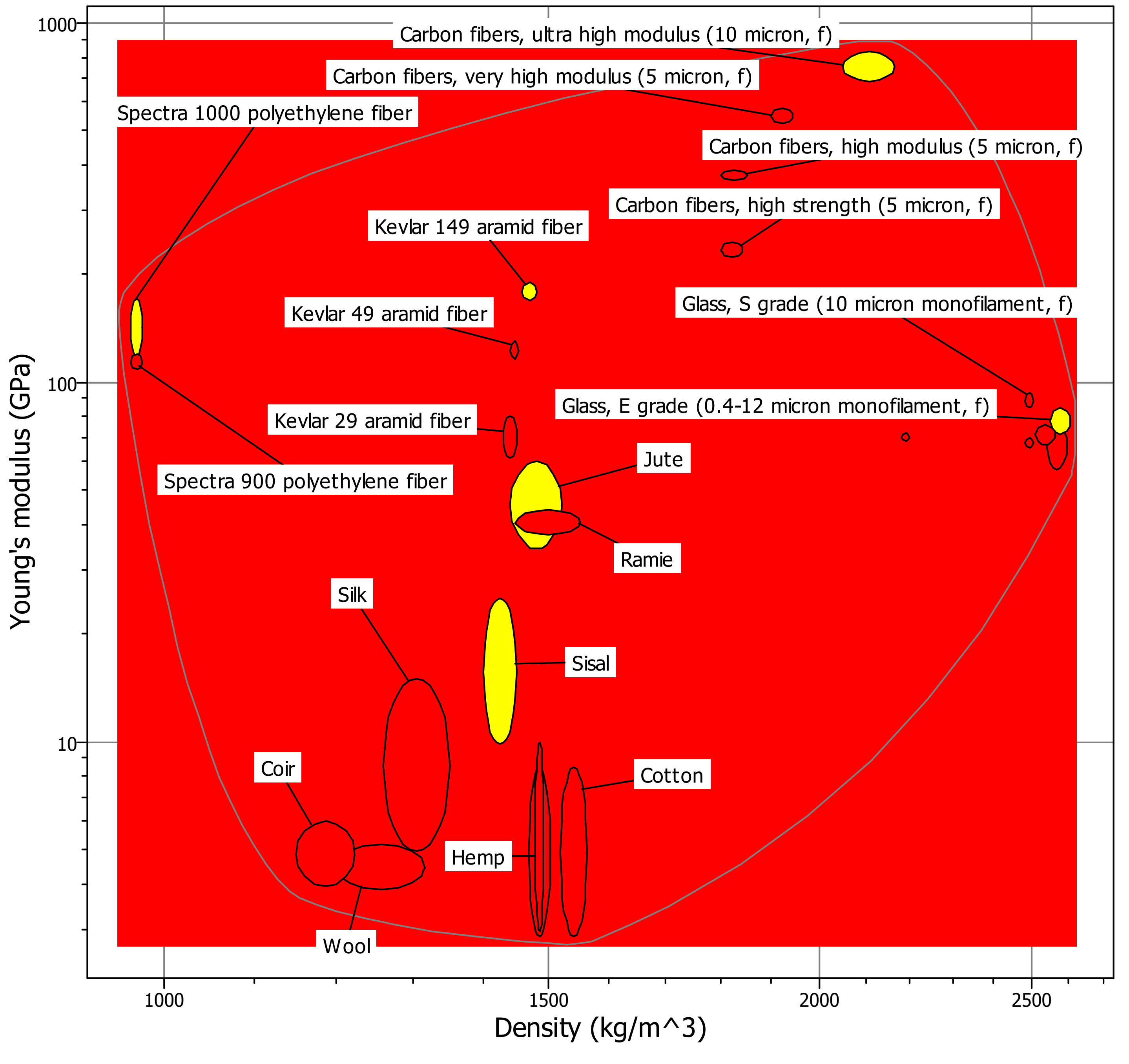
Young's modulus		10	-	25	GPa
Shear modulus	*	3.67	-	9.17	GPa
Poisson's ratio	*	0.359	-	0.374	
Yield strength (elastic limit)		495	-	711	MPa
Tensile strength		550	-	790	MPa
Elongation		4	-	6	%

UNIVERSITY OF BATH

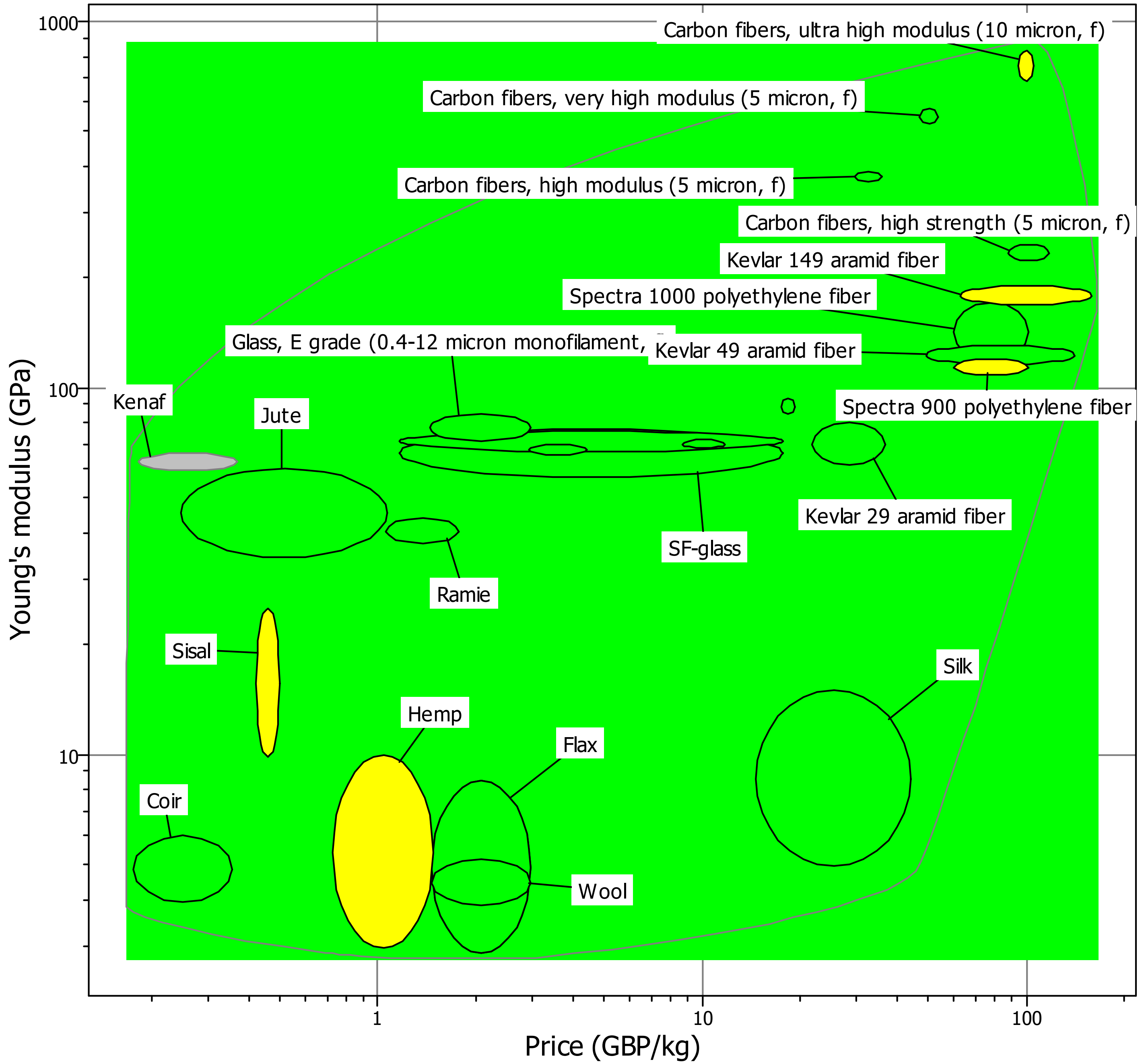
Primary material production: energy, CO_2 and water				
Embodied energy, primary production	7.2	-	7.96	MJ/kg
CO_2 footprint, primary production	0.427	-	0.472	kg/kg
Water usage	500	-	1.5e3	l/kg
Material processing: energy				
Assembly and construction energy *	0.475	-	0.525	MJ/kg
Material processing: CO_2 footprint				
Assembly and construction CO_2 *	0.038	-	0.042	kg/kg
Material recycling: energy, CO_2 and recycle fraction				
Recycle	False			
Recycle fraction in current supply	8.55	-	9.45	%
Downcycle	True			
Combust for energy recovery	True			
Heat of combustion (net) *	19.3	-	20.2	MJ/kg
Combustion CO_2 *	1.5	-	1.58	kg/kg
Landfill	True			
Biodegrade	True			
A renewable resource?	True			

Granta for Education
CES 2010 EDUPACK

YOUNG'S MODULUS VERSUS DENSITY FOR SYNTHETIC AND PLANT FIBRES

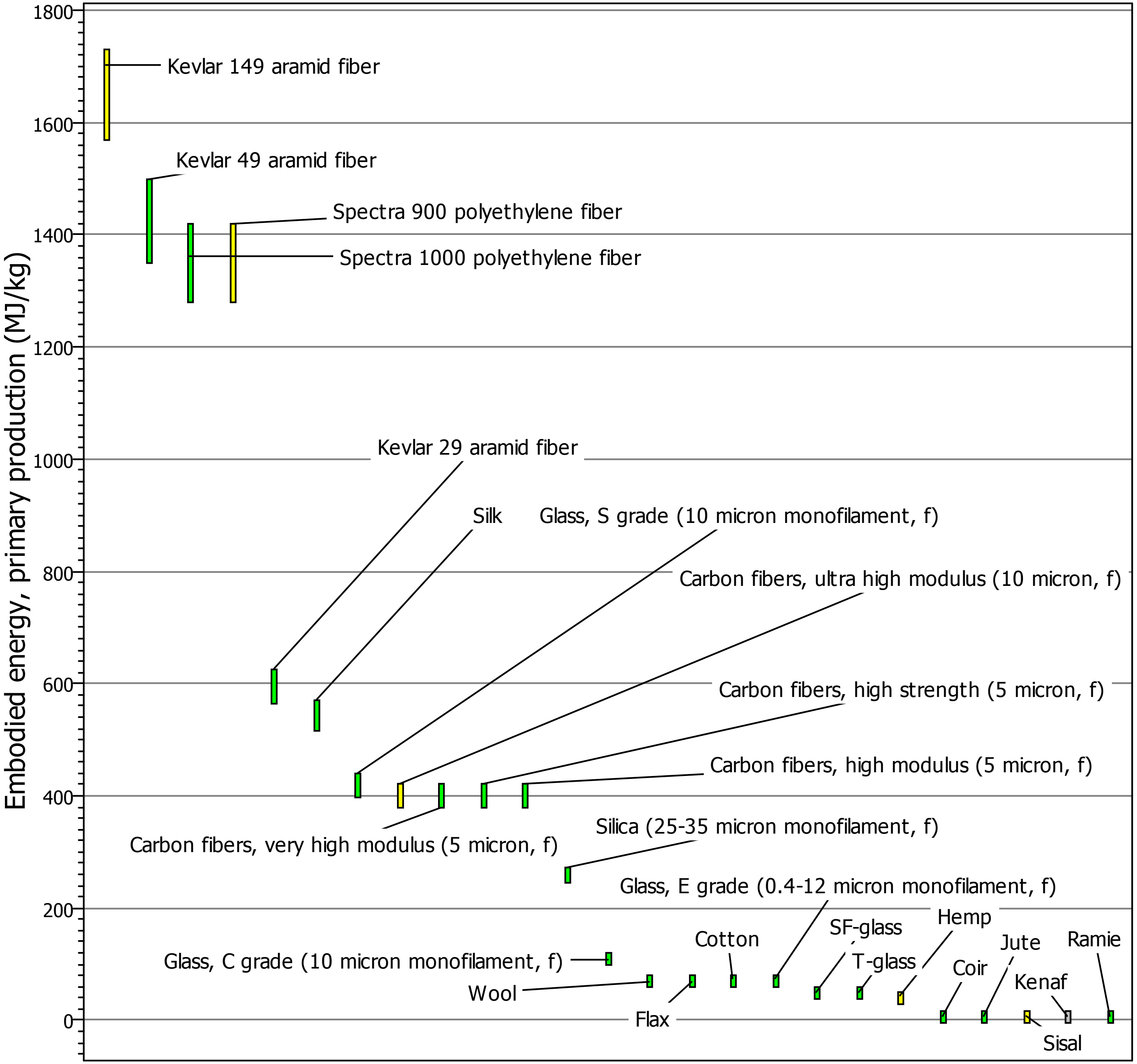


YOUNG'S MODULUS VERSUS PRICE FOR SYNTHETIC AND PLANT FIBRES



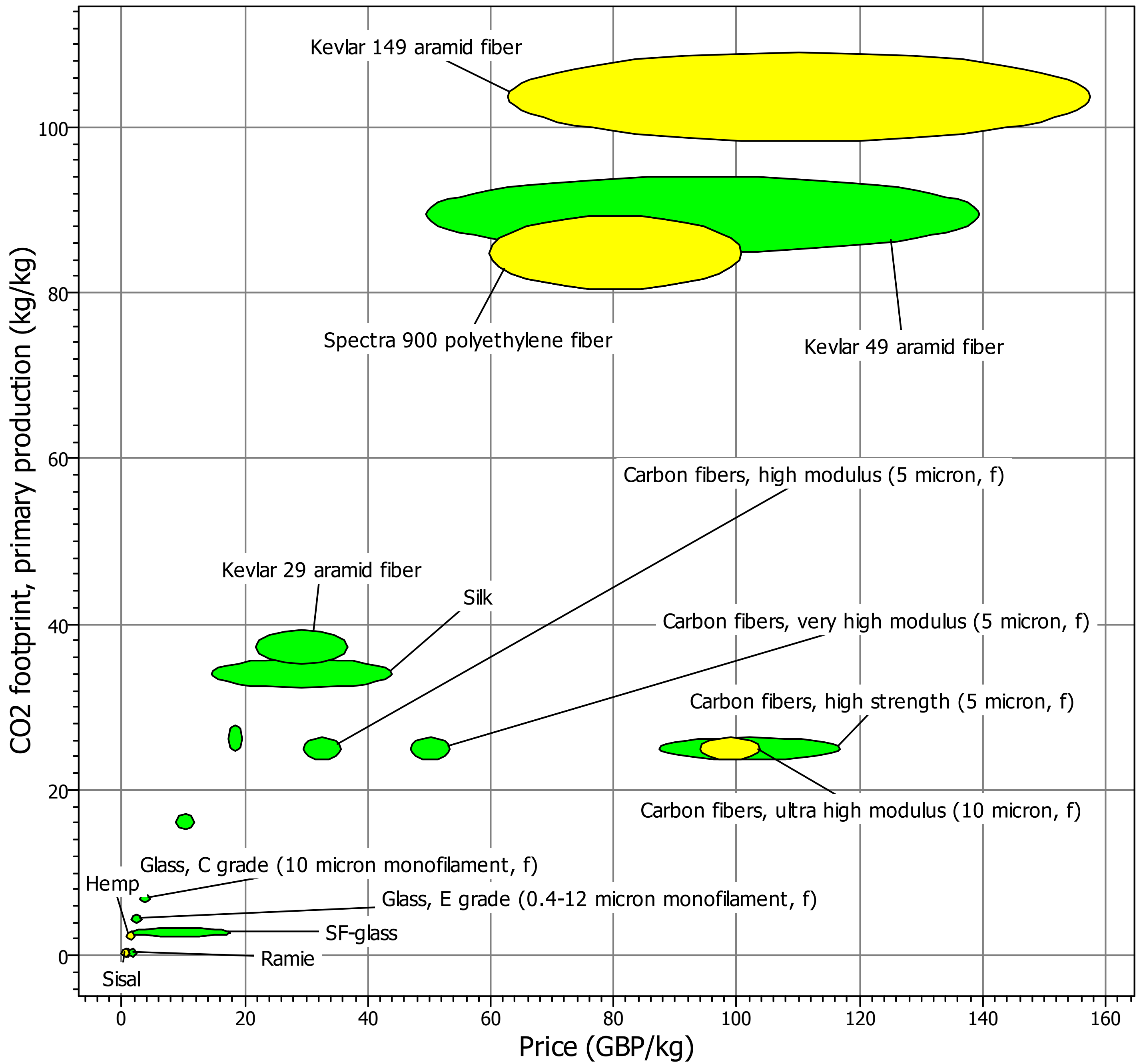
UNIVERSITY OF BATH

EMBODIED ENERGY FOR SYNTHETIC AND PLANT FIBRES



UNIVERSITY OF BATH

CO_2 FOOTPRINT VERSUS PRICE FOR SYNTHETIC AND PLANT FIBRES



UNIVERSITY OF BATH

RESEARCHERS AT THE UNIVERSITY OF BATH

Elifas Bisanda: Sisal-epoxy, sisal-CNSL, fibre treatments, manufacture of prototype roof panels.

Leonard Mwaikambo: Sisal, hemp, jute, kapok, alkalisation, acetylation, index of crystallinity, CNSL-formaldehyde-rosin.

Arnold Towo: Sisal-epoxy, fibre strengths, interfacial shear strength, Weibull statistics, fatigue, DMTA.

Cesar Gonzalez Murillo: Henequen-epoxy, sisal-epoxy, connections for NFCs, in-line and moment-resisting joints, densification, FE modelling.

Marek Prajer: Thermoplastic bio-matrix composites, sisal-PLA, hot-stage digital microscopy.

MATERIALS

SISAL FIBRES:

- Rope grade sisal fibre obtained from Tanzania

RESIN:

- Unsaturated polyester resin from Scott Bader, UK
- Methyl ethyl ketone peroxide hardener in dimethyl phthalate (MEKP) from Scott Bader Co., UK
- Araldite LY5052 epoxy resin with Araldite hardener HY5052 supplied by Aeropia Limited, UK

SURFACE TREATMENT:

- Sodium hydroxide solution diluted to 0.06M

FIBRE PREPARATION AND DENSITY MEASUREMENT

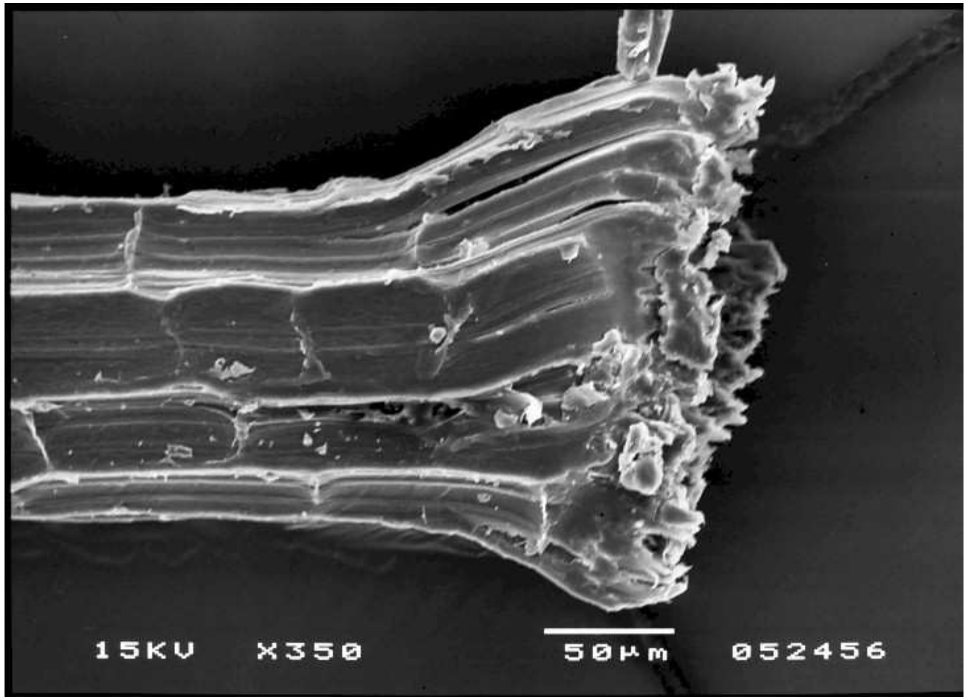
- Fibres soaked in water for approximately 3 hours to clean surface and dried between tissue overnight followed by oven drying at 80°C overnight.

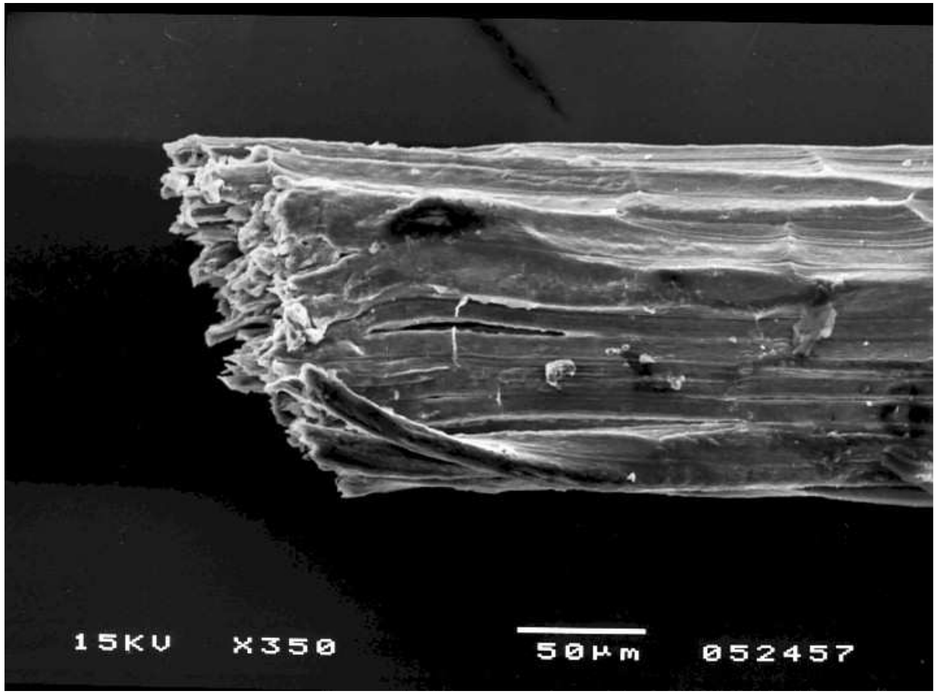
- Fibres soaked in 0.06M NaOH solution for 48 hours followed by rinsing in distilled water. Excess NaOH neutralised using dilute acetic acid (1%) and followed by drying.

- Density of fibres determined using Archimedes principle

UNIVERSITY OF BATH

SEM IMAGES OF UNTREATED AND TREATED FIBRE





- Untreated (left) and 0.06M NaOH treated (right) sisal fibre ends obtained from a cut on the same fibre.
- Treatment removes surface debris and smooths the surface profile.

UNIVERSITY OF BATH

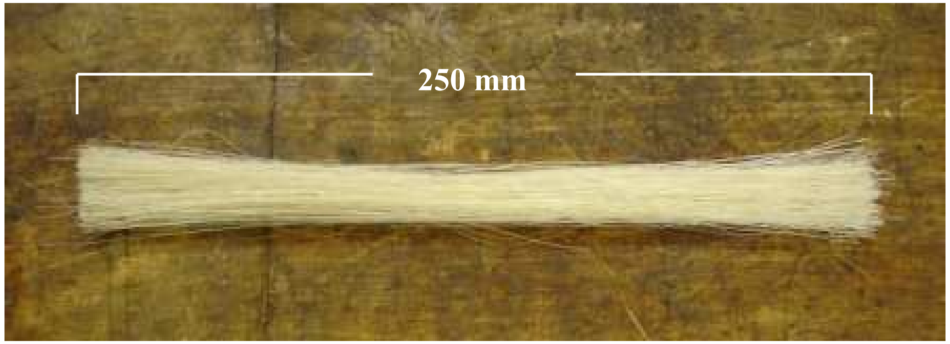
PREPARATION OF SISAL FIBRE BUNDLES

•Fibre bale cut to ~30cm lengths to fit in soaking tank

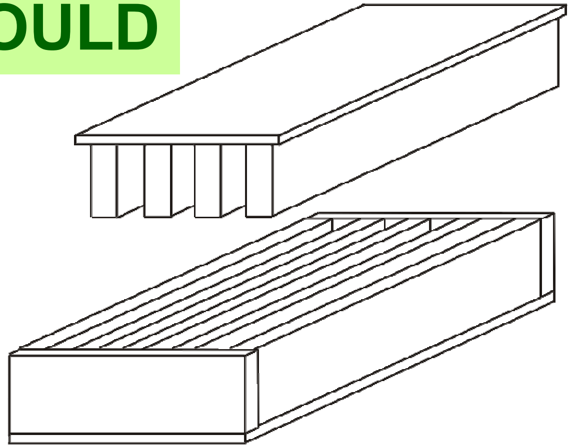
•Lengths are combed out and soaked in water for four hours.
•Caustic soda treatment optional

UNIVERSITY OF BATH

PRODUCTION OF NFCs IN LOSSY MOULD



•Standard length of fibre bundles



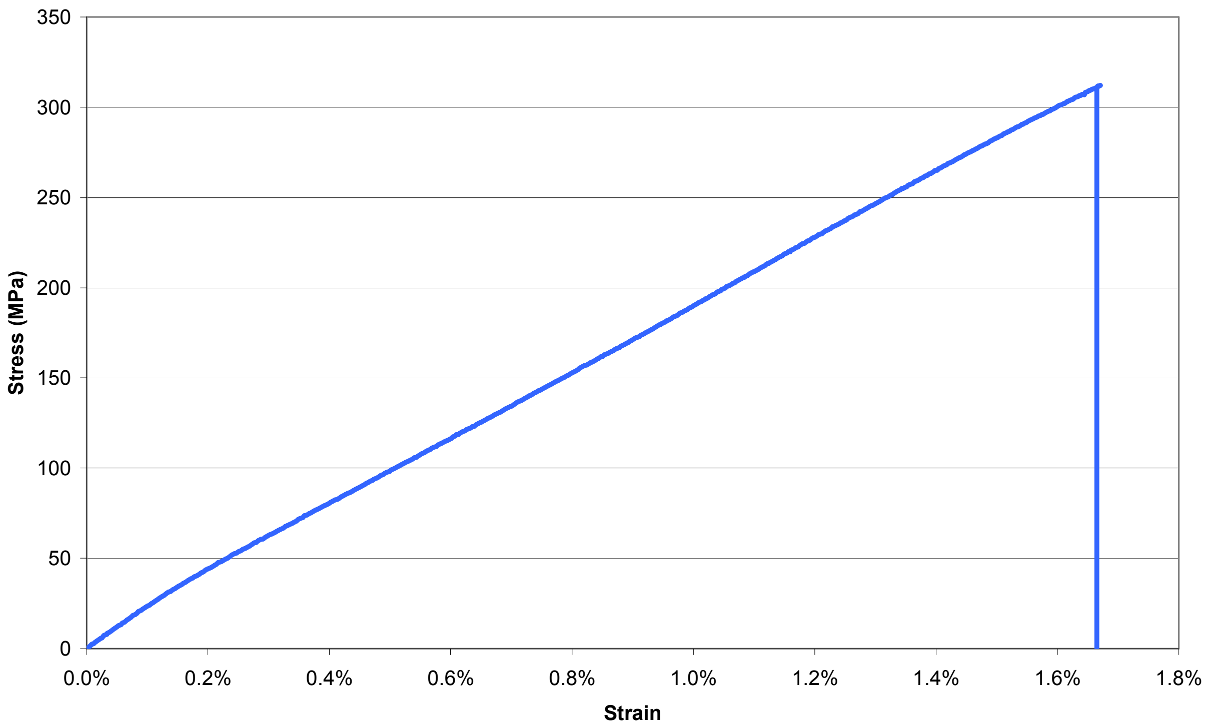
•mould design

•Epoxy resin spread evenly onto fibres - mould is a lossy unit
•Pressure of 60 bar (6 MPa) applied at 80ºC for 30 mins then post-cure at 100ºC

•Mould in hot press

•Specimen released from press

STRESS-STRAIN CHARACTERISTIC FOR TENSILE SPECIMEN

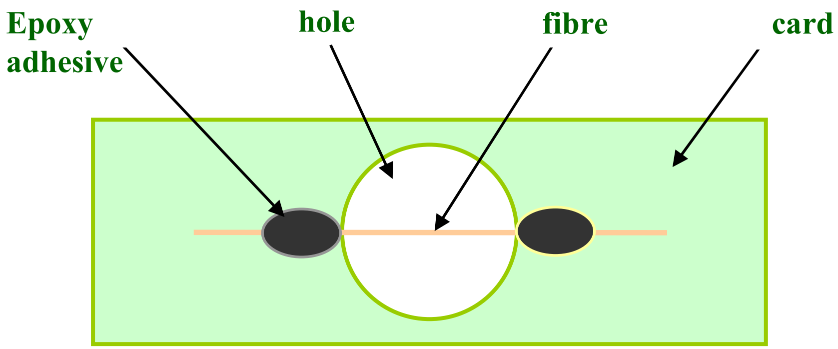


- Essentially linearly elastic to failure
- Young's modulus ~20GPa
- Strength ~300MPa

- Fracture characterised by long splits propagating into the tabs

UNIVERSITY OF BATH

FIBRE TENSILE STRENGTH

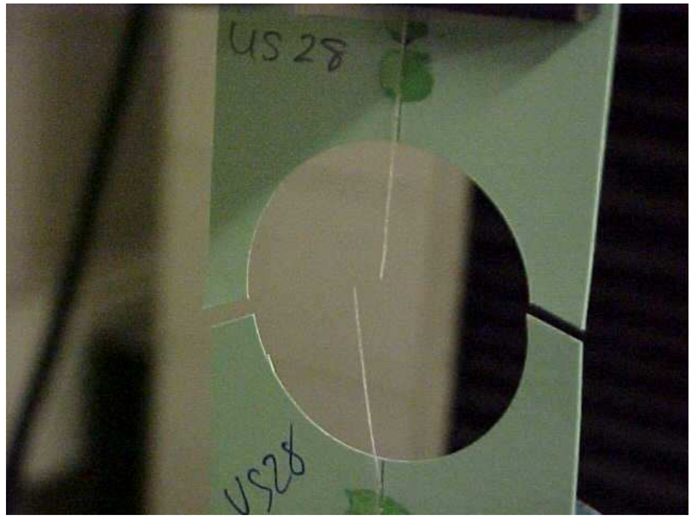


DENSITY METHOD FOR CSA

Tensile strength, $\sigma_{T,d}$ was determined using the cross-section area obtained from the weight and density of the fibres

$$\sigma_{T,d} = \frac{\rho F_{\max} l_f}{m_f}$$

Fibre cross-sectional area : $A = \dfrac{m_f}{\rho l_f}$

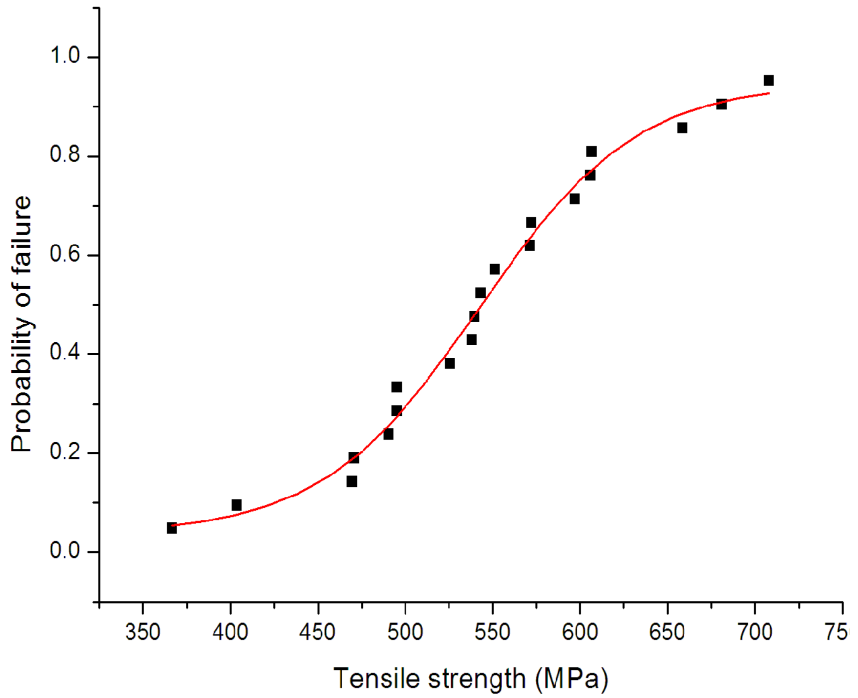


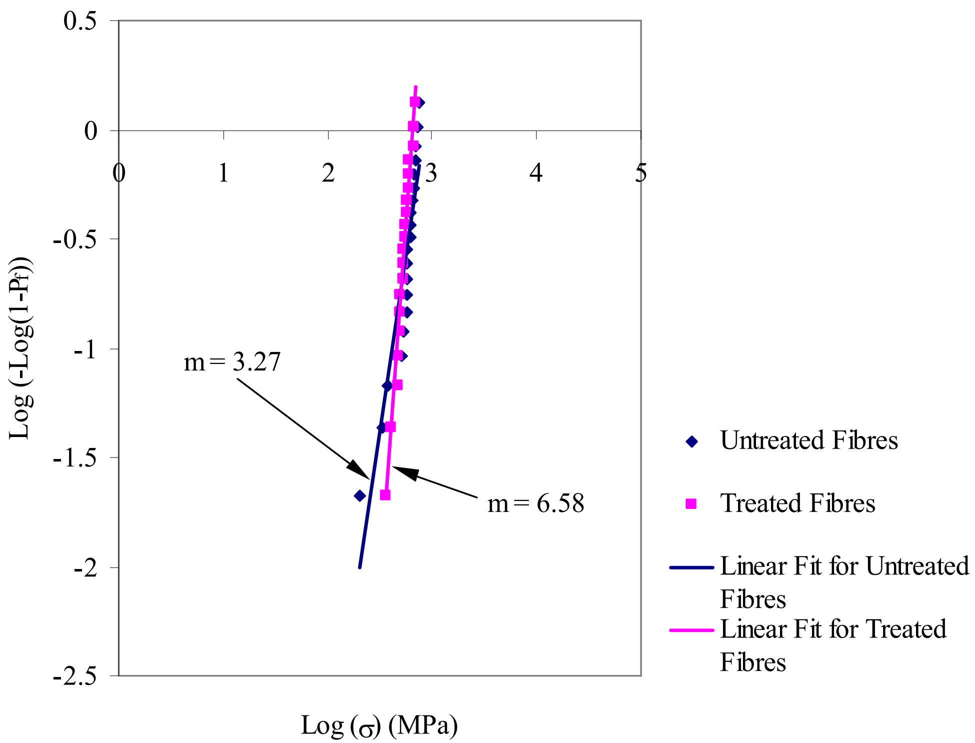
ρ = apparent density ($kg.m^{-3}$)
F_{max} = peak force (N)
l_f = fibre length
m_f = mass of fibre of length l_f (kg)

Tensile tests conducted according to ASTM D2256.

UNIVERSITY OF BATH

TENSILE STRENGTH RESULTS



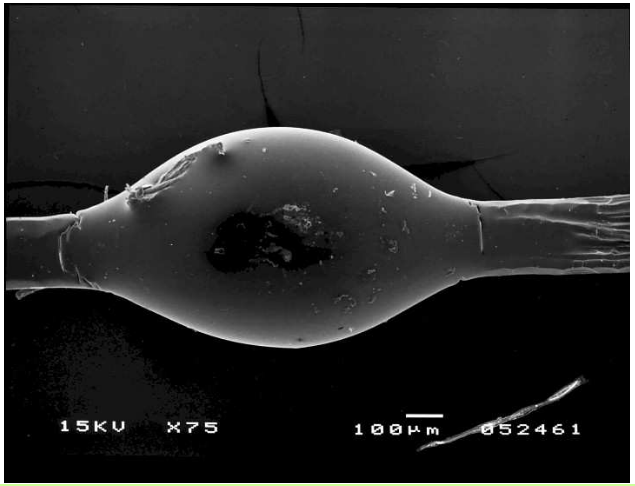


Type of Sisal Fibre	Mean Strength (MPa)	Standard Deviation (MPa)	Maximum Value of Strength (MPa)	Minimum Value of Strength (MPa)	Median Strength (MPa)	Weibull Modulus *m*
Untreated	576.6	135.6	748.0	205.8	598.1	3.27
Treated	544.5	86.2	708.1	366.7	541.3	6.58

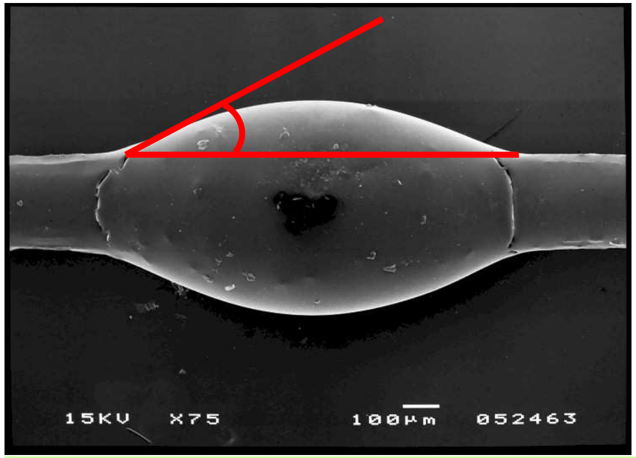
MICROBOND SHEAR STRENGTH

- The interfacial adhesion between polyester resin and epoxy resin droplets and sisal fibre bundles were investigated using droplet shear tests.
- The sisal fibre bundles were tested both (a) untreated and

  (b) treated with a 0.06M solution of sodium hydroxide to improve adhesion and reduce the severity of surface flaws.
- Level of adhesion is reflected in the droplet contact angle.



Droplet on untreated fibre



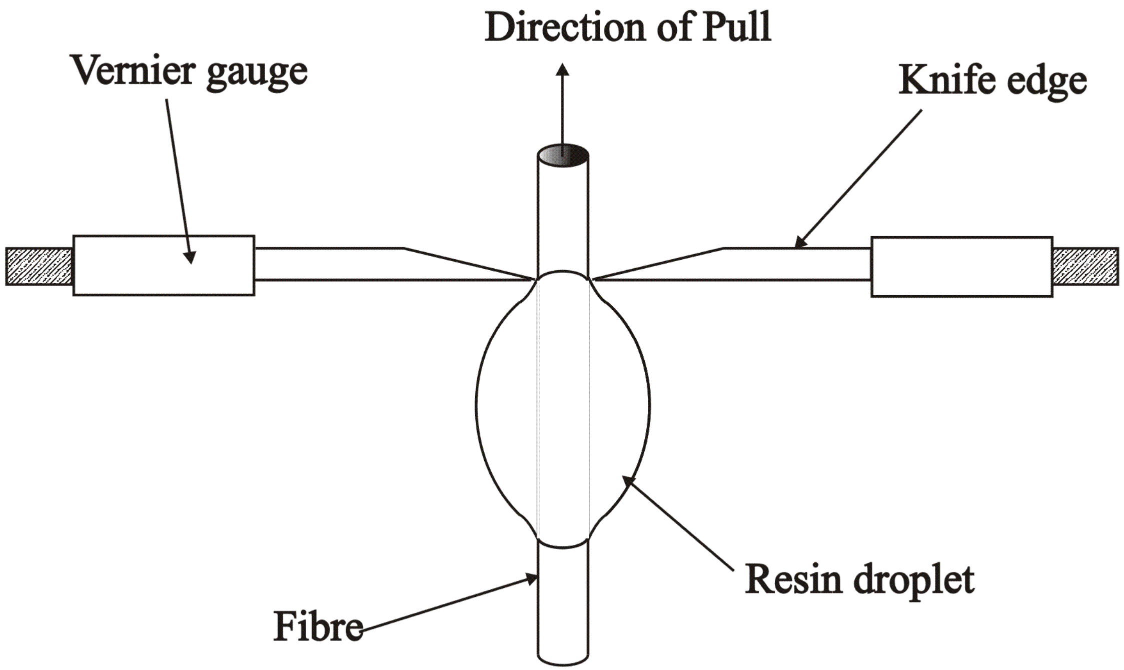
Droplet on treated fibre

UNIVERSITY OF BATH

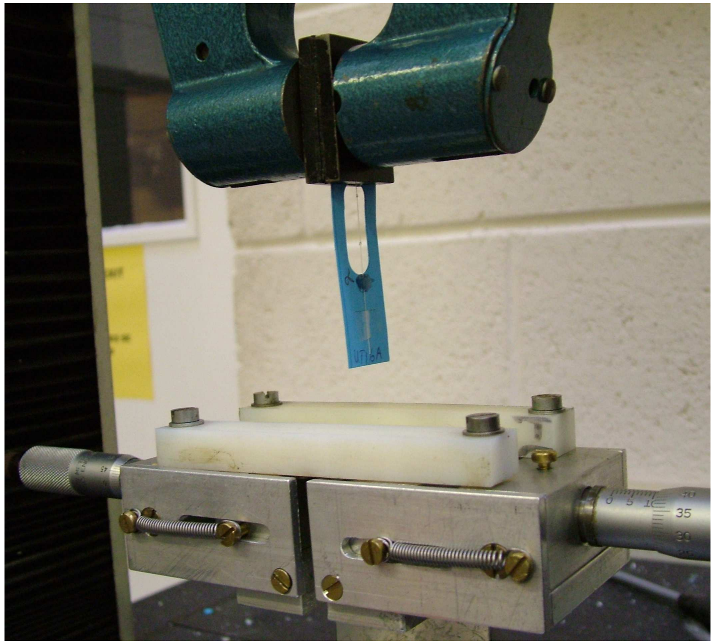
INTERFACIAL SHEAR STRENGTH (IFSS)

A microbond test was conducted to evaluate the interfacial shear strength (IFSS) between the sisal fibre and matrix.

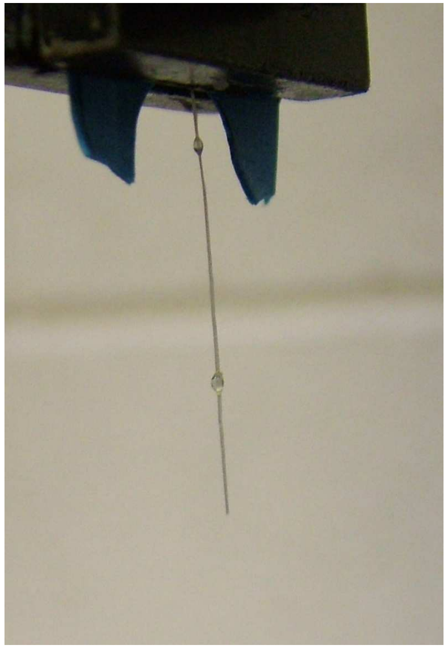
Separation of droplet from the fibre surface made possible by use of two knife edges



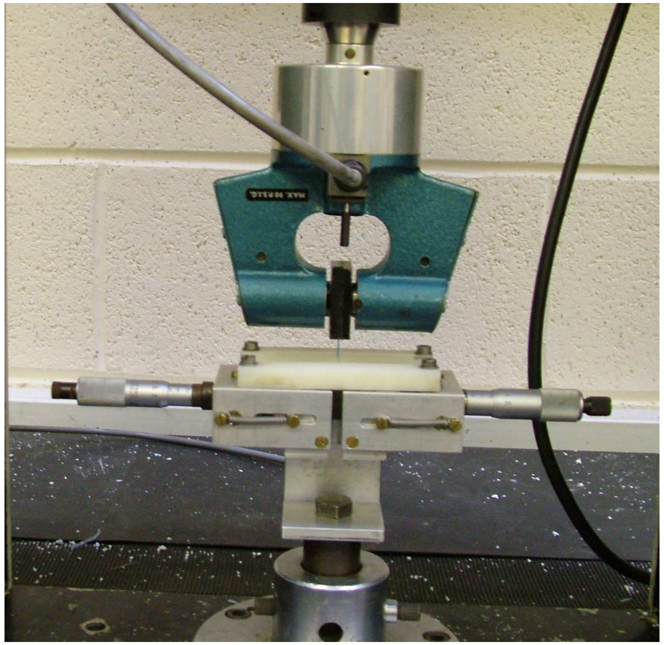
MICROBOND TEST



Fibre mounted on card support



Two droplets on fibre bundle



Whole micro-droplet test assembly

UNIVERSITY OF BATH

CALCULATION OF MICROBOND SHEAR STRENGTH (force/contact surface area)

$$\tau = \frac{F_{max}}{l_e \sqrt{4\pi \frac{m_f}{\rho l_f}}}$$

$$\tau = 0.282 \frac{F_{max}}{l_e} \sqrt{\frac{\rho l_f}{m_f}}$$

F_{max} = peak force (N)

ρ = apparent density ($Kg.m^{-3}$)

l_f = fibre length

l_e = embedded length

m_f = mass of fibre of length l_f (Kg)

UNIVERSITY OF BATH

INTERFACIAL SHEAR STRENGTH RESULTS

Polyester resin (droplets sheared away from fibre)

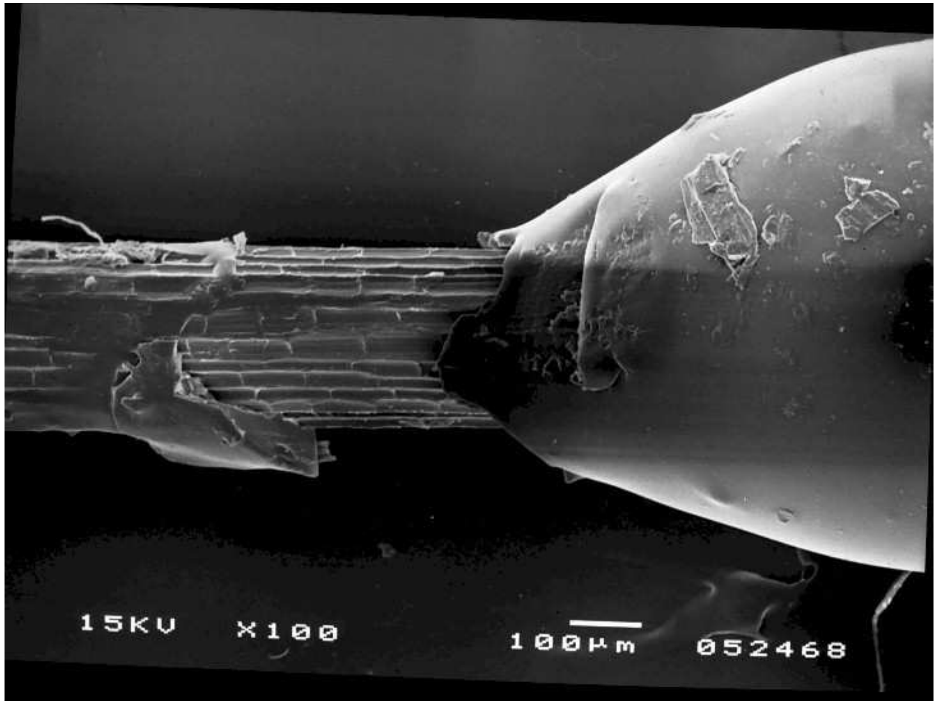
Type of Sisal Fibre	Mean Shear Strength (MPa)	Standard Deviation (MPa)	Median Strength (MPa)	Weibull Modulus *m*
Untreated	6.69	2.48	6.33	2.73
Treated	10.43	1.86	10.69	5.69

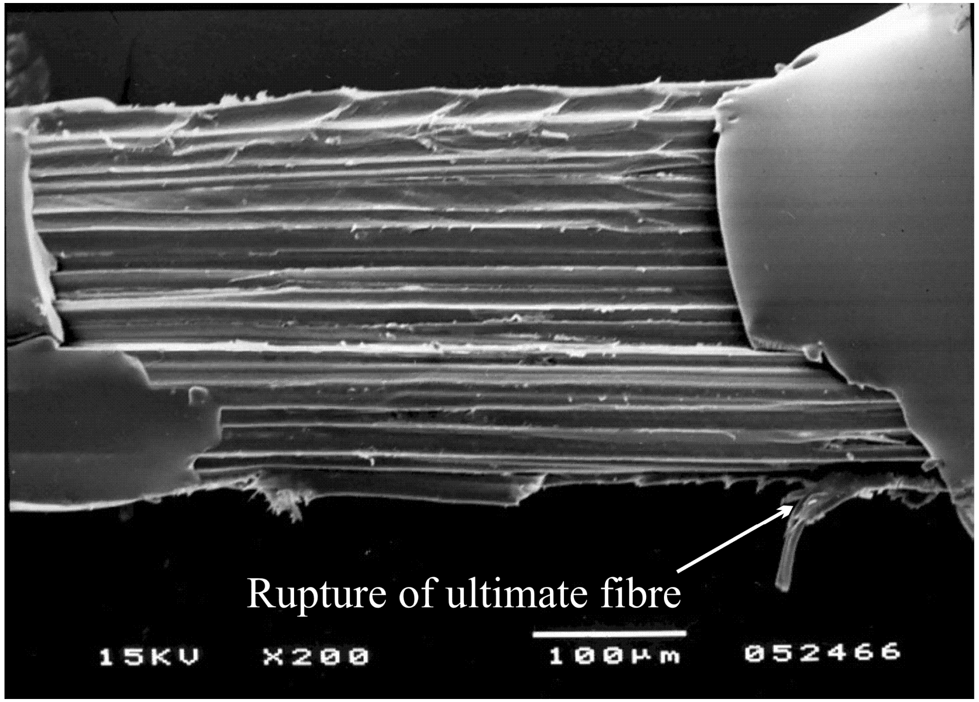
Epoxy resin (droplets not sheared, fibres fail in tension)

Type of Sisal Fibre	Mean Max Shear Stress (MPa)	Standard Deviation (MPa)	Median Strength (MPa)	Weibull Modulus *m*
Untreated	21.42	2.92	21.42	6.95
Treated	20.13	4.38	19.69	4.59

UNIVERSITY OF BATH

SEM IMAGES OF FAILED DROPLET





Polyester droplet shear on untreated sisal fibre surface (left) and treated sisal fibre surface (right)

Towo, A.N., Ansell, M.P., Pastor, Marie-Laetitia and Packham, D.E., (2005), "Weibull analysis of microbond shear strength at sisal fibre–polyester resin interfaces" Composite Interfaces, Vol. 12, No. 1, pp77-93.

UNIVERSITY OF BATH

SISAL FIBRE BUNDLE CRITICAL LENGTH PREDICTIONS

Critical length for stress transfer in unidirectionally-reinforced fibre composites,

$l_c = \sigma_{f,t} \, . \, r \, / \, \tau$,

where $\sigma_{f,t}$ = fibre bundle tensile strength,
r = fibre bundle radius
τ = interfacial shear strength.
*no shear failure, peak shear stress.

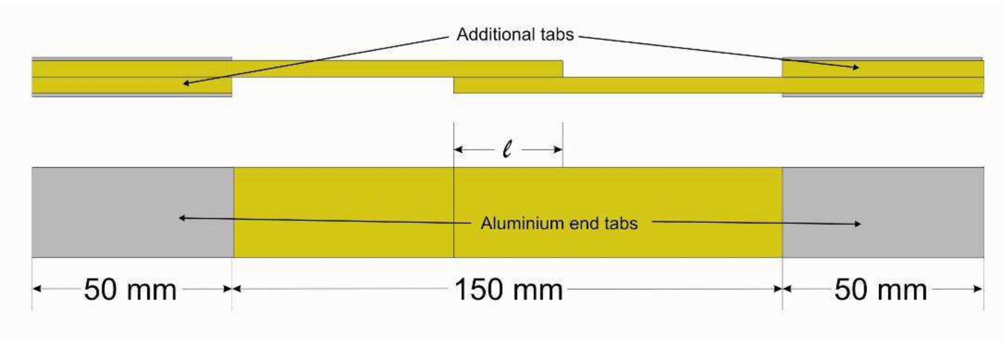
$\gamma_f = \sigma_{f,t} \, . \, l_c \, . V_f \, /24$

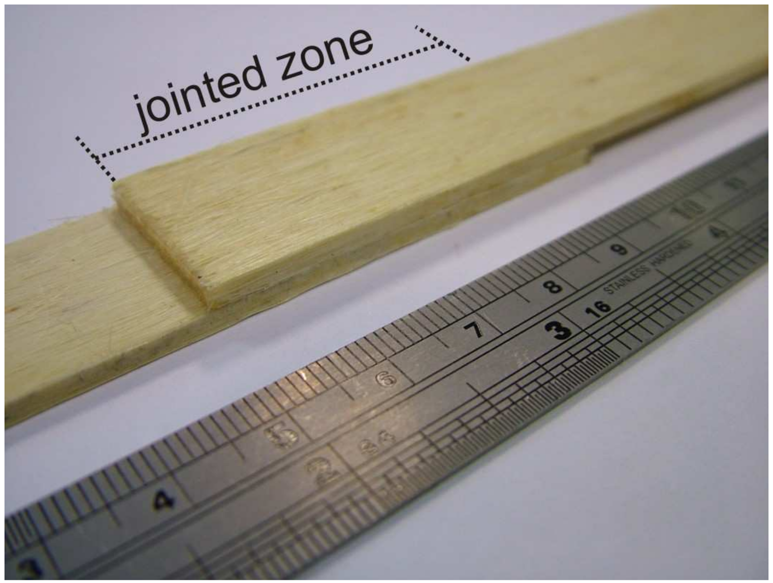
Kelly and Tyson expression for work of fracture ($J.m^{-2}$)

Fibre/resin combination	Mean $\sigma_{f,t}$ (MPa)	Mean radius r (μm)	IFSS (MPa)	Critical length, l_c (predicted) (mm)	Work of fracture (predicted) ($10^4.Jm^{-2}$)
Untreated polyester	577	80	6.7	6.85	10.89
Treated polyester	544	74	10.4	3.84	5.27
Untreated epoxy	577	83	21.4*	2.24*	3.88*
Treated epoxy	544	79	20.1*	2.12*	3.32*

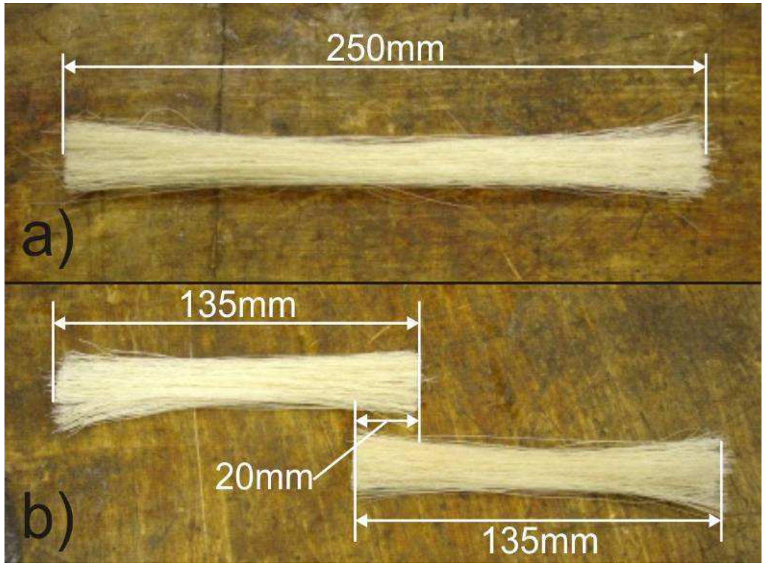
JOINTS: In-line joints, densification, L-shaped moment resisting joints, FE modelling.

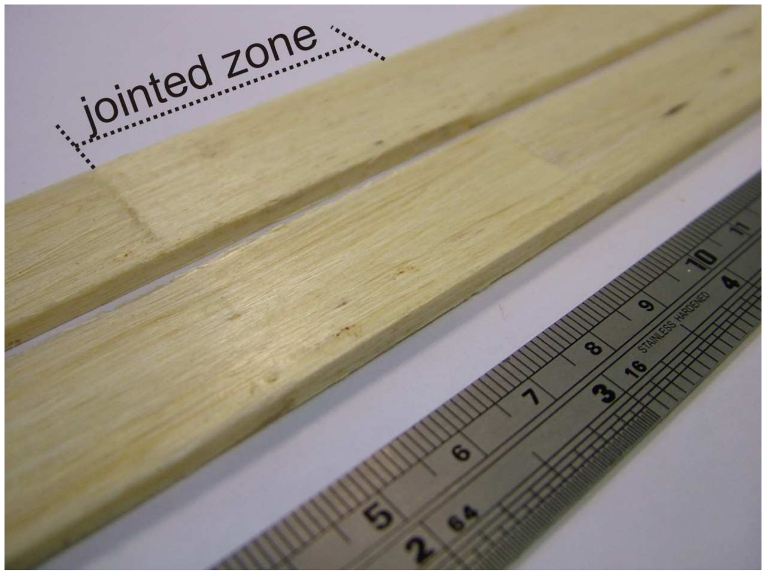
Single-lap joint



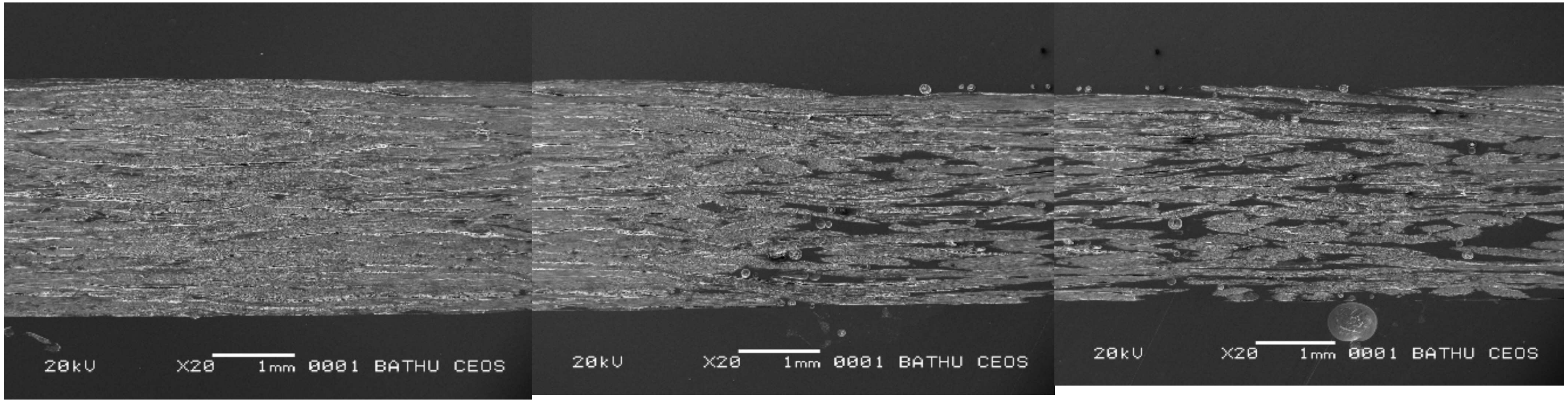


Co-cured joint





JOINTS: In-line joints, longitudinal section of laminated fibre joint viewed in SEM



Overlapped zone **Outside central zone**

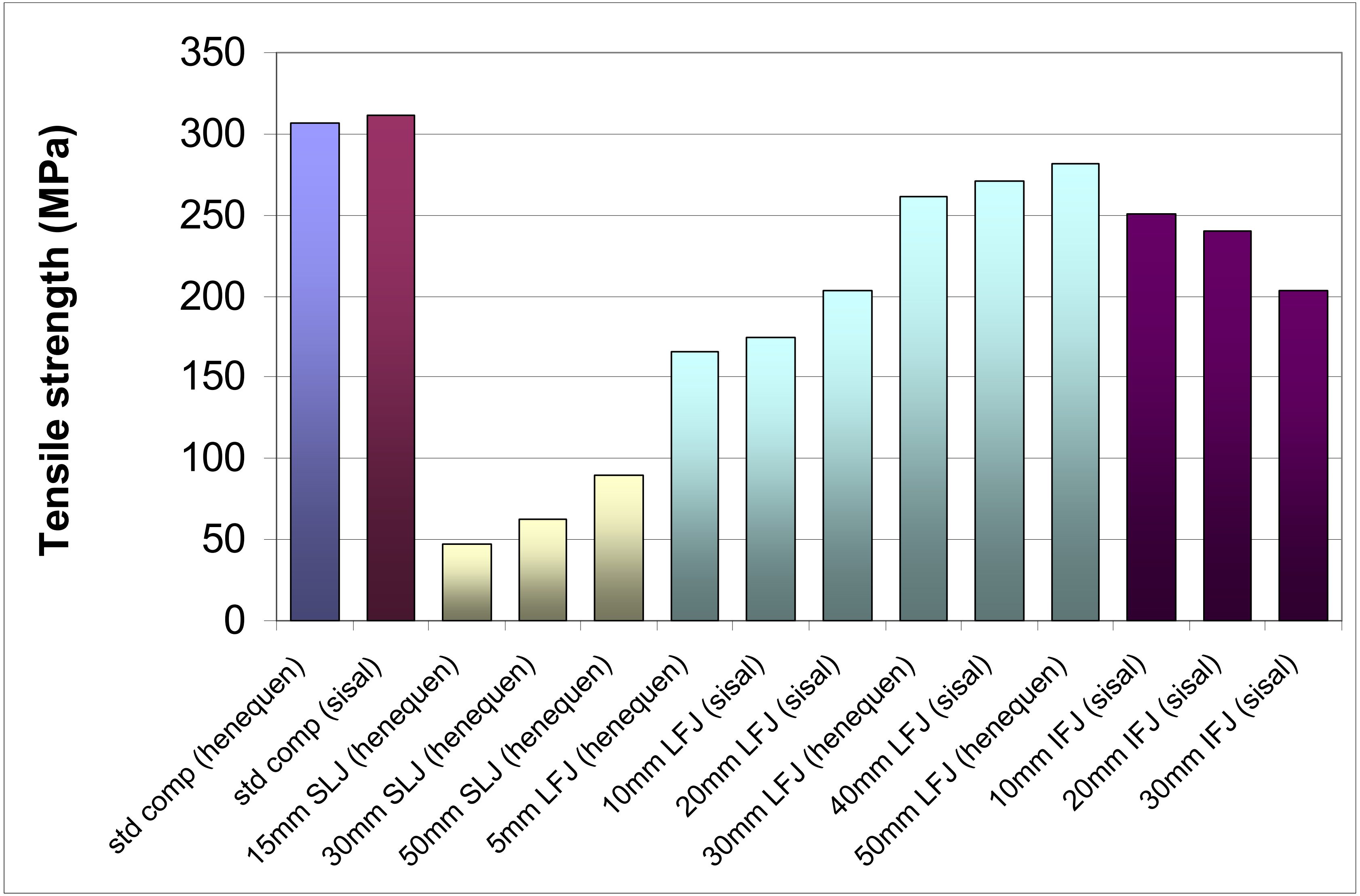
Gonzalez Murillo, C. and Ansell, M.P., (2010), "Co-cured in-line joints for natural fibre composites", Composites Science and Technology, Volume 70, Issue 3, pp 442-449.

UNIVERSITY OF BATH

JOINTS: In-line joints, tensile strength results for sisal fibre plain composites and LFJ and IFJ jointed composites

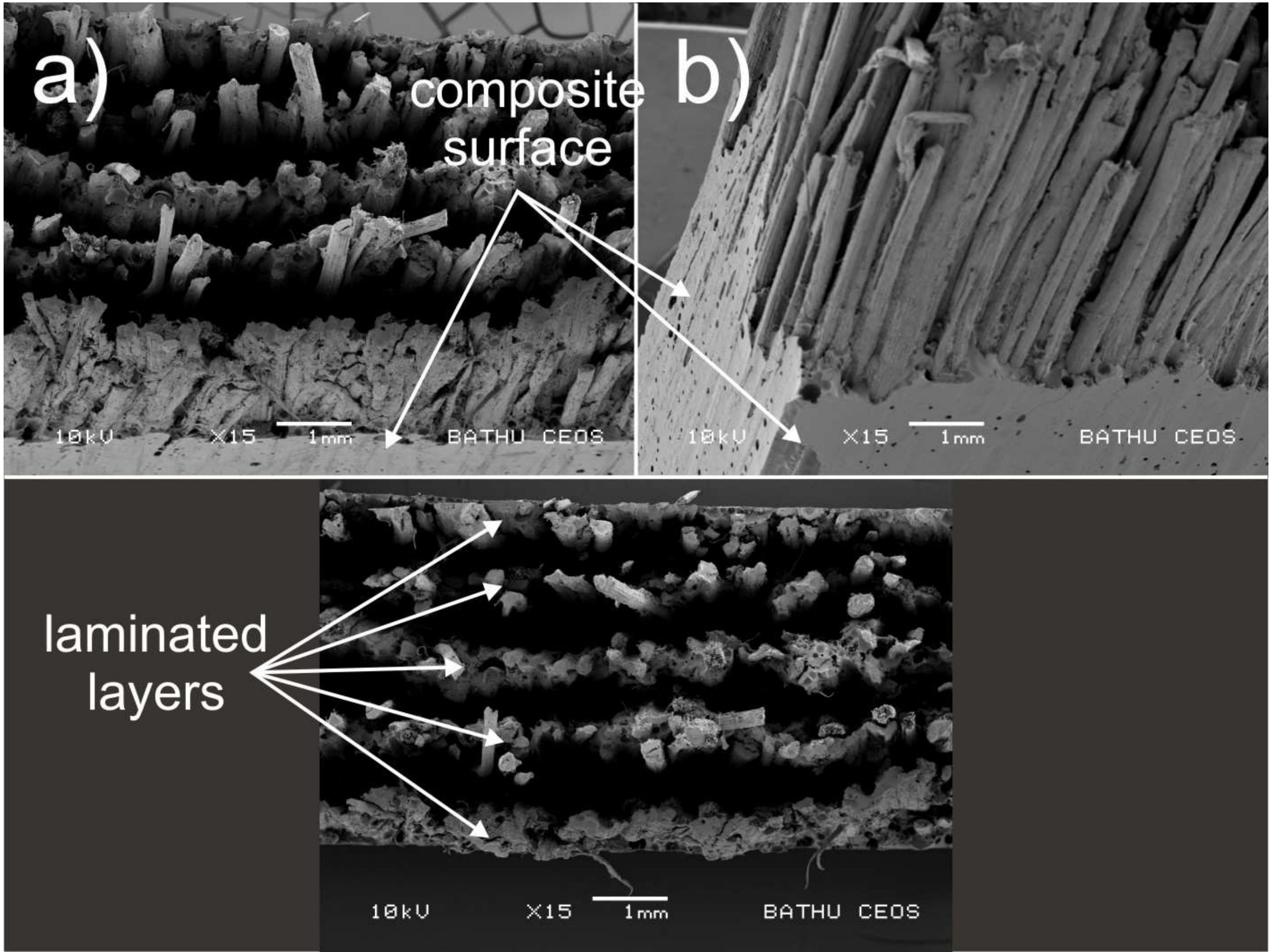
Composite configuration	Mean strength (MPa)	Young's modulus (GPa)	Average fibre vol. fraction (%)	Density of composite (g/cm^3)
Untreated plain composite	311.69 ± 14.8	22.13 ± 1.05	68.73 ± 0.02	1.34
Treated plain composite	331.01 ± 8.51	25.17 ± 0.65	63.68 ± 0.02	1.34
10mm LFJs	174.83 ± 13.2	-	55.85 ± 0.01	1.32
20mm LFJs	203.06 ± 7.1	-	57.91 ± 0.01	1.32
40mm LFJs	271.05 ± 4.3	-	55.74 ± 0.02	1.31
10mm IFJs	251.00 ± 10.5	-	60.91 ± 0.02	1.33
20mm IFJs	240.02 ± 23.3	-	63.16 ± 0.01	1.33
30mm IFJs	203.03 ± 2.9	-	60.79 ± 0.01	1.33

JOINTS: In-line joints, tensile strength results for sisal fibre plain composites and SLJ, LFJ and IFJ jointed composites

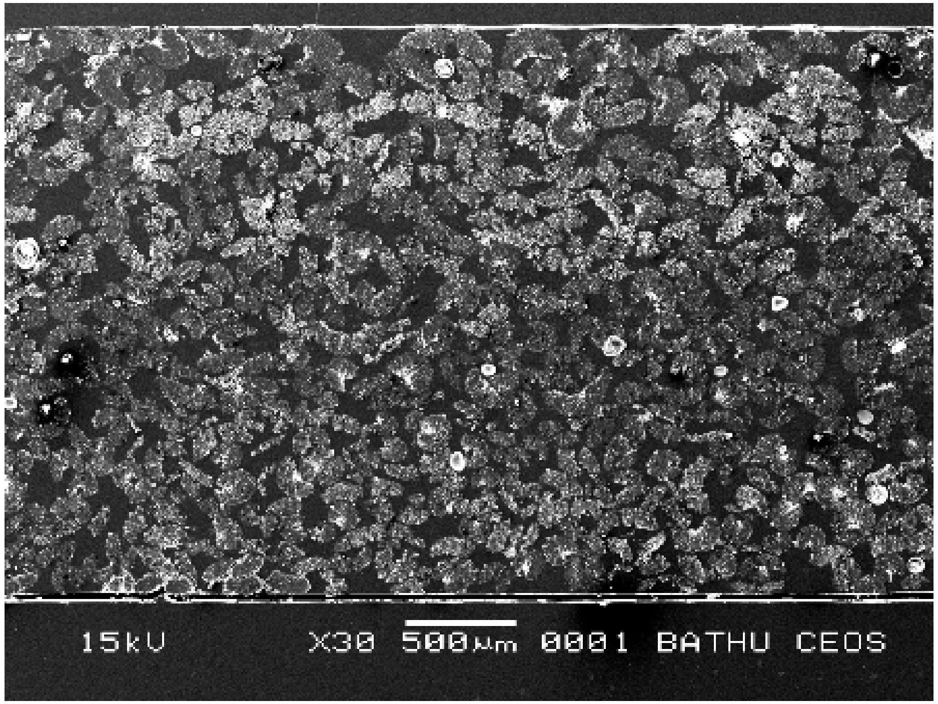


UNIVERSITY OF BATH

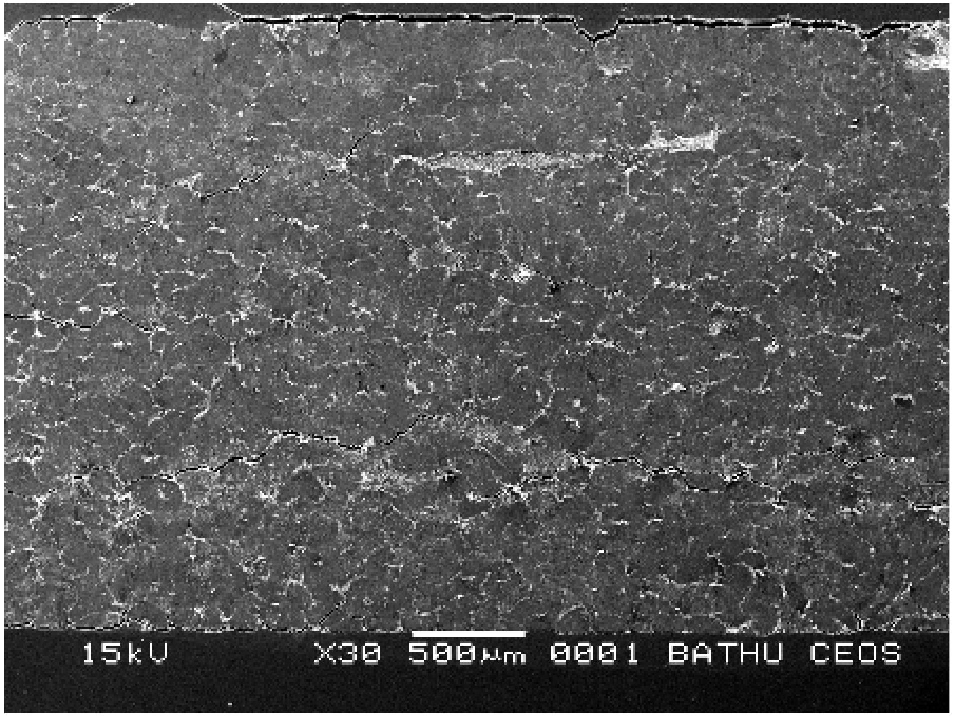
JOINTS: In-line joints, LFJ failure mode



EFFECT OF PRESSURE ON MICROSTRUCTURE



•Composite pressed at 6MPa



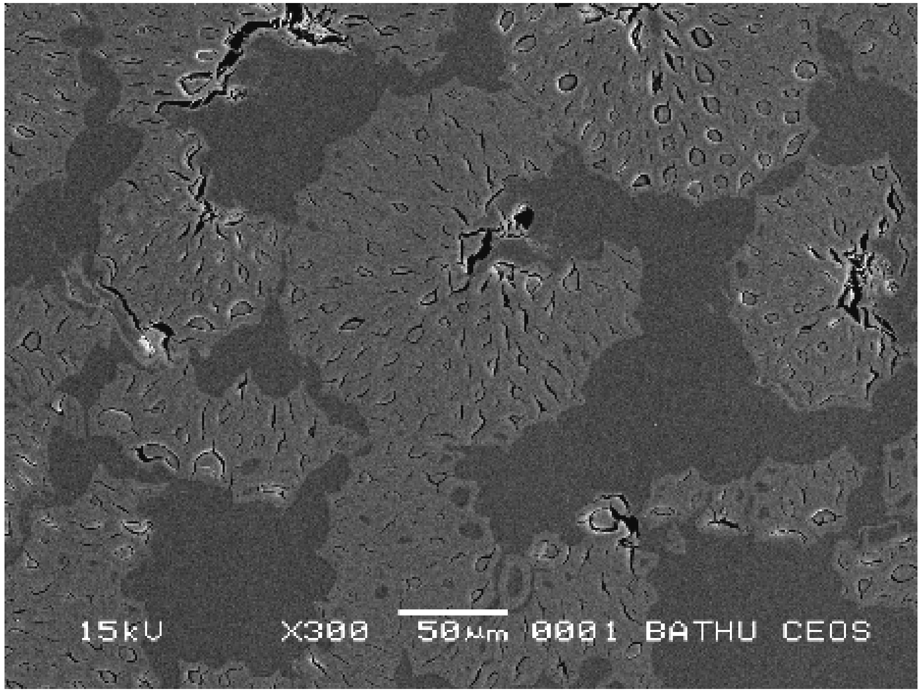
•Composite pressed at 15MPa

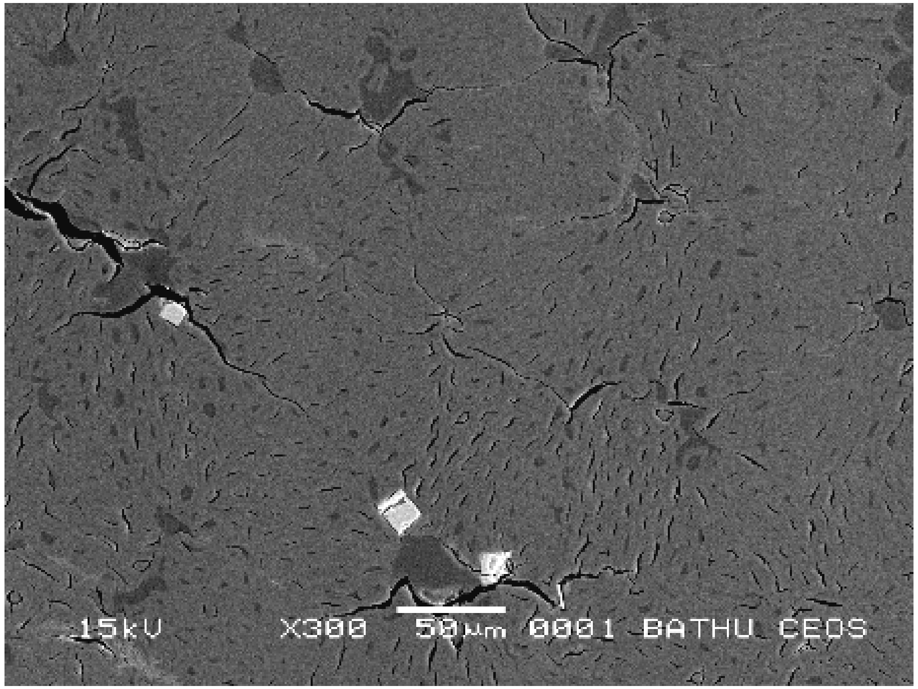
•Fibre volume fractions exceed those of conventional synthetic composites.

•Similar microstructure to oriented strandboard (OSB).

UNIVERSITY OF BATH

FIBRE PACKING AT 6 MPa AND 15 MPa

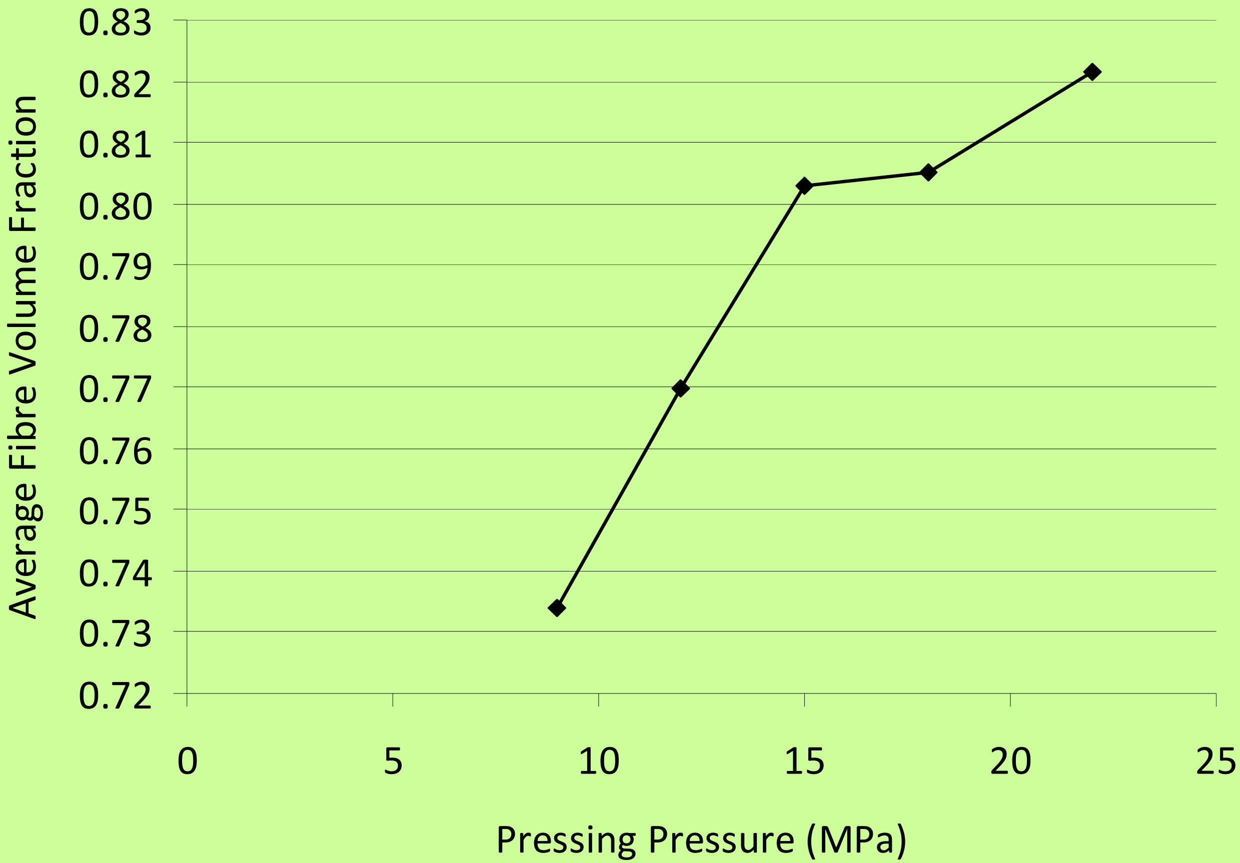




Low pressure composite
- **Vf = 0.6-0.65**
- **Micro-cracks are associated with fibre bundles**

High pressure composite
- **Vf up to 0.95, some densification**
- **Polishing medium visible**
- **Some micro-cracking**

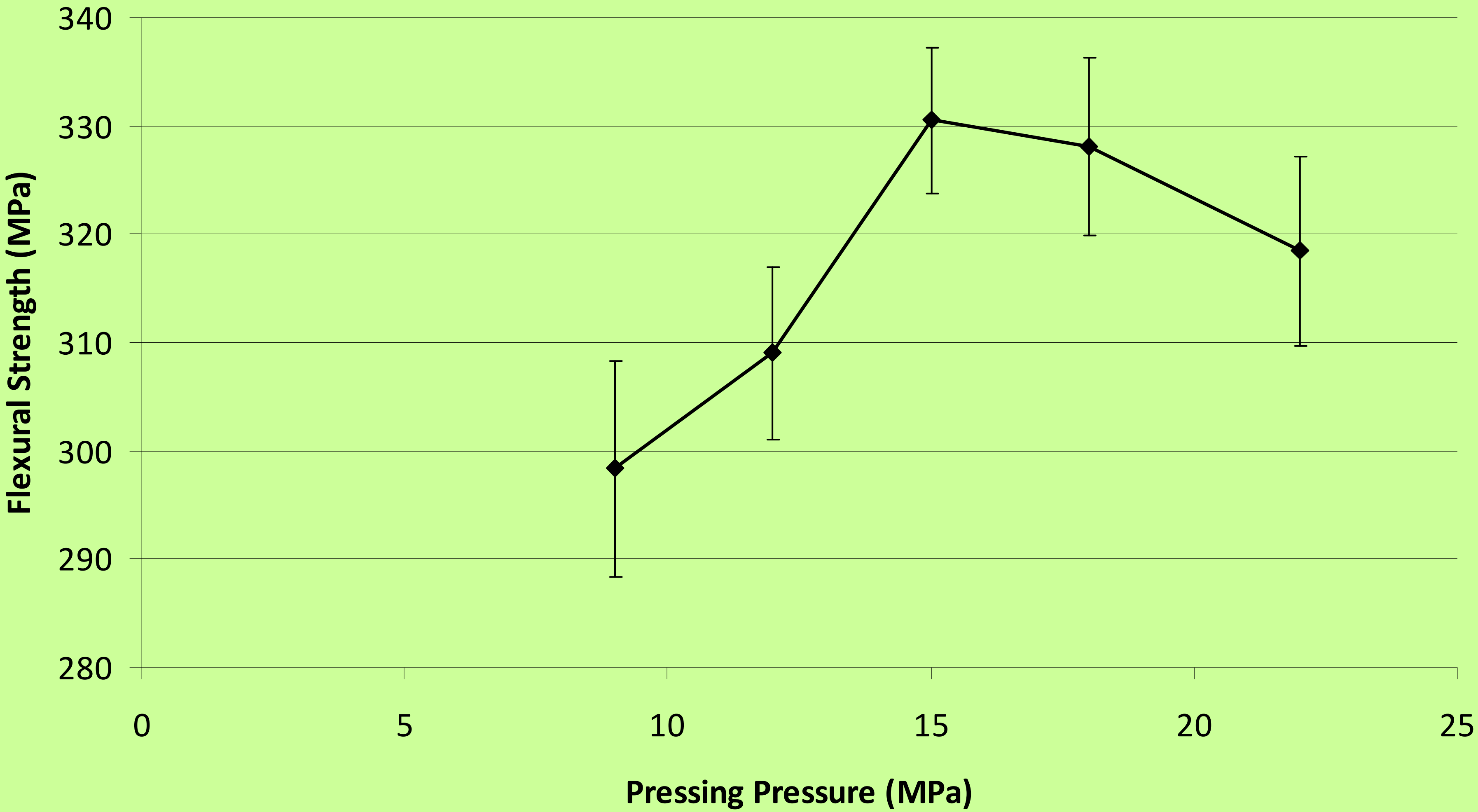
EFFECT OF PRESSURE ON FIBRE VOLUME FRACTION



- High fibre volume fractions of fibre in NFCs mean less matrix and hence lower environmental impact if synthetic adhesives are used. Less incentive to use bio-resins?

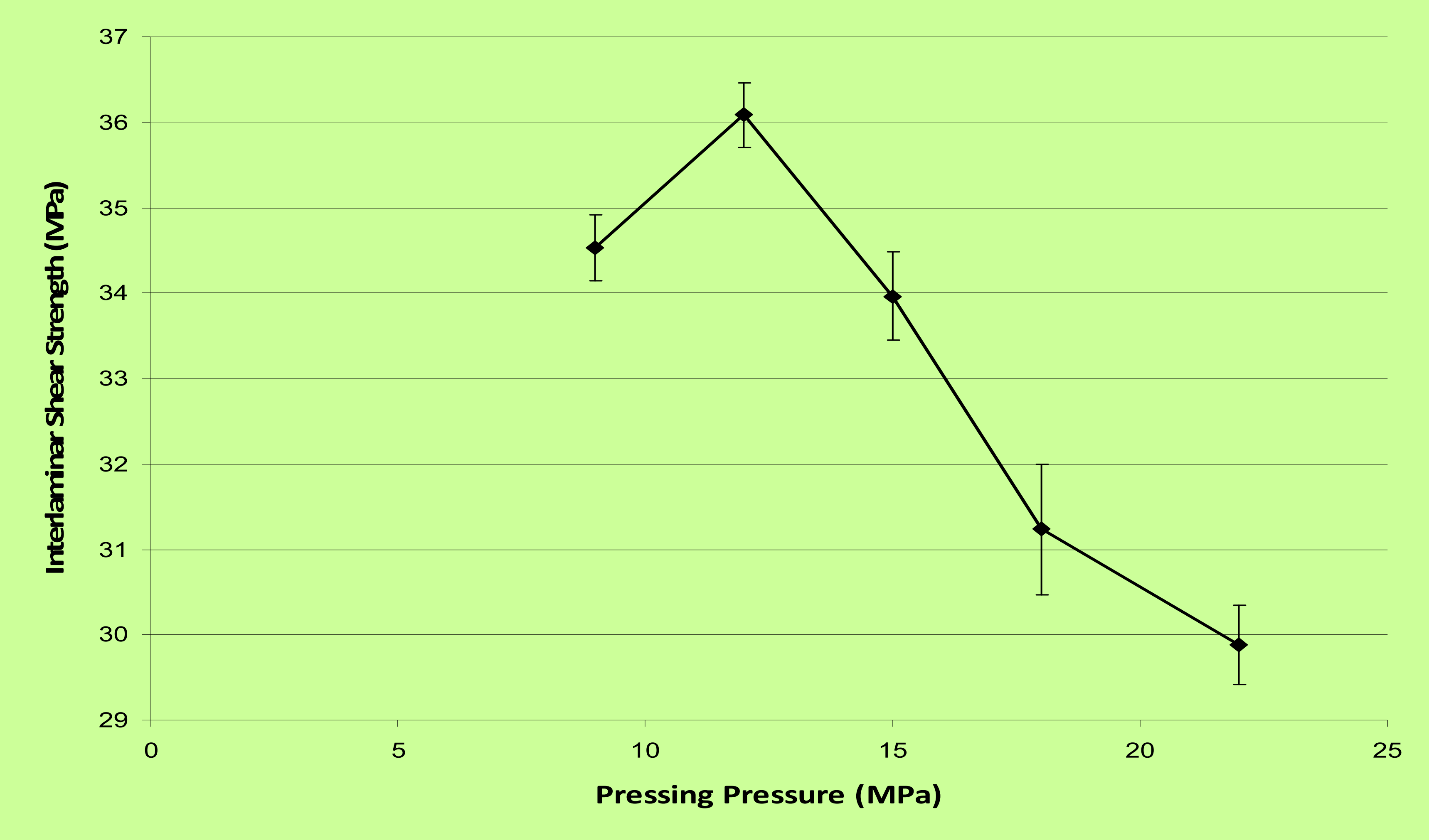
UNIVERSITY OF BATH

EFFECT OF PRESSURE ON MECHANICAL PROPERTIES - FLEXURAL STRENGTH

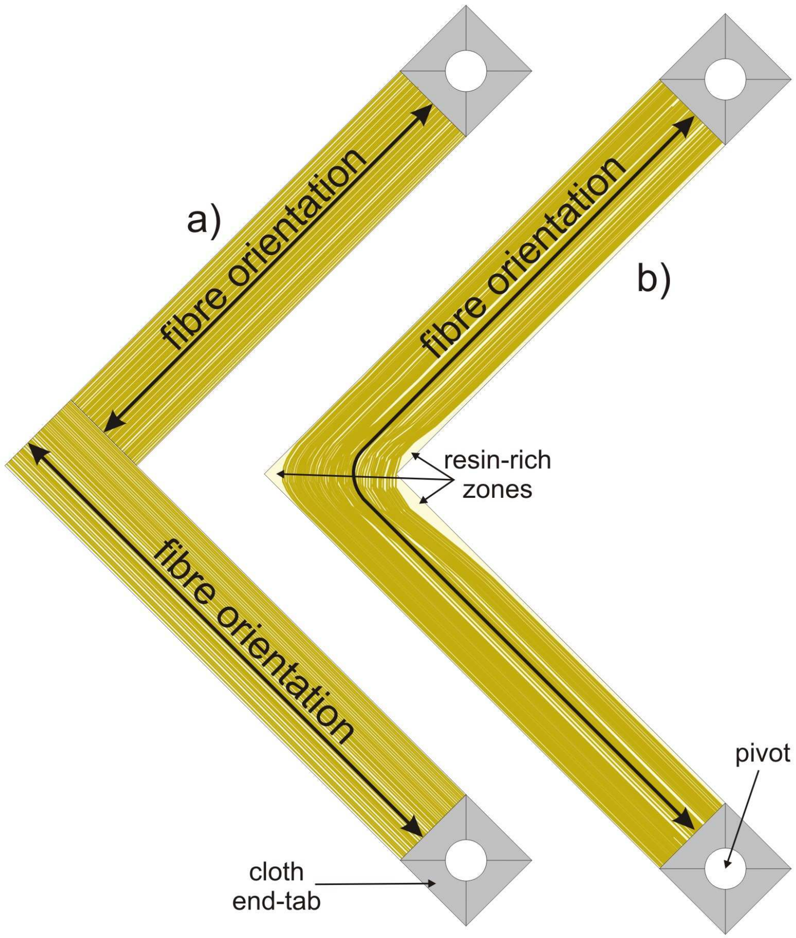


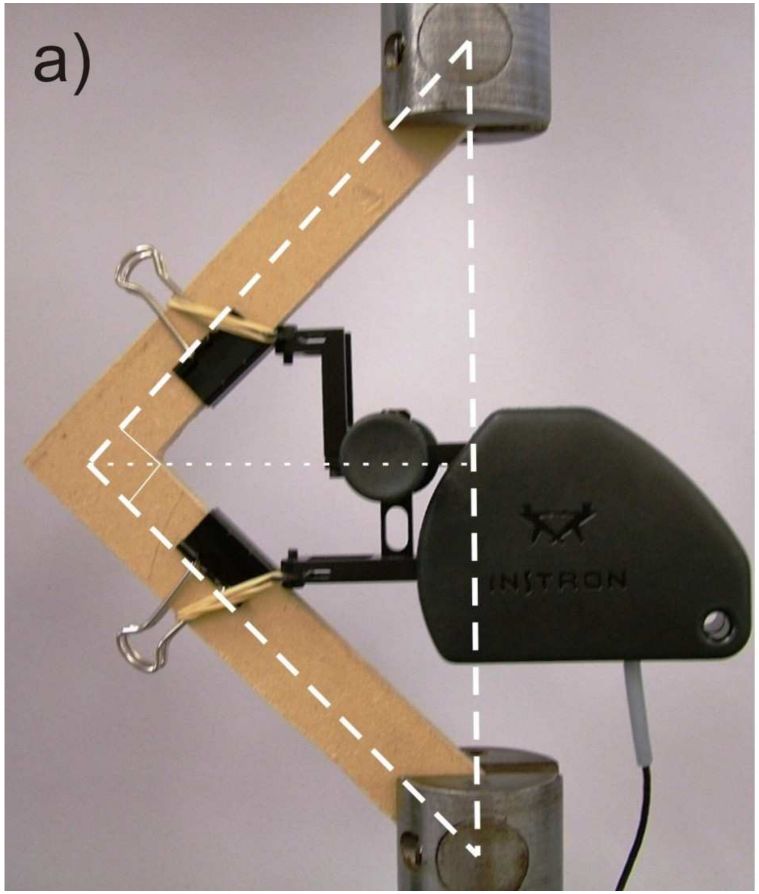
UNIVERSITY OF BATH

EFFECT OF PRESSURE ON INTER-LAMINAR SHEAR STRENGTH



SISAL-EPOXY MOMENT-RESISTING JOINTS



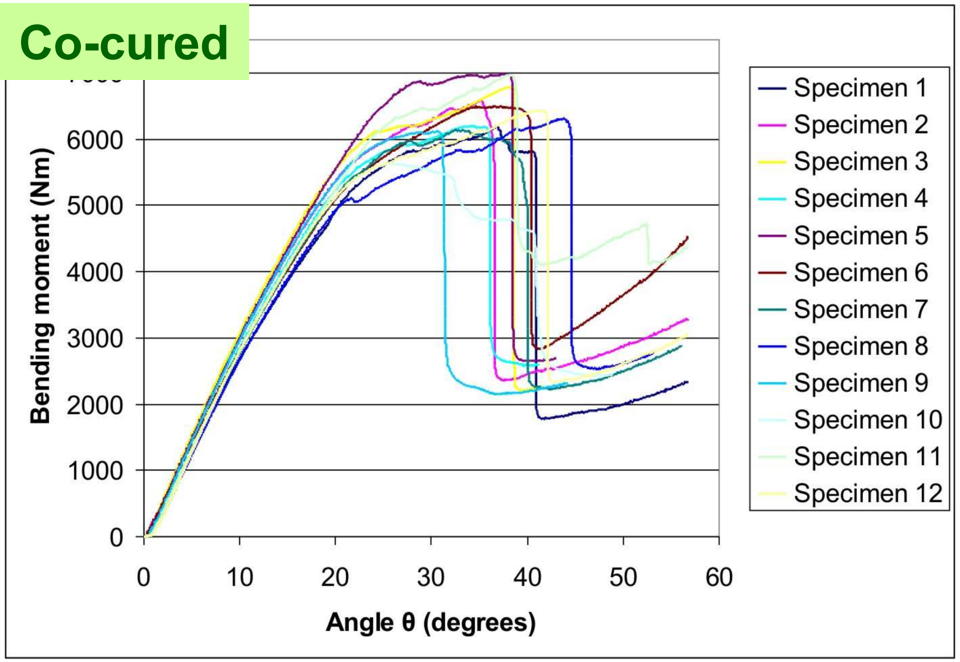


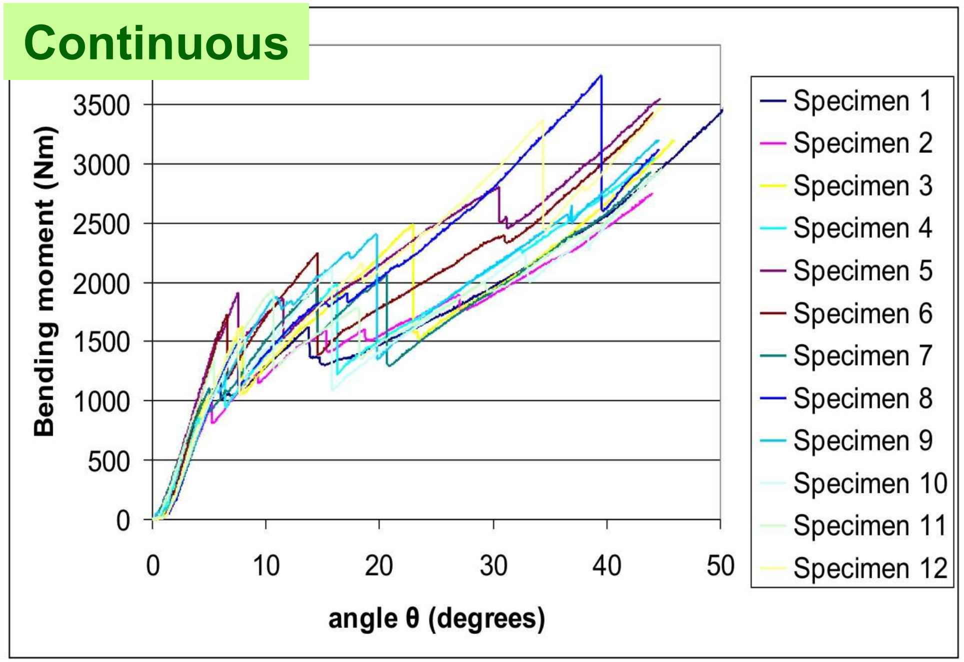
- L-shaped joints, overlapped and continuous geometries

- Test fixture for moment-resisting tests

JOINTS: L-shaped moment resisting joints, co-cured versus continuous fibre joints

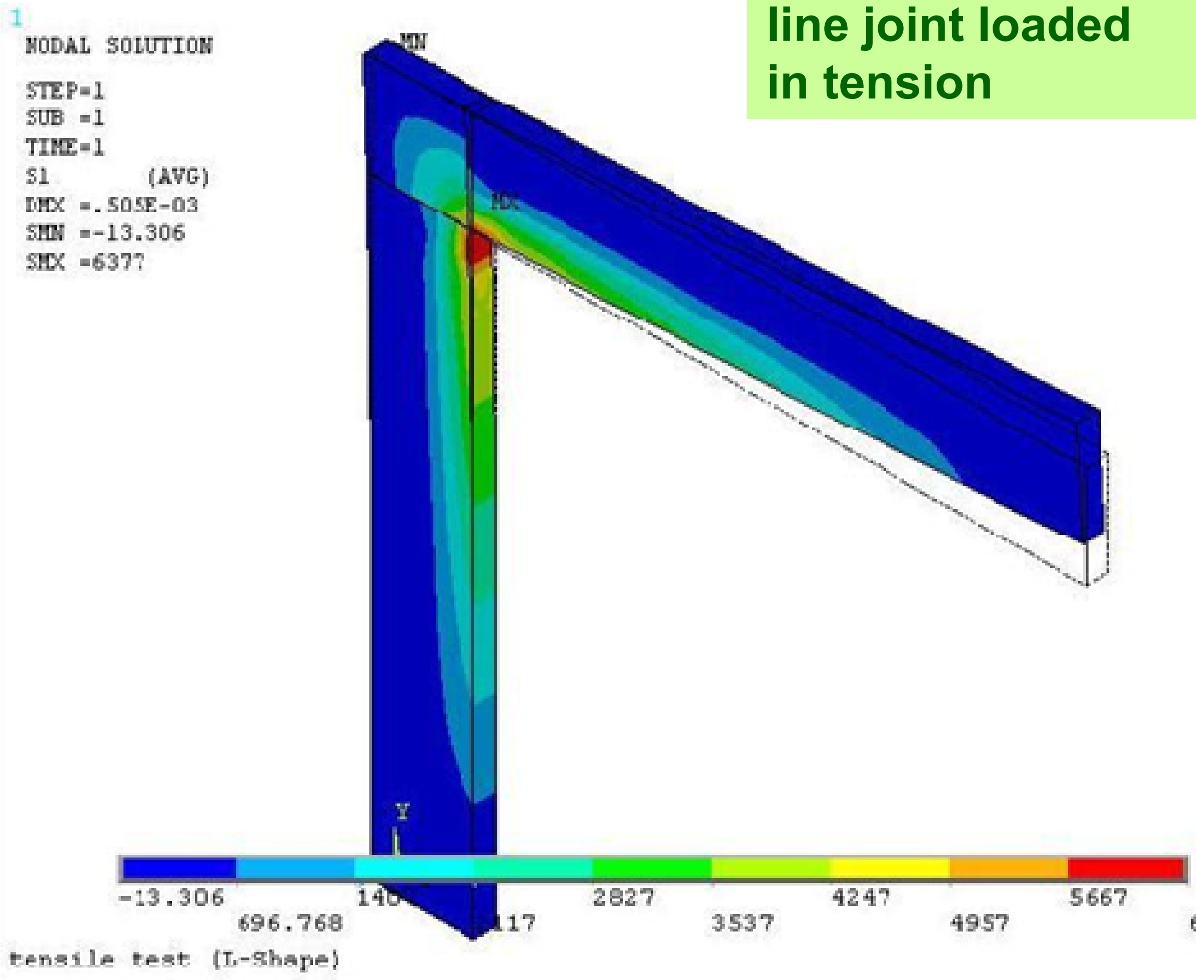
Composite configuration	Mean maximum force (N)	Mean maximum bending moment (Nm)	Average fibre vol. fraction (%)	Density of composite (g/cm^3)
L-shaped co-cured joint	379.17 ± 21.10	5884.84 ± 429.52	63.34 ± 0.02	1.36
L-shaped continuous fibre joint	112.60 ± 21.71	1412.54 ± 283.74	65.72 ± 0.02	1.37

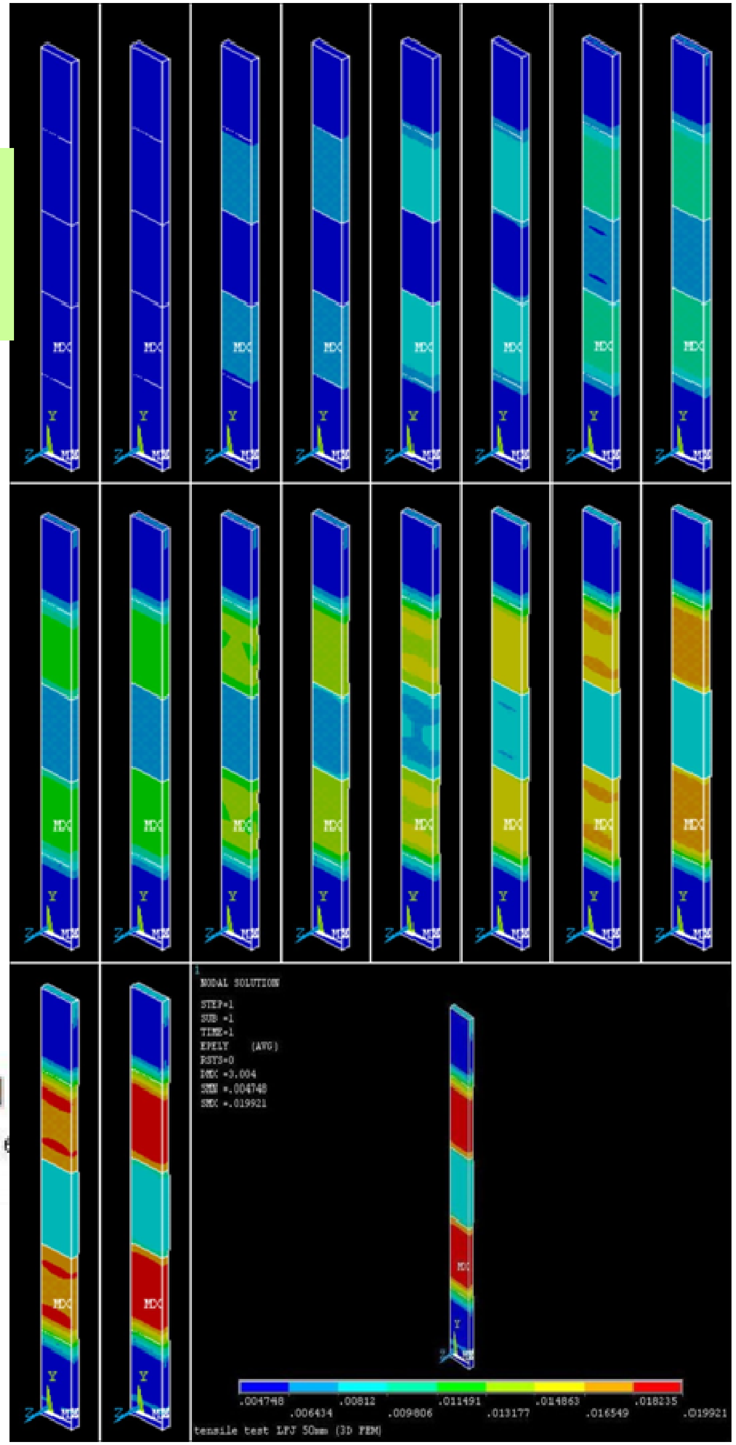




JOINTS: FE modelling

•FE model of in-line joint loaded in tension

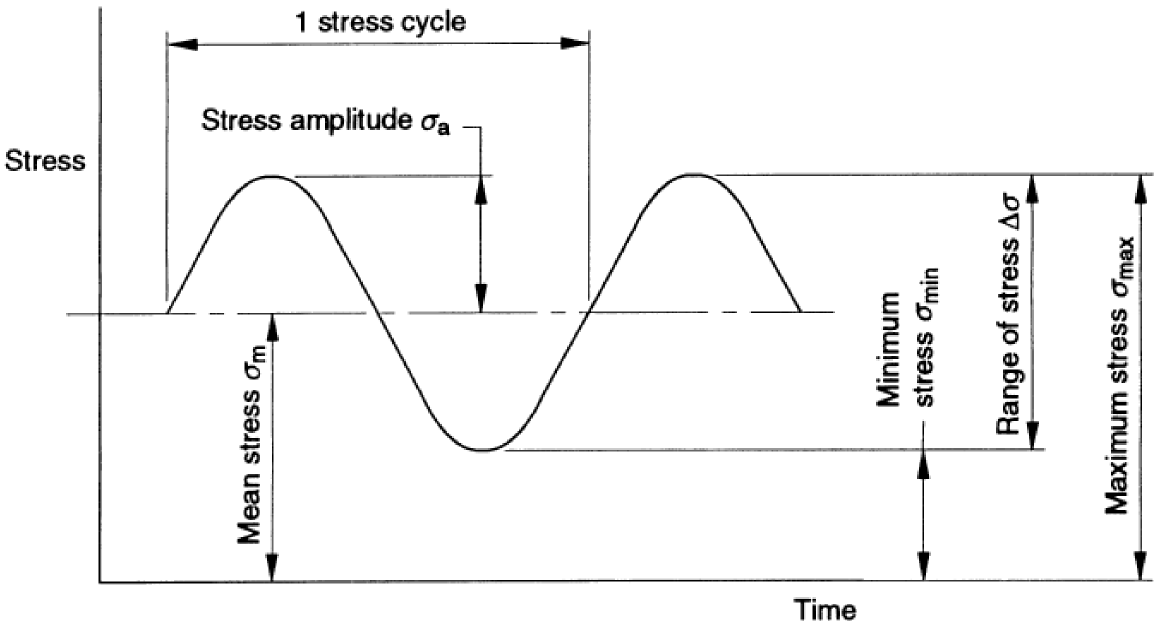




•FE model of stressed overlapping L-shaped joint

FATIGUE OF NATURAL FIBRE COMPOSITES

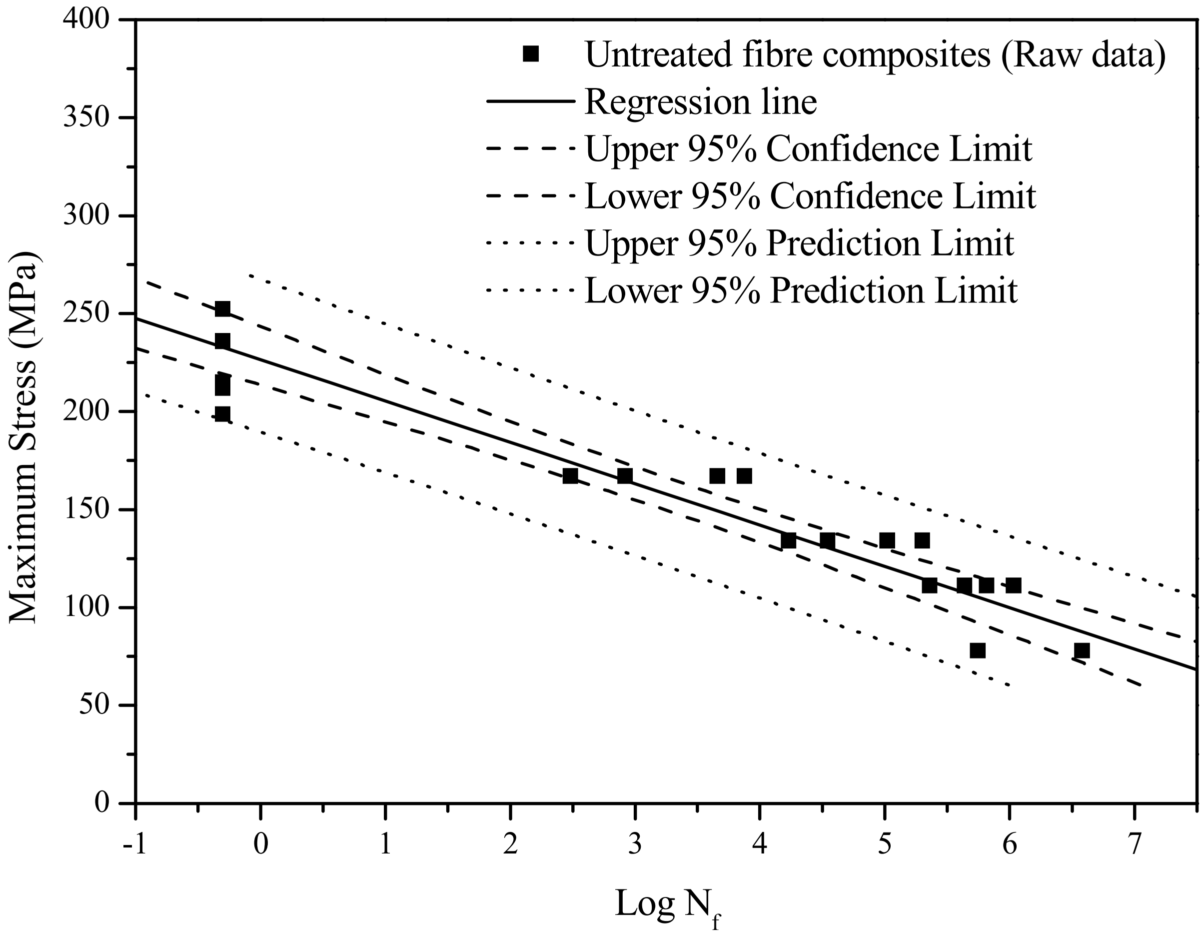
- Almost no literature on the fatigue of natural fibre composites.
- Structural applications in automotive and aerospace disciplines require knowledge of the fatigue performance of NFCs.
- Generation of S-N curves over a range of R ratios.
- Evaluation of failure modes in fatigue.



$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

UNIVERSITY OF BATH

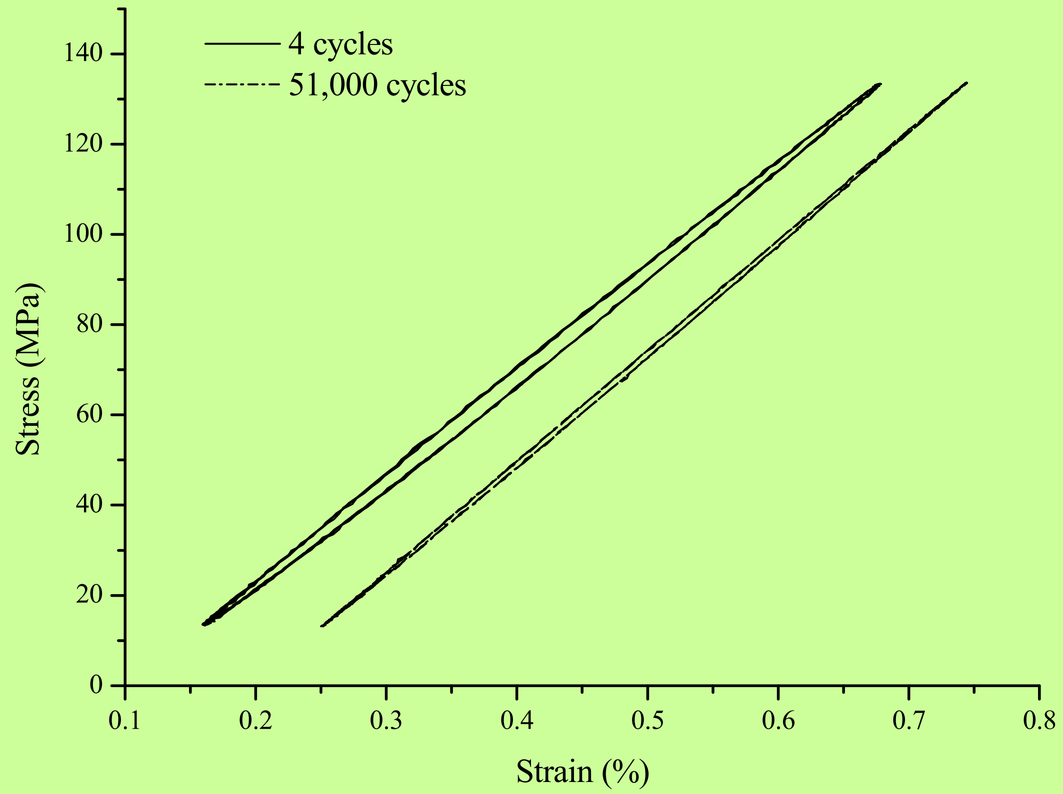
S-N CURVE FOR SISAL POLYESTER COMPOSITE AT R=0.1

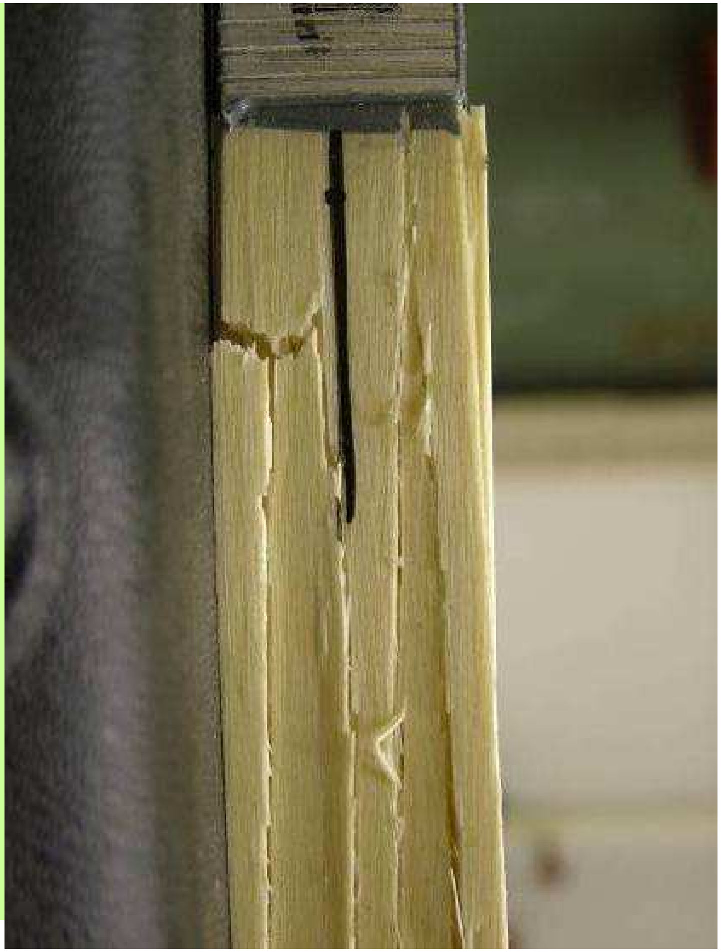


Stress-life data for untreated fibre polyester resin composites at maximum stresses of 75%, 60%, 50% and 35% of failure stress at R=0.1 (tension-tension).

UNIVERSITY OF BATH

FATIGUE RESPONSE IN TENSION-TENSION

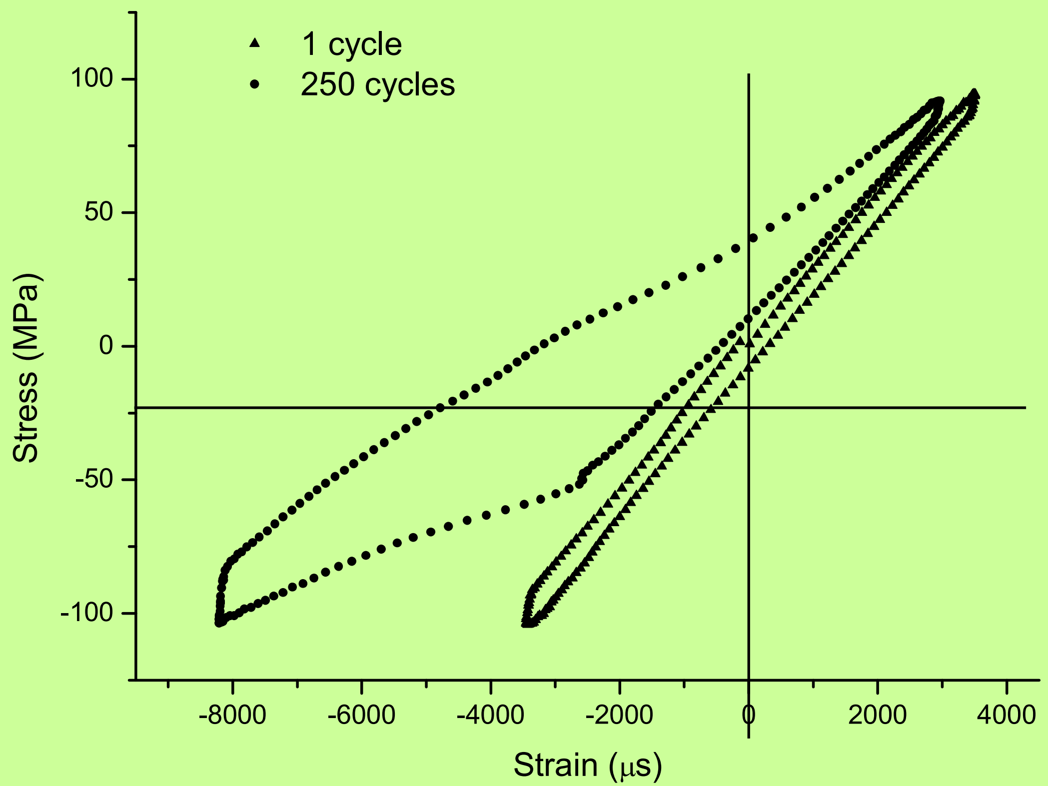


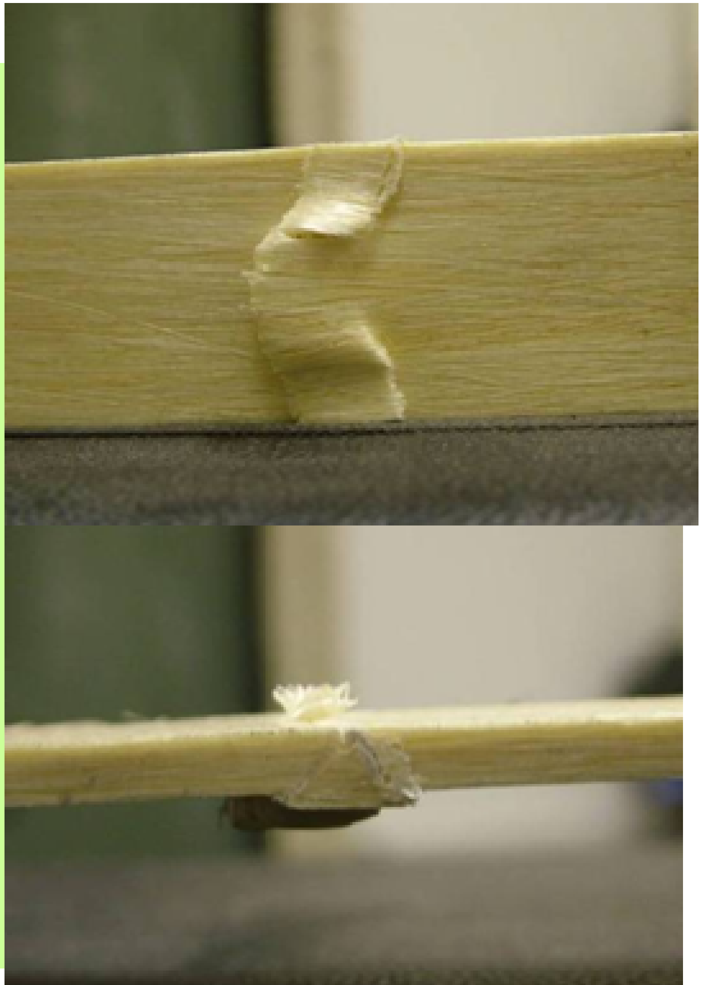


- Hysteresis loops close up as cyclic loading proceeds
- Longitudinal splits in the fatigued composite at fracture

UNIVERSITY OF BATH

FATIGUE RESPONSE IN REVERSED LOADING





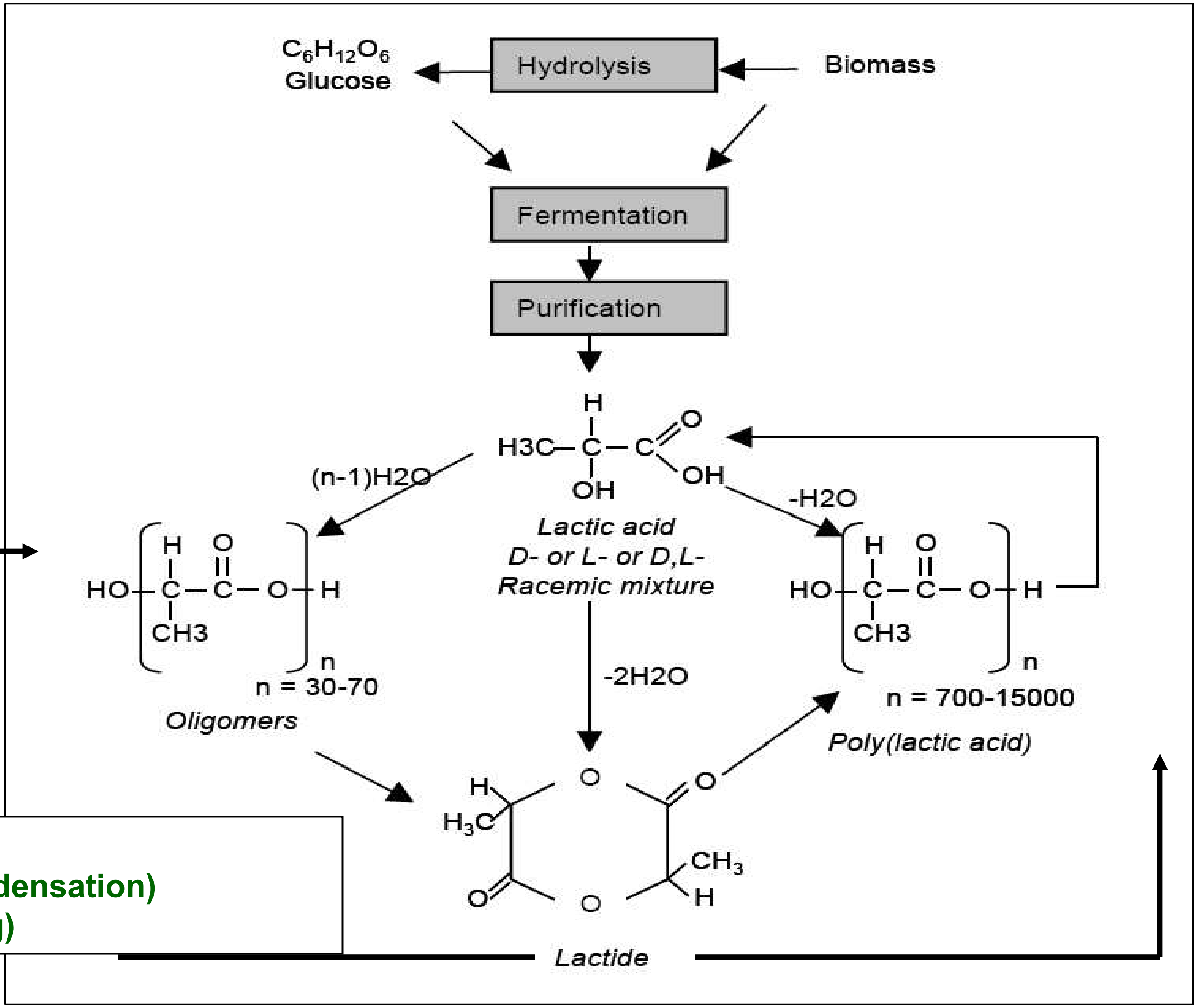
- Hysteresis loops open up as cyclic loading proceeds
- Compression buckling at failure in reversed loading

Towo, A.N., Ansell, M.P. (2008), "Fatigue evaluation and dynamic mechanical thermal analysis of sisal fibre - thermosetting resin composites", Composites Science and Technology, 68, 925-932.

Towo, A.N., Ansell, M.P. (2008), "Fatigue of sisal fibre reinforced composites: constant life diagrams and hysteresis loop capture", Composites Science and Technology, 68, 915-924.

UNIVERSITY OF BATH

POLY (LACTIC ACID) (PLA) - PRODUCTION FROM BIOMASS



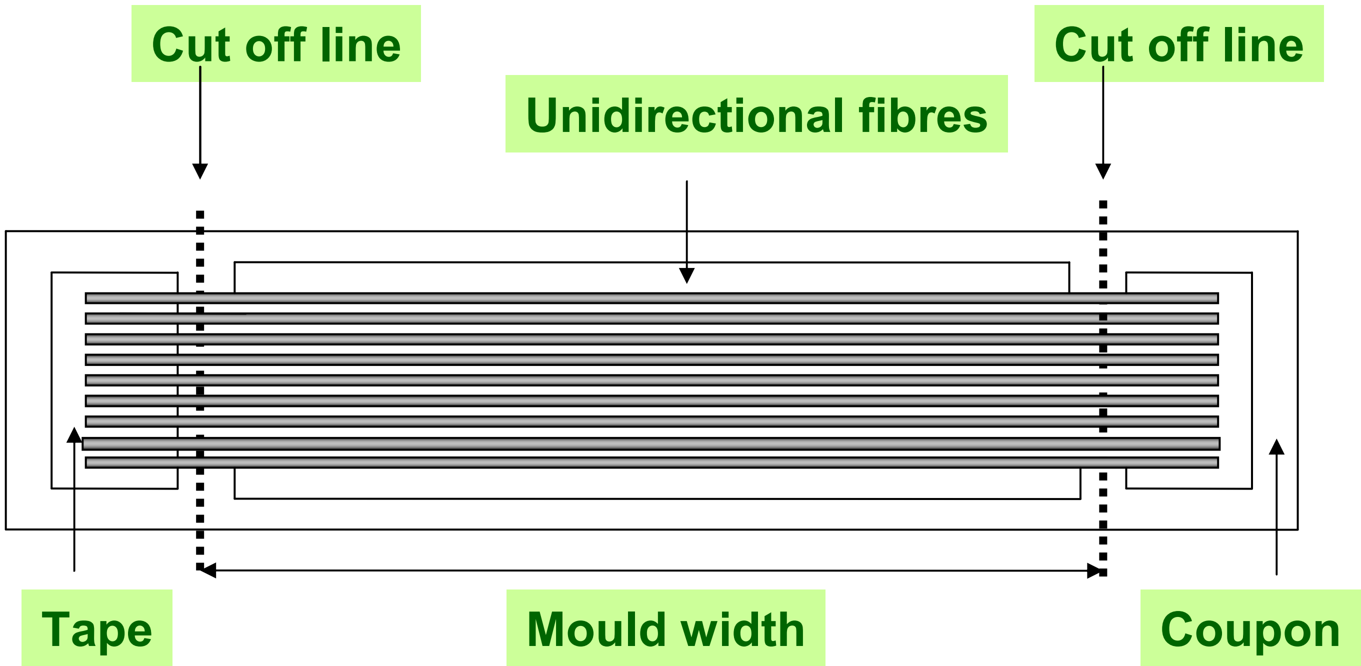
Technology:
- **Mitsui Toatsu (direct condensation)**
- **Cargill-Dow (ring opening)**

UNIVERSITY OF BATH

PROCESSING PLA THERMOPLASTIC MATRIX COMPOSITES

Matrix: Biomer L9000 polylactic acid.
Reinforcement: long sisal fibre bundles.
Processing: compression moulding at 200ºC.
Cellulosic fibres are sufficiently stable.

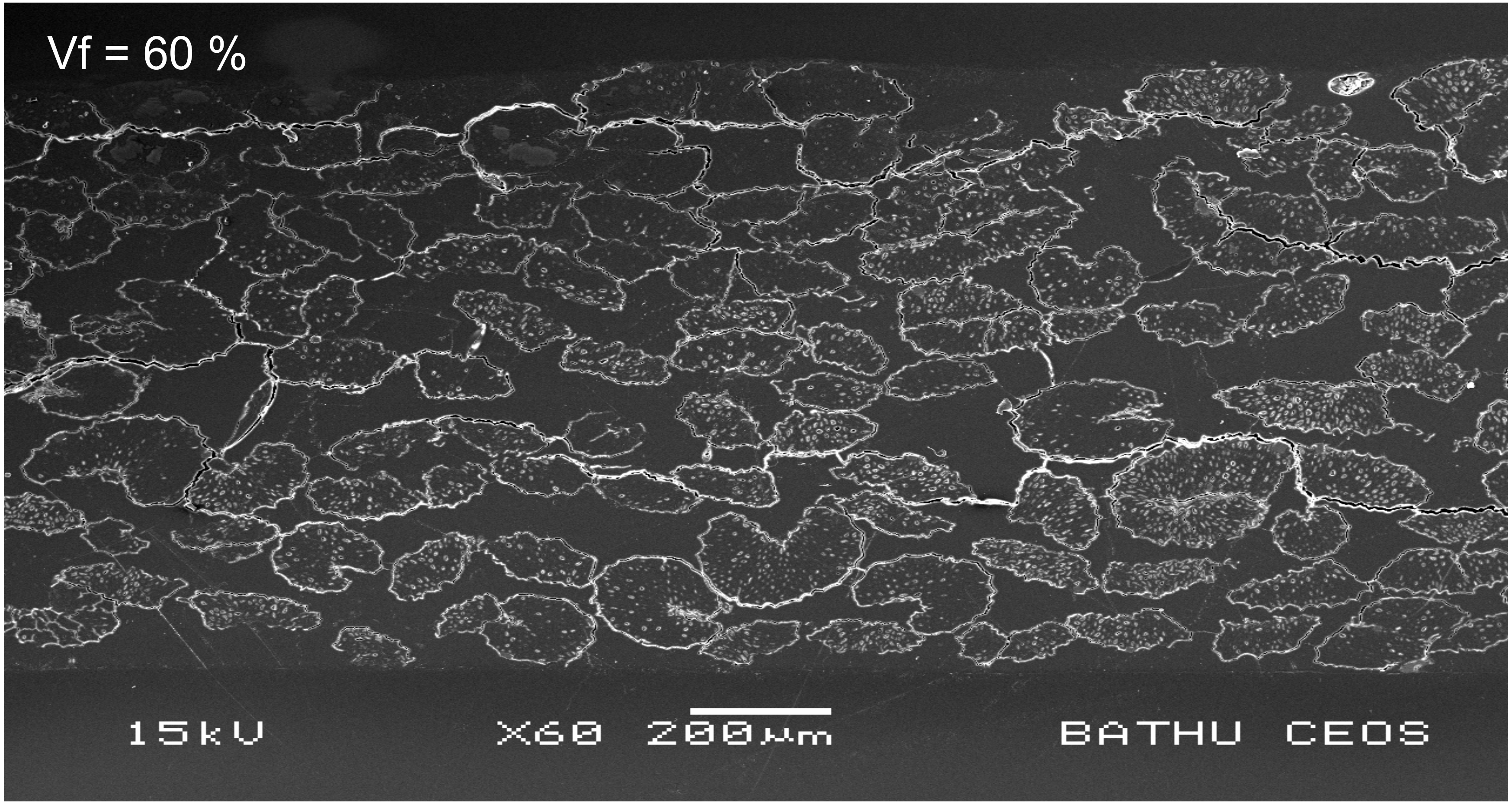
- High strength unidirectional thermoplastic
- Fully bio-based composites



<u>Fibre preforms:</u> Aligned and unidirectional sisal fibres attached to quarto paper with double-sided sticky tape.

UNIVERSITY OF BATH

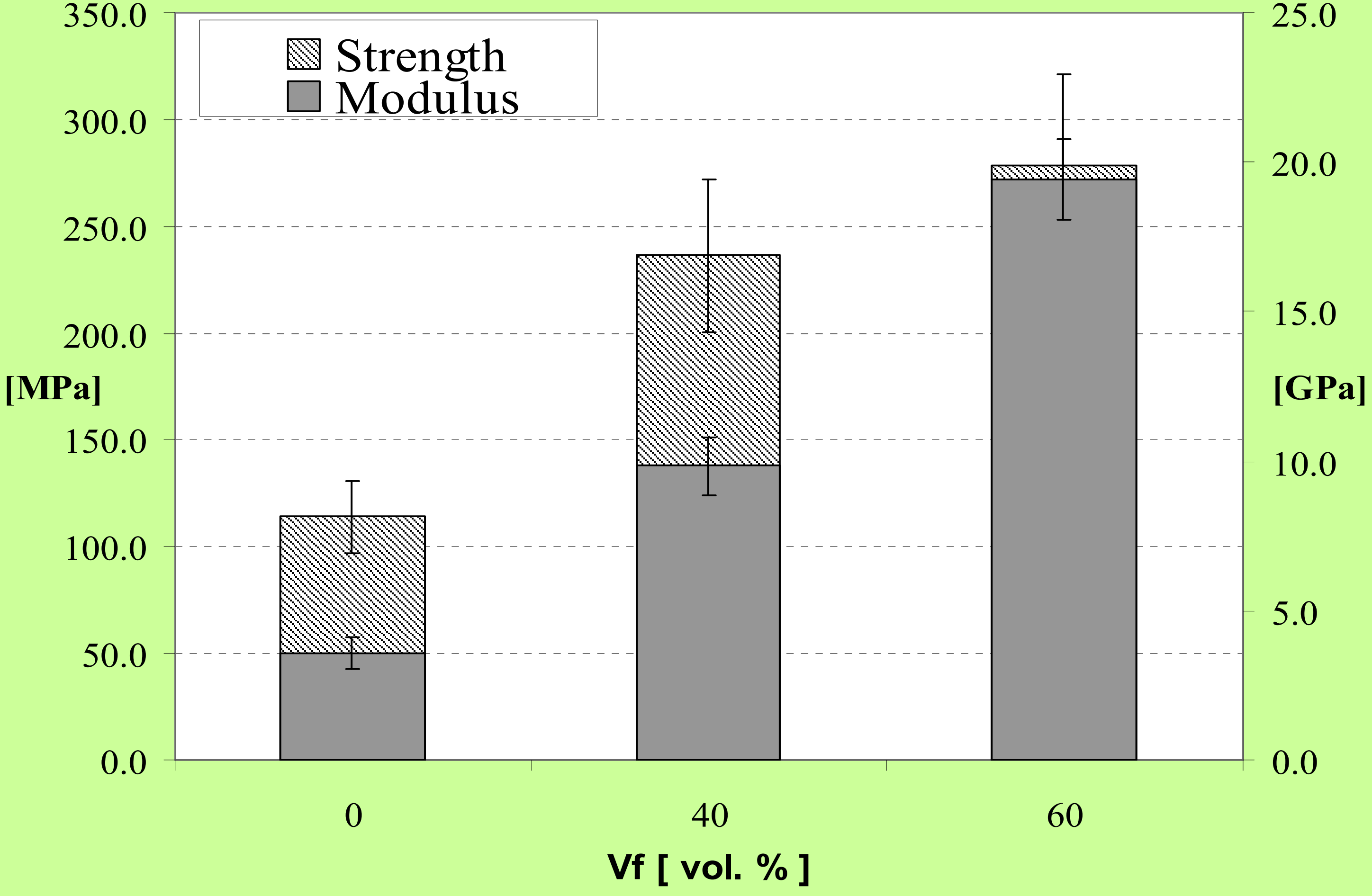
SEM CROSS-SECTION, Vf = 60%



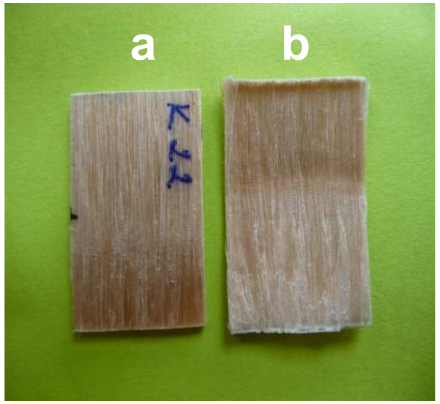
- Relatively short moulding times.
- High volume fractions.
- Low porosity.
- Good fibre to matrix adhesion.

FLEXURAL PROPERTIES

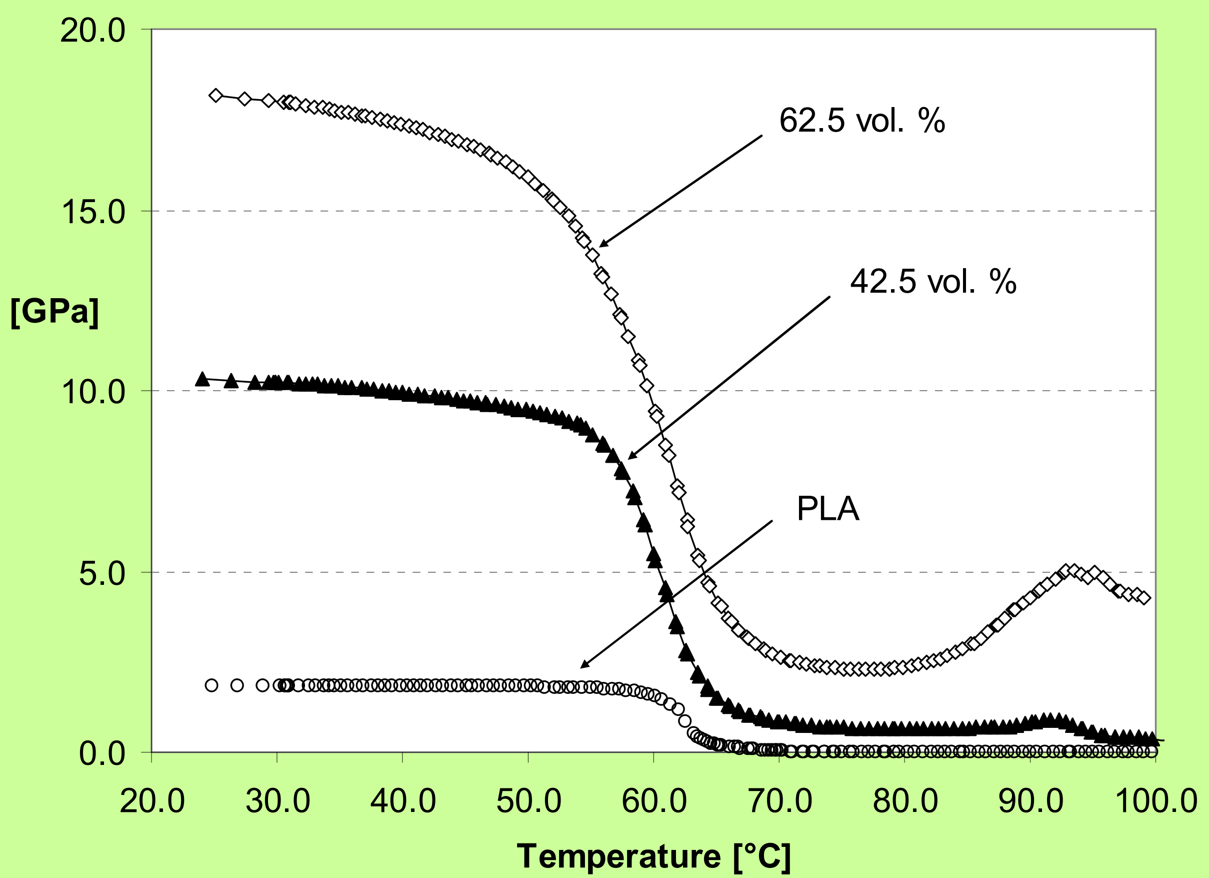
<u>Test conditions</u>: BS EN ISO 14125: 1998, Instron 3369, 50 kN load cell, cross head speed: 2 mm/min, L / h = 16



<u>Failure:</u>
(a) tension side
(b) compression side



DMTA – STORAGE MODULUS



Test conditions:
- Single cantilever fixture.
- frequency 1 Hz.
- heating rate 2°C/min.

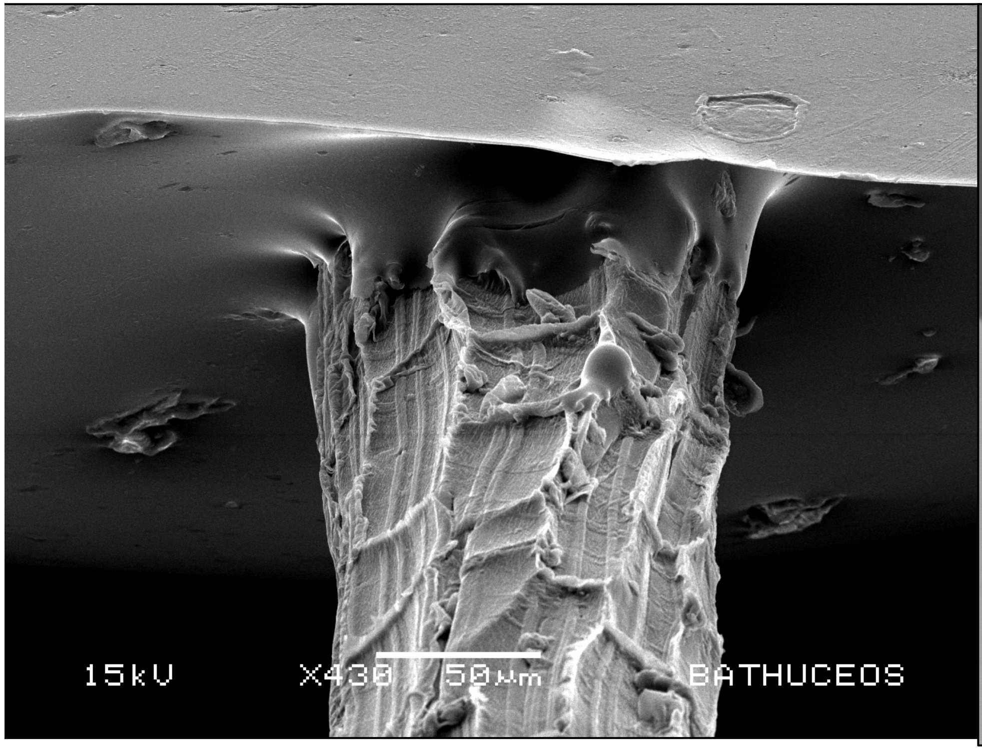
Conclusions:
- Tg decreases with Vf.
- Composite properties are temp-sensitive above 50°C.
- Thermoplastic PLA can be pressed into shaped components above Tg.

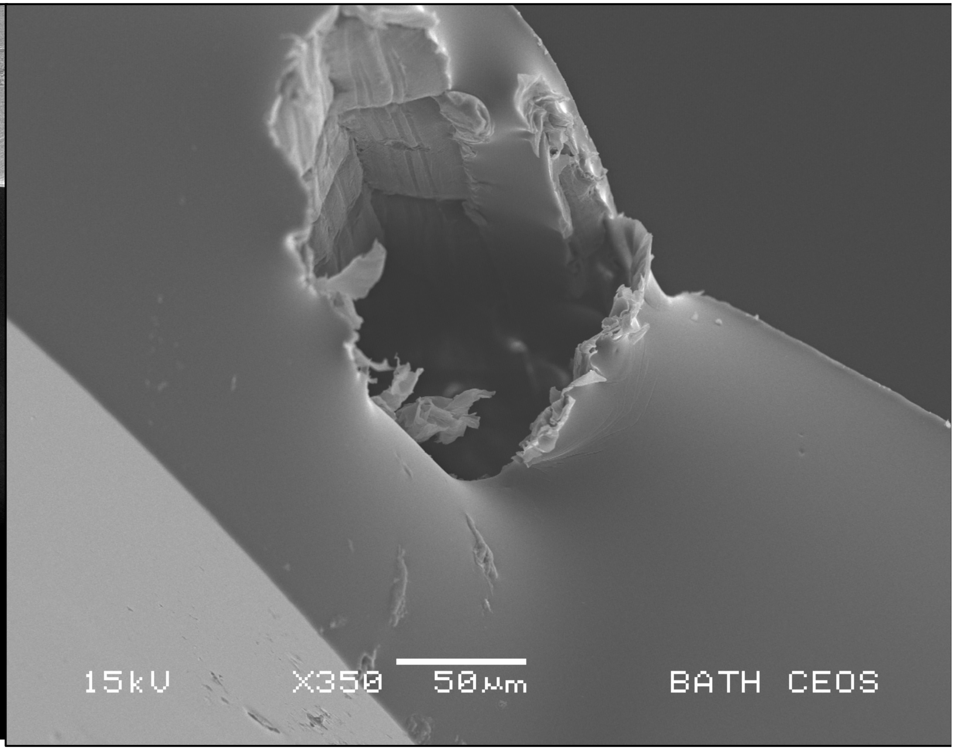
V_f [%]	Tg [°C] (Extrapolated onset E')	Storage modulus [GPa] at 25°C	Storage modulus [GPa] at 40°C	Storage modulus [GPa] at 60 °C
0	58.4	1.9	1.8	1.5
42.5	56.1	10.3	10	5.5
62.5	53.5	18.2	17.4	9.5

UNIVERSITY OF BATH

INTERFACIAL ADHESION BETWEEN SISAL AND PLA

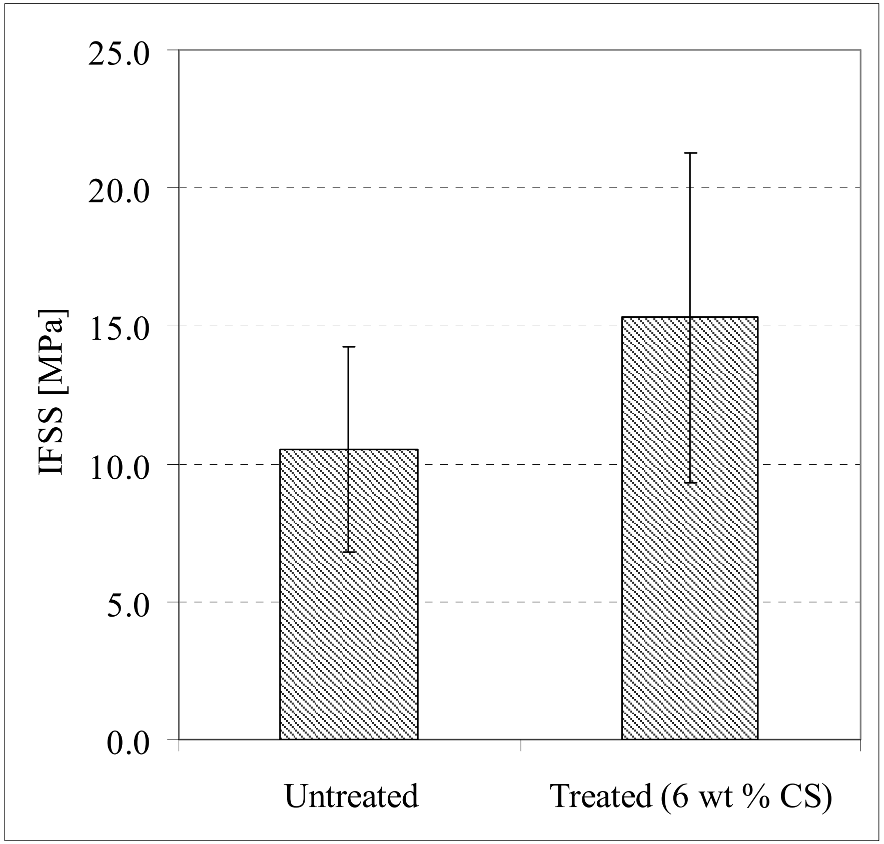
- **Caustic soda treatment increases the interfacial shear strength (IFSS) measured in a single fibre shear test**





UNIVERSITY OF BATH

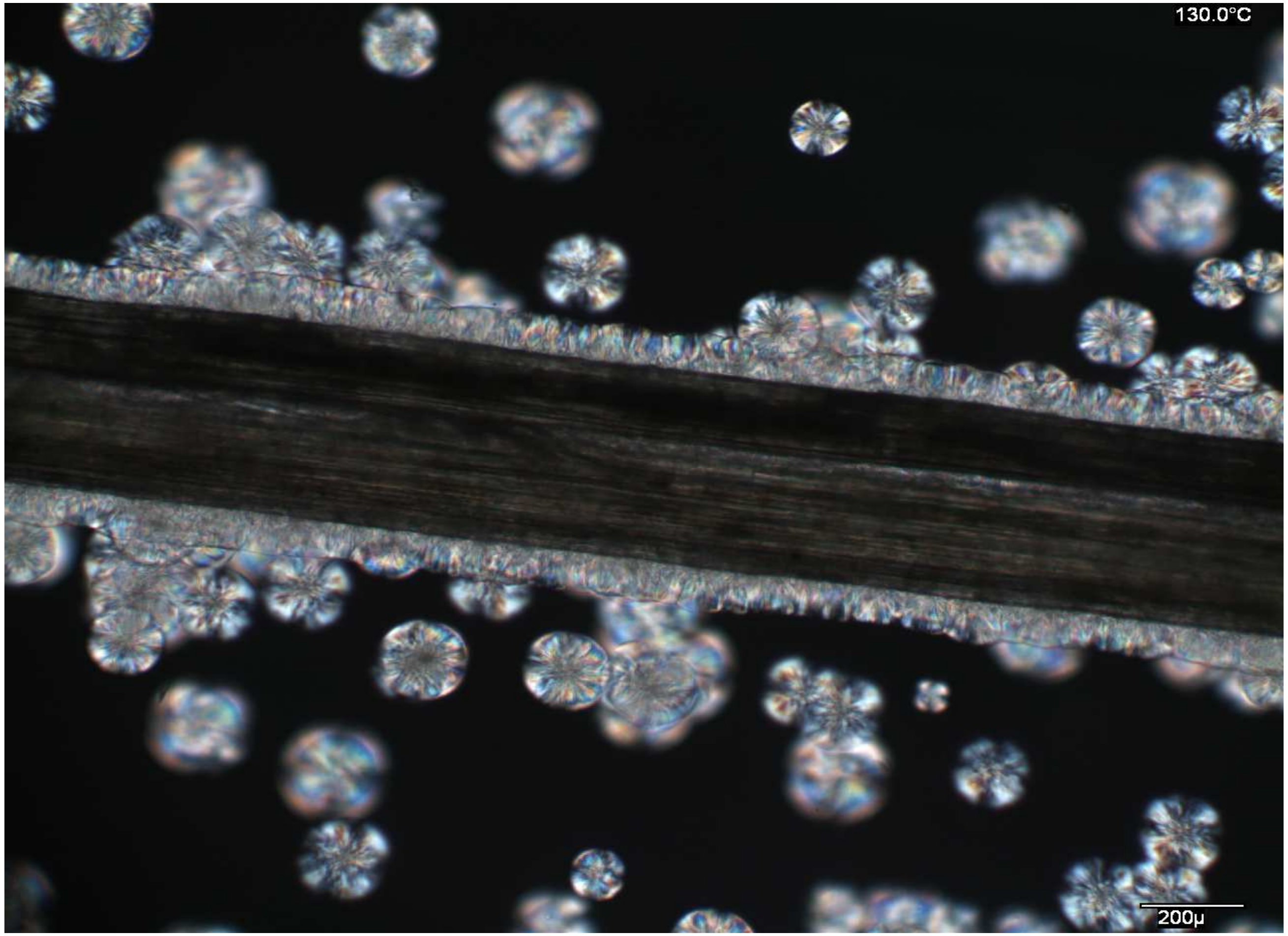
MICROBOND SHEAR STRENGTH FOR SISAL-PLA



Sisal fibre	Samples tested	Weibull modulus m	Mean strength [MPa]	Standard deviation [MPa]
Untreated	33	3.1	10.5	3.72
Treated	25	2.8	15.3	5.96

UNIVERSITY OF BATH

DEVELOPMENT OF TRANSCRYSTALLINITY IN PLA / SISAL COMPOSITES: IMAGE IN HOT STAGE MICROSCOPE

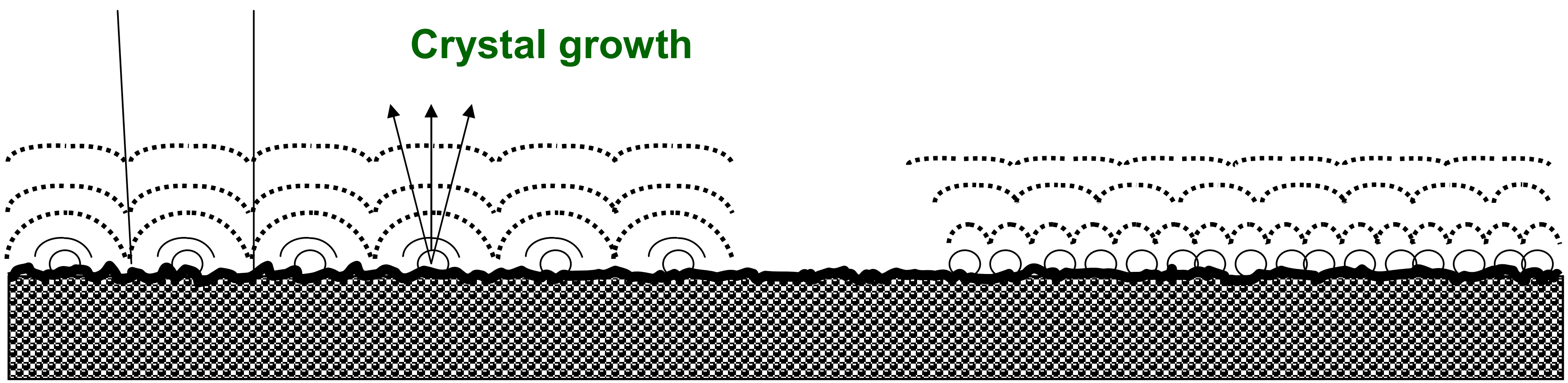


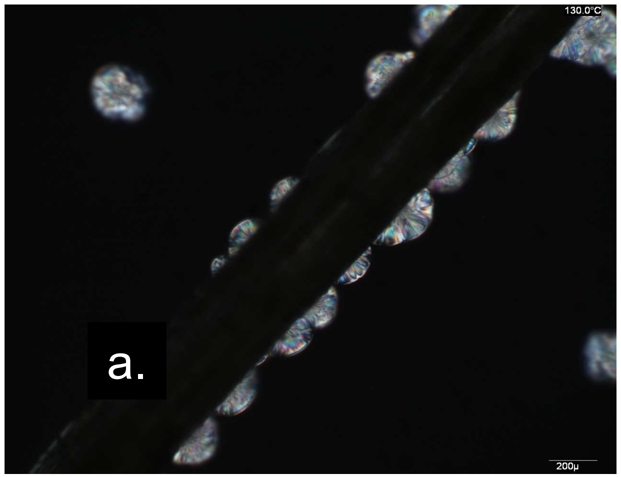
- **Transcrystalline layer on sisal fibre treated with 6 wt% NaOH solution (cooling rate 5°C/min; isothermal crystallization at 130°C for 15 min.**

Prajer, M. and Ansell, M.P. (2009), "Thermomechanical evaluation of sisal-PLA composites", Procs. of the 17th International Conference on Composite Materials, 27-31 July 2009, Edinburgh.

UNIVERSITY OF BATH

DEVELOPMENT OF TRANSCRYSTALLINITY IN PLA / SISAL COMPOSITES: CRYSTAL GROWTH





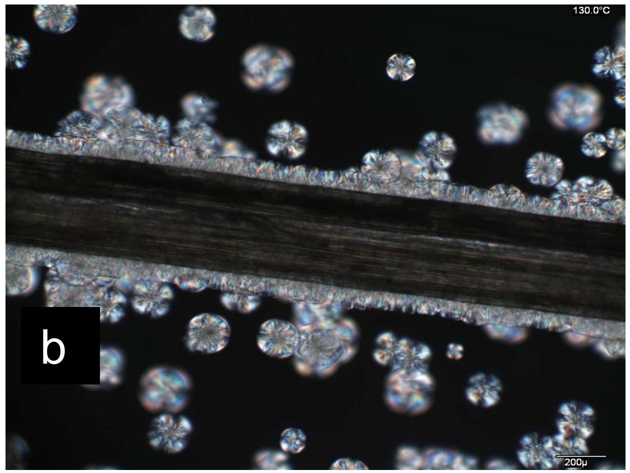
Fibre:

- NaOH treated
- Untreated

Conditions:

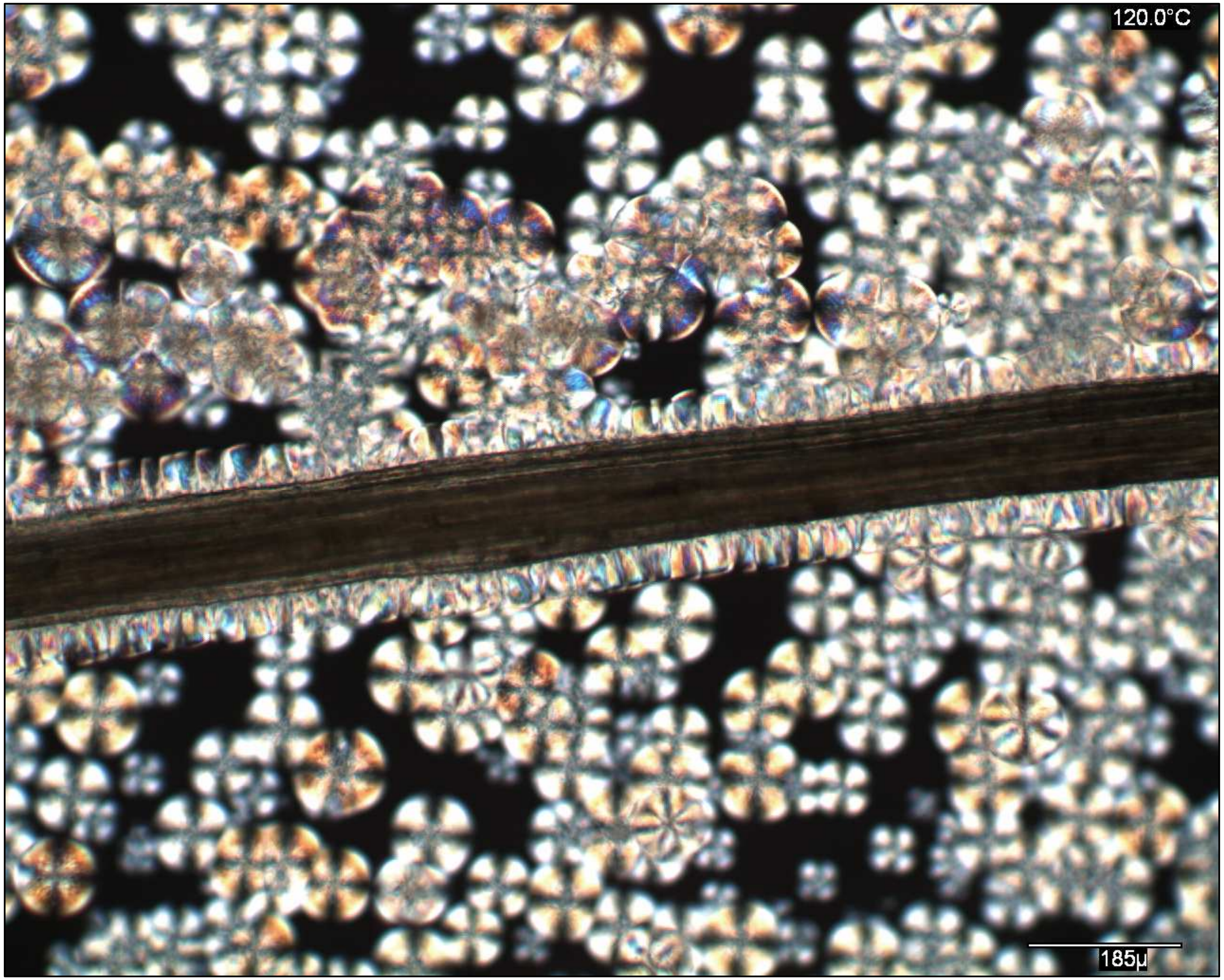
•Cooling rate: 5°C/min.

•Isothermal: 130°C/15 min.



UNIVERSITY OF BATH

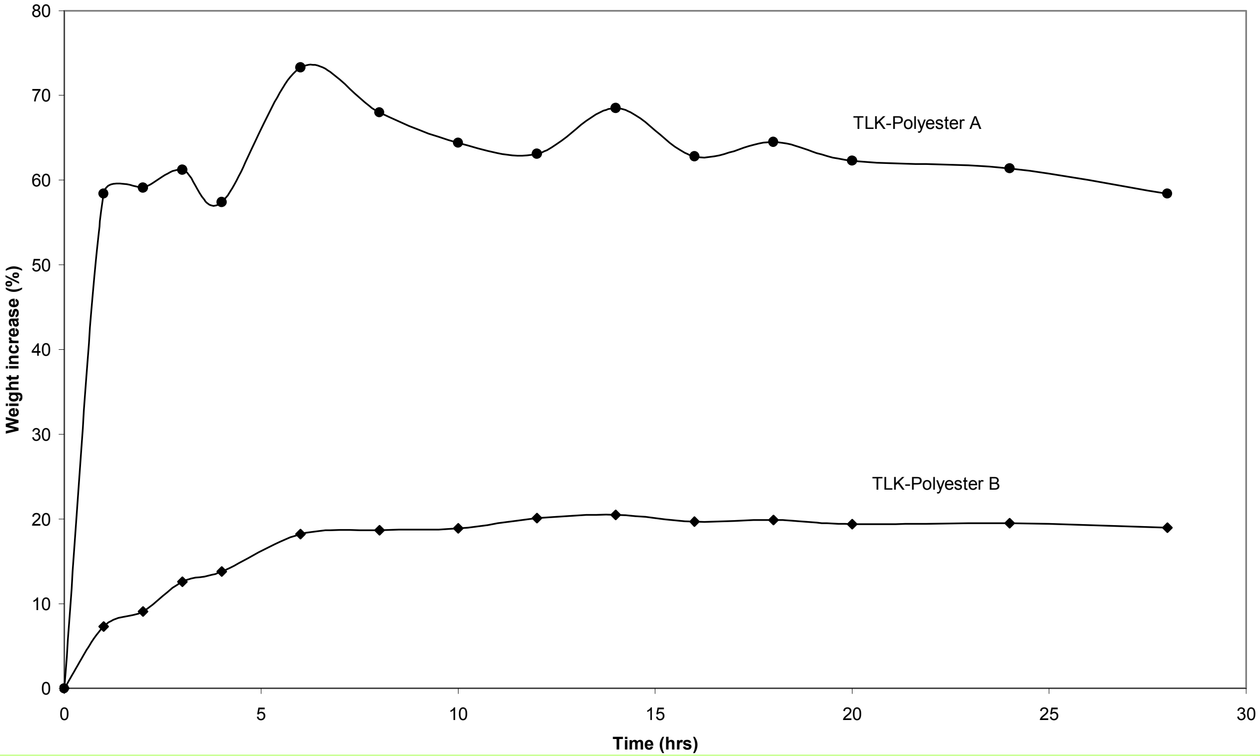
Sisal treated with 6 wt % NaOH / 48 h / room temperature.
Isothermal transcrystalline growth at 120°C after 20 minutes.
Cooling rate from 180°C to 120°C: 5°C/min.



UNIVERSITY OF BATH

ENVIRONMENTAL STABILITY OF NATURAL FIBRE COMPOSITES ?

- Natural fibres have a high affinity for moisture and are susceptible to biodegradation.
- University of Bath worked with Scott Bader Ltd to develop polyester resins with more polar character (more hydrophilic). An additional monomer was added, designed to interact or bond with OH groups on natural fibre surfaces.
- Composites were still deemed unsuitable for boat building applications.



Average percentage weight increase (water absorption) of NaOH-treated kenaf-polyester A and kenaf-polyester B composites against time following immersion in boiling water.

Aziz, S.H., Ansell, M.P., Clarke, S.J. and Panteney, S.R., (2005), "Modified polyester resins for kenaf natural fibre composites", Composites Science and Technology, Volume 65, Issues 3-4, pp 525-535.

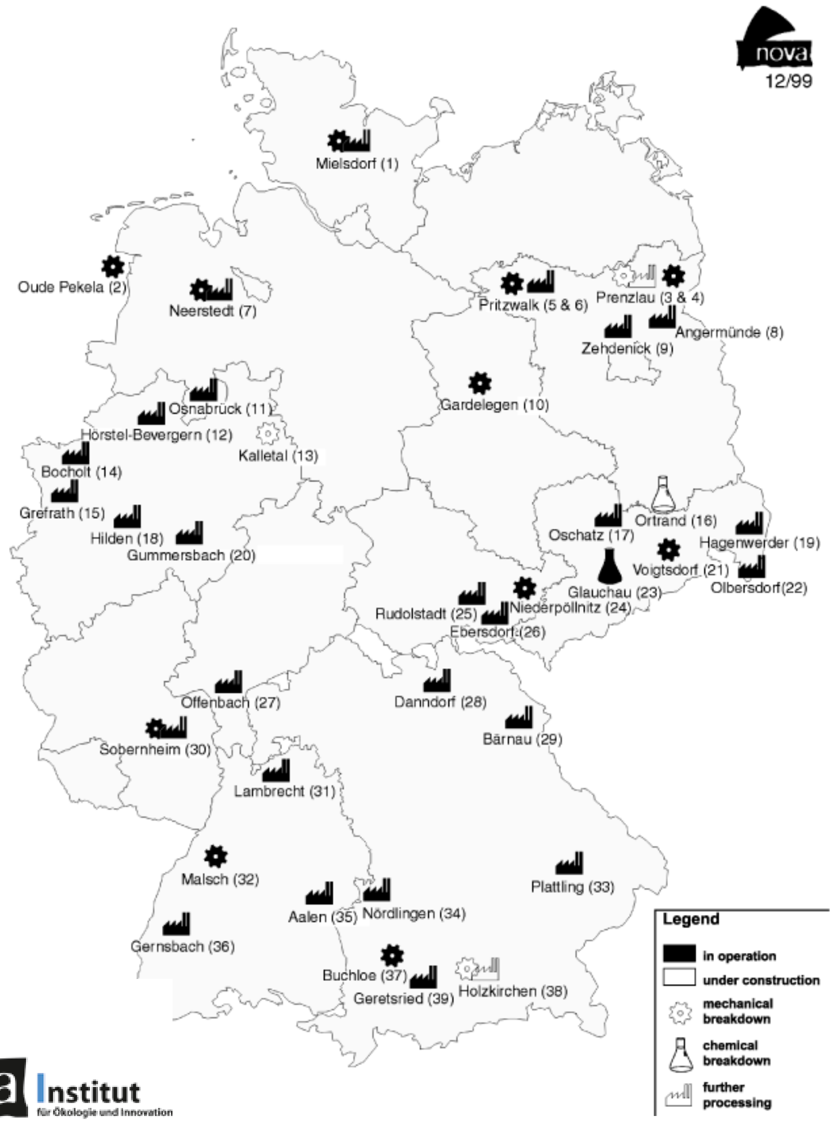
UNIVERSITY OF BATH

MERCEDES-BENZ – NATURAL FIBRE COMPOSITE PANELS

E-CLASS

A-CLASS

Fibre extraction factories and reprocessors of hemp and flax in Germany



WARWICK UNIVERSITY F3 CAR

Potato starch matrix for the body, carrot fibres in the steering wheel

CELLUCOMP FISHING ROD

Cellulose extracted from carrots is nano-fibrous reinforcement for Carrot Stix composite rod

UNIVERSITY OF BATH

FUTURE WORK: Automotive, aerospace?

- Automotive applications for NFCs are the most advanced.
- Aerospace industries are very unlikely to use NFCs in primary structures because of modest stiffness (NFC~20GPa, GFRP~45GPa, CFRP>100GPa).
- Difficult to manufacture high volume fraction NFCs with bio-thermoplastic matrices, but “sustainable” composites result.
- Challenge now to upsize into manufacture of large-scale components.
- High pressure forming of well-aligned continuous fibres using out of autoclave techniques is desirable.
- Assessment of bio-stability is a major research objective.





THANK YOU FOR YOUR ATTENTION