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The Challenges of Natural Fibres as Engineering Composite Reinforcements

Jim Thomason, Fiona Gentles, Jamie Carruthers

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September 28-30th 2011
Vienna, Austria
Natural Fibre Composites

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

<table>
<thead>
<tr>
<th></th>
<th>Sisal</th>
<th>Jute</th>
<th>Flax</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (GPa)</td>
<td>17-28</td>
<td>20-45</td>
<td>27-70</td>
<td>75</td>
</tr>
<tr>
<td>Strength (GPa)</td>
<td>0.1-0.8</td>
<td>0.2-0.9</td>
<td>0.3-0.9</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Density</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Specific</td>
<td>13-21</td>
<td>15-35</td>
<td>18-47</td>
<td>29</td>
</tr>
<tr>
<td>Modulus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Fibre Content (% weight)</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Fibre</td>
<td>10</td>
</tr>
<tr>
<td>NF 20 GPa (Sisal)</td>
<td>8</td>
</tr>
<tr>
<td>NF 40 GPa (Jute)</td>
<td>6</td>
</tr>
<tr>
<td>NF 60 GPa (Flax)</td>
<td>4</td>
</tr>
</tbody>
</table>

Remember – comparison on weight content (i.e. specific fibre properties) means NO weight saving advantage!
Thermoelastic Anisotropy of Flax and Sisal Fibres

• Goal
  – Quantify anisotropy of Flax & Sisal fibres
  – Full thermoelastic characterisation

• Measure
  – UD fibre-epoxy laminates $E(\theta,T), G_{12},\nu_{12}, \nu_{21},\alpha(\theta,T)$
  – Epoxy matrix $E_m(T),\nu_m, \alpha_m(T)$
  – Laminate fibre volume fraction ?
  – Flax & Sisal fibre $E_{1f}(T)$ (fibre cross section ?)

• Calculate
  – $E_{1f}(T), E_{2f}(T), G_{12f}(T), \nu_{12f}(T), \alpha_{1f}(T), \alpha_{2f}(T)$
Water Absorption for Fibre Content

Sisal Fibres, $\Delta m_m = \Delta M_m / M_m$

Sisal-Epoxy Composites, $\Delta m_c = \Delta M_c / M_c$

Epoxy Matrix, $\Delta m_m = \Delta M_m / M_m$
NF Composite Fibre Volume Fraction

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

- Sisal fibre density \( \rho_f = 1400 \text{ kg/m}^3 \)
- Flax fibre density \( \rho_f = 1400 \text{ kg/m}^3 \)
- Epoxy matrix density \( \rho_m = 1100 \text{ kg/m}^3 \)

- Sisal composite \( W_f = 0.46, \quad V_f = 0.4 \)
- Flax composite \( W_f = 0.36, \quad V_f = 0.31 \)
Anisotropy of Fibre Modulus

Temperature (°C)

Modulus (GPa)

-60 -40 -20 0 20 40 60

0.1 1 10 100

Flax E1
Flax E2
Flax G12
Sisal E1
Sisal E2
Sisal G12
Fibre Expansion Coefficients

Temperature (°C)

CLTE (m/m°C)

Fibre Transverse
- Sisal Transverse
- Flax Transverse

Fibre Axial
- Sisal Axial
- Flax Axial
## Summary Thermo-Mechanical Properties NF

<table>
<thead>
<tr>
<th></th>
<th>Glass</th>
<th>Flax</th>
<th>Sisal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal Modulus (GPa)</strong></td>
<td>75</td>
<td>61.5</td>
<td>24.9</td>
</tr>
<tr>
<td><strong>Transverse Modulus (GPa)</strong></td>
<td>75</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Shear Modulus (GPa)</strong></td>
<td>30</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Axial LCTE (µm/m.°C)</strong></td>
<td>5</td>
<td>-7.3</td>
<td>-2.7</td>
</tr>
<tr>
<td><strong>Transverse LCTE (µm/m.°C)</strong></td>
<td>5</td>
<td>71</td>
<td>73</td>
</tr>
</tbody>
</table>
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 Measurements

<table>
<thead>
<tr>
<th>Series 1</th>
<th>Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Single flax and sisal fibres mounted on test card windows</td>
<td>1. Single fibre “diameter” determined by averaging 4 transverse measurements</td>
</tr>
<tr>
<td>• Fibre “diameter” determined by averaging 4 transverse measurements</td>
<td>2. Fibres embedded, cut and polished</td>
</tr>
<tr>
<td>• Fibre tensile testing (10,15,20,25,30 mm gauge)</td>
<td>3. “true” cross sectional area determined</td>
</tr>
<tr>
<td>• Residual fibre ends glued to card tab sectioned in 2 places and “true” cross sectional area determined</td>
<td>4. Sample ground down 2mm and polished</td>
</tr>
<tr>
<td></td>
<td>5. Steps 3-4 repeated 10x</td>
</tr>
</tbody>
</table>
Single Fibre Cross Section Area

Sisal SEM

Sisal Optical

Flax SEM

Flax Optical
Single Flax Fibre CSA Variability

Fibre Cross Section (mm$^2$)

Measurement Position Along Fibre (mm)
Single Sisal Fibre CSA Variability

Fibre Cross Section (mm$^2$)

Measurement Position Along Fibre (mm)

- S1
- S2
- S3
- S4
- S5
- S6
- S7
- S8
- S9
- S10
- S11
- S12
- Average
Variability in CSA Determination

<table>
<thead>
<tr>
<th></th>
<th>Average CSA (mm²)</th>
<th>% standard deviation of the average CSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Intra-fibre</td>
</tr>
<tr>
<td>Sisal</td>
<td>0.0272</td>
<td>7.3%</td>
</tr>
<tr>
<td>Flax</td>
<td>0.0125</td>
<td>9.2%</td>
</tr>
</tbody>
</table>

CSA variability

- Flax > Sisal
- Inter-fibre >> Intra-fibre

Better to focus on measuring many different fibres rather than many measurements along the same fibre.
Natural Fibre CSA Evaluation

"Diameter" CSA (mm²) vs. Measured CSA (mm²)

- Flax
- Sisal

- y = 1.97x
- y = 2.55x
- y = x
Single Fibre Modulus

\[
\frac{1}{E_f} = \frac{1}{E_f^*} + C \frac{A_f}{L_0}
\]

Sisal, \( \frac{1000}{33} = 30 \) GPa

Flax, \( \frac{1000}{14.1} = 71 \) GPa

\[
y = 10.7x + 33.0
\]

\[
y = 11.4x + 14.1
\]
Natural Fibre CSA Evaluation

"Diameter" CSA/True CSA vs. Average "Diameter" (mm)

- Red diamonds: Flax
- Blue circles: Sisal
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

<table>
<thead>
<tr>
<th>CSA method</th>
<th>Diameter</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flax Strength (MPa)</strong></td>
<td>293</td>
<td>688</td>
</tr>
<tr>
<td><strong>Sisal Strength (MPa)</strong></td>
<td>255</td>
<td>530</td>
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<td>71</td>
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Effect of “Diameter” CSA on Apparent NF Modulus

Assume a diameter independent modulus

- Flax, $E_{1f}=71.0$ GPa
- Sisal, $E_{1f}=30.5$ GPa

Average “Diameter” (mm) vs. Apparent Modulus (GPa)
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.

Transverse view from microscope
Parameteric Ellipse Analysis

True CSA = 0.25πAB

"Diameter" CSA = 0.25πD²

X(t) = 0.5ACos(t)Cos(φ) − 0.5BSin(t)Sin(φ)

Can solve for X_max for any φ and then average over φ=0-90° for different A:B ratios
Natural Fibre CSA Evaluation

Lines of fixed CSA and varying ellipse A:B ratio
<table>
<thead>
<tr>
<th></th>
<th>Abaca</th>
<th>Coir</th>
<th>Kenaf</th>
<th>Jute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipse A:B</td>
<td>1.15</td>
<td>2.41</td>
<td>2.62</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>1.23</td>
<td>1.38</td>
<td>1.43</td>
<td>1.42</td>
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Similar issues probable in CSA estimation from fibre “diameter”
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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 \( \eta_0 \)

\[ \eta_0 = \cos^4(\theta) \]

• NF is more like an orthotropic composite material
• Apply laminate theory to model reinforcement performance
**Engineering Stiffness, Off-axis Orthotropic Lamina**

\[
E_x = \frac{\sigma_x}{\varepsilon_x} \quad \varepsilon_{xy} = \overline{S} \sigma_{xy} \quad \text{set} \quad \sigma_{xy} = \{\sigma_x, 0, 0\}
\]

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

hence \( \varepsilon_x = \overline{S}_{11} \sigma_x \)

and for all \( \theta \), \( E_x = \frac{1}{\overline{S}_{11}} \)

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

The terms \( S_{11}, \) etc., are found from

\[
S =
\begin{bmatrix}
\frac{1}{E_{11}} & \frac{-v_{21}}{E_{22}} & 0 \\
\frac{-v_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\
0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\]
Off-axis Stiffness Contribution of Anisotropic Fibre

Fibre Modulus Contribution

Off-axis Angle (°)

- Flax Krenchel
- Flax "Laminate"
- Sisal Krenchel
- Sisal "Laminate"
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
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.