Comparison of Wood and Non-wood Market Pulps for Tissue Applications

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Ronalds Gonzalez ¹, Lee Reisinger ³, Dale Kavalew ⁴, Clay Cambell ²

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⁴ Dale Kavalew and Associates LLC
Objectives and Goals

✓ Understand what **fibers features** are desired for a given **tissue property**
✓ Evaluate what **fibers** are suitable for a specific **tissue application**
✓ Create a **data base (fibers vs properties)** to optimize performance and/or **cost** of tissue products

Systematic evaluation of the **impact of different fibers** (wood, non-wood and recycled) on the **performance** and **value** of tissue paper
Price and Performance

LDC = Light Dry Crepe
UCTAD = Un-Creped Through Air Drying
CTAD = Creped Through Air Drying
DRC = Double Re-Crepe
ATMOS = Advanced Tissue Molding System

R² = 0.72

USD 230 for additional g H₂O / g tissue

de Assis et al. (2018), BioResources 13(3).
# Cellulosic Fibers and Tissue Paper Performance

<table>
<thead>
<tr>
<th>Hardwood Fibers</th>
<th>Softwood Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Short Fibers (length ~ 1 mm)</td>
<td>• Long Fibers (length ~ 2.5 mm)</td>
</tr>
<tr>
<td>• Source of Softness and Absorbency</td>
<td>• Source of Strength and Absorbency</td>
</tr>
<tr>
<td>• Single Species</td>
<td>• Single Species</td>
</tr>
<tr>
<td>Northern: birch, aspen</td>
<td>Northern: spruce</td>
</tr>
<tr>
<td>Southern: eucalyptus, acacia</td>
<td>Southern: radiata pine</td>
</tr>
<tr>
<td>• Multiple Species</td>
<td>• Multiple Species</td>
</tr>
<tr>
<td>Northern: aspen, maple, birch, beech</td>
<td>Northern: pine, spruce, fir, hemlock, cedar, larch</td>
</tr>
<tr>
<td>Southern: gum, oak, poplar, ash, beech</td>
<td>Southern: pines-loblolly, slash, shortleaf, longleaf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Wood Fibers</th>
<th>Recycled Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Diverse Fiber Morphology</td>
<td>• Fiber Blend (long and short fibers)</td>
</tr>
<tr>
<td>• Diverse Performance</td>
<td>• Low Performance (stiff fibers, fines, impurities)</td>
</tr>
<tr>
<td>• High Content of Fines</td>
<td>• Cheaper than Virgin Fibers</td>
</tr>
<tr>
<td>• Examples: wheat straw, bagasse, bamboo</td>
<td>Examples: SOP (Sorted Office Paper)</td>
</tr>
<tr>
<td></td>
<td>OCC (Old Corrugated Containers)</td>
</tr>
</tbody>
</table>

Nanko et al. (2005), The World of Market Pulp.
Woody, Non-woody and Recycled Pulps

• Morphology (Fiber Quality Analyzer - OpTest)

<table>
<thead>
<tr>
<th>Width (μm)</th>
<th>BEK</th>
<th>Acacia</th>
<th>SBHK</th>
<th>NBHK</th>
<th>SBSK</th>
<th>NBSK</th>
<th>DIP</th>
<th>BWS</th>
<th>SBWS Bamboo</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.4</td>
<td>17.0</td>
<td>18.5</td>
<td>16.6</td>
<td>28.1</td>
<td>28.4</td>
<td>18.1</td>
<td>14.8</td>
<td>16.5</td>
<td>15.4</td>
</tr>
<tr>
<td>Coarseness (mg/km)</td>
<td>73</td>
<td>62</td>
<td>110</td>
<td>72</td>
<td>216</td>
<td>135</td>
<td>98</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td>Length Weighted Fines (%)</td>
<td>4.5</td>
<td>5.0</td>
<td>14.9</td>
<td>9.5</td>
<td>5.0</td>
<td>3.8</td>
<td>10.4</td>
<td>18.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Population (million fibers/g)</td>
<td>18.8</td>
<td>23.5</td>
<td>10.4</td>
<td>22.9</td>
<td>2.7</td>
<td>4.3</td>
<td>13.5</td>
<td>19.3</td>
<td>16.6</td>
</tr>
</tbody>
</table>

10 Fibers Evaluated

<table>
<thead>
<tr>
<th>Hardwoods</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEK = Bleached Eucalyptus Kraft</td>
</tr>
<tr>
<td>Acacia = Bleached Acacia Kraft</td>
</tr>
<tr>
<td>SBHK = Southern Bleached Hardwood Kraft</td>
</tr>
<tr>
<td>NBHK = Northern Bleached Hardwood Kraft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Softwoods</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBSK = Southern Bleached Softwood Kraft</td>
</tr>
<tr>
<td>NBSK = Northern Bleached Softwood Kraft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recycled</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIP = Deinked Pulp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWS = Bleached Wheat Straw Soda</td>
</tr>
<tr>
<td>SBWS = Semi-bleached Wheat Straw Soda</td>
</tr>
<tr>
<td>Bamboo = Bleached Bamboo Soda</td>
</tr>
</tbody>
</table>
Handsheets Making

- Modified TAPPI handsheet making procedure (30 g/m², uncreped)
Tensile Strength

- Tensile Strength vs Freeness

Breaking Length (km)

Freeness (CSF)

Longer fibers

• Tensile Strength vs Freeness
Fibers/Sheet Structure and Water Absorbency

• Water Absorbtion in Tissue Paper

✓ Ability to absorb and retain water
✓ Essential property for toweling products
✓ Absorbency rate: how fast
✓ Absorbency capacity: how much
✓ High absorbency → hydrophilic fibers forming a porous and stable fiber web structure

1 Ko et al. (2016), J. of Korea Tappi 48(5);
Water Absorbency and Bulk

Water Absorbency (g/g)

Bulk (cm³/g)

R² = 0.77

Tissue Paper Cross Section
Water Absorbency vs Bulk

- Longer fibers: Higher coarseness
- Shorter fibers: Lower coarseness

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Water Absorbency (g/g)</th>
<th>Bulk (cm³/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acacia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBHK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NBHK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBSK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NBSK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BWS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBWS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bamboo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Water Absorbency vs Fiber Dimensions

Water Absorbency (g/g) vs Bulk (cm³/g)

- **BEK**
- **Acacia**
- **SBHK**
- **NBHK**

### Width (µm)
- BEK: 16.4
- Acacia: 17.0
- SBHK: 18.5
- NBHK: 16.6

### Coarseness (mg/km)
- BEK: 73
- Acacia: 62
- SBHK: 110
- NBHK: 72

### Length Weighted Fines (%)
- BEK: 4.5
- Acacia: 5.0
- SBHK: 14.9
- NBHK: 9.5

### Population (million fibers/g)
- BEK: 18.8
- Acacia: 23.5
- SBHK: 10.4
- NBHK: 22.9

### Length Weighted Fiber Length (mm)
- BEK: 0.82
- Acacia: 0.78
- SBHK: 1.11
- NBHK: 0.70
Water Absorbency and Swelling

• Sheet Swelling

\[ V_{\text{swelling}} = V_{\text{sheet wet}} - V_{\text{sheet dry}} \]

Measures change in pore volume and change in fiber dimensions

\[
ABS_{\text{swelling}} \left( \frac{g_{\text{water}}}{g_{\text{fiber}}} \right) = \frac{m_{\text{water}}}{m_{\text{sheet}}} = \frac{\rho_{\text{water}}}{\rho_{\text{sheet wet}}} - \frac{\rho_{\text{water}}}{\rho_{\text{sheet dry}}} 
\]

<table>
<thead>
<tr>
<th>Market Pulp</th>
<th>PFI Refining Revolutions</th>
<th>Dry Caliper (μm)</th>
<th>Wet Caliper (μm)</th>
<th>Sheet Swelling (%)</th>
<th>ABS_{\text{swelling}} (\frac{g_{\text{water}}}{g_{\text{fiber}}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEK</td>
<td>Unrefined</td>
<td>151</td>
<td>180</td>
<td>19.5</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>141</td>
<td>176</td>
<td>25.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>131</td>
<td>162</td>
<td>24.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Acacia</td>
<td>Unrefined</td>
<td>150</td>
<td>173</td>
<td>15.1</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>141</td>
<td>164</td>
<td>16.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>131</td>
<td>151</td>
<td>15.0</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>134</td>
<td>154</td>
<td>15.2</td>
<td>0.6</td>
</tr>
<tr>
<td>SBHK</td>
<td>Unrefined</td>
<td>176</td>
<td>202</td>
<td>14.9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>139</td>
<td>167</td>
<td>20.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>125</td>
<td>157</td>
<td>25.5</td>
<td>1.1</td>
</tr>
<tr>
<td>NBHK</td>
<td>Unrefined</td>
<td>129</td>
<td>164</td>
<td>27.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>126</td>
<td>158</td>
<td>25.9</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>121</td>
<td>152</td>
<td>26.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Factors affecting fiber swelling

- Hemicellulose, carboxyl groups, cell wall porosity and amorphous cellulose (positive effect)
- Lignin and extractives (negative effect)

<table>
<thead>
<tr>
<th>Market Pulp</th>
<th>O/C Ratio</th>
<th>C – C or C – H</th>
<th>C – O</th>
<th>C = O or O – C – O</th>
<th>O = C – O</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEK</td>
<td>0.78</td>
<td>21</td>
<td>59</td>
<td>20</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Acacia</td>
<td>0.75</td>
<td>28</td>
<td>51</td>
<td>20</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>SBHK</td>
<td>0.84</td>
<td>19</td>
<td>60</td>
<td>21</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>NBHK</td>
<td>0.80</td>
<td>23</td>
<td>55</td>
<td>22</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Concentration of hydrophobic material on fiber surface

1 Neto et al. (2004), Nordic P&P Res. J. 19(4); 2 Perng et al. (2018), Pan Pacific Fibre Value Chain Conference.
Water Absorbency

- Water Absorbency vs Tensile Strength

![Graph showing water absorbency and breaking length for different fiber types.](image)

- Longer fibers
Conclusions

• Fiber Properties
  ✓ As tensile strength increases with refining - bulk decreases
  ✓ Bulk (pore volume) → major contributor for water absorbency
  ✓ Other properties are also important (e.g. hydrophilicity, swellability, surface area)
  ✓ Long and coarse fibers → bigger pores (absorbency rate and capacity)
  ✓ Short and thin fibers → smaller pores (capacity and water retention)

• Market Pulps
  ✓ Bamboo, SBSK, NBSK, SBHK, BEK → superior water absorbency at given strength
  ✓ DIP, SBWS → intermediate water absorbency at given strength
  ✓ NBHK, Acacia, BWS → inferior water absorbency at given strength
Fibers and Tissue Paper Performance

• Fiber Blending Optimization Models
  ✓ Database (10 different fibers + different refining levels + major tissue properties)

✓ Tissue products → manufactured with fiber blending and different levels of refining

✓ Optimize performance and cost of tissue furnish with fiber blending
✓ Develop mathematical models to optimize performance
Fibers and Tissue Paper Performance

• Fiber Blending Optimization Models

Case Study - Water Absorbency

✓ Linear Regression (y = ax + b)
\[ \text{ABS}_n = f(\text{Tensile Strength}_n) \]
\[ \text{ABS}_n = f(\text{Canadian Standard Freeness}_n) \]
\[ \text{ABS}_n = f(\text{PFI revolutions}_n) \rightarrow \text{indirect measure of refining energy} \]

✓ Assumption - Properties of fiber blend follows a linear mixing rule \(^1,^2,^3\)
\[ P_{\text{Fiber Blend}} = P_1^*X_1 + P_2^*X_2 + ... + P_n^*X_n; \quad P_n = \text{property of pulp n}; \quad X_n = \text{mass fraction of pulp n} \]

✓ Nonlinear Optimization

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\(^1\) Kullander et al. (2012), Nordic P&P Res. J.; \(^2\) Tutuș et al. (2017), Drvna Industrija (68)4; \(^3\) Perng et al. (2018), Pan Pacific Fibre Value Chain Conference.
Fibers and Tissue Paper Performance

• Model 1: Maximize water absorbency @ required tensile strength

✓ Variables: $X_n = \text{mass fraction of fiber } n$
  $T_n = \text{tensile strength of fiber } n$
  $n = 2$ (pairs of HW and SW)

✓ Objective function: MAX ( $ABS = ABS_1*X_1 + ABS_2*X_2$ )
  $ABS_n = (a_n*T_n + b_n)$ (linear regression)
  MAX { $ABS = (a_1*T_1 + b_1)*X_1 + (a_2*T_2 + b_2)*X_2$ }

✓ Constrains: $T_1*X_1 + T_2*X_2 \geq T_{\text{min}}$; $T_{\text{min}} = 2.67 \text{ km (kitchen towel)}$
  $T_{n \text{ MIN}} \leq T_n \leq T_{n \text{ MAX}}$ (values are within the refining levels evaluated)
Fibers and Tissue Paper Performance

Maximize water absorbency @ required tensile strength

- SW & HW refined
- Only SW refined

Maximum absorbency was calculated at a given SW/HW ratio
Trade-off between absorbency and manufacturing variables can be analyzed
Fibers and Tissue Paper Performance

• Minimize fiber cost @ required strength and absorbency

✓ Variables: $X_n = \text{mass fraction of fiber } n$
  $T_n = \text{tensile strength of fiber } n$
  $P_n = \text{price of fiber } n$

✓ Objective function: $\text{MIN } (P = P_1*X_1 + P_2*X_2 + \ldots + P_n*X_n )$

✓ Constrains: $T_1*X_1 + T_2*X_2 + \ldots + T_n*X_n \geq T_{\text{min}}; \quad T_{\text{min}} = 2.67 \text{ km (kitchen towel)}$
  $ABS_1*X_1 + ABS_2*X_2 + \ldots + ABS_n*X_n \geq ABS_{\text{min}}; \quad ABS_{\text{min}} = 5.8 \text{ g/g}$
  $T_{n_{\text{MIN}}} \leq T_n \leq T_{n_{\text{MAX}}} \quad \text{(values are within the refining levels evaluated)}$
  $X_1 + X_2 + \ldots + X_n = 1; \quad 0 \leq X_n \leq 1$
Fibers and Tissue Paper Performance

• Minimize fiber cost @ required strength and absorbency

<table>
<thead>
<tr>
<th>RISI - Q2 2019 - Delivered List Price @ 20% Discount - US East</th>
<th>Fisher Solve - Q1 2019 - Delivered Price - US Southeast</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Market Pulp</strong></td>
<td><strong>USD/tonne</strong></td>
</tr>
<tr>
<td>BEK</td>
<td>885.60</td>
</tr>
<tr>
<td>SBHK</td>
<td>883.20</td>
</tr>
<tr>
<td>NBHK</td>
<td>883.20</td>
</tr>
<tr>
<td>SBSK</td>
<td>948.80</td>
</tr>
<tr>
<td>NBSK</td>
<td>1036.00</td>
</tr>
<tr>
<td>DIP</td>
<td>712.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Market Pulp</strong></th>
<th><strong>X (mass fraction)</strong></th>
<th><strong>Fiber Cost (USD/tonne)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>SBHK (unrefined)</td>
<td>0.48</td>
<td>883.20</td>
</tr>
<tr>
<td>SBSK (refined)</td>
<td>0.35</td>
<td>948.80</td>
</tr>
<tr>
<td>DIP (refined)</td>
<td>0.17</td>
<td>712.00</td>
</tr>
<tr>
<td>Fiber Blend</td>
<td>1.00</td>
<td>875.93</td>
</tr>
</tbody>
</table>

- Similar performance can be achieved with different fiber blends
- Market pulp prices determine the composition of the fiber blend that minimizes cost

![TISSUECON](image-url)
Fiber Blending Optimization Models and Tissue Paper Performance

• Non-linear modeling can be used to optimize tissue furnish performance and cost via fiber blending

• The trade-off among manufacturing variables (e.g. refining energy, freeness, fiber cost) and tissue properties (e.g. strength, softness, absorbency) can be evaluated systematically

• Models can be specifically developed according to the goals and constraints of a given mill
Creping Process and Tissue Paper Performance
Creping Process and Tissue Performance

- Methodology
  - Creping
    - Simulator
      - Unit
      - Kemira

- Temperature 115 °C
- Coating Dosage 300 g/min @ 40 psi
- Coating Chemistry 2.4 mg/m² Adhesive - PAE
- Transfer Roll
  - Hand Sheet Consistency 40% to 45%
- Fabric Moisture 15% to 18%
- Vertical Force 1450 N
  - Horizontal Force 850 N
- Impact Angle 80º
- Hand Sheet Consistency > 95%
- Speed 1 1.4 m/s
- Speed 2 2.5 m/s

Spraying and Transfer
- Drying and Creping
### Creped Handsheets vs Commercial Products

<table>
<thead>
<tr>
<th>Tissue Product</th>
<th>Creped Hand Sheets (BEK 850 PFI rev.)</th>
<th>Consumer Bath Tissue</th>
<th>Professional Bath Tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Creping Simulator</td>
<td>Advanced*</td>
<td>Conventional**</td>
</tr>
<tr>
<td>Tensile Strength Index (Nm/g)</td>
<td>4.7</td>
<td>5.5 ± 1.8</td>
<td>6.2 ± 2.9</td>
</tr>
<tr>
<td>Apparent Density (kg/m³)</td>
<td>144</td>
<td>92 ± 24</td>
<td>124 ± 24</td>
</tr>
<tr>
<td>Water Absorbency (g/g)</td>
<td>8.1</td>
<td>9.8 ± 0.8</td>
<td>7.7 ± 1.0</td>
</tr>
<tr>
<td>TSA Softness (TS7 - dB)</td>
<td>11.6</td>
<td>10.1 ± 1.9</td>
<td>14.0 ± 3.0</td>
</tr>
</tbody>
</table>

*Advanced Technology: CTAD (Creped Through-Air Drying) or UCTAD (Uncreped Through-Air Drying)

**Conventional Technology LDC (Light Cry Crepe)
Creping Process and Tissue Performance

- Crepe Structure, Tissue Properties (BEK 850 PFI rev; SBSK 700 PFI rev → similar strength)

Uncreped Handsheets

Creped Handsheets

- Crepe folds
- Buckling and distortion of fibers
- Delamination of fiber web (surface)
- Free fiber ends
Creping Process and Tissue Performance

- Uncreped vs Creped Handsheets (BEK, SBSK, NBSK, Bamboo → different refining levels)
The performance of creped handsheets was similar to commercial products.

Creping process promotes significant changes in the fiber web structure to enhance softness and absorbency at the expense of lower strength.

Long and coarse fibers are more resistant to the creping process when compared to short and thin fibers.

A reasonable correlation was found between the properties of uncreped and creped handsheets made with different fibers.
Bath Tissue Properties - Softness

- Softness vs Tensile Strength (Panel 1)

Softness Panel (Score) vs Breaking Length (km)

Shorter fibers Lower coarseness

• BEK
- Acacia
- NBHK
- SBHK
- SBSK
- NBSK
- Bamboo
Conclusions

• Cellulosic Fibers and Tissue Paper Performance
  ✓ Important fiber features for tissue paper properties were identified
    ➢ Long fibers → strength and water absorbency
    ➢ Long and thin fibers → strength and water absorbency without sacrificing softness significantly
    ➢ Short and thin fibers → superior softness
  ✓ Data base of fibers and tissue paper properties was created
    ✓ Fiber blending models are a useful tools to optimize tissue paper furnish

• Creping Process and Tissue Paper Performance
  ✓ A methodology to study the creping process at lab scale was developed
    ✓ Performance of creped sheets is similar to commercial products
Future Work

• Fibers for Tissue Manufacturing
  ✓ Evaluate other tissue making fibers

• Fiber Blending Optimization Models
  ✓ Investigate the linearity between fiber blending and tissue properties
  ✓ Perform a case study for a tissue mill

• Creping Simulator Unit
  ✓ Investigate creping variables (e.g. basis weight, angle, adhesion) to improve sheet quality
  ✓ Develop methodology to better characterize the crepe structure
Thank you!


Contact:
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Ronalds Gonzalez - rwgonzal@ncsu.edu
Opportunities

• Understand how to **better utilize fibers to optimize manufacturing costs** and/or **increase product value**

✓ Current used fibers
✓ Underused fibers (e.g. OCC, southern HW, northern HW)
✓ Alternative fibers (e.g. non-wood, virgin unbleached)

Wheat Straw Market Pulp

“Agriculture based Market Pulp” Fibers

Unbleached Eucalyptus Pulp

1. https://columbiapulp.com/  
2. https://generaenergy.com/  
5. https://www.tissueworld.com