Facing up to the Challenges of Natural Fibres as "Potential" Engineering Composite Reinforcements

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Composites Week @Leuven
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Leuven, Belgium

GRPE
GLASGOW RESEARCH PARTNERSHIP IN ENGINEERING

University of Strathclyde

Natural Fibre Composites

- Jim – why are you so down on Natural Fibre ?
  - Some personal NF History
- Some of the NFC Challenges
  - NF Anisotropy
  - NF cross section
- Some Conclusions

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Natural Fibre some Personal History

Half Day Symposium on Natural Fibre Composites

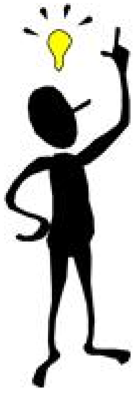
ECCM-8, Naples 1998

Prof Verpoest also attended

Held standard team meeting

ECCM-8 NF Symposium
The Natural Fibre Conundrum

NF – green, cheap, great properties can replace glass fibre



Hey – Lets make some NF composites and replace glass fibre

Hmmm – my NF composites are nowhere near what I predicted

Natural Fibre some Personal History

Potential Advantages of Natural Fibres

Potentially low cost

Low density (1.45 g/cc vs 2.6 g/cc for GF)

Very “green” image

Incinerable - thermally recyclable (with no net increase in CO_2 balance)

Modulus range exceeds that of E-glass

Non-abrasive - low wear of processing equipment

No skin irritation problems during handling

Identified Disadvantages of Natural Fibres

Fibre properties dependent on level of processing (high properties require more fibre processing = cost penalty)

Properties dependent on seasonal conditions

High levels of water adsorption and poor dimensional stability

Low strength compared to E-glass

Anisotropic structure - low transverse properties = poor flex & compression performance

Composites generally require higher fibre loading resulting in high processing viscosities.

Surface treatments and polymer coupling agents required for best composite properties

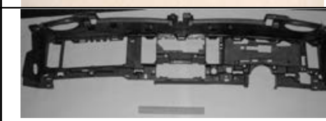
Odour problem after composite processing

Potentially Bioactive

Natural Fibre some Personal History
1999-2001 Owens Corning NFC Project

- Based on Long Fibre PP Process Technology
- 12 mm pultruded pellets, 20-50% NF-PP
- Pilot Plant capability 500kg/day
  - plan for first production plant in India
- New Sizings developed - some patented for Natural Fibre and Regenerated Cellulose Fibre (Rayon)
- Multiple Demonstrator Parts Moulded and Tested
- Huge automotive OEM, Tier 1 and Tier 2 interest

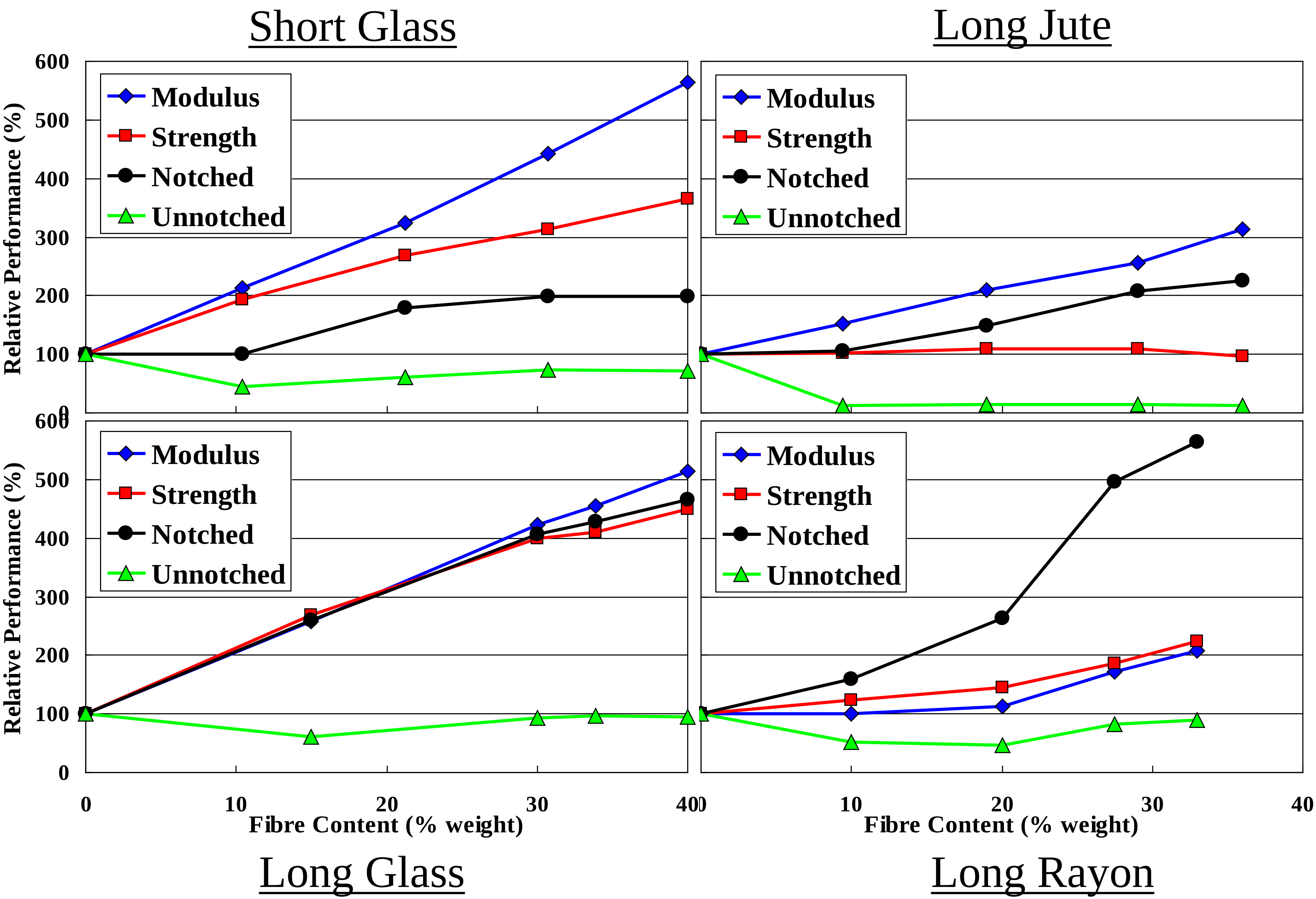
Natural Fibre Composite - Demonstrators

Organizer / Moulder	Part	Method	Part Wt. (kg)	
OC, MIG Plastics	Buick - Door handle pull	Inj. Mould	0.14	
JCI	Jeep Grand Cherokee - Door Inner	Inj. Mould	0.91	
Mayco Plastics	Chrysler - Air deflector	Inj. Mould	0.31	
Delphi, Proto Plastics	GM – Instrument panel retainer	Inj. Mould	2.6kg	
SEG Kunststoff technik	Audi A2 - Fender stiffener	Inj. Mould	0.45	
Pelzer, Clion Gmbh	DCX PT Cruiser - Underbody shield	Extrusion Compress	1.35	

Typical Properties of PP Based Compounds

	30% Talc	30% Jute-A	30% Jute-B	30% Glass*
Modulus (GPa)	3.6	4.1	4.4	**6.5**
Tensile (MPa)	30	35	45	45-**90**
Flex Str (MPa)	56	56	76	65-**145**
N Izod (J/m)	27	59	48	80-**110**
Un Izod (J/m)	203	198	177	260-**750**
HDT (°C)	92	120	135	**155**
Density	1.13	1.01	1.01	1.13

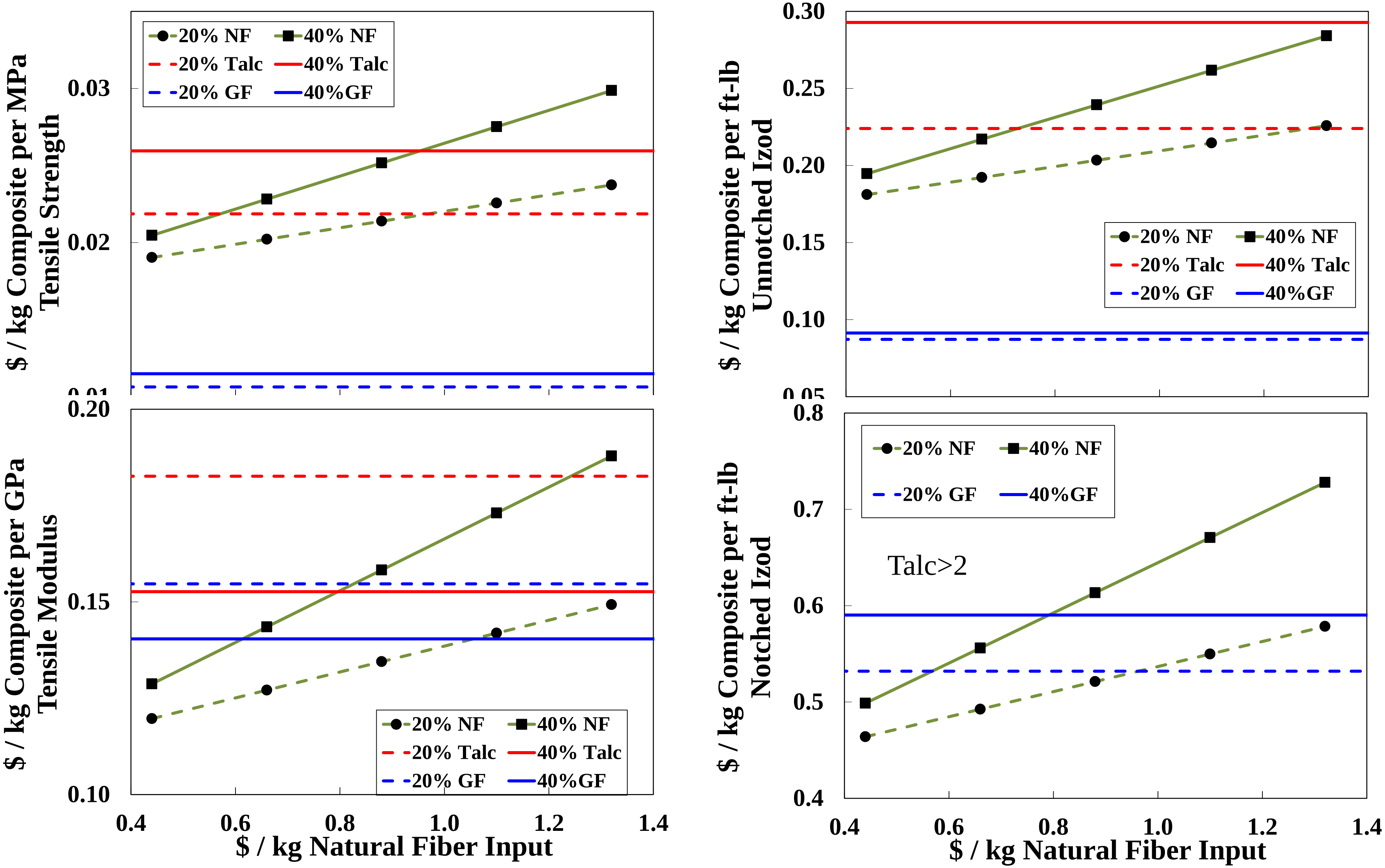
Comparison PP Composite Performance



Comparison Composite Cost/Performance

Strength

Unnotched Impact



Modulus

Notched Impact

Natural Fibre some Personal History
1999-2001 Owens Corning NFC Project

Project shelved 2002,
Natural Fibre Composites **are not**
Performance-Cost competitive with existing materials

Some Philosophy

- If you know your enemies and know yourself, you can win a hundred battles without a single loss.
- If you only know yourself, but not your opponent, you may win or may lose.
- If you know neither yourself nor your enemy, you will always endanger yourself.

The Art of War, Sun Tzu

Some of the Challenges of Working with NF

Fibre natural variability
Fibre highly anisotropic
Low transverse and shear reinforcement performance
Fibres mostly non-circular
Fibre lumen = composite voids
Fibre cross section non-uniform along length
Fibre "diameter" often much larger than man-made fibres
High moisture content in fibres at ambient RH – processing issues
Temperature sensitivity – in particular odour issues in processing
Many forms of NF not suitable for use in standard industry processes

Poor (often negative) performance in composites
Composite fibre content measurement ?
Moisture sensitivity in composite
Bio-activity (rotting,fungus, mould)
Fibre-matrix interaction - poor
Fogging/Emission issues in Automotive applications

Why Natural Fibre Composites ?

Some typical fibre properties are shown in the Table below

	Sisal	**Jute**	**Flax**	**Glass**
Modulus (GPa)	17-28	20-45	27-70	75
Strength (GPa)	0.1-0.8	0.2-0.9	0.3-0.9	>1.5
Density	1.3	1.3	1.5	2.6
Specific Modulus	13-21	15-35	18-47	29

So some natural fibre may have the potential to replace glass fibres ???

$$E_C = \eta_0 \eta_L V_f E_f + V_m E_m$$

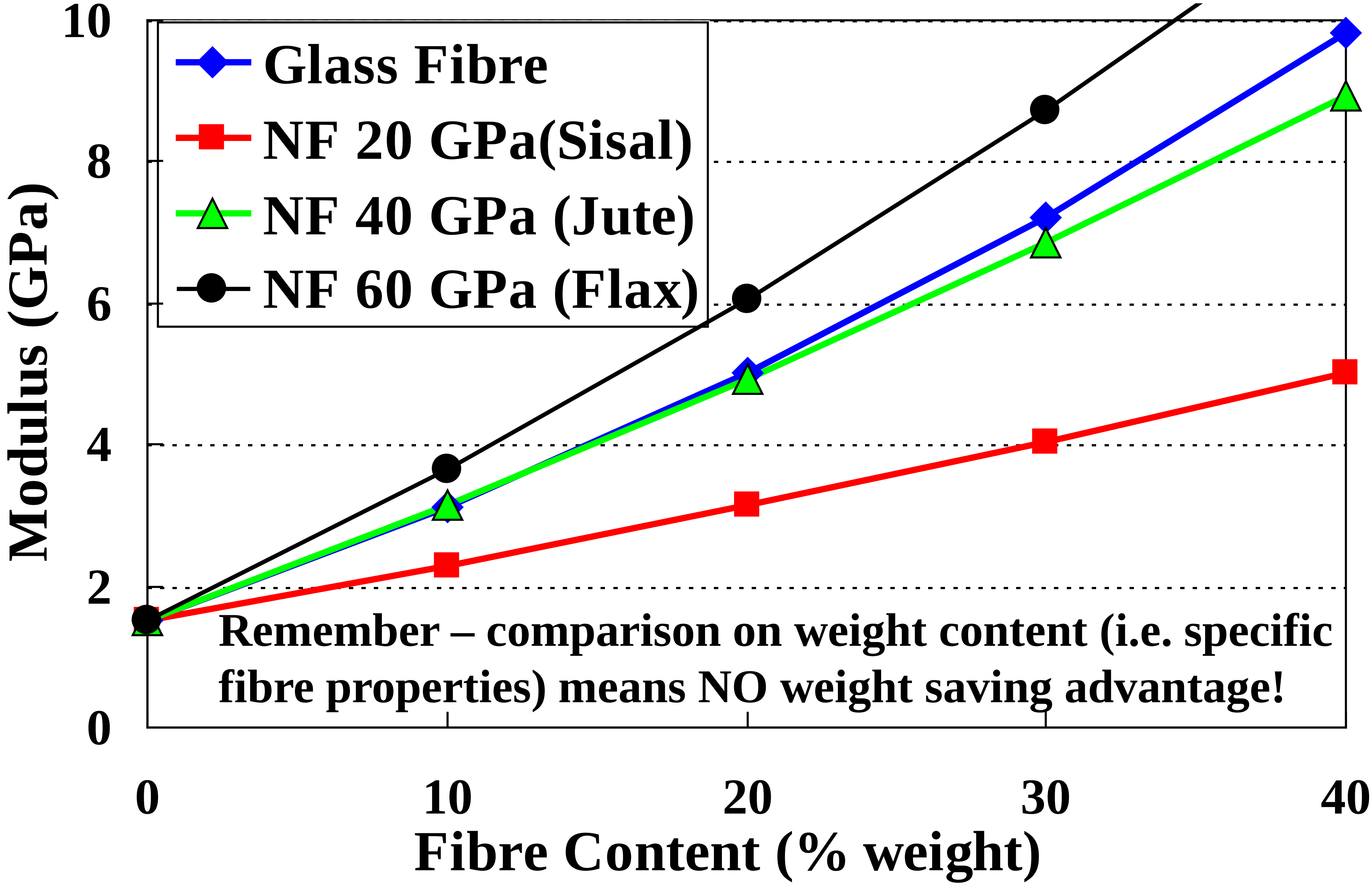
Typical Specs for Automotive Application

There are very few applications where only modulus is required!!!
A typical automotive spec sheet will need –

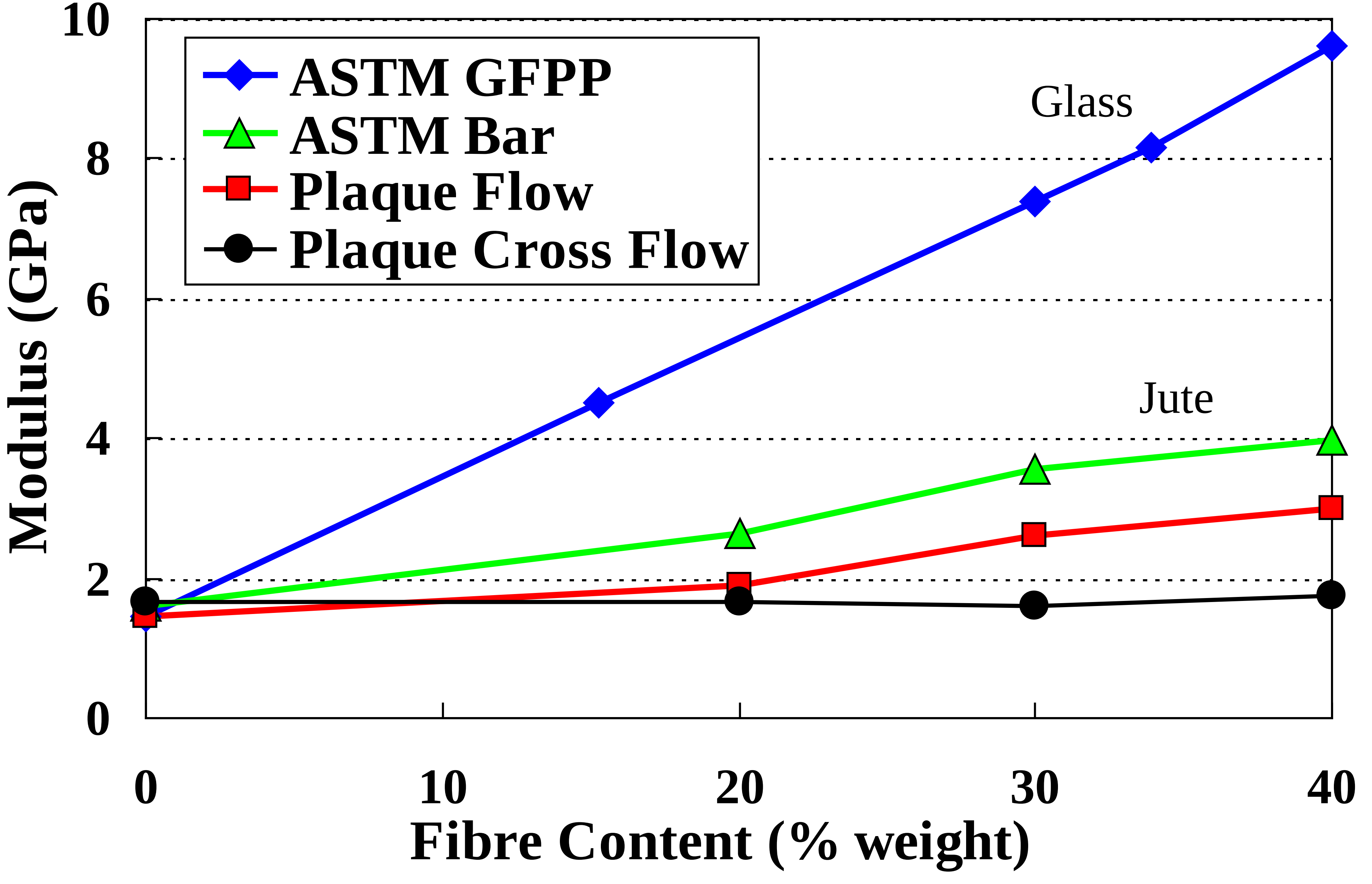
Melt Flow Rate	(ISO 1133, ASTM D1238)
Glass Fibre Content	(ISO 3451/1)
Density	(ISO 1183, ASTM D792)
Tensile Strength	(ISO R527, ASTM D638M)
Flexural Modulus	(ISO 178, ASTM D790M)
Shear Modulus	(ASTM D4065)
Impact Strength, Izod	(ISO 180, ASTM D256)
Heat Deflection temperature	(ISO 73, ASTM D648)
Heat Aging Performance	(ISO 188, ASTM D573)
Flammability	(ISO 3795)
Fogging	(FLTM BO 116-03)
Mould Shrinkage	(ISO 2577)
Coeff. of Linear Thermal Expansion	(ASTM D696)

Comparison Predicted Composite Modulus

For injection moulded long fibre polypropylene



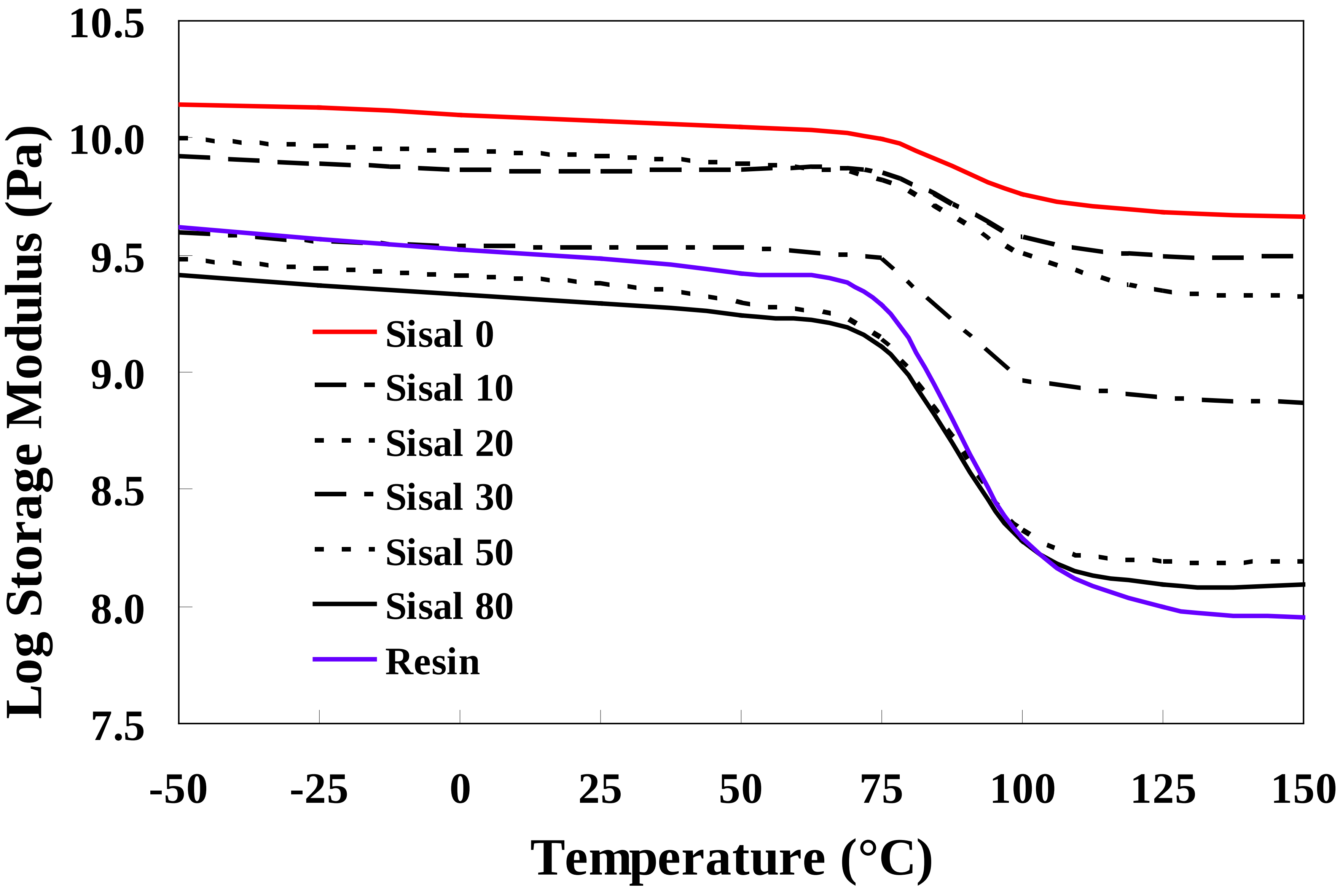
Actual Modulus Injection Moulded Jute-PP



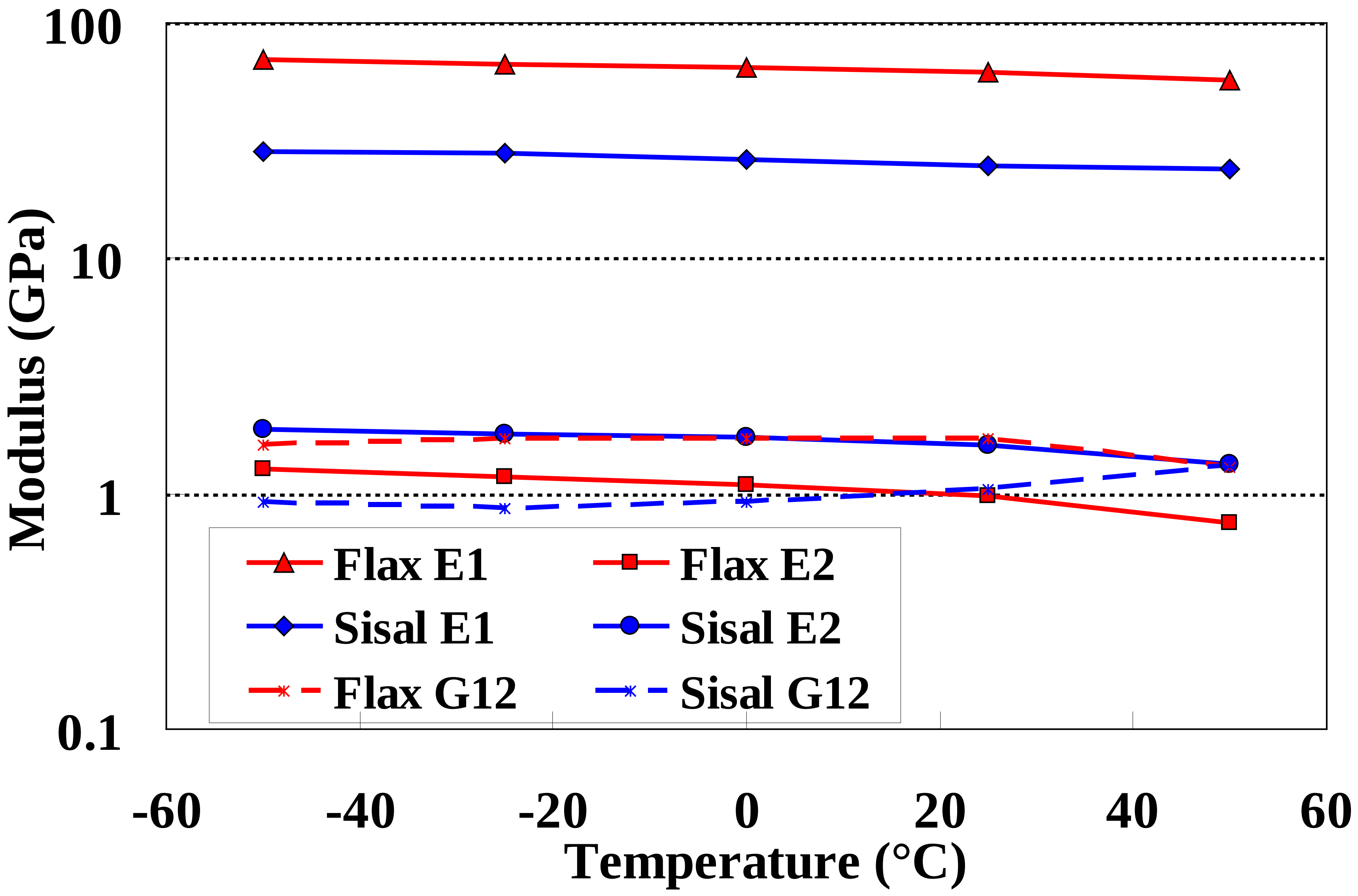
Thermoelastic Anisotropy of Flax and Sisal Fibres

- Goal
  - Quantify anisotropy of Flax & Sisal fibres
  - Full thermoelastic characterisation
- Measure
  - UD fibre-epoxy laminates $E(\theta,T)$, G_{12},ν_{12}, ν_{21} ,$\alpha(\theta,T)$
  - Epoxy matrix $E_m(T)$,ν_m, $\alpha_m(T)$
  - Laminate fibre volume fraction ?
  - Flax & Sisal fibre E_{1f} (fibre cross section ?)
- Calculate
  - $E_{1f}(T)$, $E_{2f}(T)$, $G_{12f}(T)$, ν_{12f} (T), $\alpha_{1f}(T)$, $\alpha_{2f}(T)$

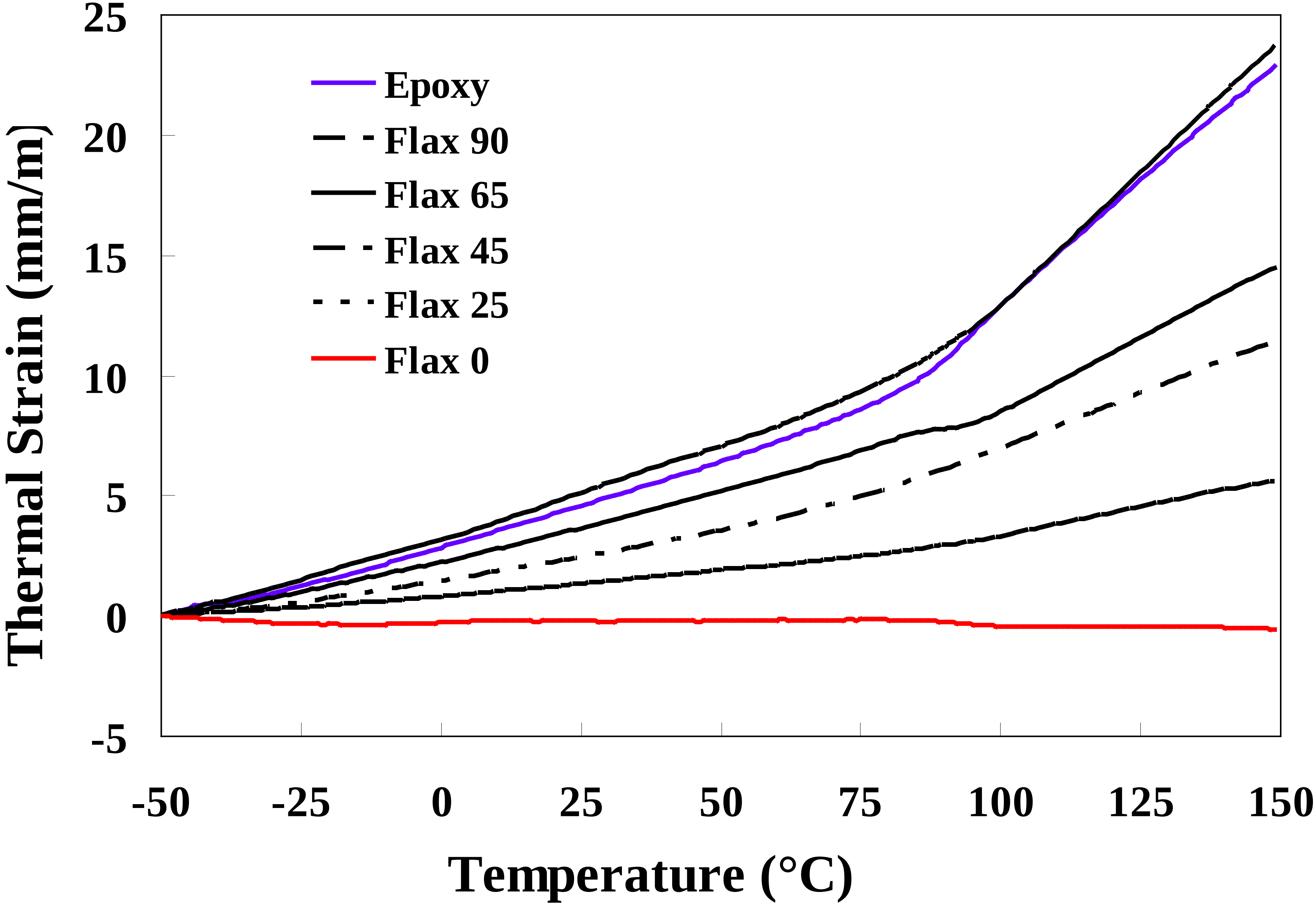
Composite DMA Results



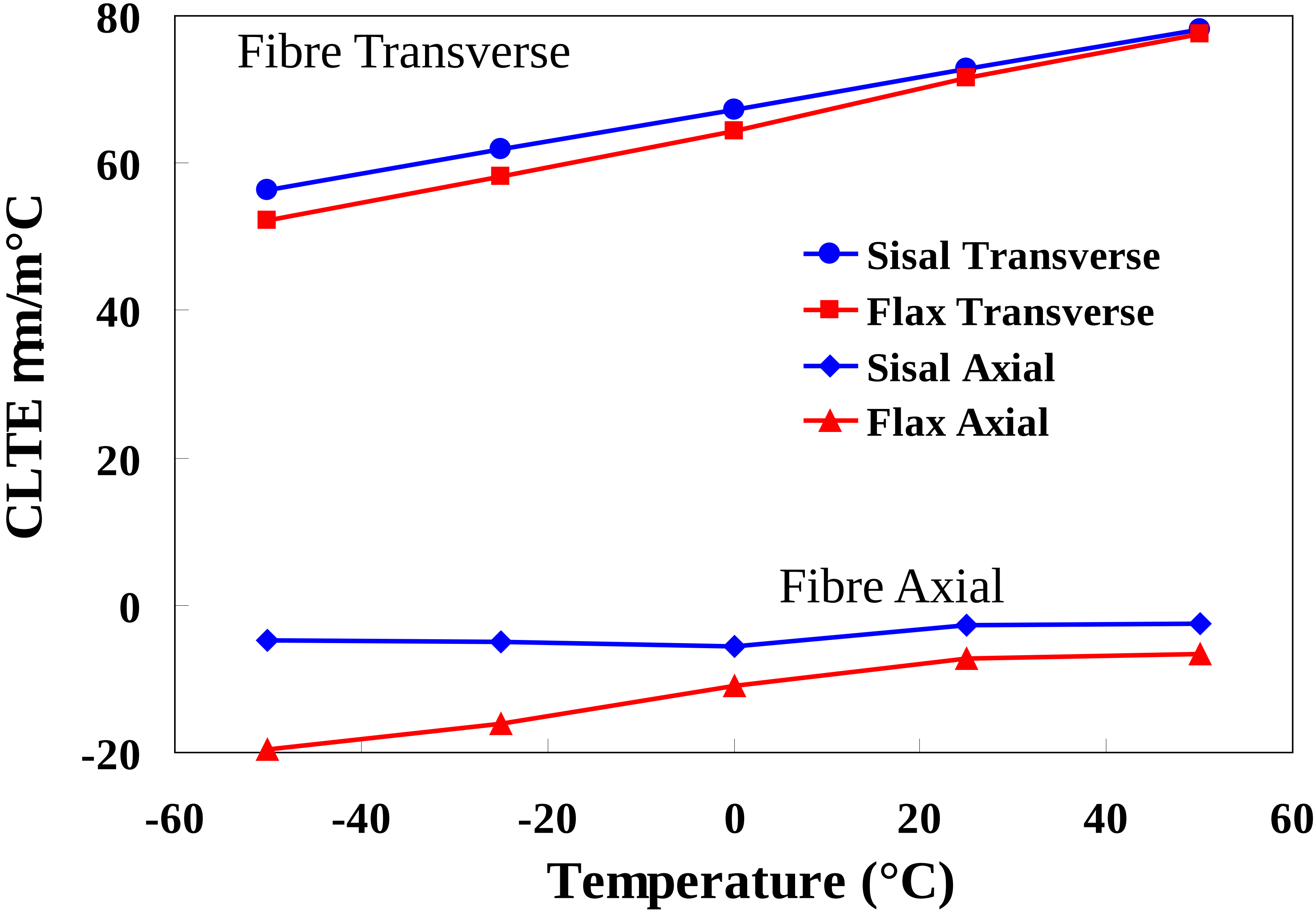
Anisotropy of Fibre Modulus



Composite Thermal Strain



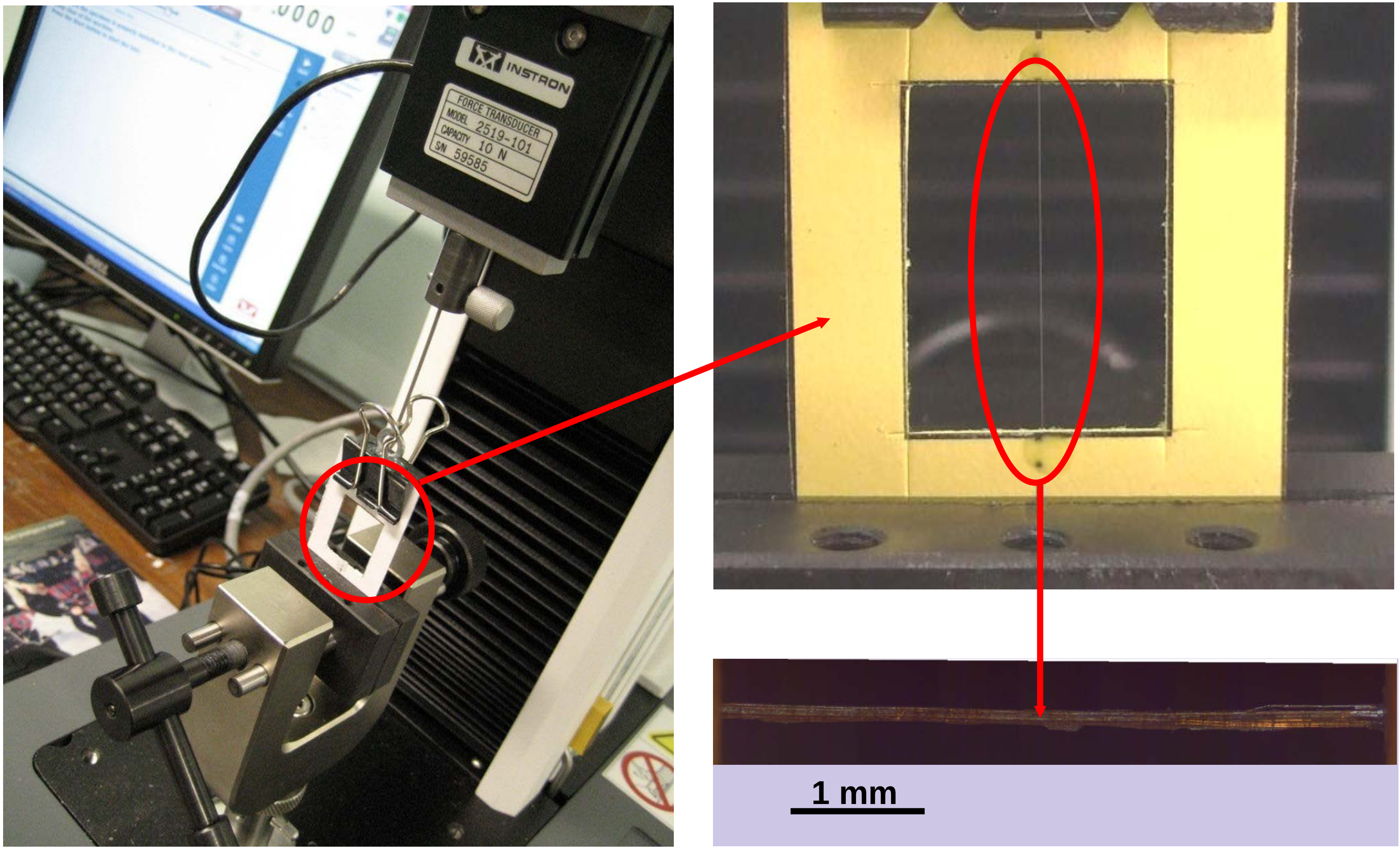
Fibre Expansion Coefficients



Summary Thermo-Mechanical Properties NF

	Glass	Flax	Sisal
Longitudinal Modulus (GPa)	75	61.5	24.9
Transverse Modulus (GPa)	75	1.2	1.6
Shear Modulus (GPa)	30	1.7	1.1
Axial LCTE (μm/m.ºC)	5	-7.3	-2.7
Transverse LCTE (μm/m.ºC)	**5**	**71**	**73**

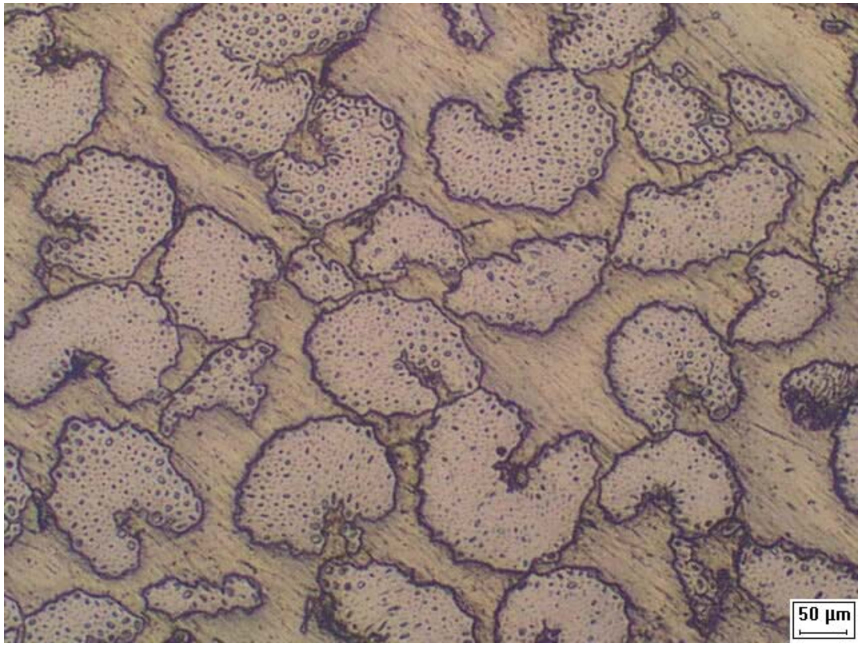
Single Fibre Testing

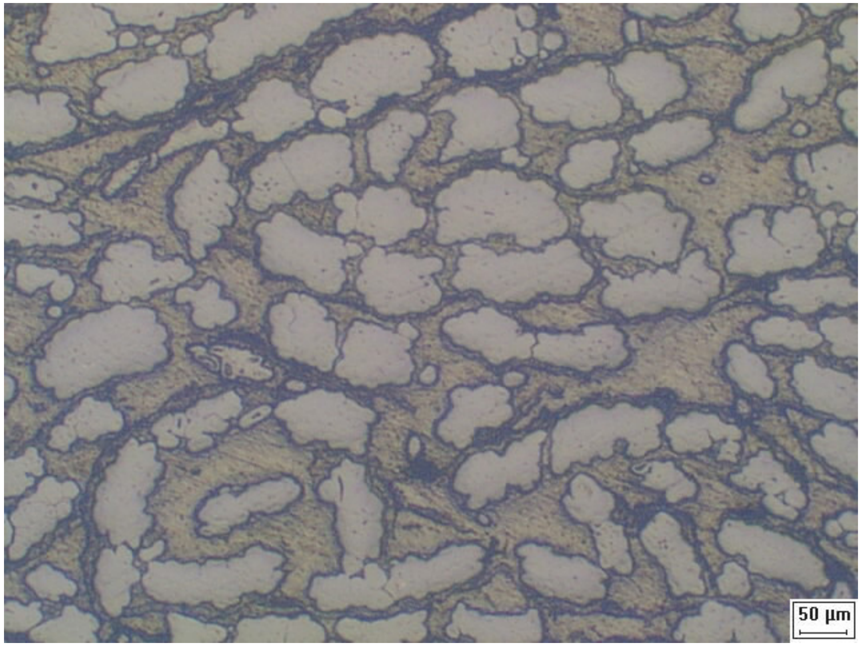


Fibre Stress = Load/Area = P/A_f ($= 4P/\pi D_f^2$???)

Single Fibre Cross Section Area

- A_f in single fibre testing is almost universally evaluated from D_f using a transverse image of fibre and assumption of circular cross-section
- Is this acceptable for Natural Fibres ??





Single Fibre CSA Measurements

1. **Single fibre "diameter" determined by averaging 4 transverse measurements at 2 mm intervals**
2. **Fibres embedded, cut and polished**
3. **"true" cross sectional area determined at approximately the same position on fibre**
4. **Sample ground down 2 mm and polished**
5. **Steps 3-4 repeated 10x**

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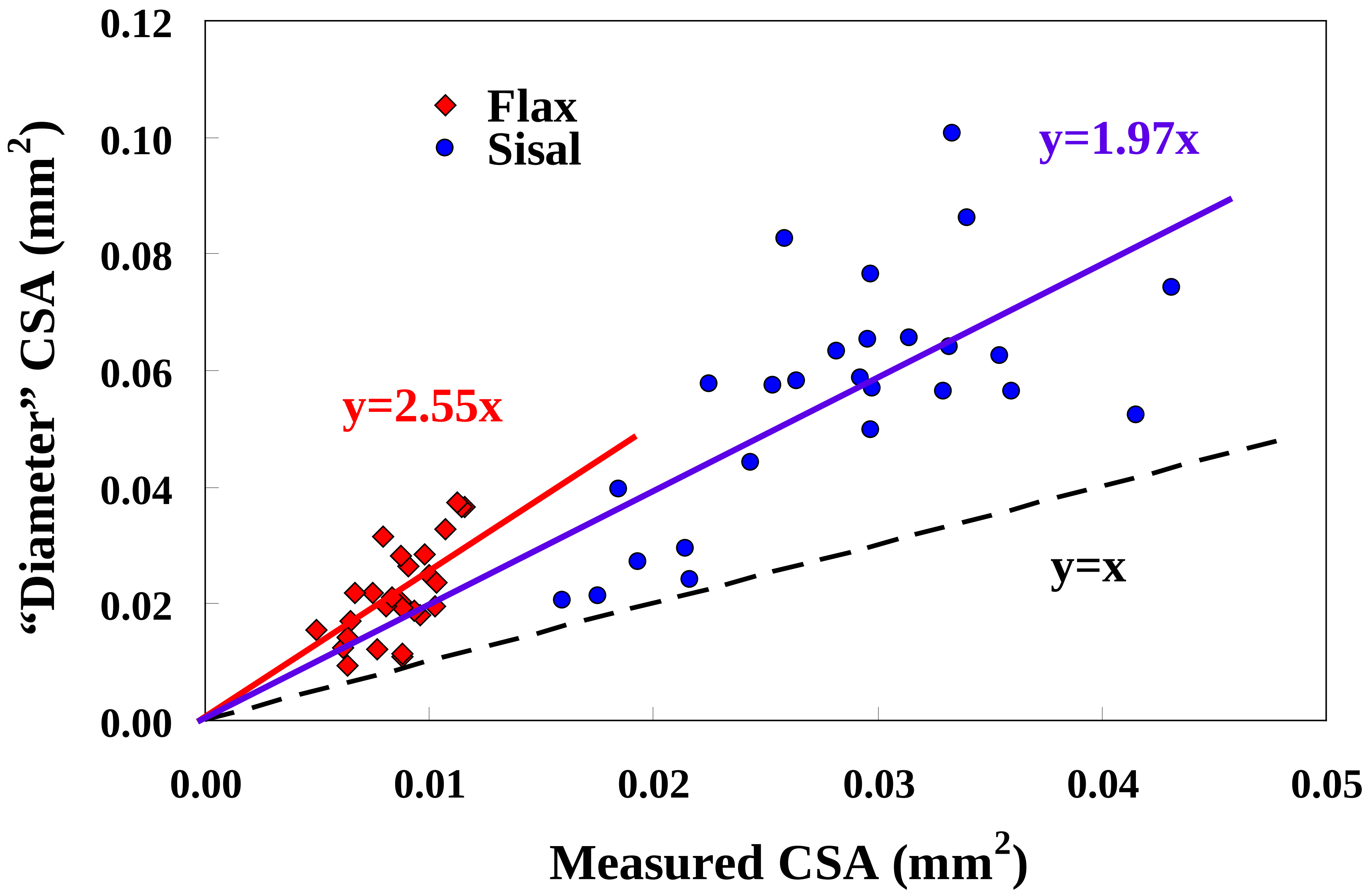
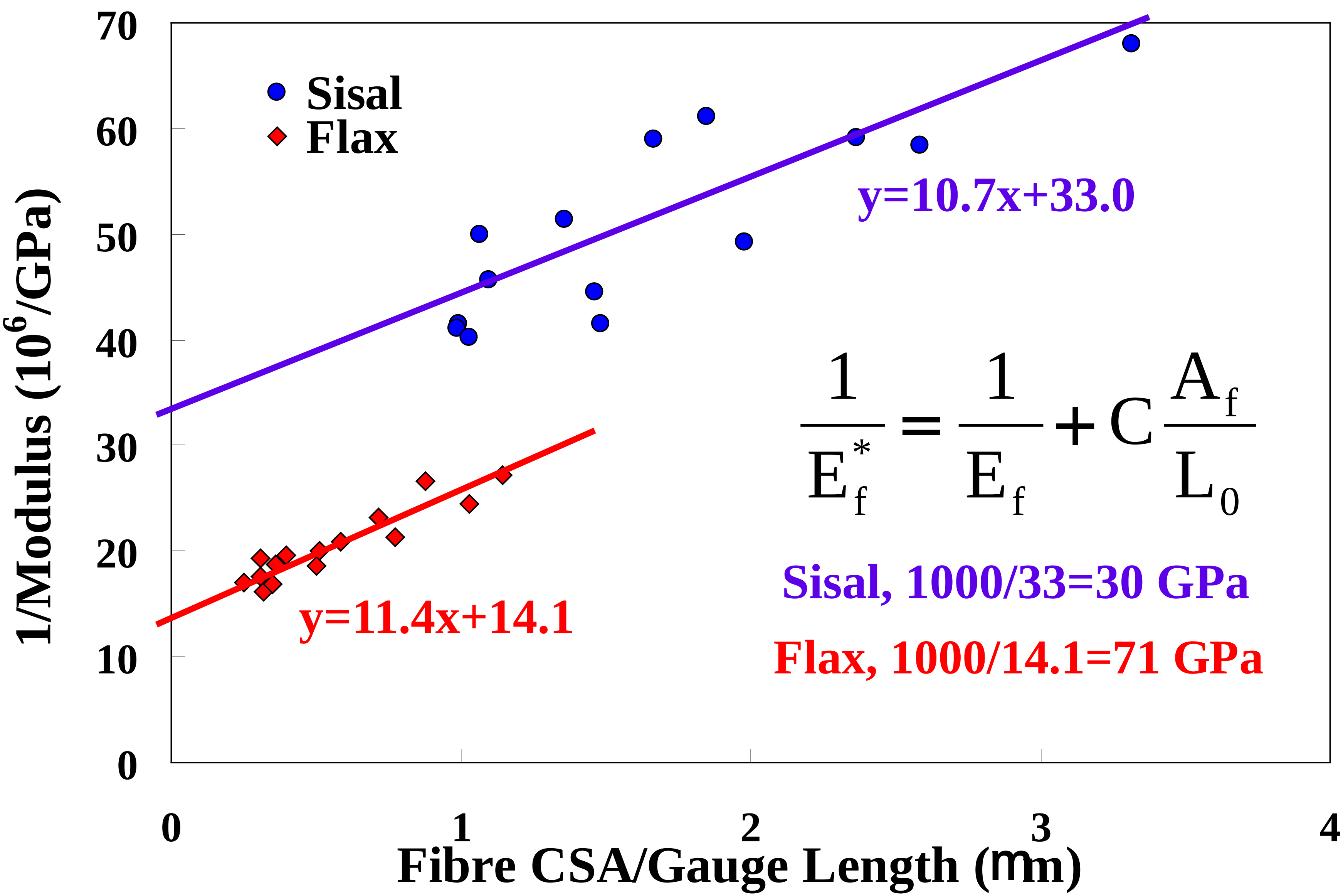
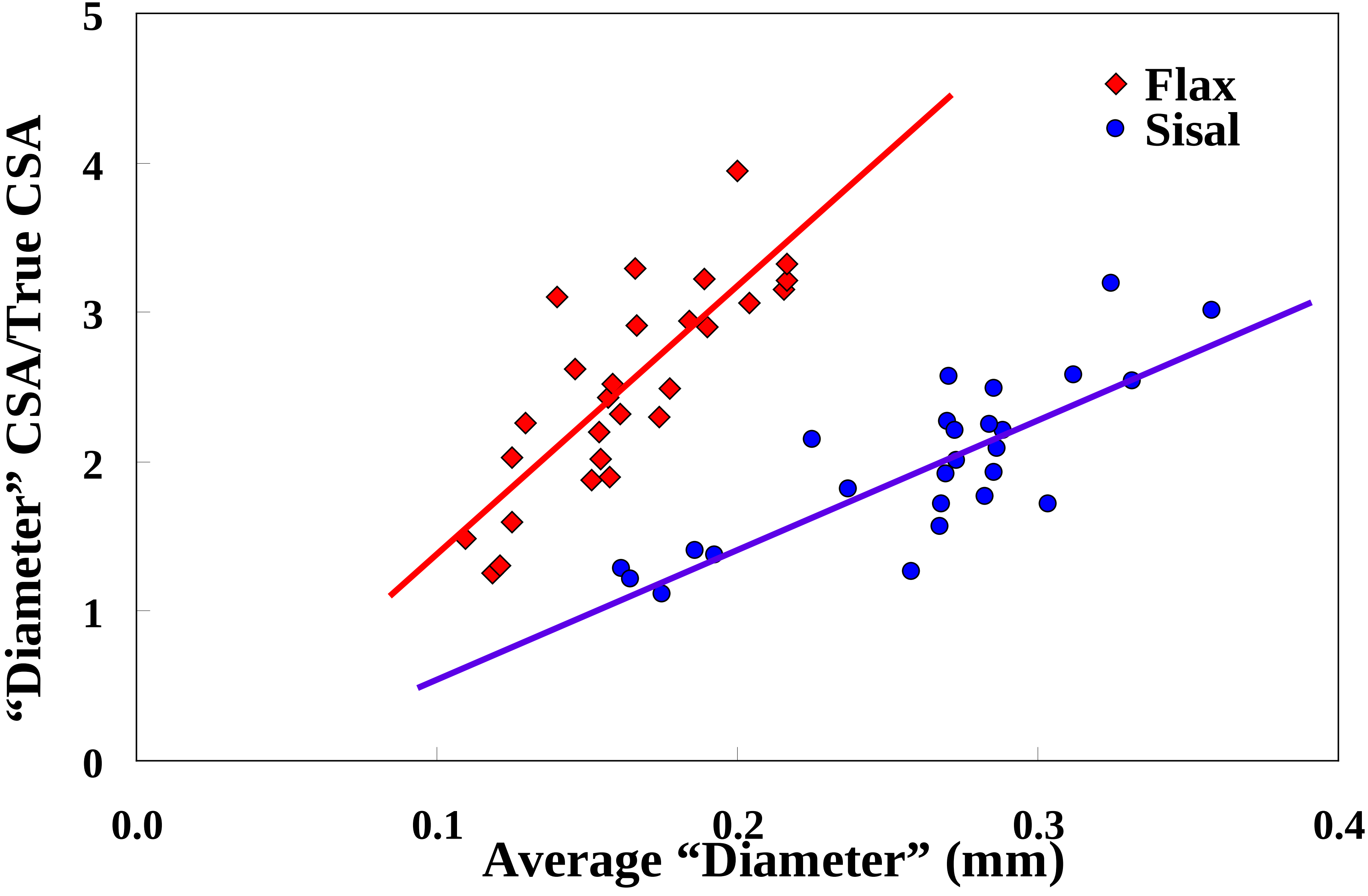
Natural Fibre CSA Evaluation



Single Fibre Modulus



Natural Fibre CSA Evaluation



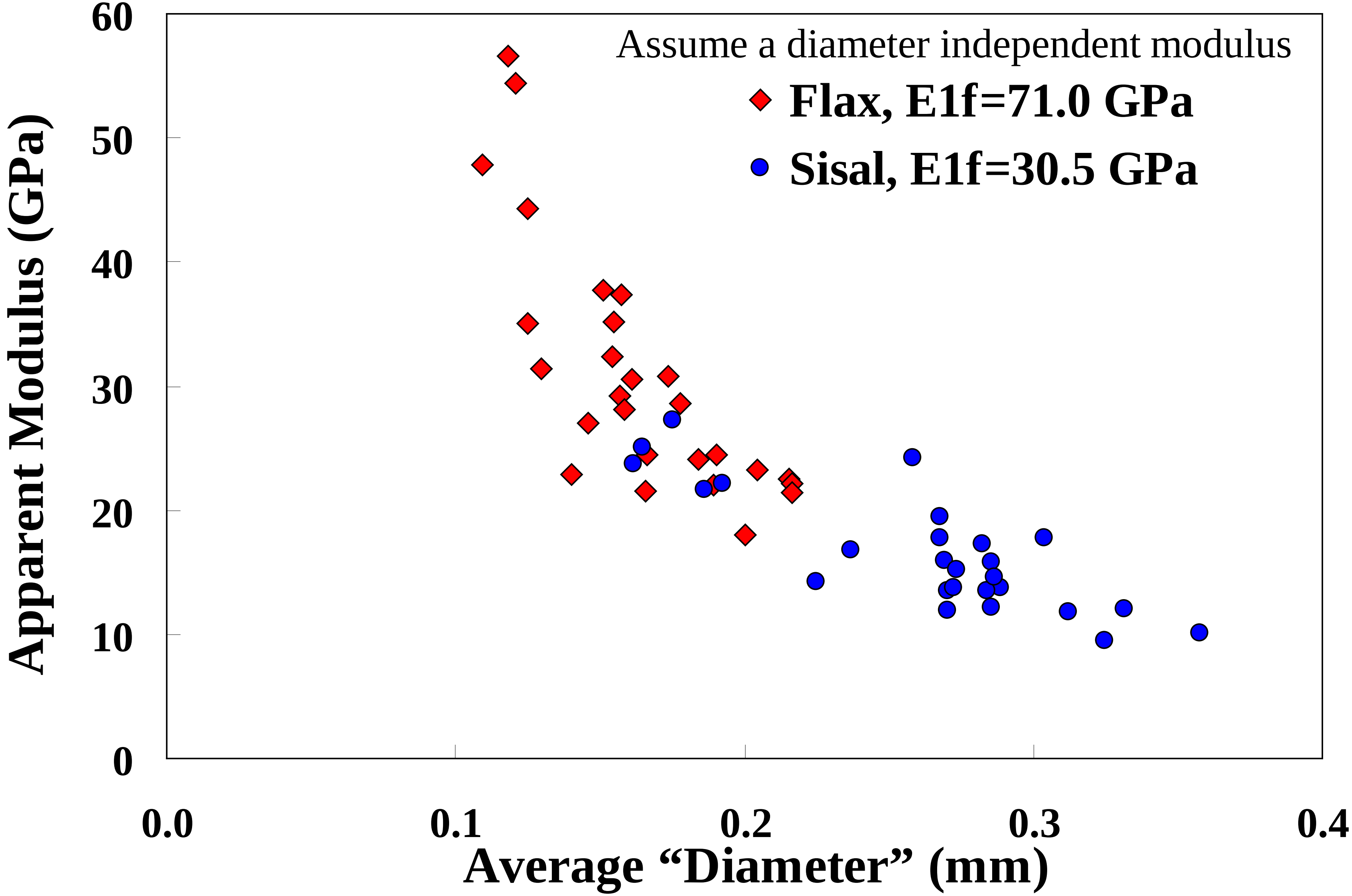
Natural Fibre CSA Evaluation

- “Diameter” method significantly overestimates CSA
- Underestimates single fibre modulus and strength
- Magnitude of error is “diameter” dependent

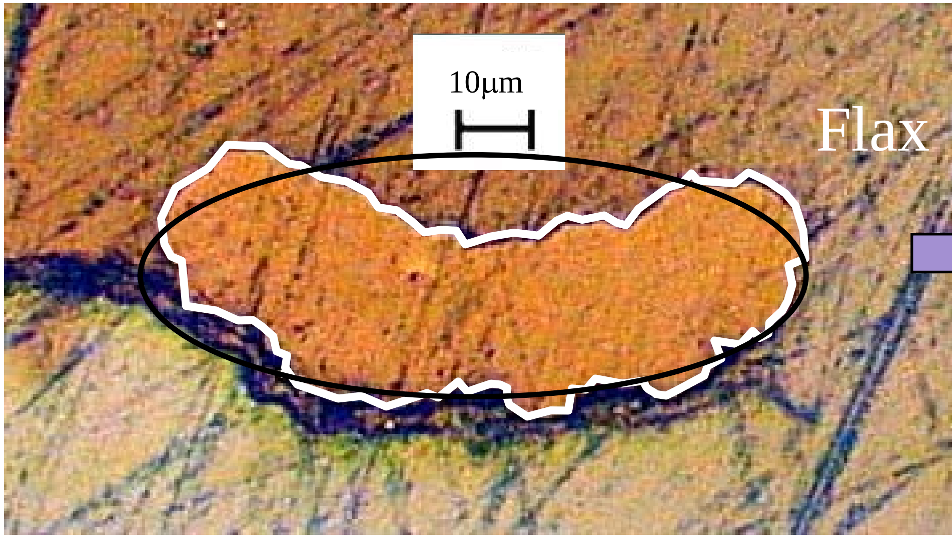
Effect CSA on Single Fibre Properties

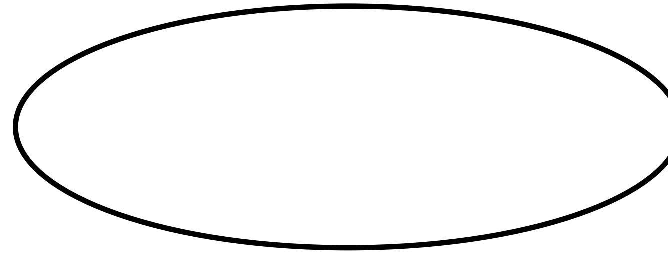
CSA method	Diameter	Actual
Flax Strength (MPa)	293	688
Sisal Strength (MPa)	255	530
Flax Modulus (GPa)	36	71
Sisal Modulus (GPa)	20	30

Effect of “Diameter” CSA on Apparent NF Modulus

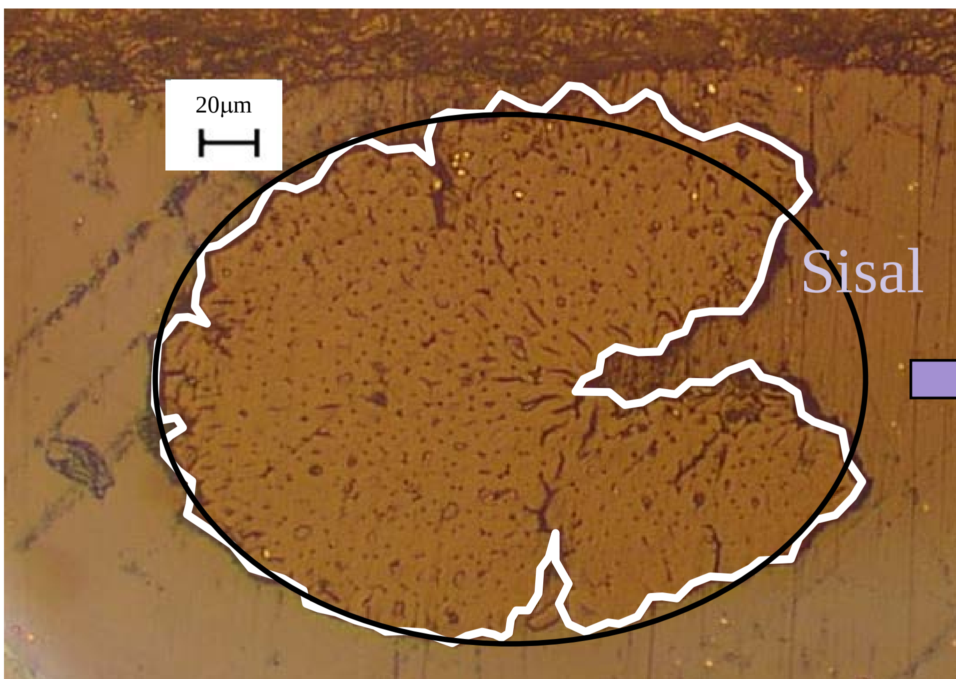


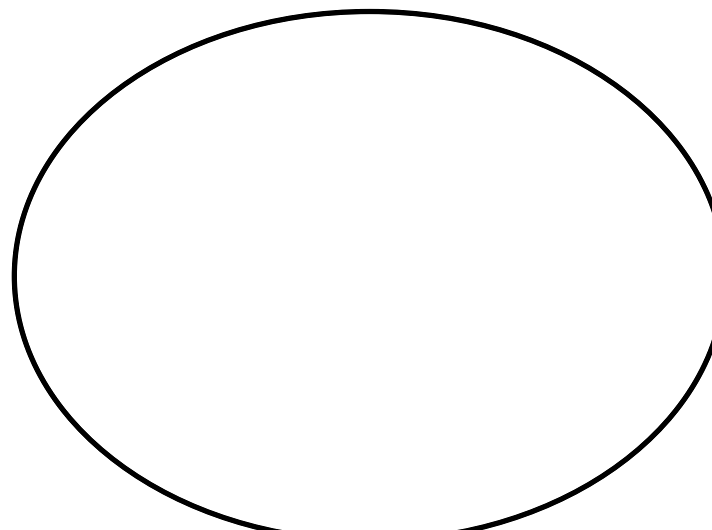
Simple Model of NF CSA“Diameter” Errors





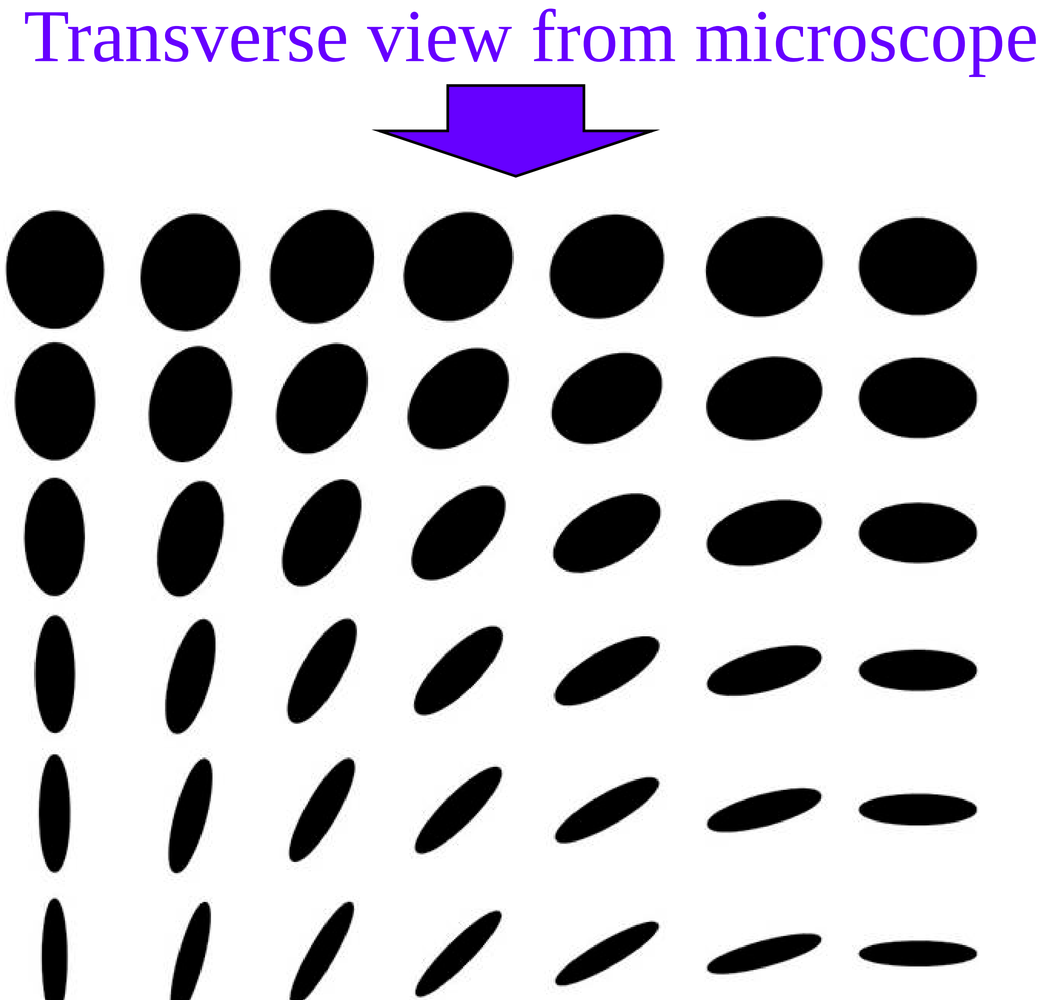
NF non-circular – simplest model is oval X-section



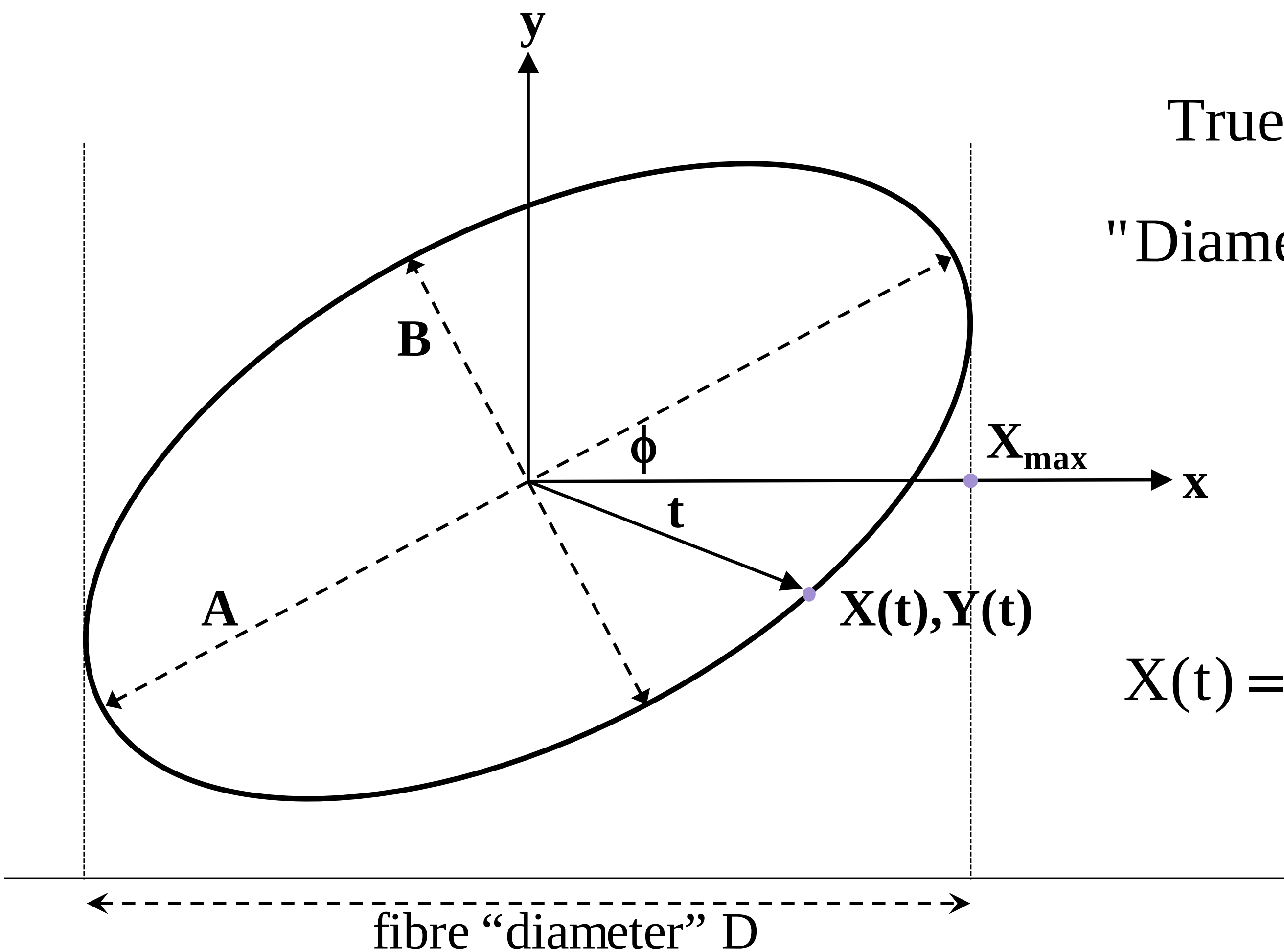


Simple Model of NF CSA"Diameter" Errors

Due to NF natural twist the oval cross section will be viewed differently at different positions along the fibre



Parameteric Ellipse Analysis



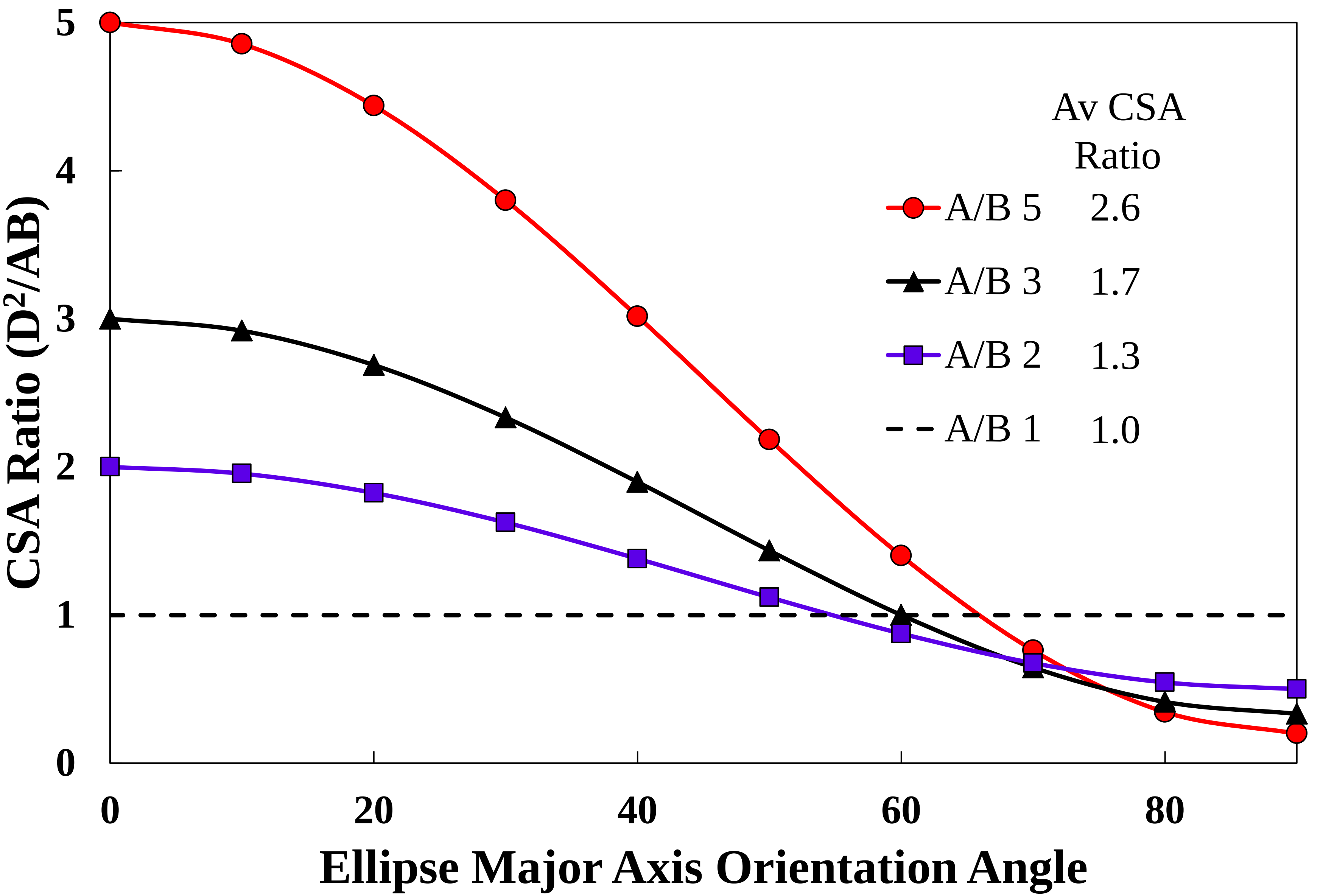
$$\text{True CSA} = 0.25\pi AB$$

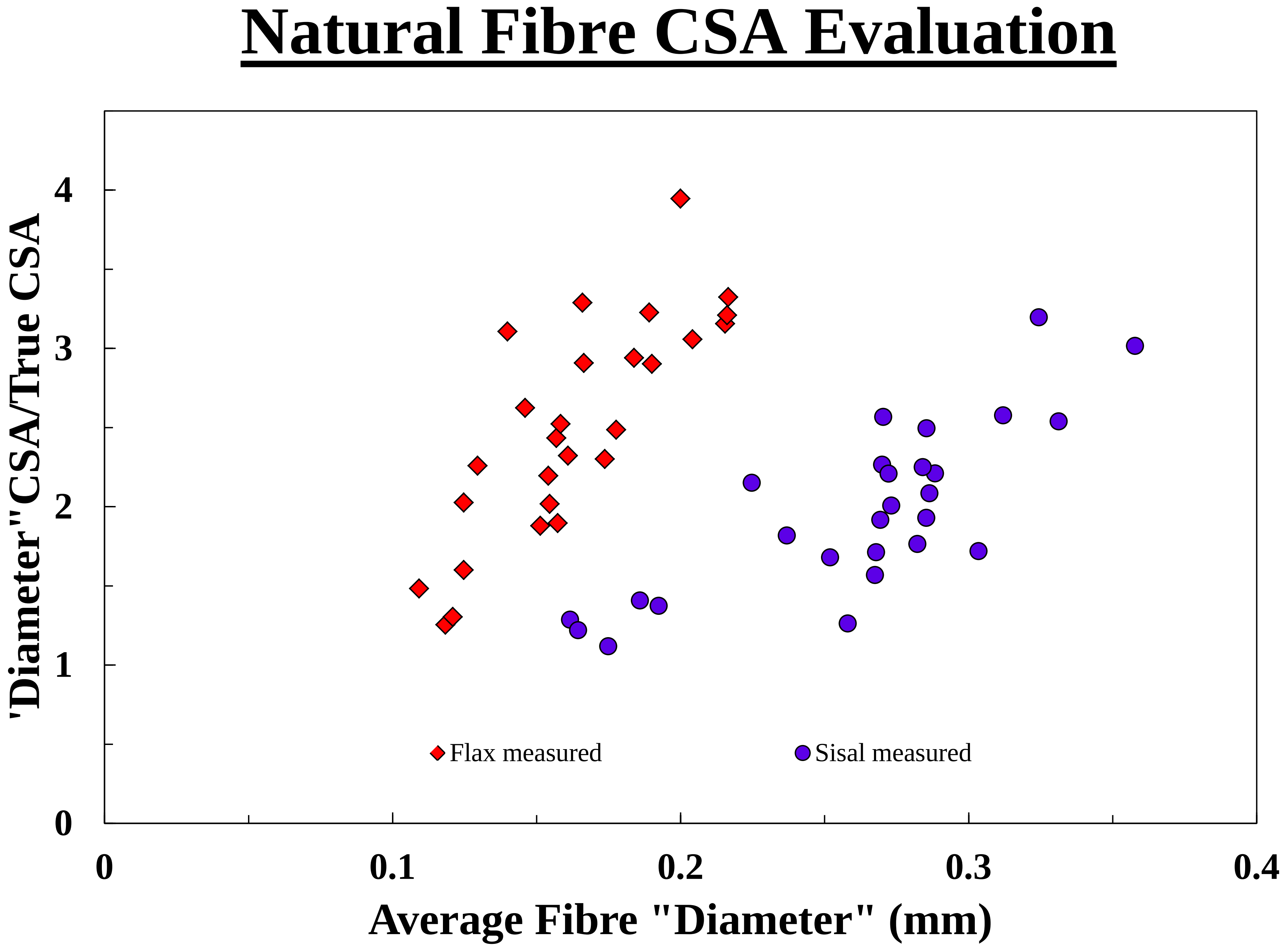
$$\text{"Diameter" CSA} = 0.25\pi D^2$$

$$X(t) = 0.5A\,\mathrm{Cos}(t)\,\mathrm{Cos}(\phi) - 0.5B\,\mathrm{Sin}(t)\,\mathrm{Sin}(\phi)$$

Can solve for X_{max} for any ϕ and then average over ϕ=0-90° for different A:B ratios

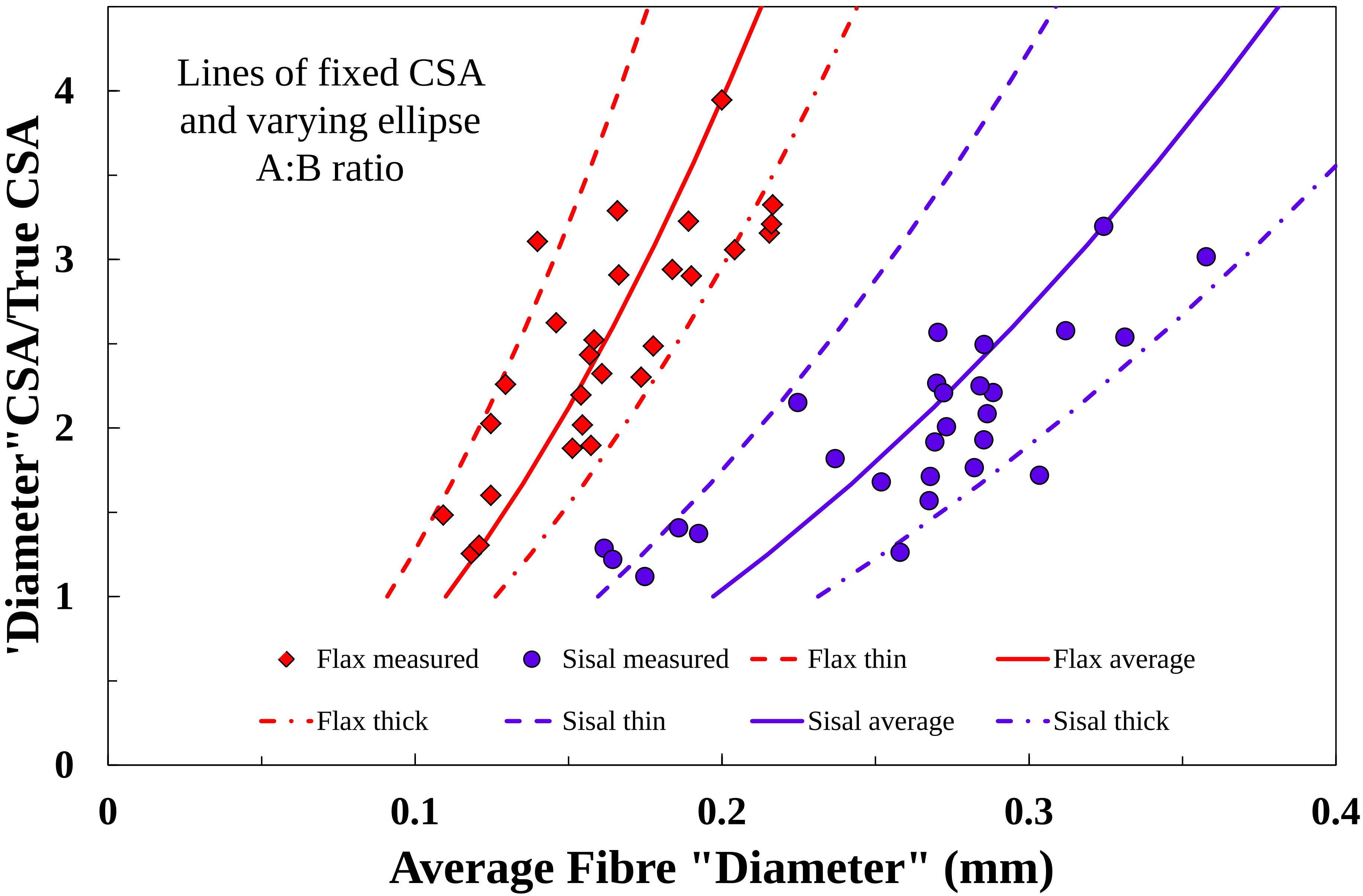
CSA Ratio from Ellipse Analysis





Natural Fibre CSA Evaluation
'Diameter"CSA/True CSA
0
1
2
3
4
0
0.1
0.2
0.3
0.4
Average Fibre "Diameter" (mm)
Flax measured
Sisal measured

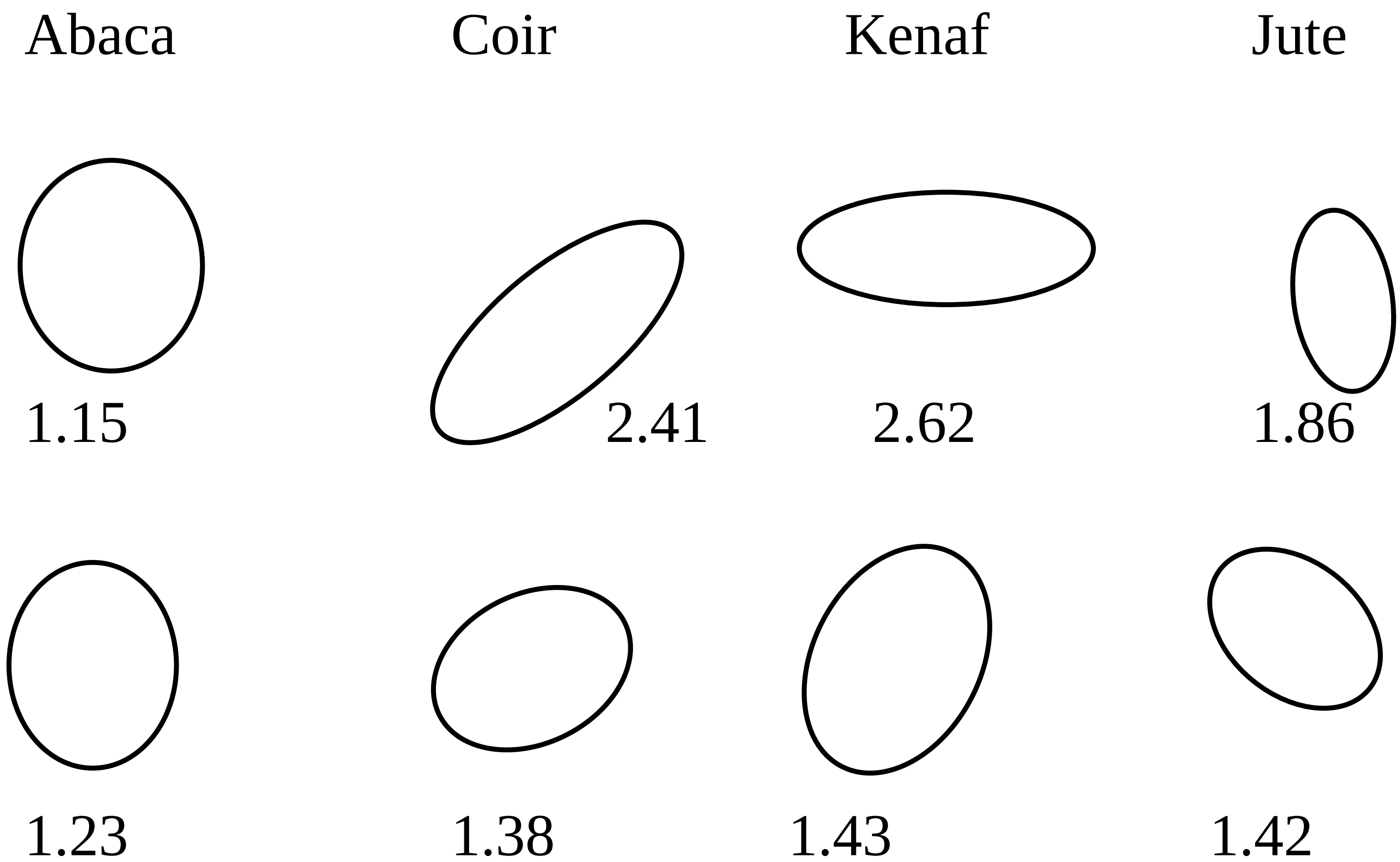
Natural Fibre CSA Evaluation



Other Fibres

Abaca Coir Kenaf Jute

Other Fibres Ellipse A:B



Similar issues probable in CSA estimation from fibre "diameter"

Natural Fibre CSA Evaluation

	Average CSA (mm^2)	Diameter CSA / True CSA
Sisal	0.0272	1.97
Flax	0.0125	2.55
Jute	0.0032	1.58
Hemp	0.0058	2.28
Kenaf	0.0061	1.71
Abaca	0.0213	1.31
Coir	0.0283	1.41

Summary Thermo-Mechanical Properties NF

	Glass	Flax	Sisal
Longitudinal Modulus (GPa)	75	61.5 (71.0)	24.9 (30.5)
Transverse Modulus (GPa)	75	1.2	1.6
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Axial LCTE (μm/m.ºC)	5	-7.3	-2.7
Transverse LCTE (μm/m.ºC)	**5**	**71**	**73**

What does this anisotropy mean for the reinforcement performance of natural fibres ?

$$E_C = \eta_0 \eta_L V_f E_f + V_m E_m$$

- Comparison NF and GF often "assumes" isotropic fibre
- Hence simple Krenchel analysis for η_0

$$\eta_0 = \overline{\cos^4(\theta)}$$

- NF is more like an orthotropic composite material
- Apply laminate theory to model reinforcement performance

Engineering Stiffness, Off-axis Orthotropic Lamina

$$E_x = \frac{\sigma_x}{\varepsilon_x} \qquad \varepsilon_{xy} = \bar{S}\sigma_{xy} \qquad \text{set } \boldsymbol{\sigma}_{xy} = \{\sigma_x \ 0 \ 0\}$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} & \bar{S}_{13} \\ \bar{S}_{21} & \bar{S}_{22} & \bar{S}_{23} \\ \bar{S}_{31} & \bar{S}_{32} & \bar{S}_{33} \end{bmatrix} \begin{bmatrix} \sigma_x \\ 0 \\ 0 \end{bmatrix}$$

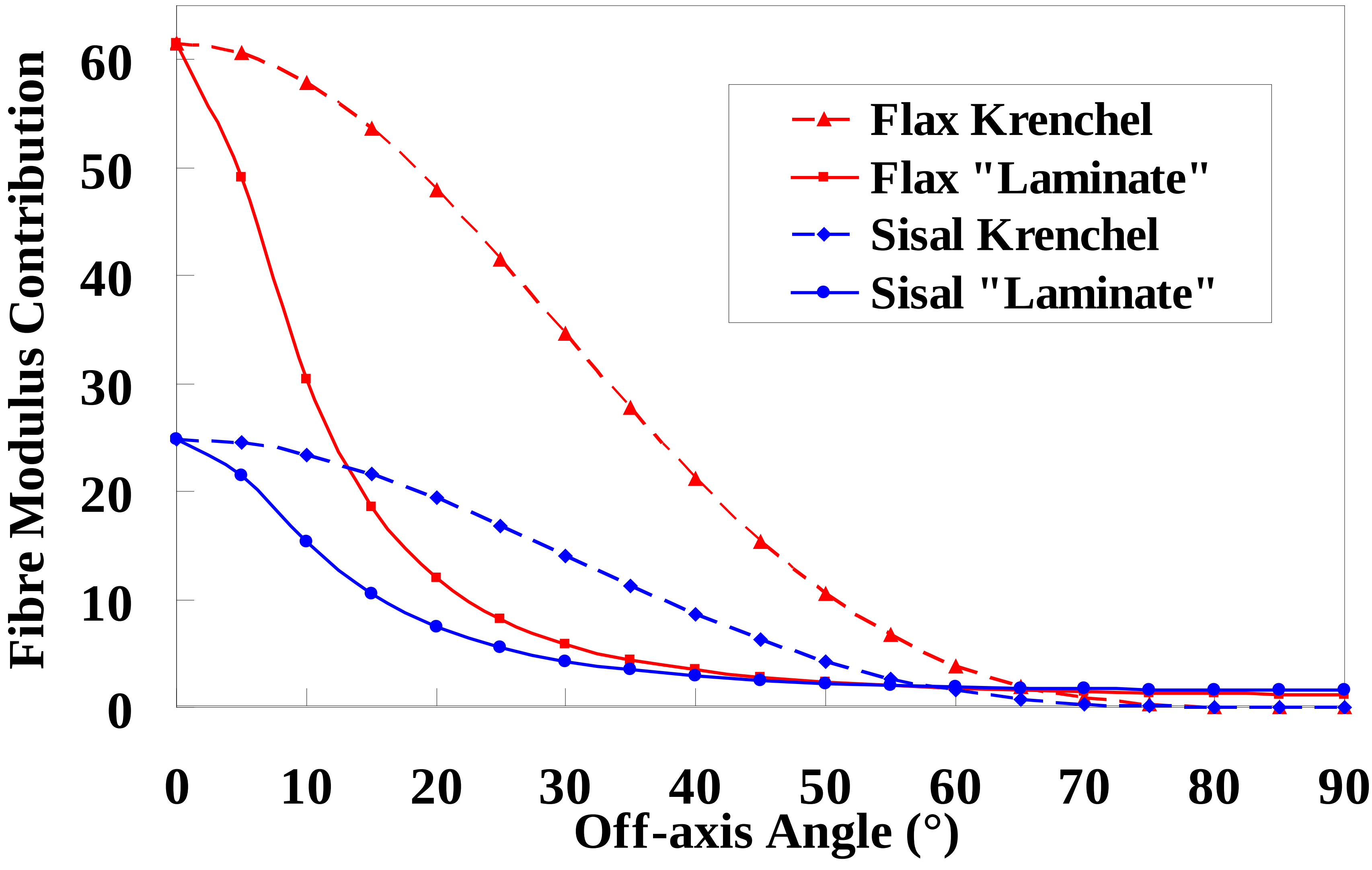
hence $\boldsymbol{\varepsilon}_x = \bar{S}_{11}\boldsymbol{\sigma}_x$

and for all θ, $E_x = \frac{1}{\bar{S}_{11}}$

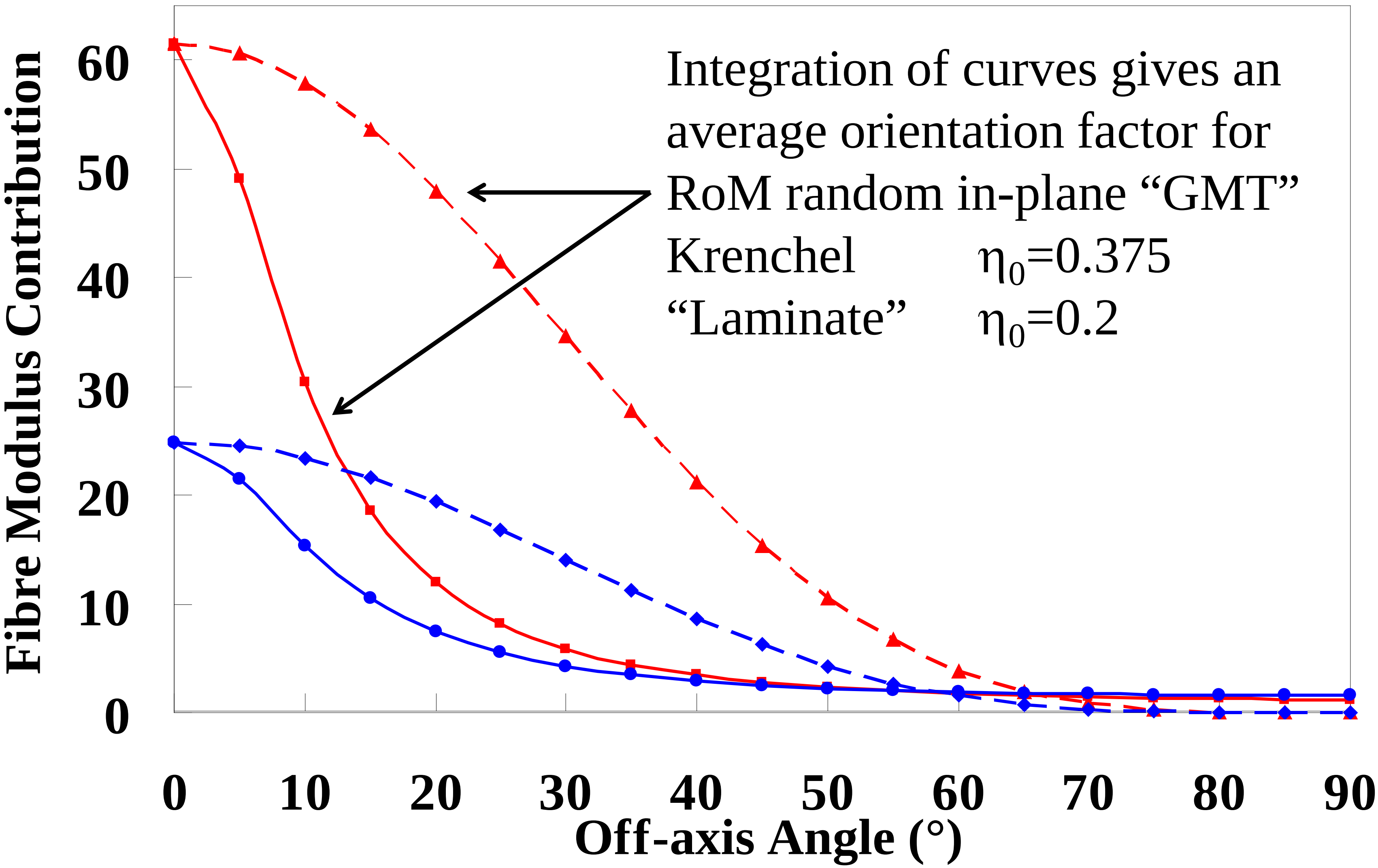
$$\bar{S}_{11} = S_{11}\cos^4\theta + (2S_{12} + S_{33})\sin^2\theta\cos^2\theta + S_{22}\sin^4\theta$$

The terms S_{11}, etc., are found from $S = \begin{bmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$

Offaxis Stiffness Contribution of Anisotropic Fibre

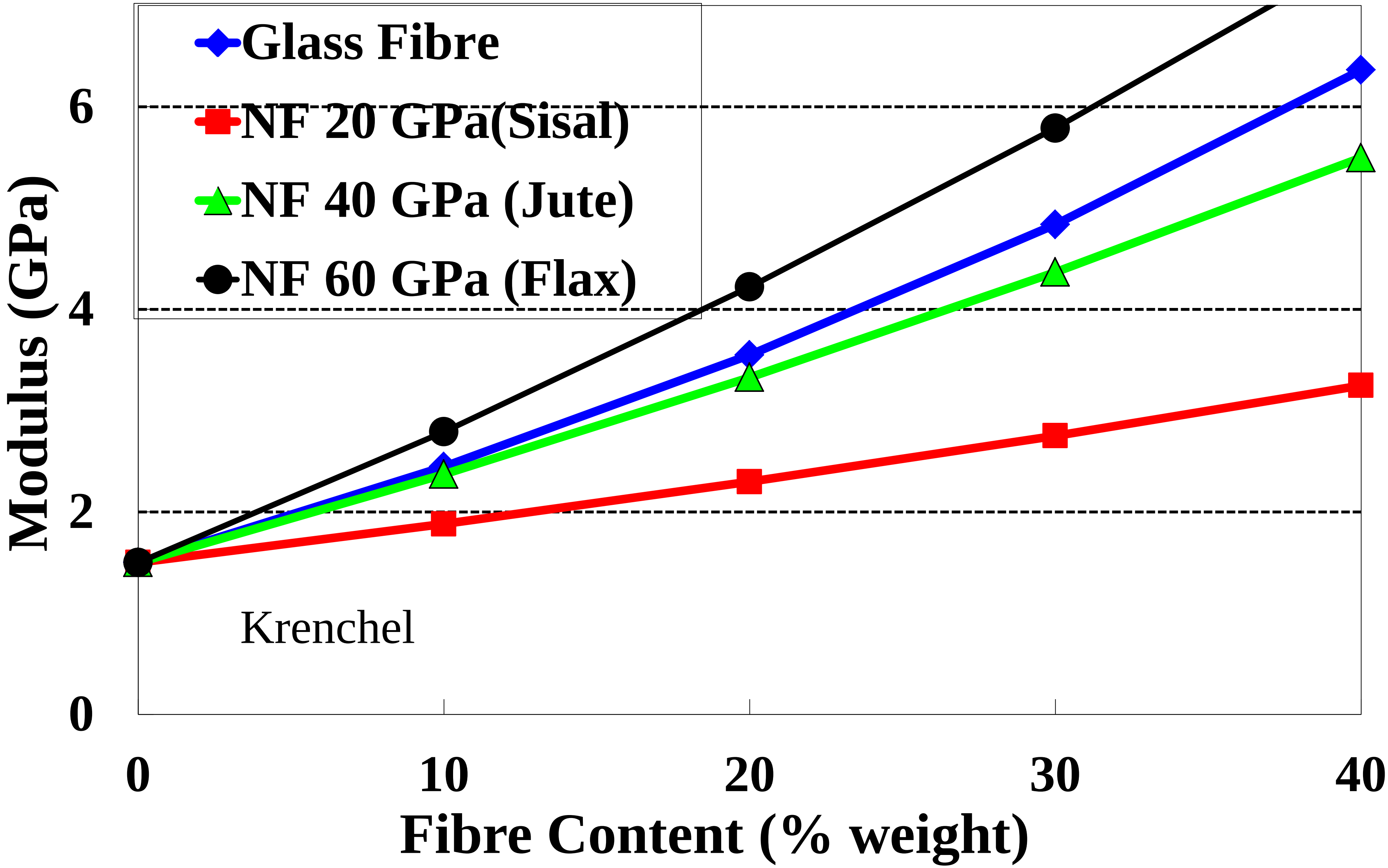


Offaxis Stiffness Contribution of Anisotropic Fibre



Comparison Predicted Composite Modulus

For Randon Inplane moulded long fibre polypropylene “GMT”



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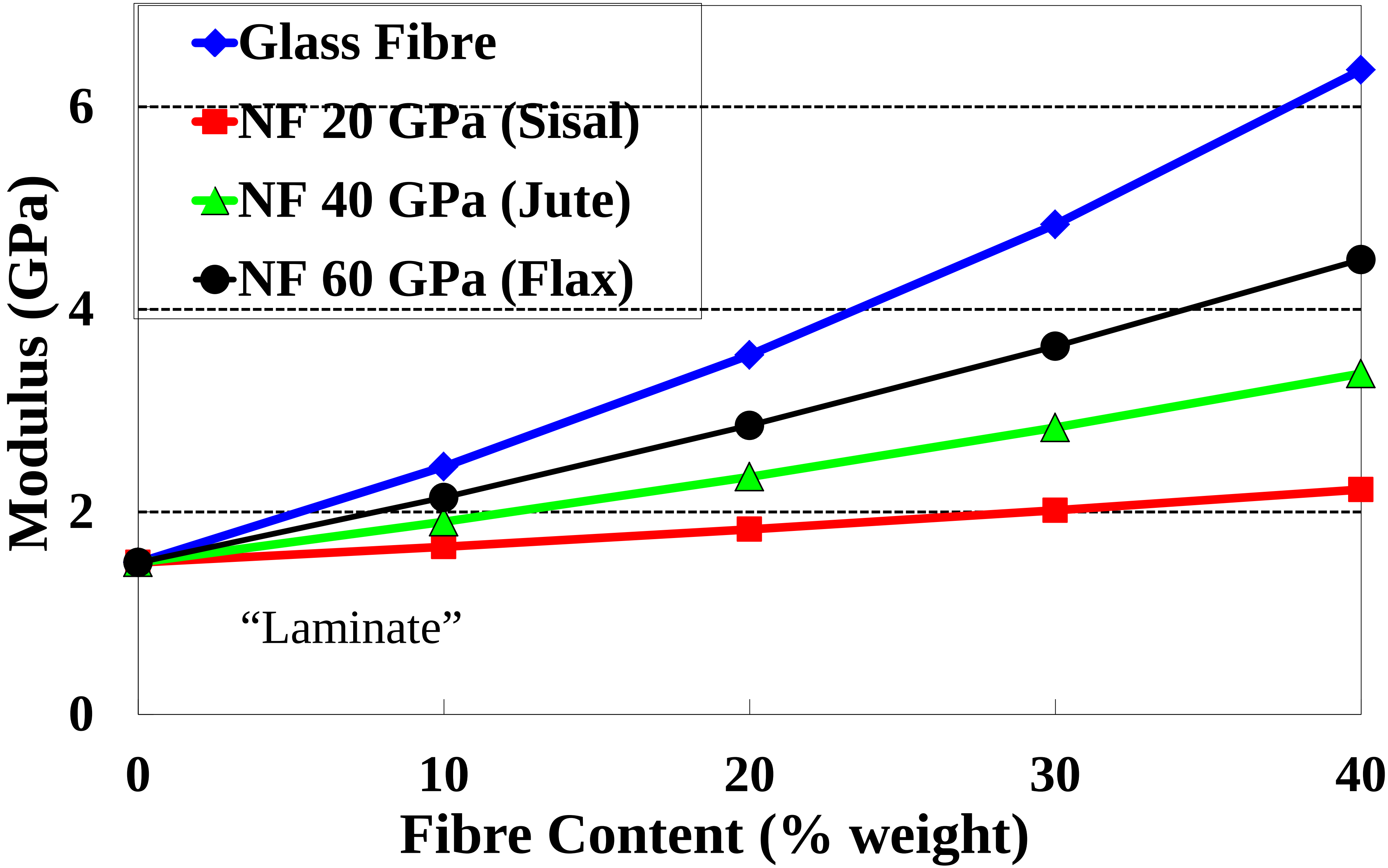
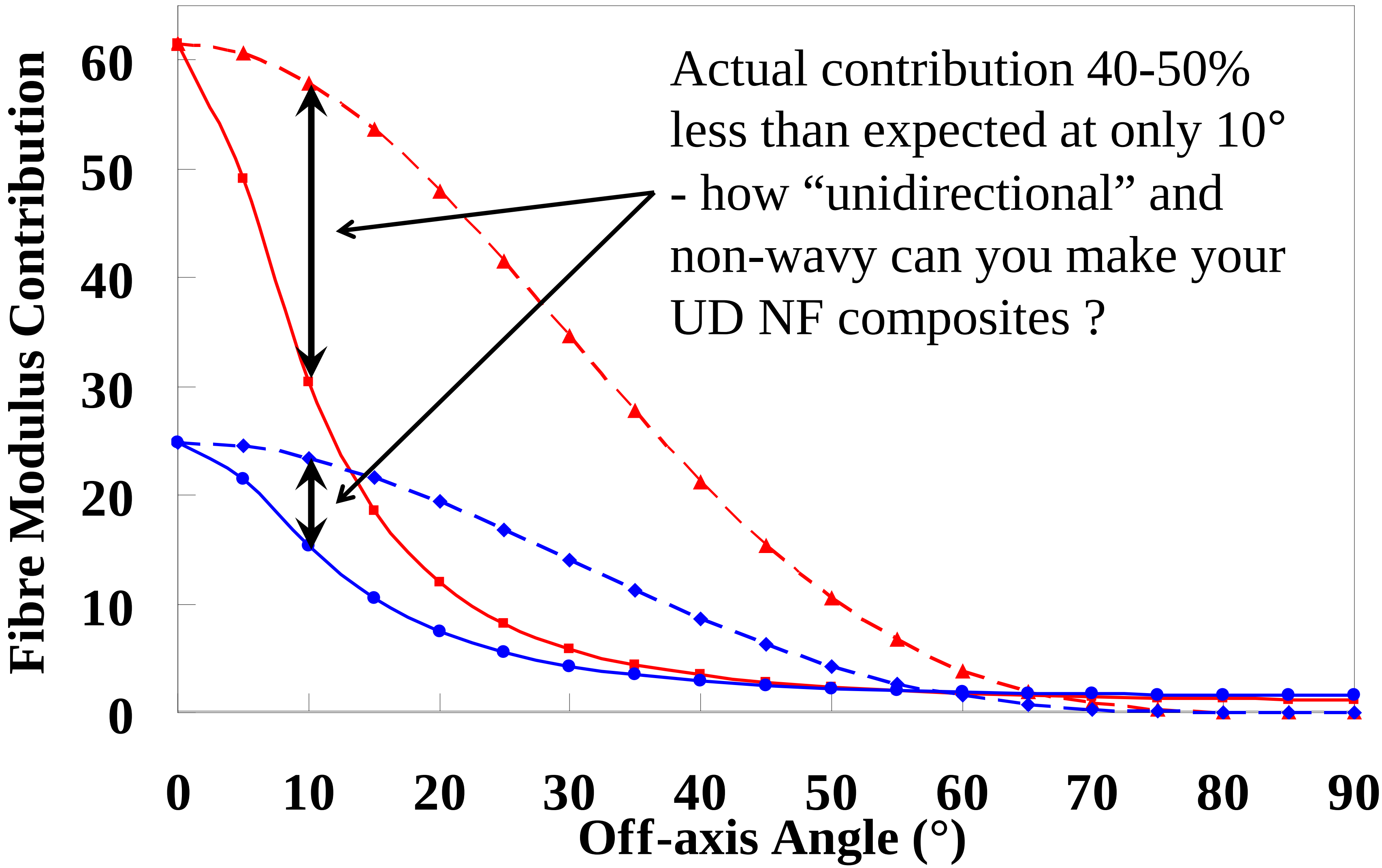


NF Anisotropy Challenge

OK - Lets just make Unidirectional Composites ?



Conclusions (1)

- **Estimation of natural fibre cross section area via the 'diameter' method leads to significant overestimation of CSA.**
  - **results in significant underestimation of mechanical properties obtained by single fibre testing.**
  - **also contributes significantly to the variability observed in the measurement of natural fibres properties.**
  - **since the magnitude of the CSA error is "diameter" dependent – single fibre properties will appear to be diameter dependent.**

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Conclusions (2)

- **Flax and Sisal fibres exhibit very high levels of mechanical and thermomechanical anisotropy.**
- **Ignoring natural fibre anisotropy and using only the axial modulus of natural fibres in estimating their composite reinforcing ability will significantly overestimate their potential in any off-axis composite loading scenario.**

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Announcement
Sustainable Composites

In August 2013 the Advanced Composites Group at the University of Strathclyde filed its first patent application in the area of

Glass Fibre Recovery

covering cost effective, industrially applicable, treatments to regenerate the strength of thermally recycled glass fibres.