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The Challenges of Natural Fibres as Engineering Composite Reinforcements

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GRPE
GLASGOW RESEARCH PARTNERSHIP IN ENGINEERING

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Natural Fibre Composites

- Introduction
- Composite fibre content
- Thermo-mechanical anisotropy of natural fibres
- Natural fibre non-circular cross section
- Conclusions

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Natural Fibre Composites - Challenges

Low cost = technical fibre

- Fibre natural variability
- Fibre anisotropy
- Fibre non-circular
- Composite fibre content measurement
- Moisture sensitivity
- Fibre-matrix interaction

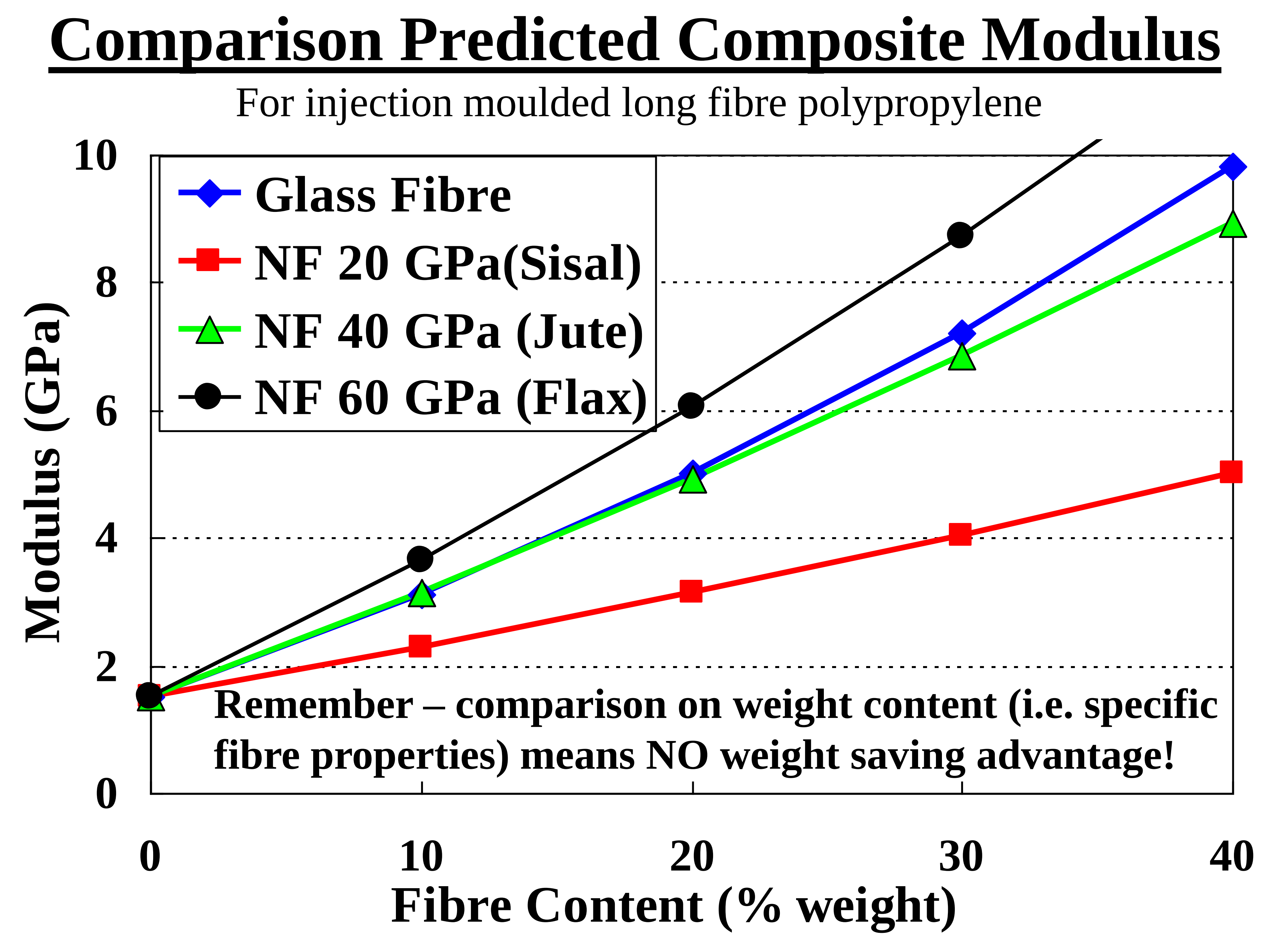
Why Natural Fibre Composites ?

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

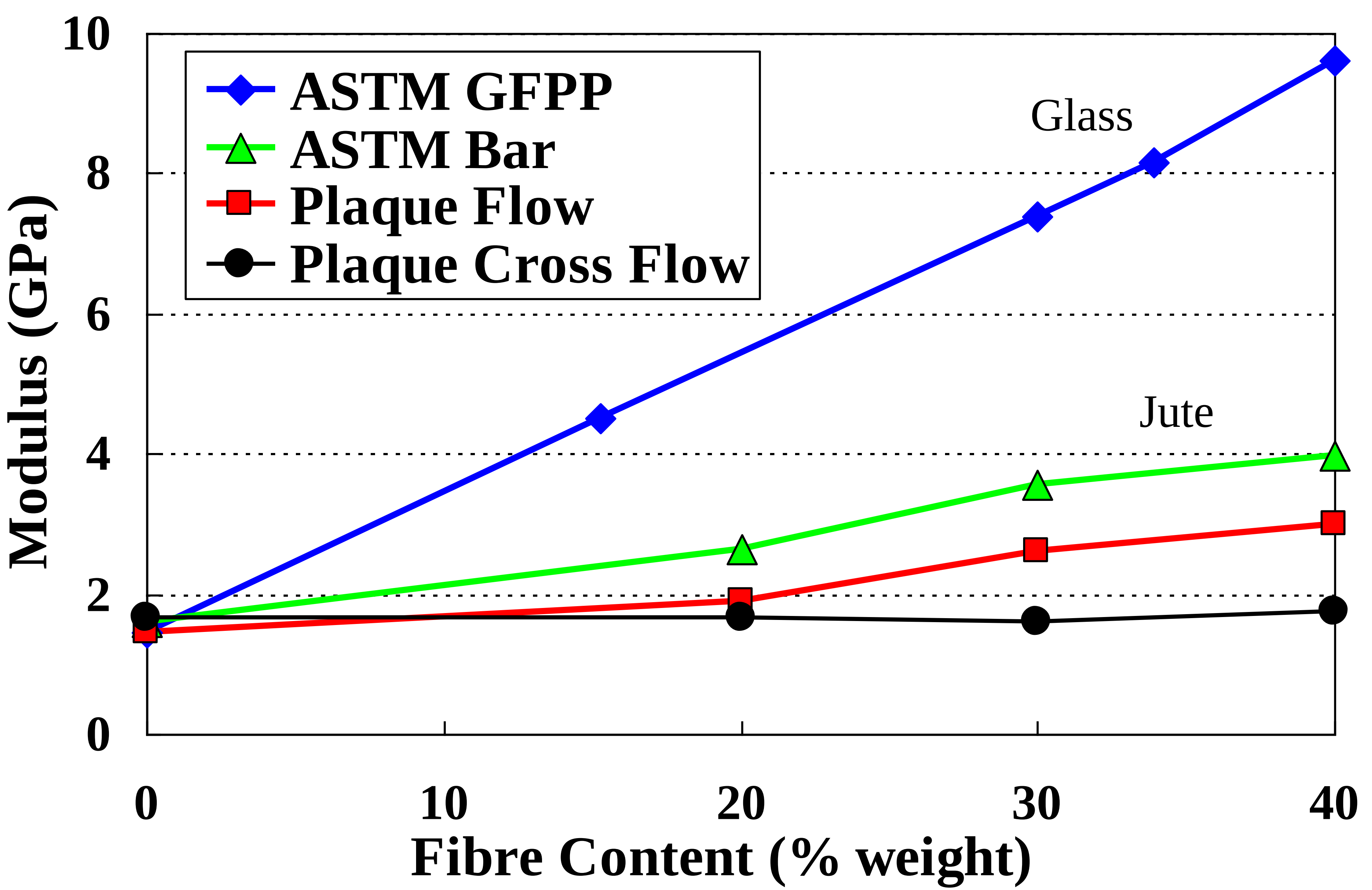
So some natural fibre may have the potential to replace glass fibres ???

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



Comparison Predicted Composite Modulus
For injection moulded long fibre polypropylene
Glass Fibre
NF 20 GPa(Sisal)
NF 40 GPa (Jute)
NF 60 GPa (Flax)
Remember – comparison on weight content (i.e. specific fibre properties) means NO weight saving advantage!
Modulus (GPa)
0
2
4
6
8
10
0
10
20
30
40
Fibre Content (% weight)

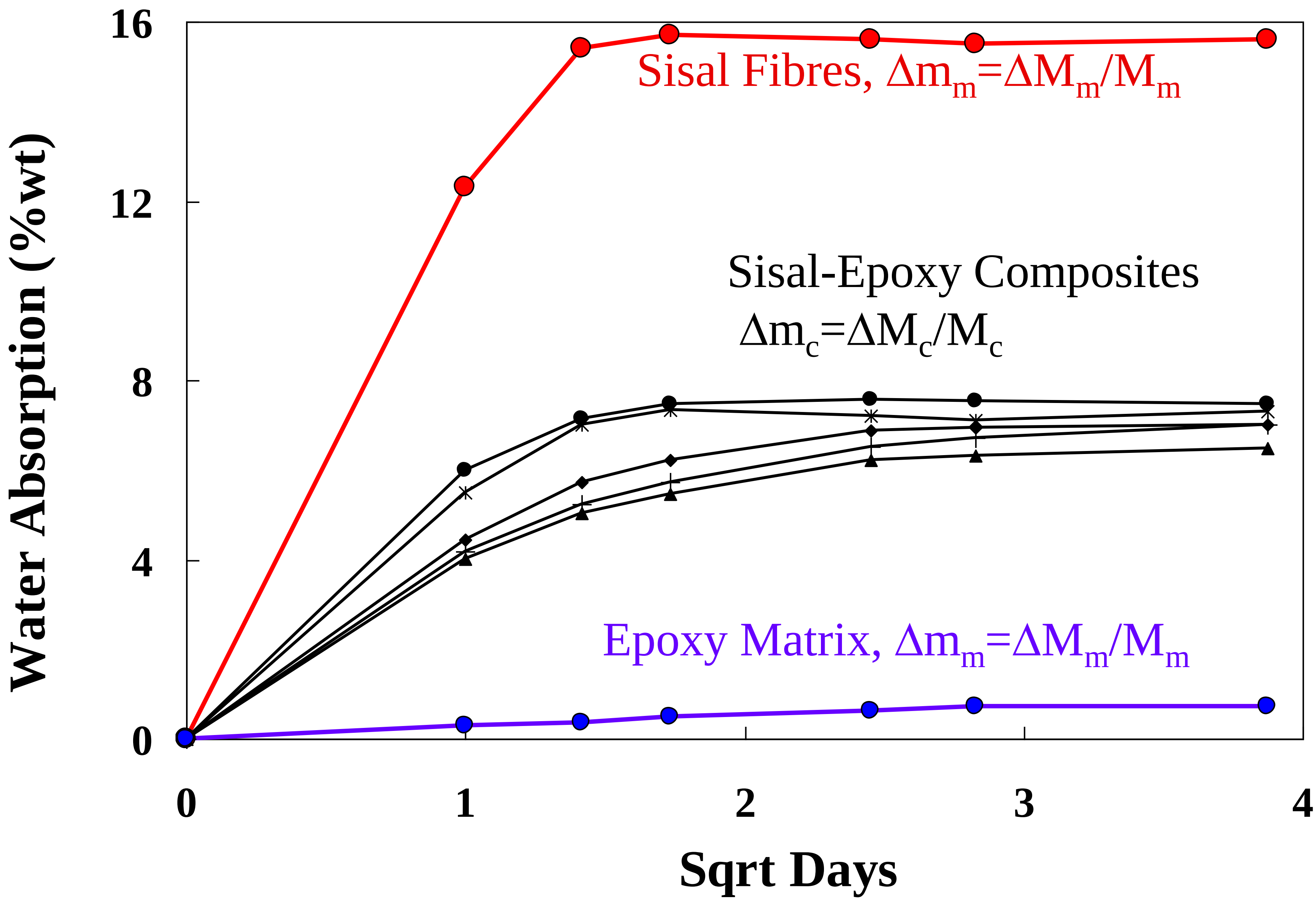
Actual Modulus Injection Moulded Jute-PP



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), $\alpha_{1f}(T)$, $\alpha_{2f}(T)$

Water Absorption for Fibre Content



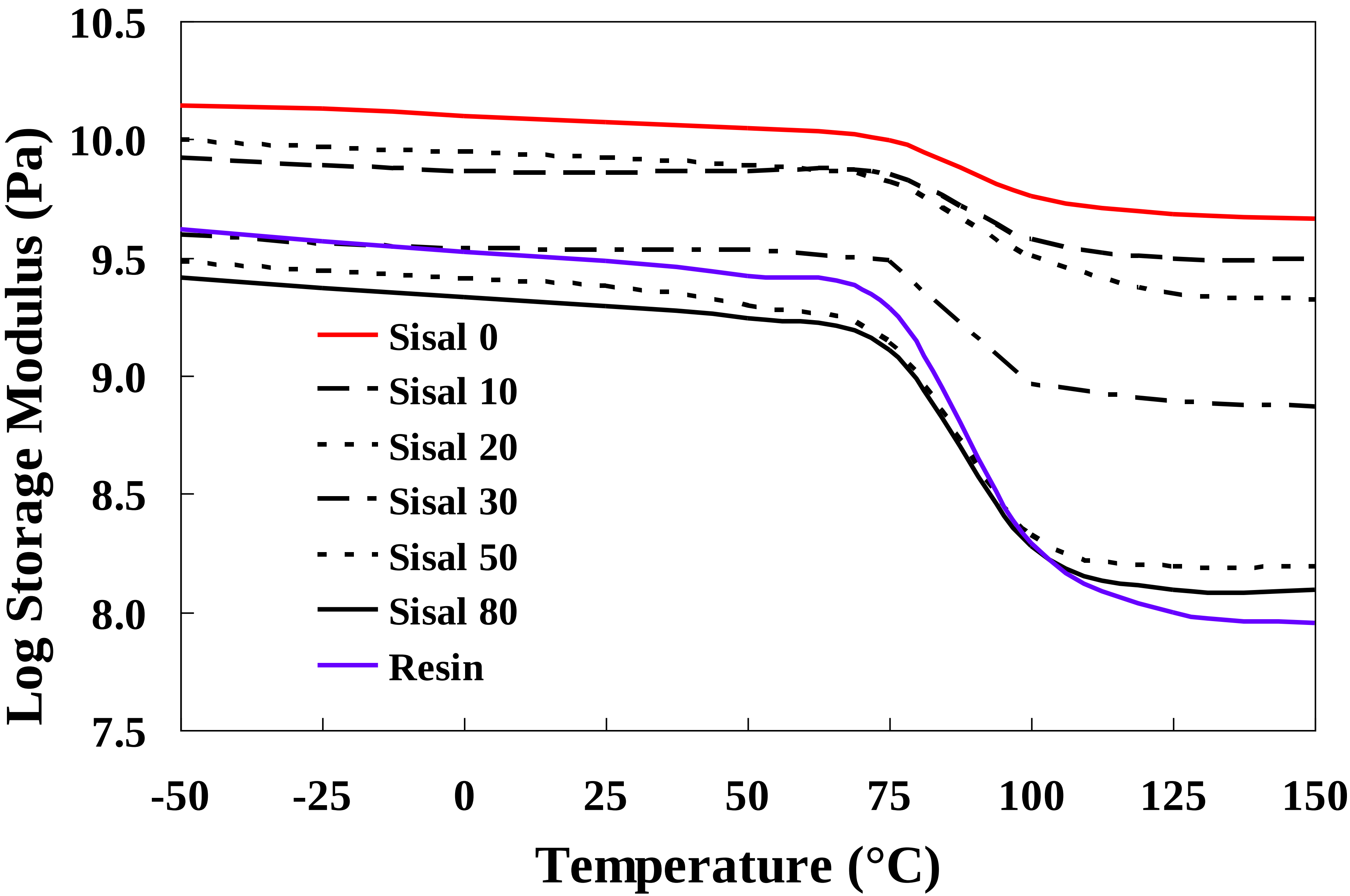
NF Composite Fibre Volume Fraction

$$W_f = \frac{\Delta m_c - \Delta m_m}{\Delta m_f - \Delta m_m} \qquad V_f = \left[1 + \frac{\rho_f}{\rho_m}\frac{(1 - W_f)}{W_f}\right]^{-1}$$

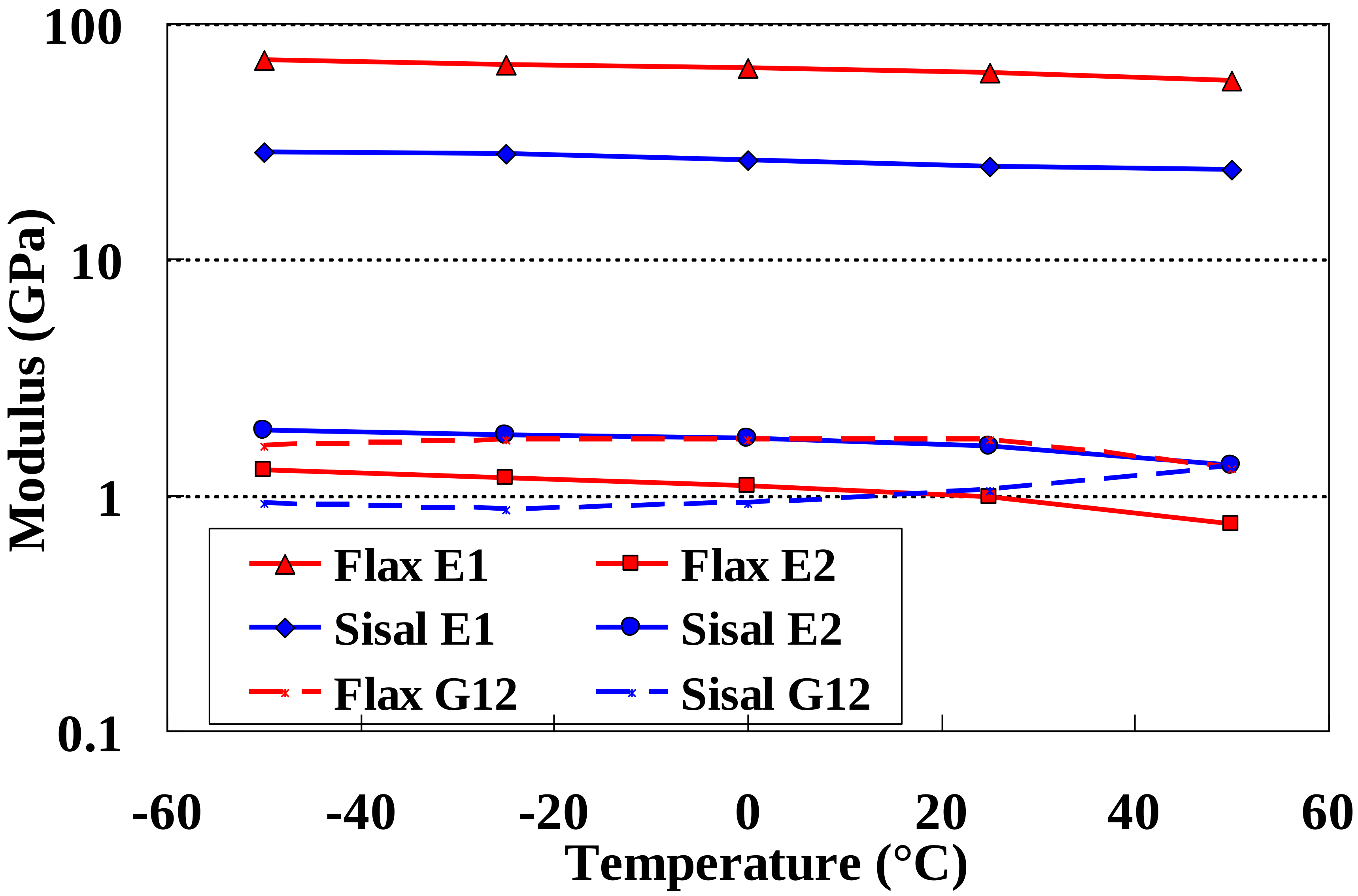
- **Sisal fibre density ρ_f = 1400 kg/m^3**
- **Flax fibre density ρ_f = 1400 kg/m^3**
- **Epoxy matrix density ρ_m = 1100 kg/m^3**

- **Sisal composite W_f = 0.46, V_f = 0.4**
- **Flax composite W_f = 0.36, V_f = 0.31**

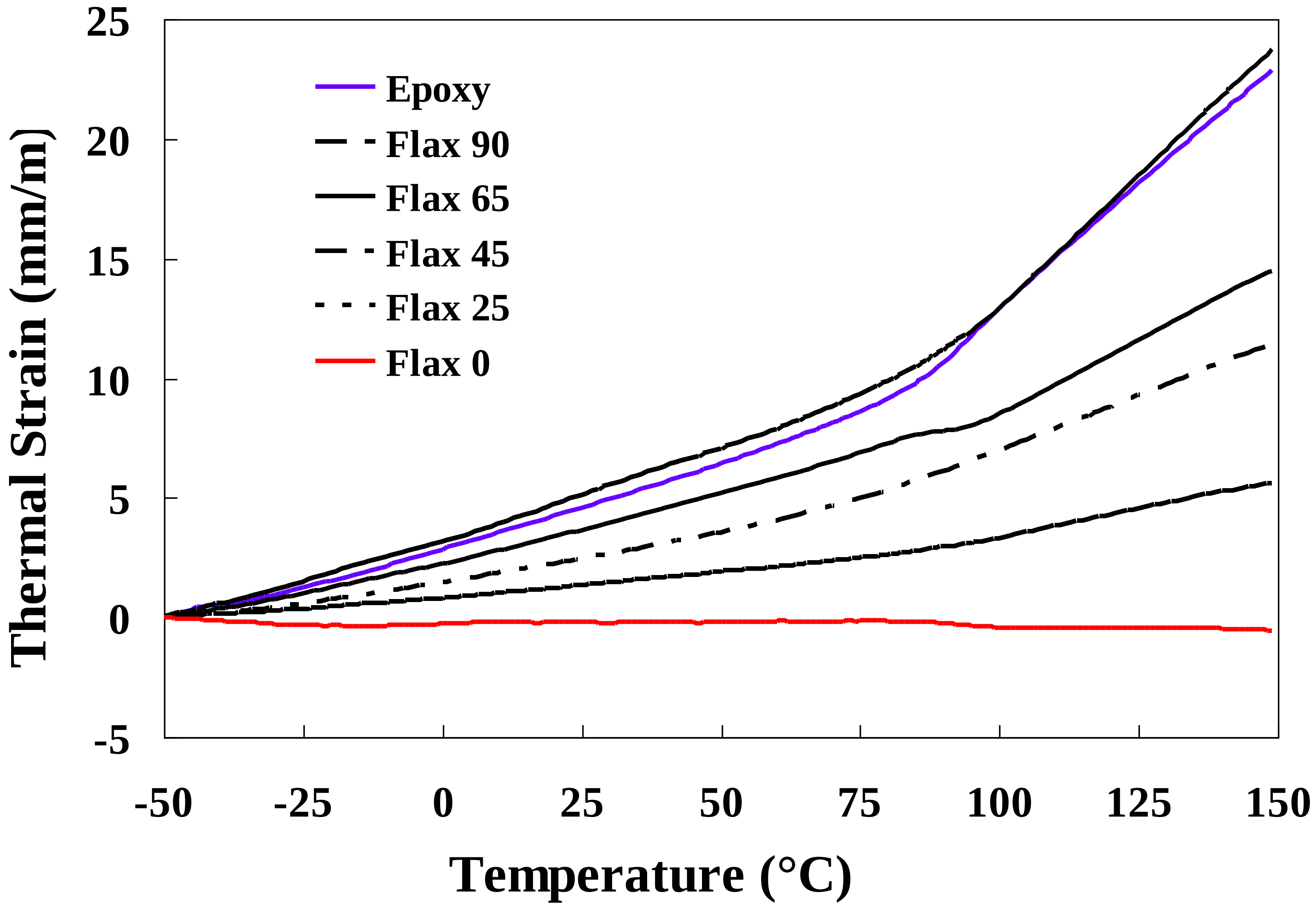
Composite DMA Results



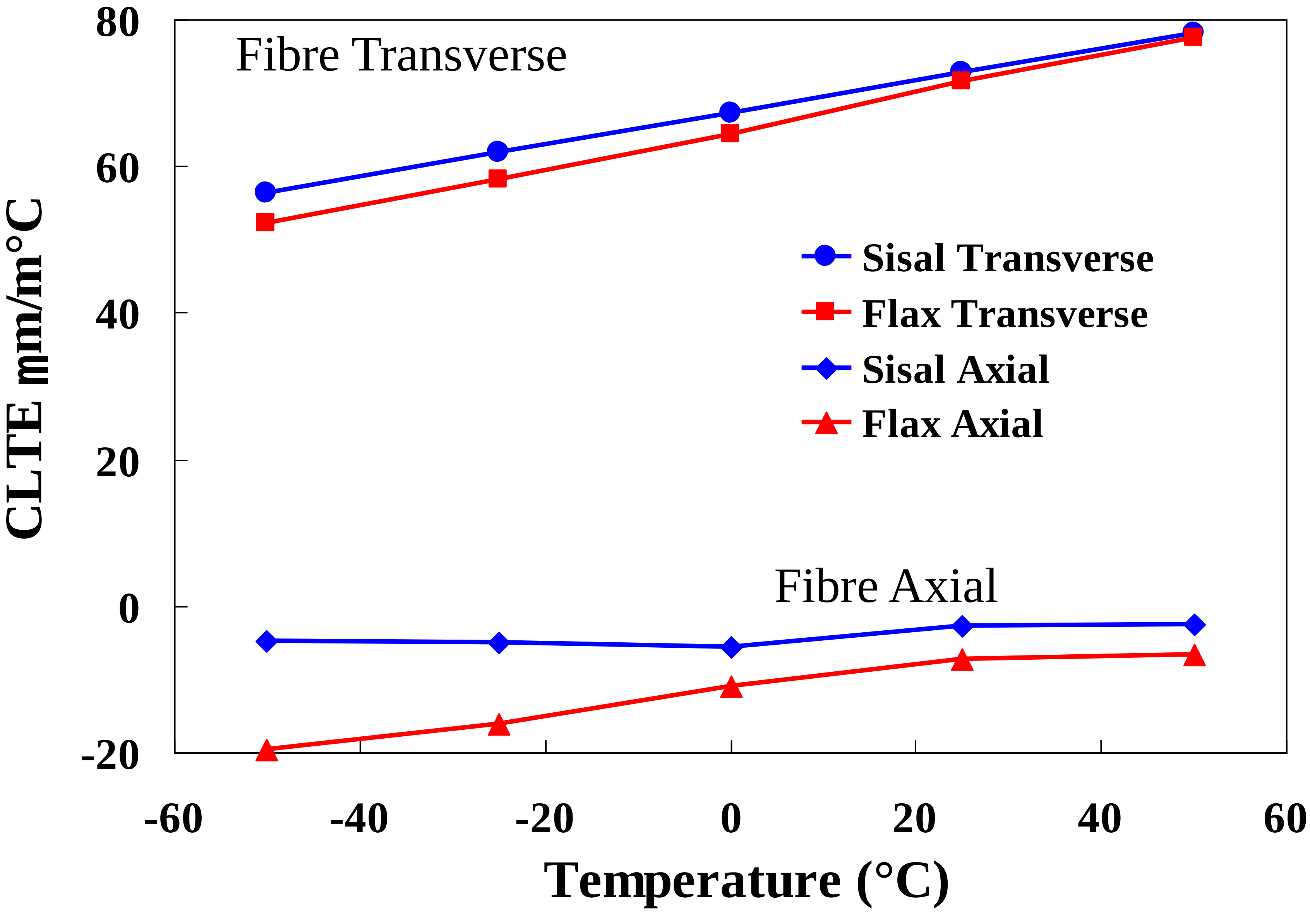
Anisotropy of Fibre Modulus



Composite Thermal Strain



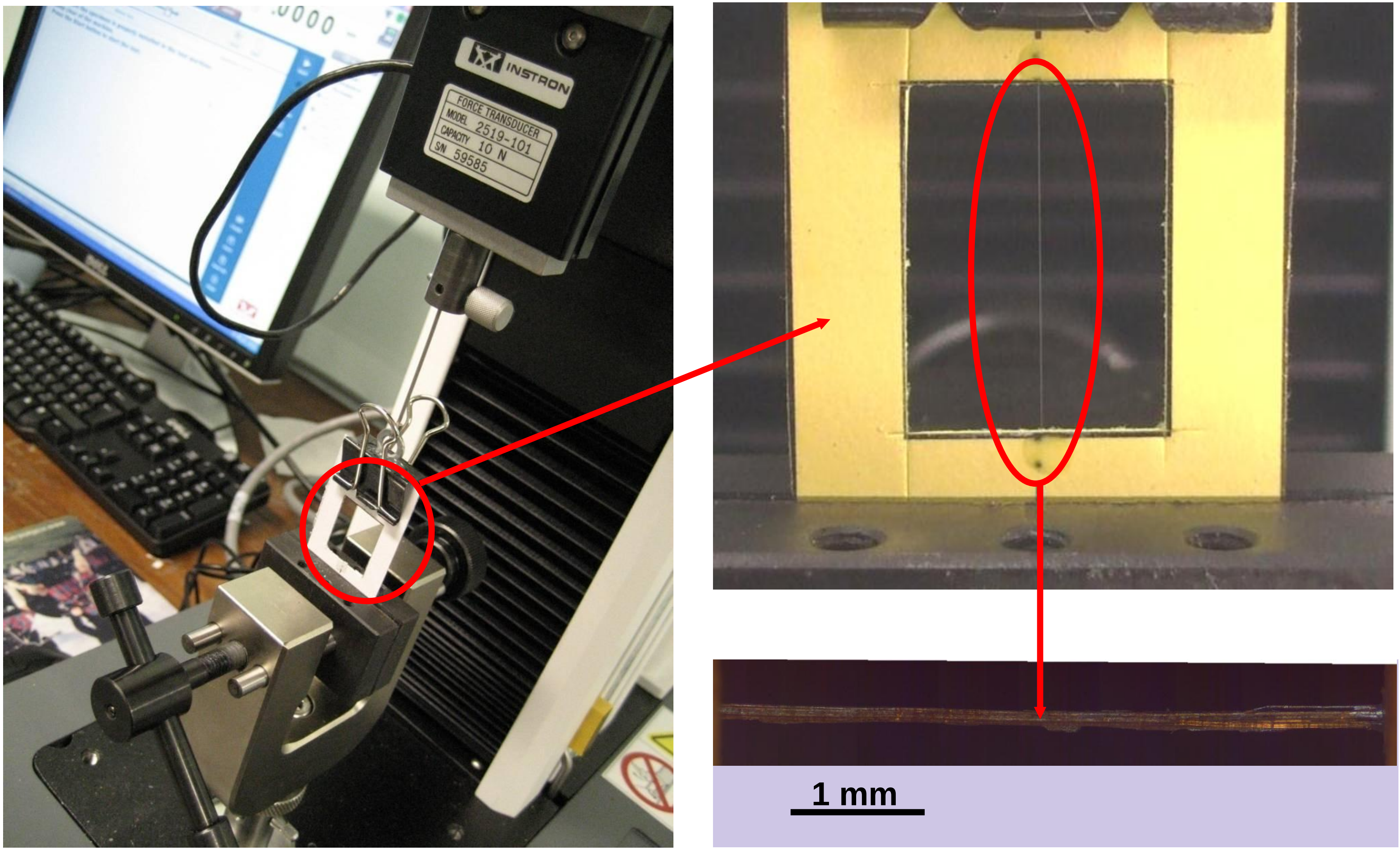
Fibre Expansion Coefficients



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**

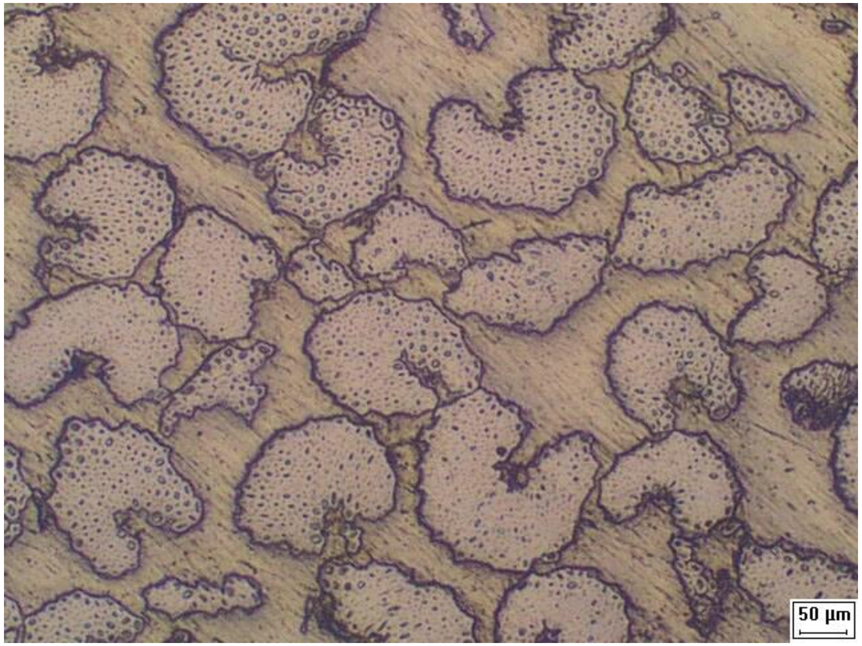
Single Fibre Testing

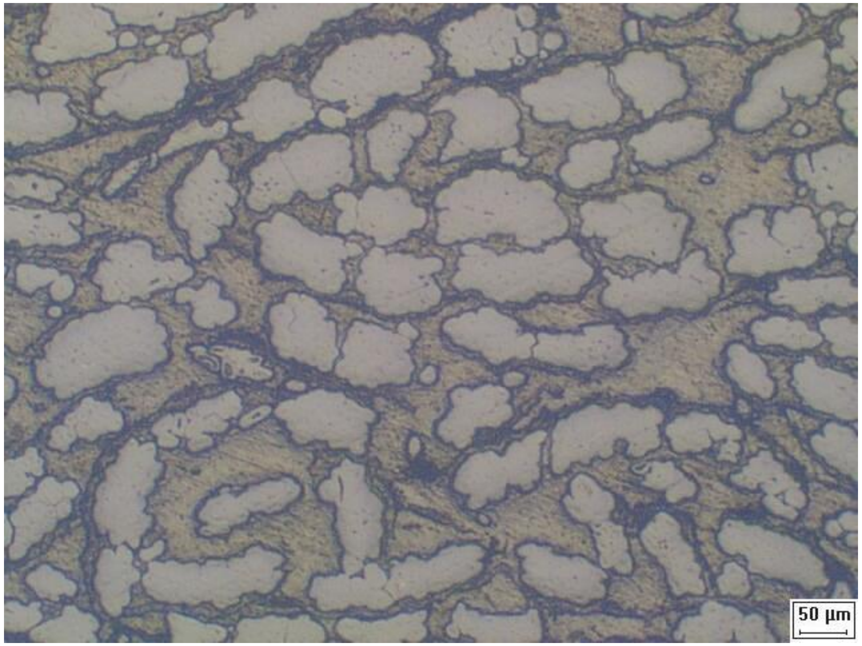


$$\text{Fibre Stress} = \text{Load/Area} = P/A_f \ (= 4P/\pi D_f^2 \ \ ???)$$

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 Measurements

Series 1

- Single flax and sisal fibres mounted on test card windows
- Fibre "diameter" determined by averaging 4 transverse measurements
- Fibre tensile testing (10,15,20,25,30 mm gauge)
- Residual fibre ends glued to card tab sectioned in 2 places and "true" cross sectional area determined

Series 2

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

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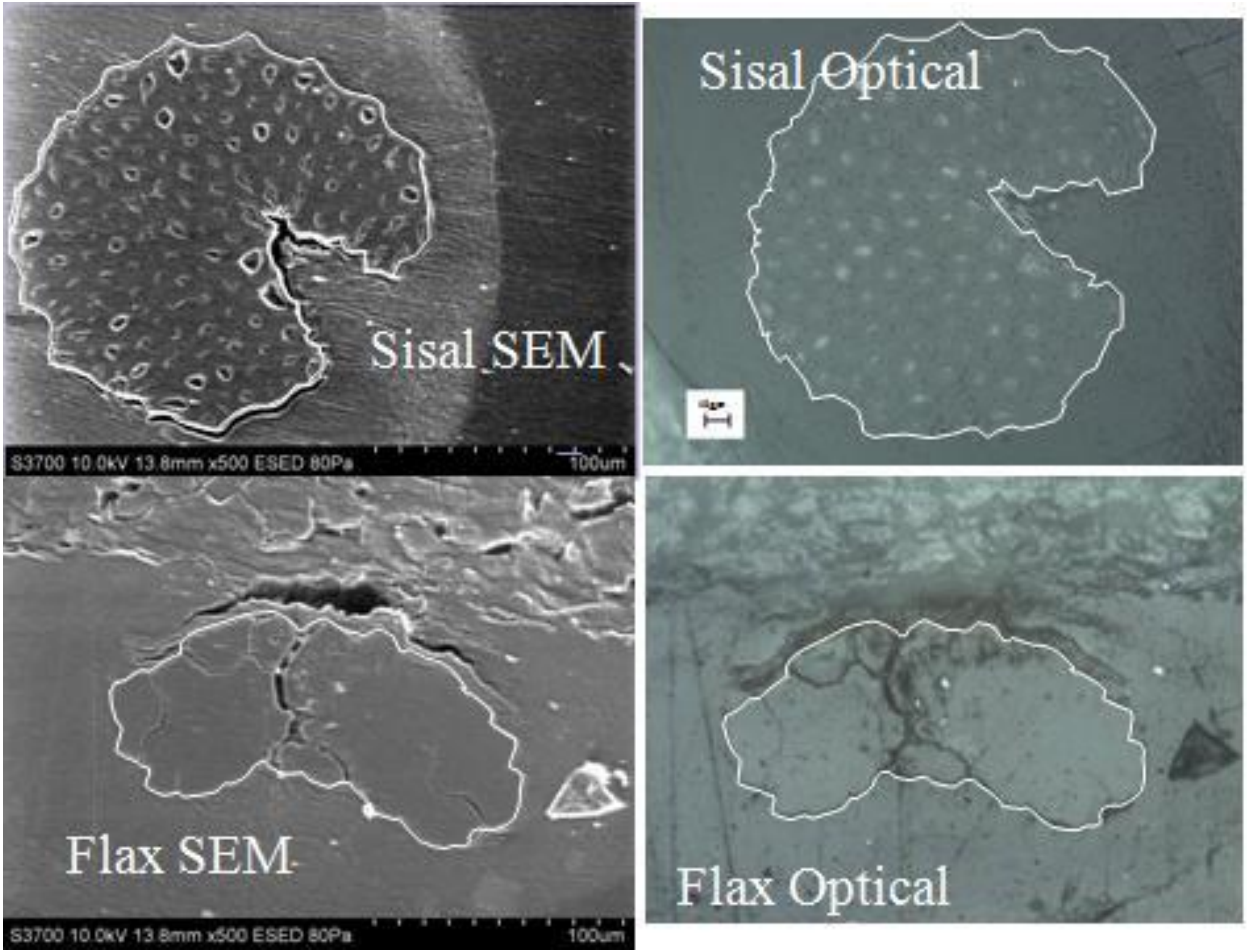
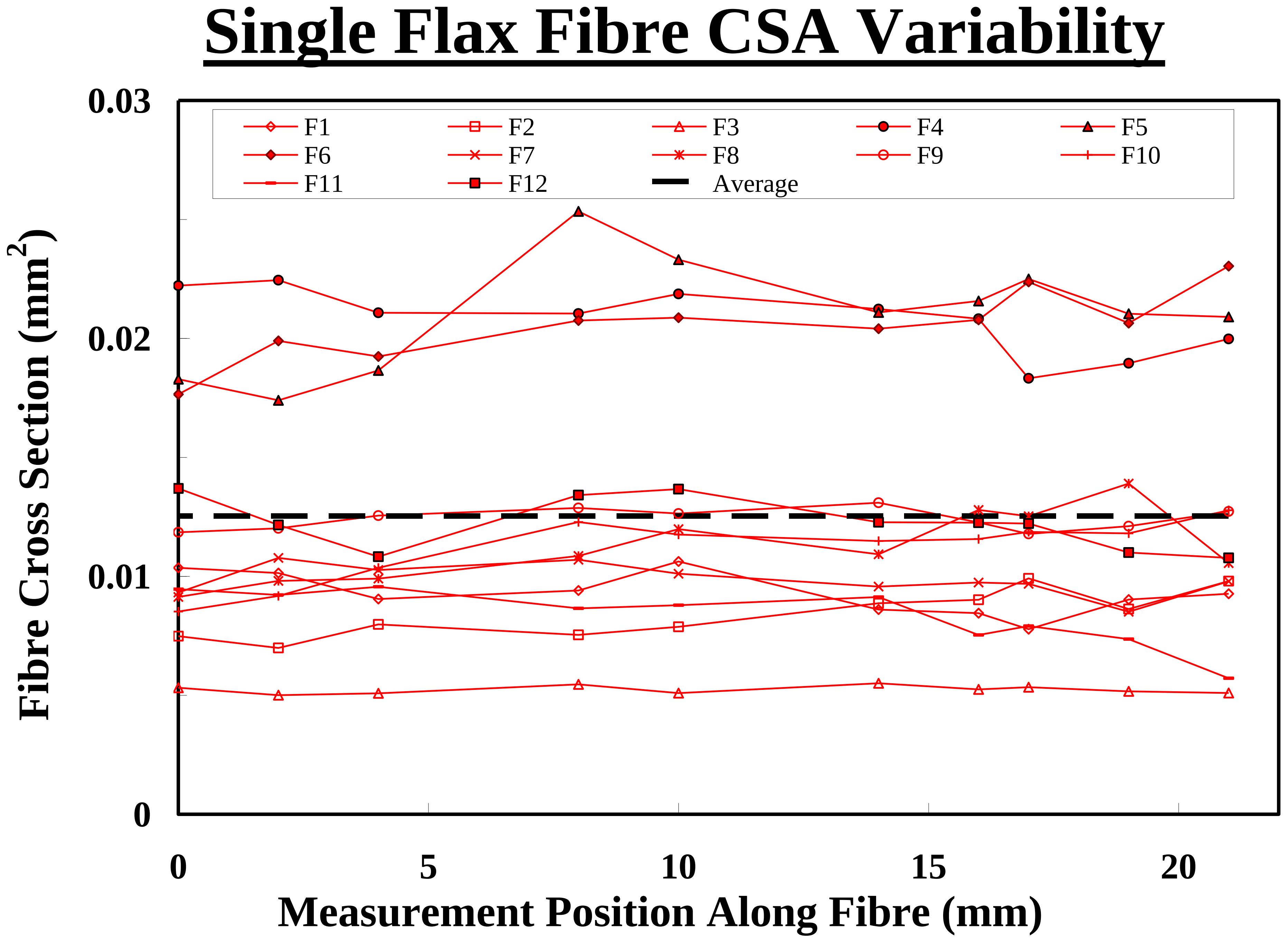
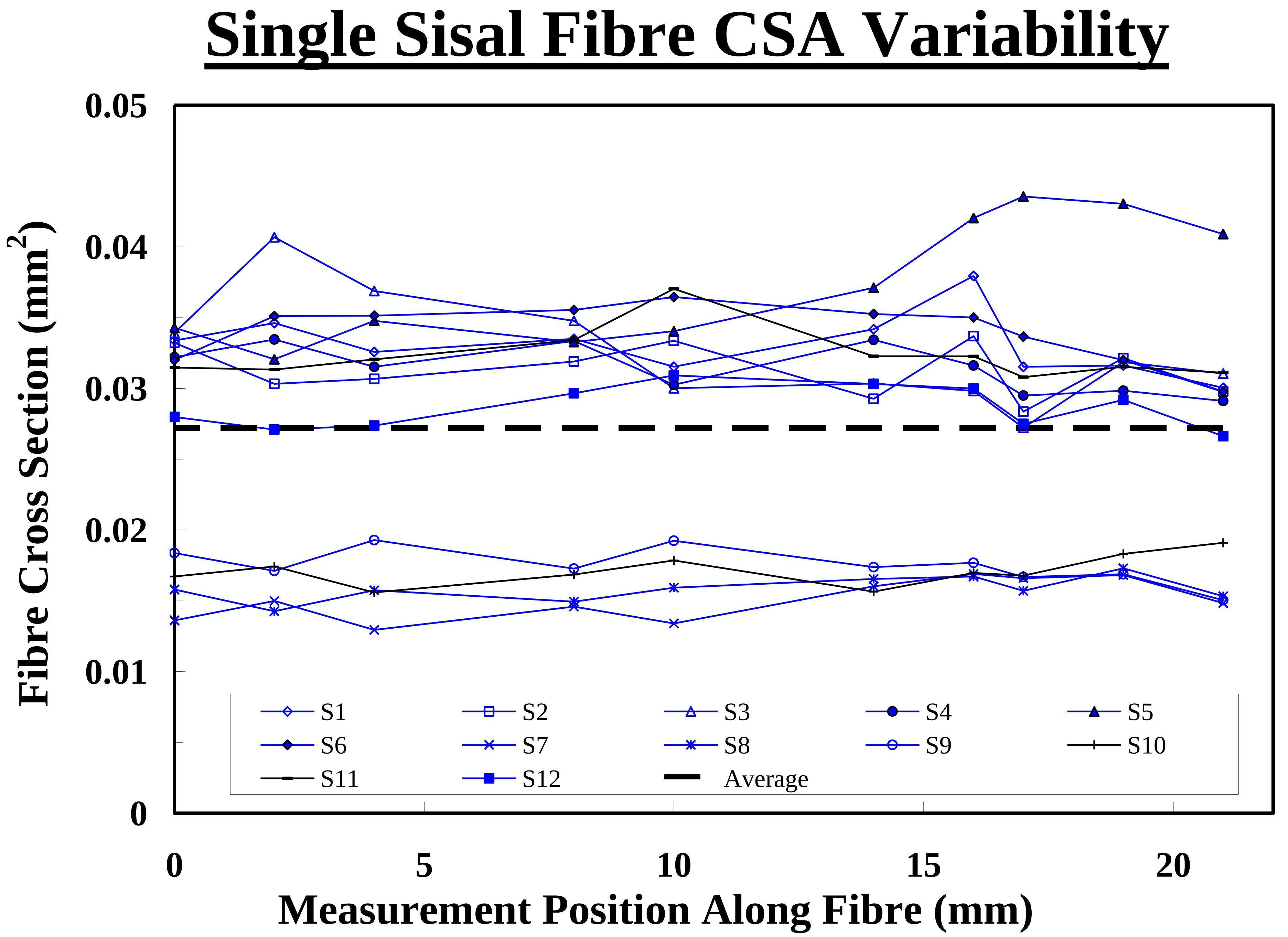
Single Fibre Cross Section Area




Single Flax Fibre CSA Variability
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
F11
F12
Average
0.03
0.02
0.01
0
0
5
10
15
20
Fibre Cross Section (mm2)
Measurement Position Along Fibre (mm)


Single Sisal Fibre CSA Variability
Fibre Cross Section (mm2)
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
Measurement Position Along Fibre (mm)
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
Average

Variability in CSA Determination

	Average CSA (mm^2)	% standard deviation of the average CSA	
		Intra-fibre	Inter-fibre
Sisal	0.0272	7.3%	30.3%
Flax	0.0125	9.2%	42.0%

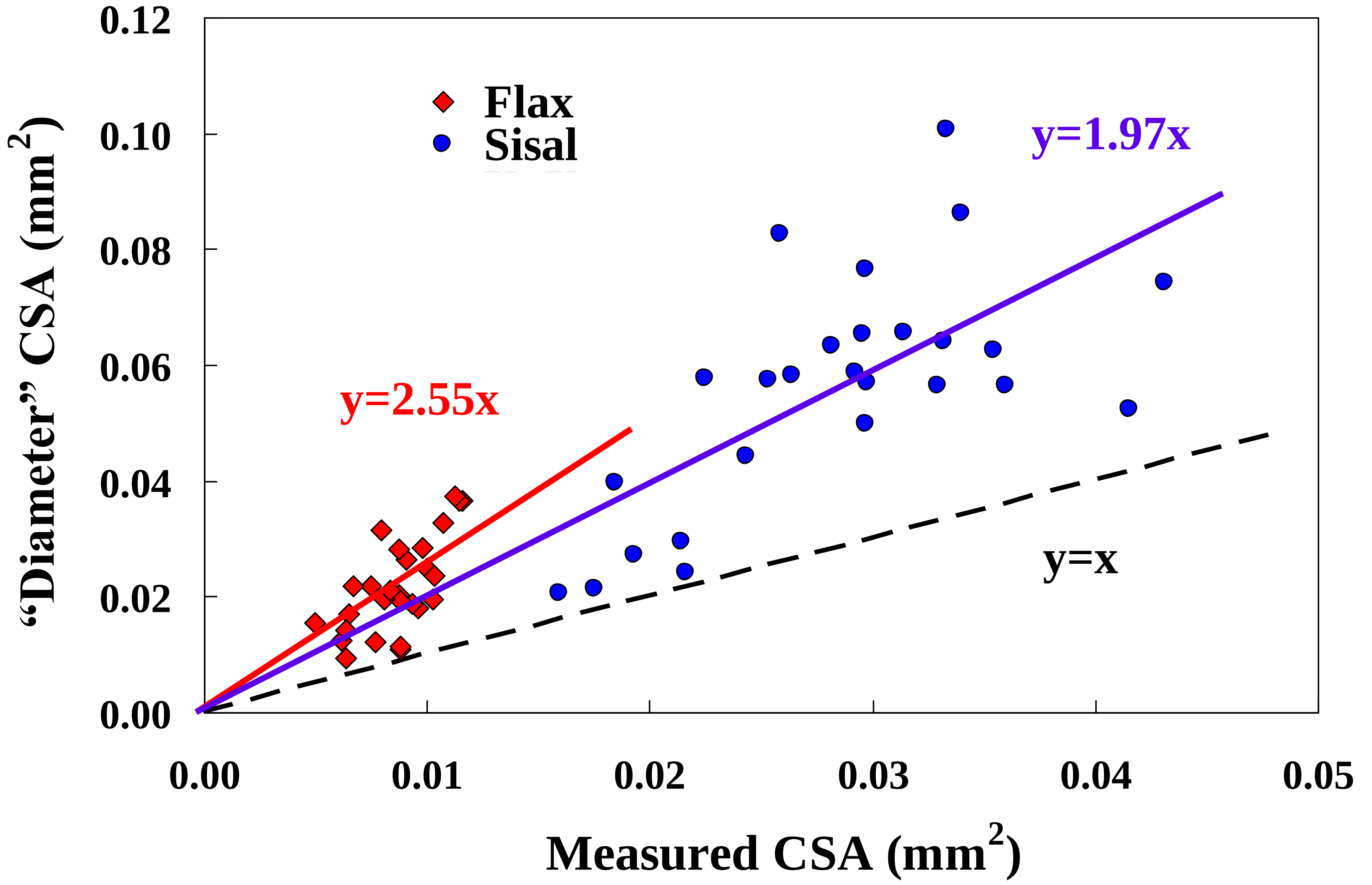
CSA variability

Flax > Sisal

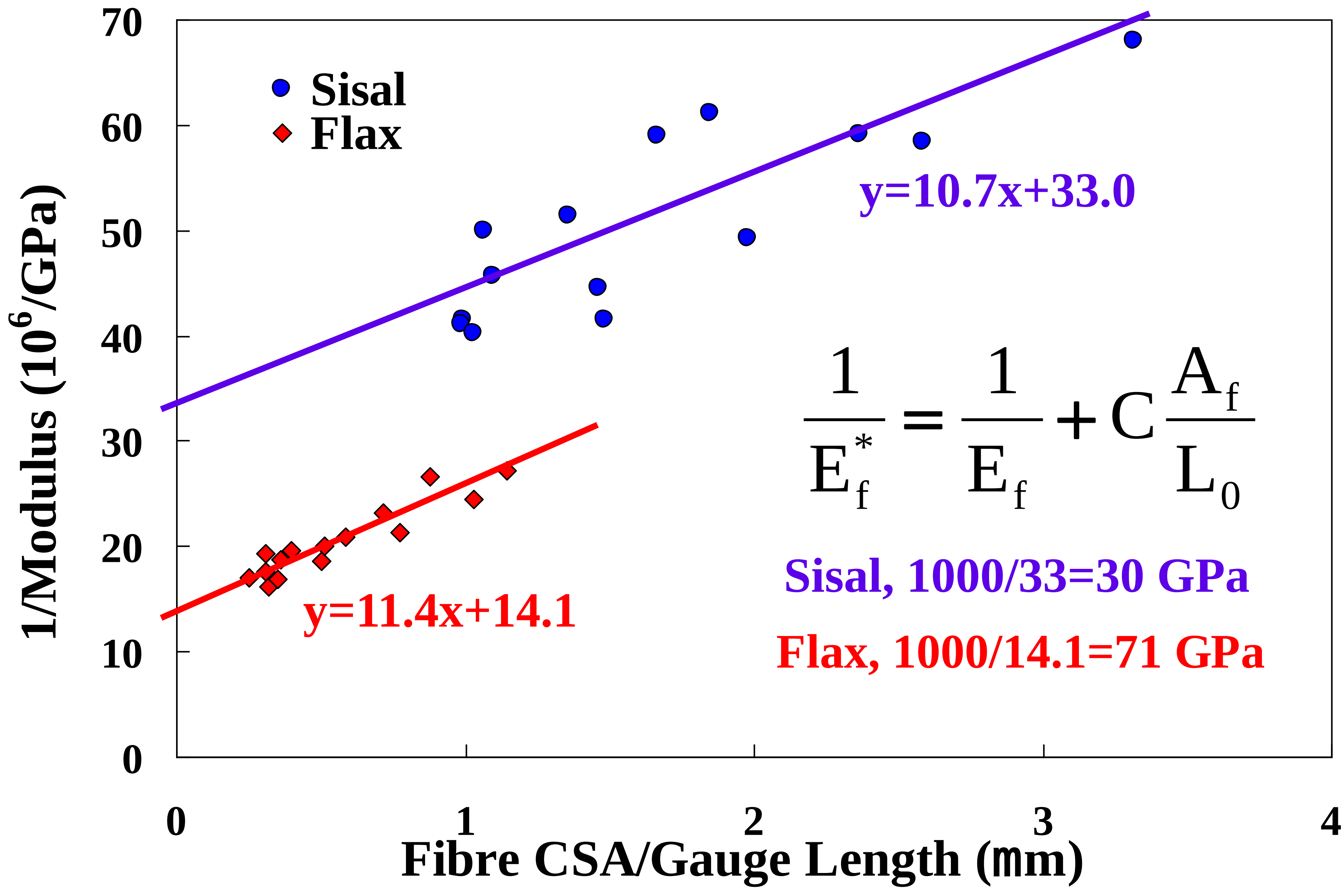
Inter-fibre >> Intra-fibre

Better to focus on measuring many different fibres rather than many measurement along the same fibre

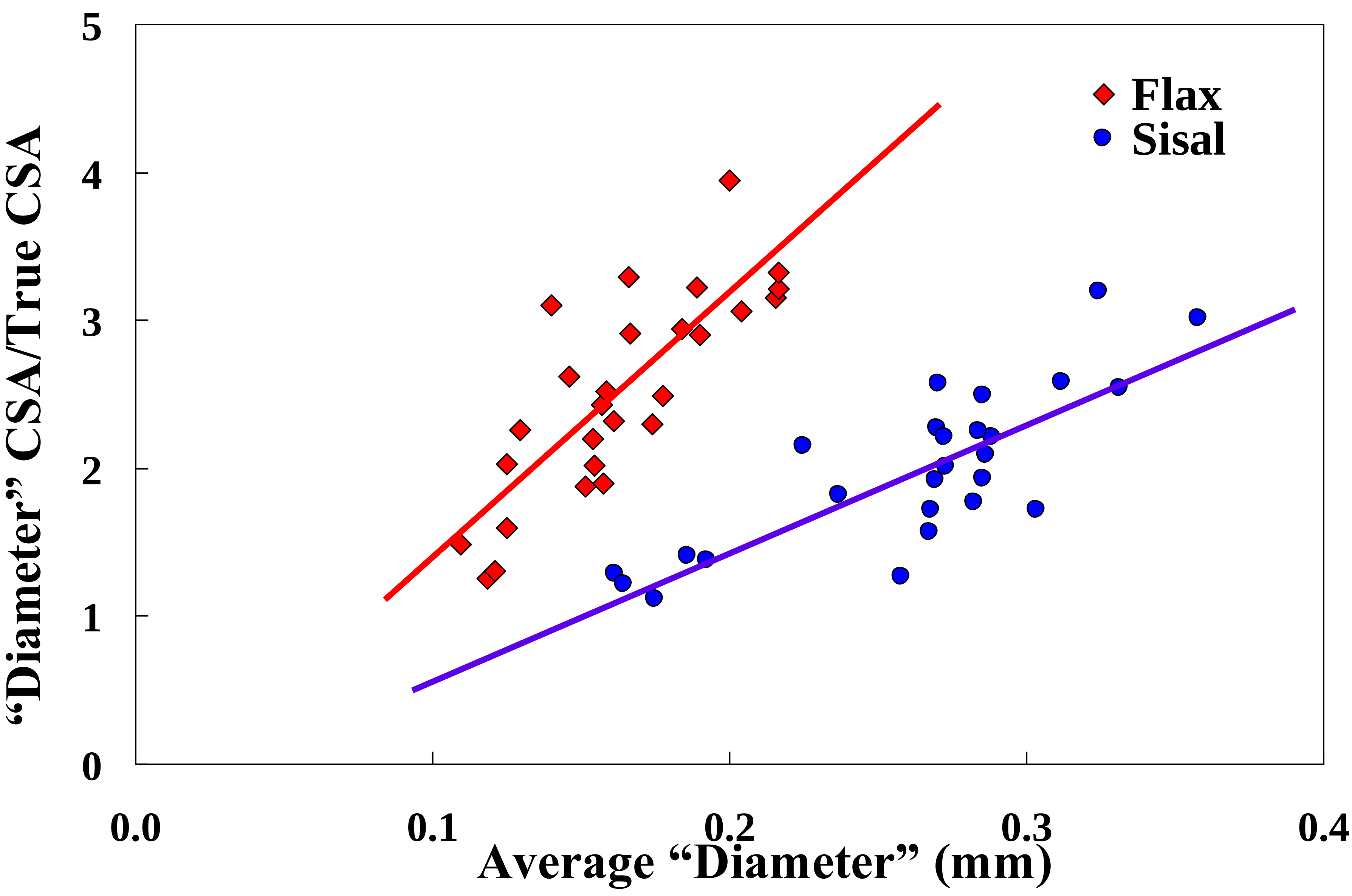
Natural Fibre CSA Evaluation



Single Fibre Modulus



Natural Fibre CSA Evaluation



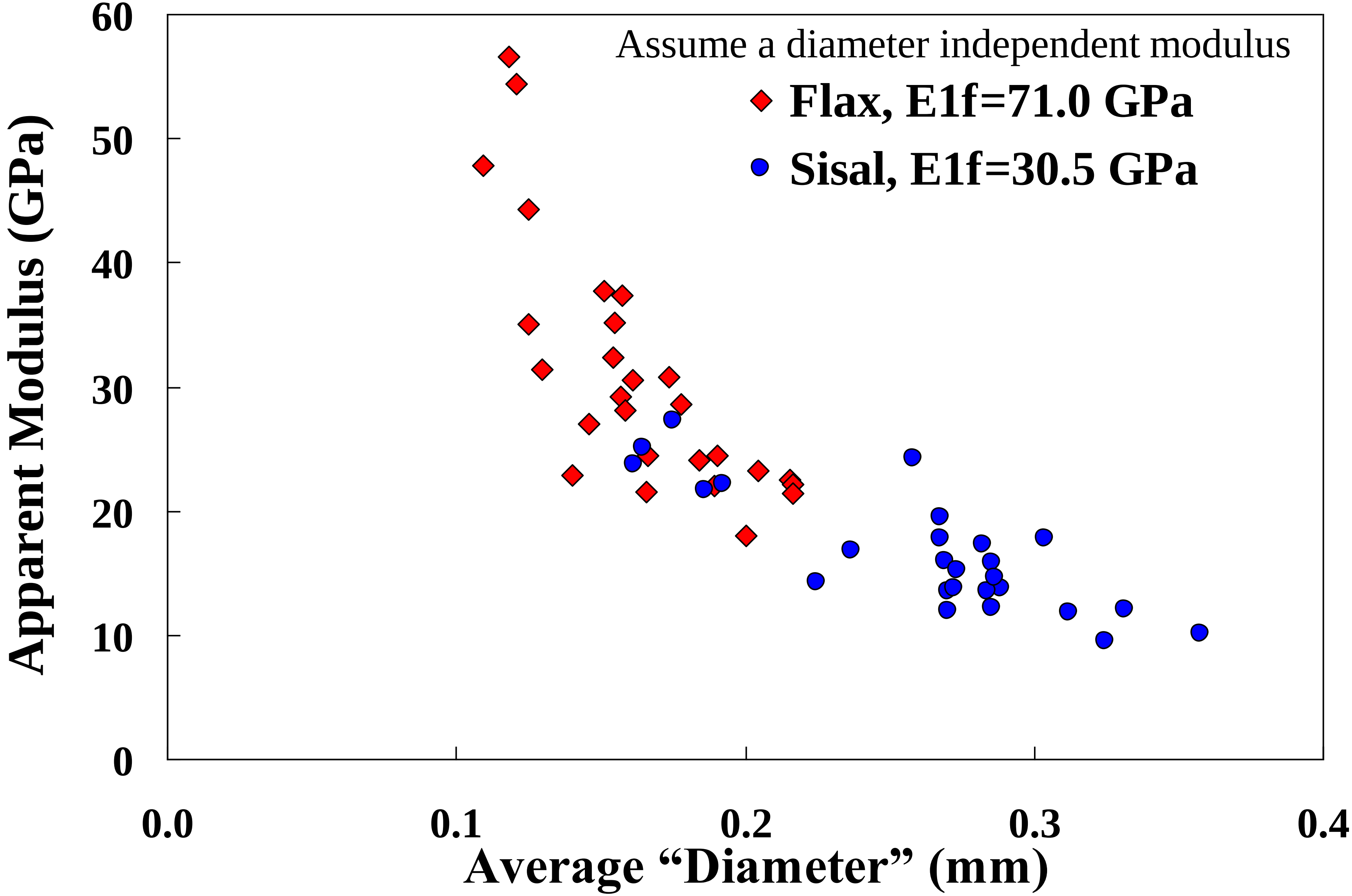
Natural Fibre CSA Evaluation

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

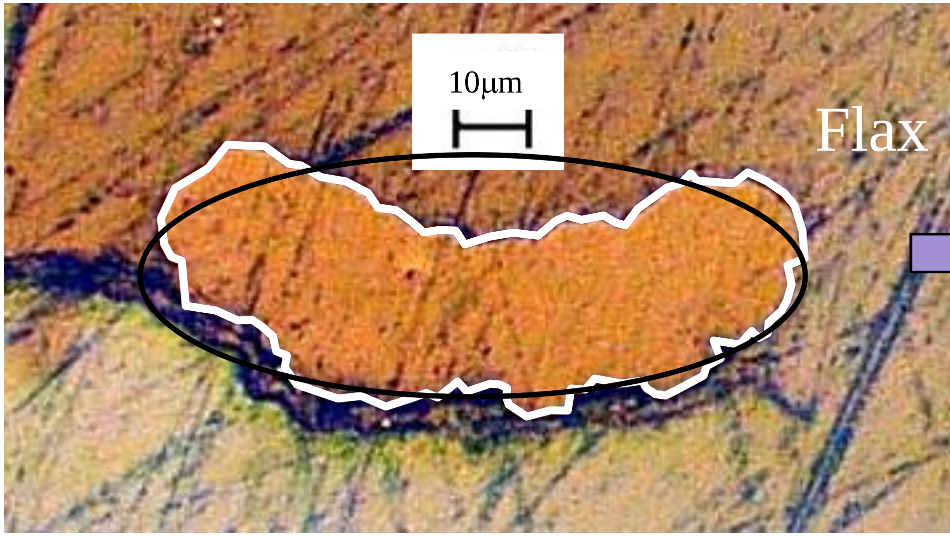
Effect CSA on Single Fibre Properties

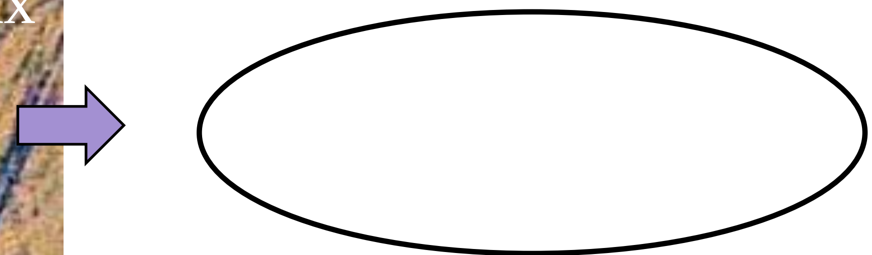
CSA method	Diameter	Actual
Flax Strength (MPa)	293	688
Sisal Strength (MPa)	255	530
Flax Modulus (GPa)	36	71
Sisal Modulus (GPa)	20	30

Effect of "Diameter" CSA on Apparent NF Modulus

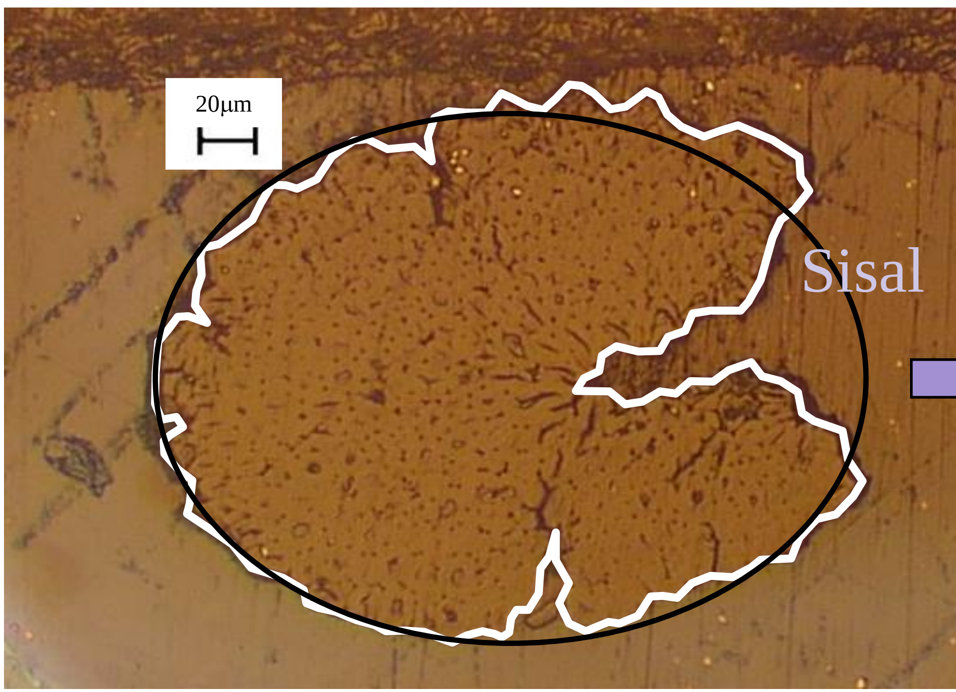


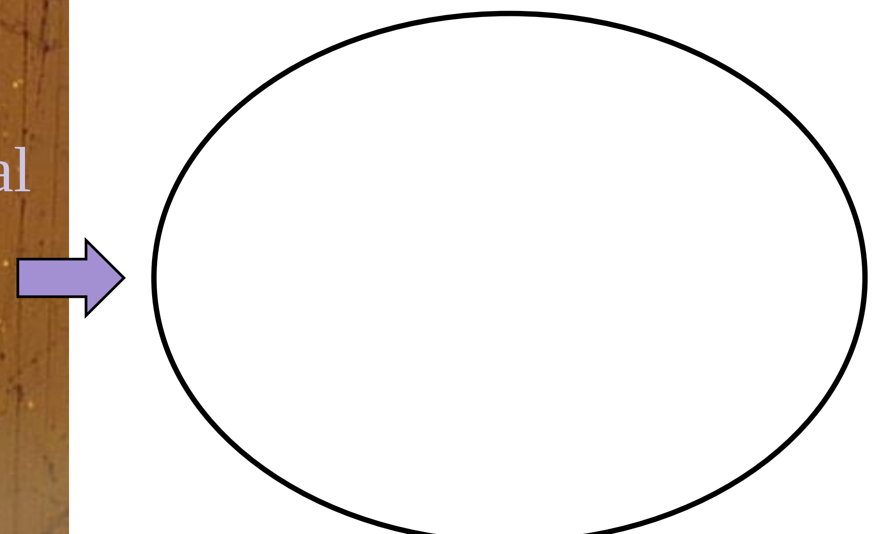
Simple Model of NF CSA "Diameter" Errors





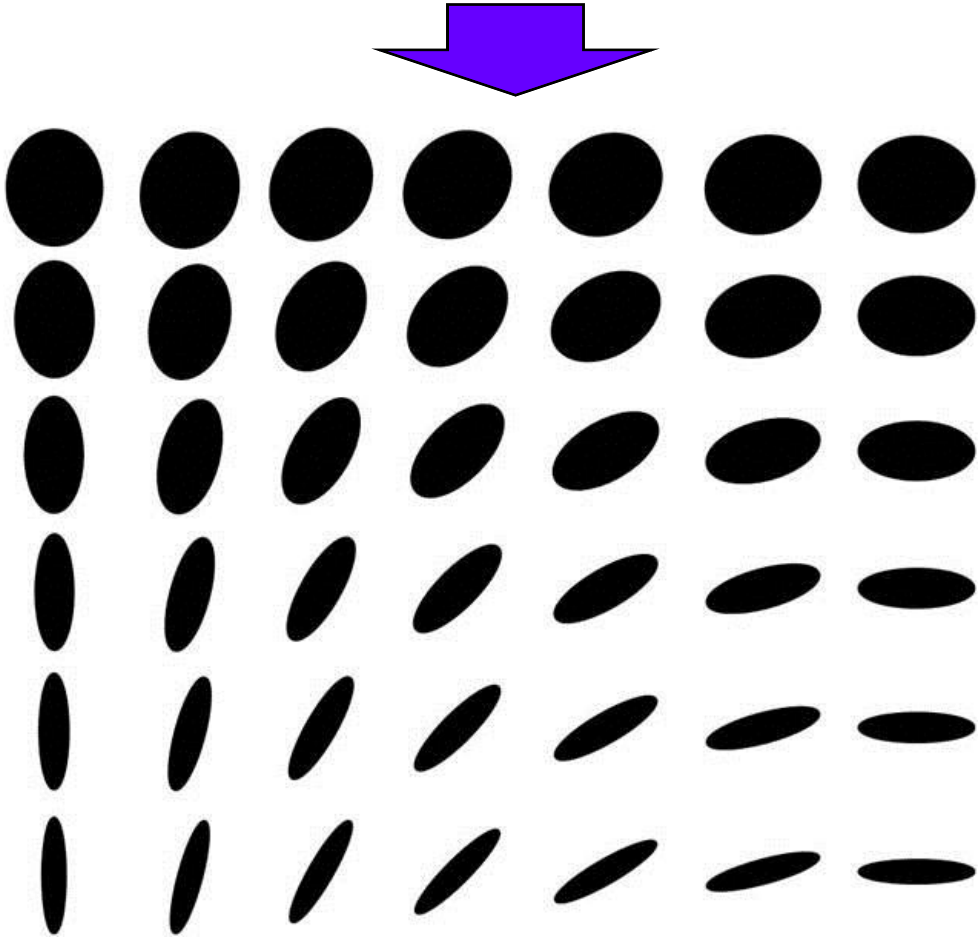
NF non-circular – simplest model is oval X-section



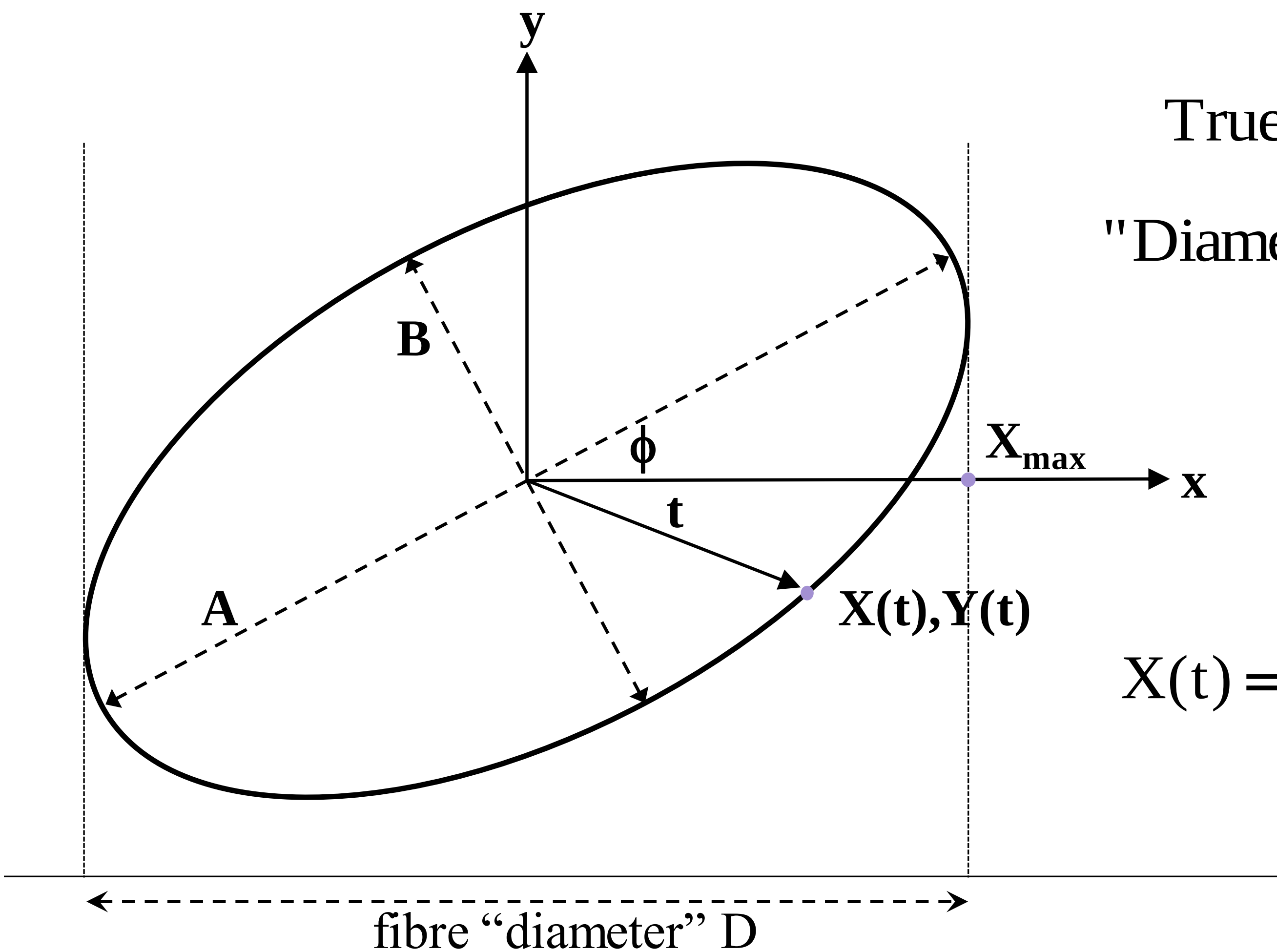


Simple Model of NF CSA "Diameter" Errors

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



Parameteric Ellipse Analysis



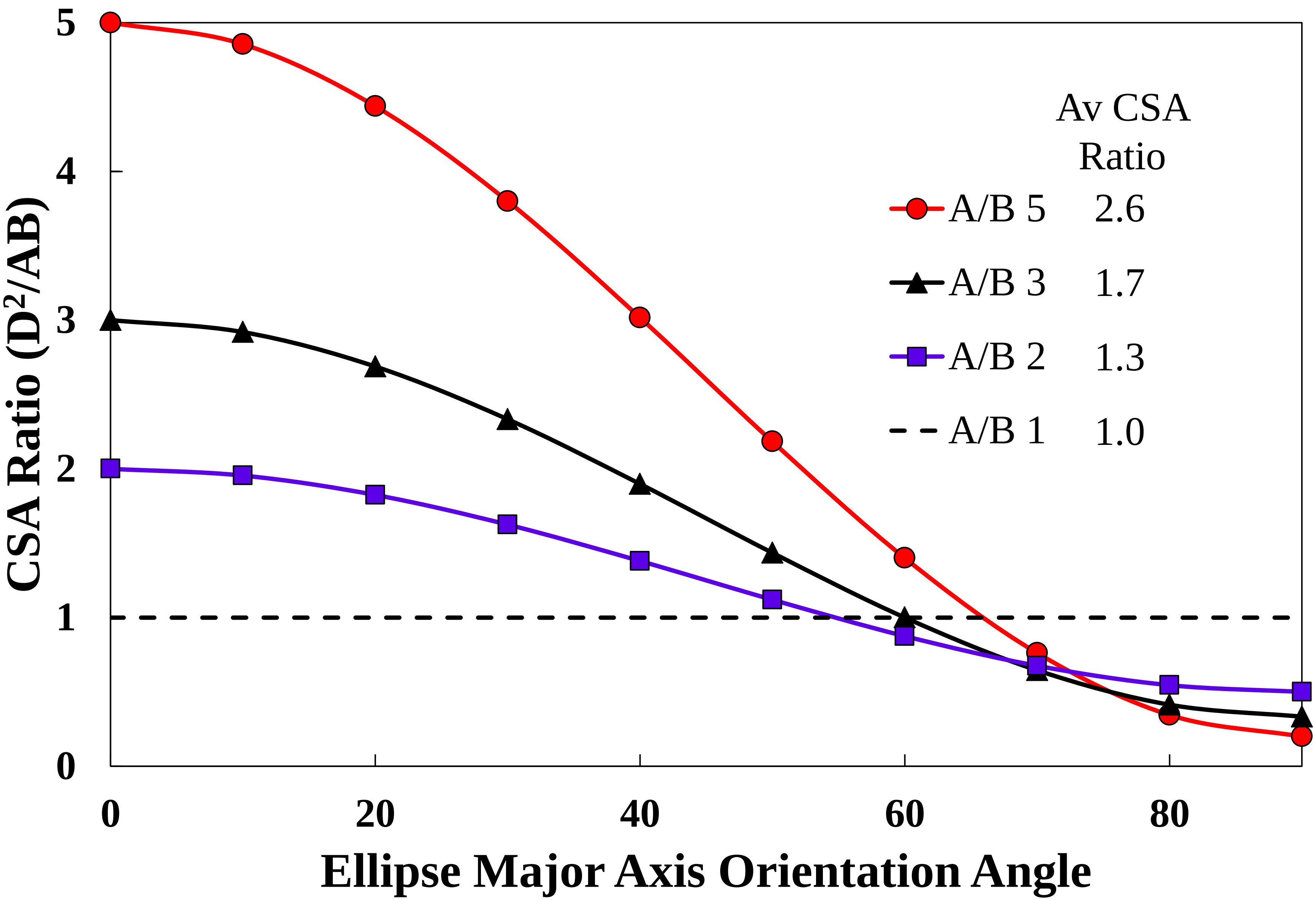
$$\text{True CSA} = 0.25\pi AB$$

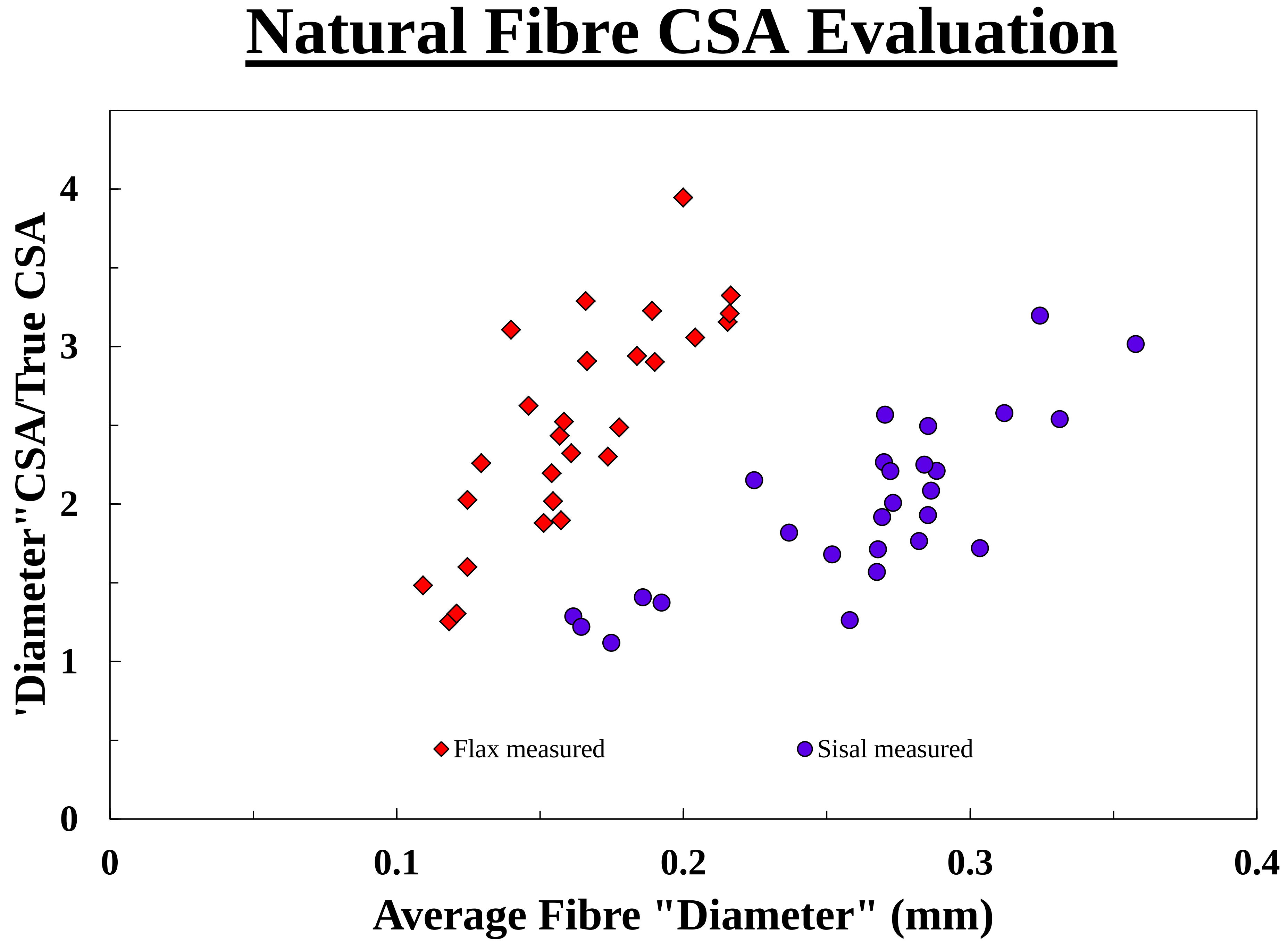
$$\text{"Diameter" CSA} = 0.25\pi D^2$$

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

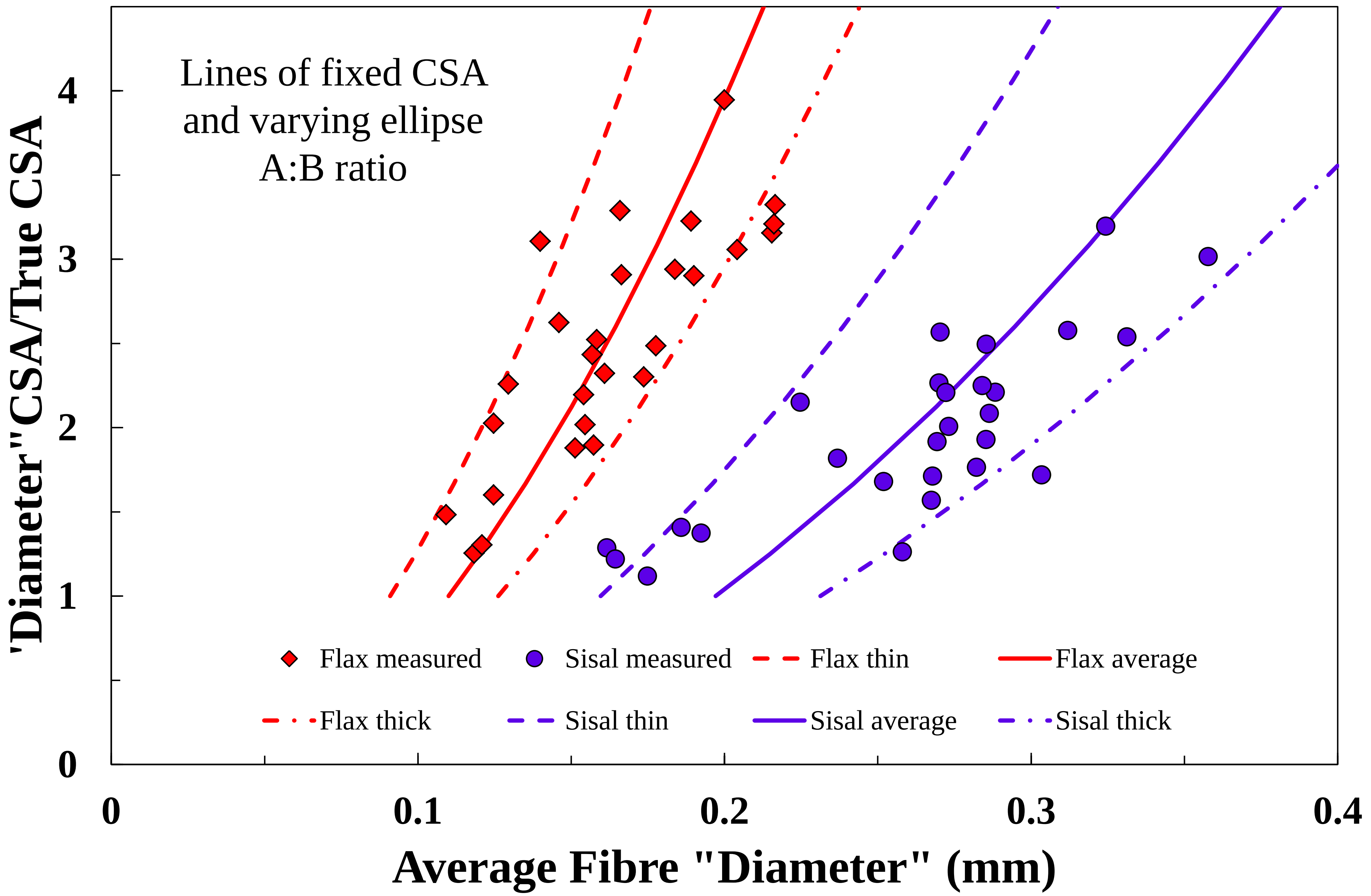
Can solve for X_{max} for any ϕ and then average over ϕ=0-90° for different A:B ratios

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

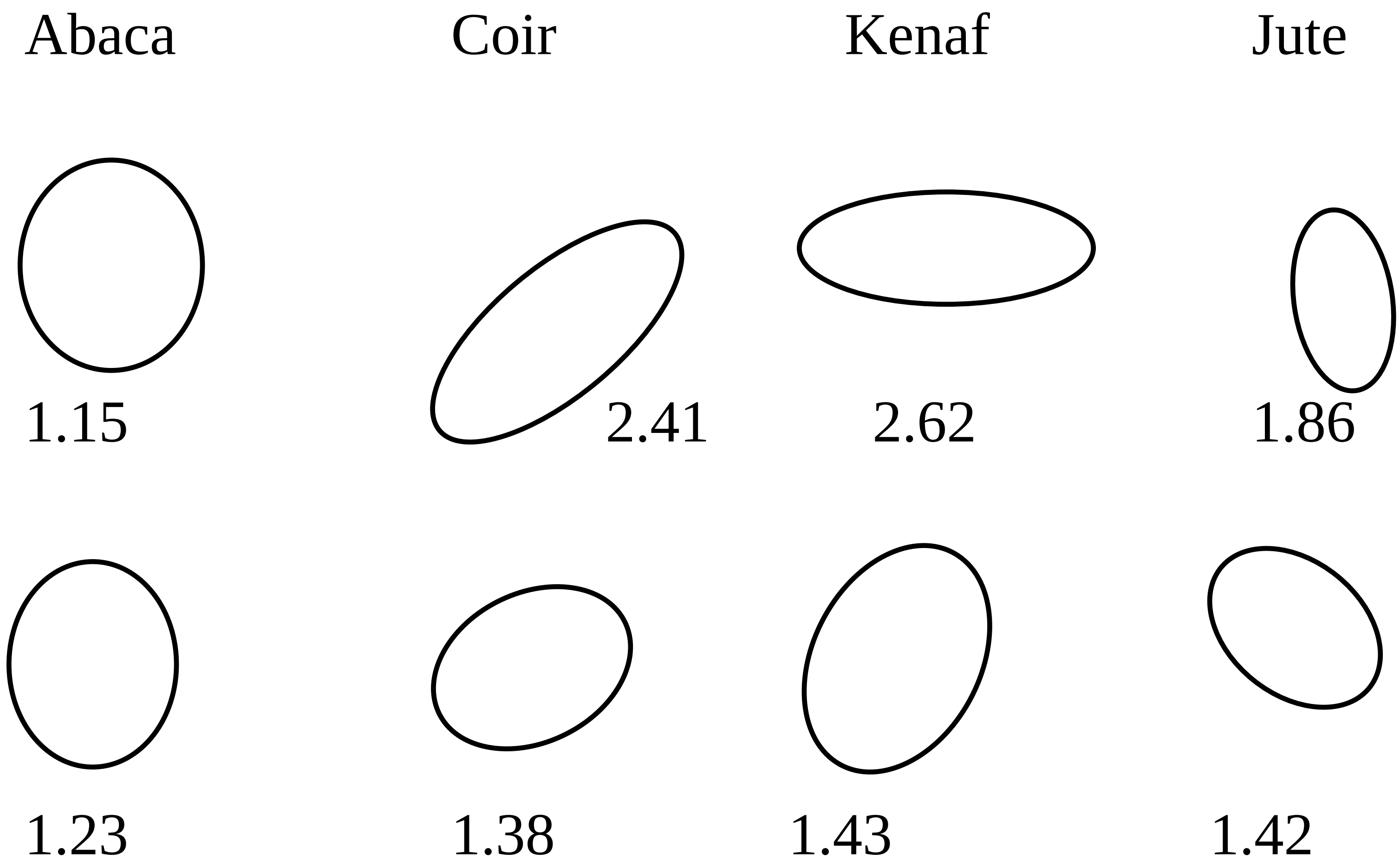
Natural Fibre CSA Evaluation



Other Fibres

Abaca Coir Kenaf Jute

Other Fibres Ellipse A:B



Similar issues probable in CSA estimation from fibre “diameter”

Summary Thermo-Mechanical Properties NF

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Shear Modulus (GPa)	30	1.7	1.1
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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

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

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

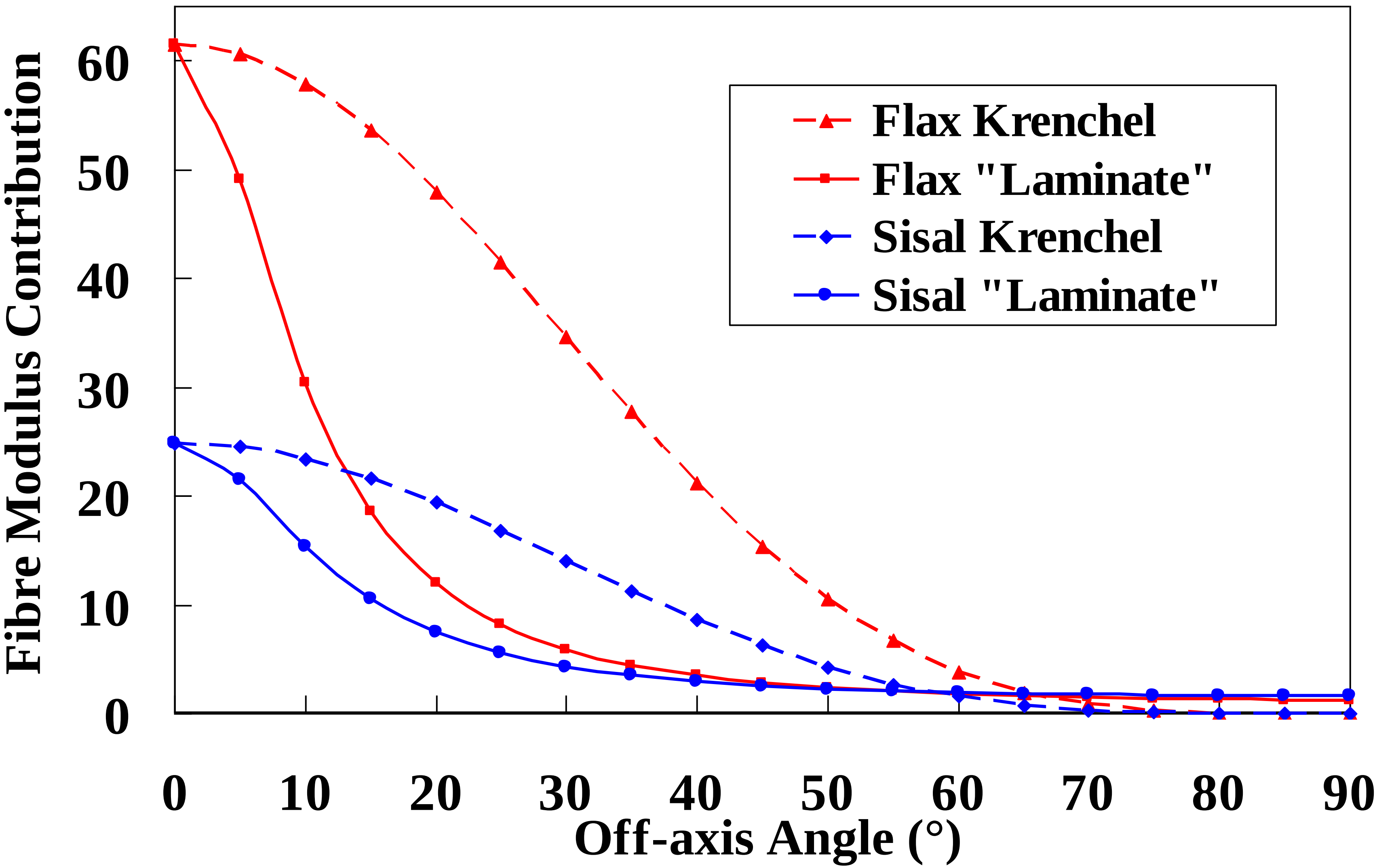
hence $\boldsymbol{\varepsilon}_x = \bar{S}_{11}\boldsymbol{\sigma}_x$

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

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

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



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.**
- **Comparison of the CSA of single Flax and Sisal fibre along their lengths indicated that –**
  - **Inter-fibre CSA variability >> Intra-fibre CSA variability**

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Conclusions (2)

- **A value for the fibre content of NFCs can be obtained from study of their moisture absorption characteristics.**
- **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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