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

Tiago de Assis [2], Hasan Jameel [1]
Ronalds Gonzalez [1], Lee Reisinger [3], Dale Kavalew [4], Clay Cambell [2]

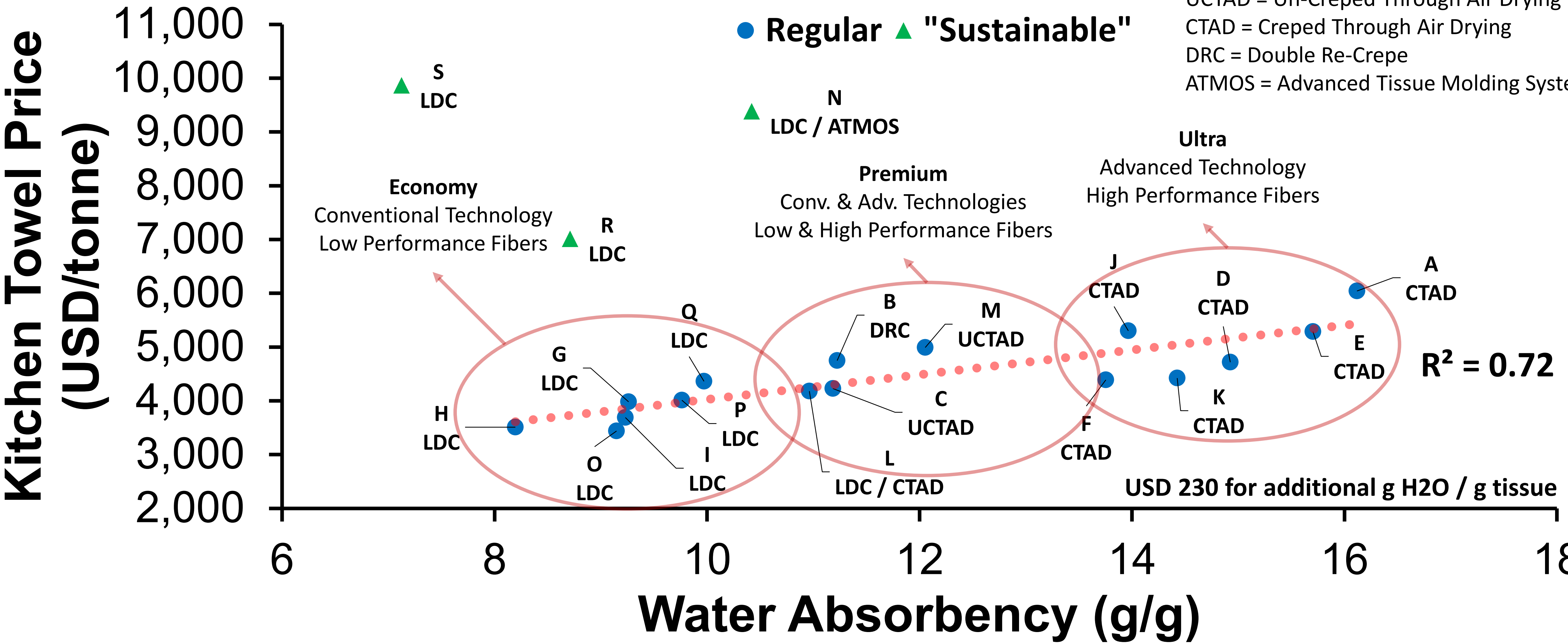
[1] NC State University - Department of Forest Biomaterials
[2] Kemira
[3] ReiTech Incorporated
[4] Dale Kavalew and Associates LLC

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

de Assis *et al*. (2018), BioResources 13(3).

Cellulosic Fibers and Tissue Paper Performance

Hardwood Fibers

- **Short Fibers (length ~ 1 mm)**
- **Source of Softness and Absorbency**

- Single Species
  - Northern: birch, aspen
  - Southern: eucalyptus, acacia

- Multiple Species
  - Northern: aspen, maple, birch, beech
  - Southern: gum, oak, poplar, ash, beech

Softwood Fibers

- **Long Fibers (length ~ 2.5 mm)**
- **Source of Strength and Absorbency**

- Single Species
  - Northern: spruce
  - Southern: radiata pine

- Multiple Species
  - Northern: pine, spruce, fir, hemlock, cedar, larch
  - Southern: pines-loblolly, slash, shortleaf, longleaf

Non-Wood Fibers

- **Diverse Fiber Morphology**
- **Diverse Performance**
- **High Content of Fines**
- Examples: wheat straw, bagasse, bamboo

Recycled Fibers

- **Fiber Blend (long and short fibers)**
- **Low Performance (stiff fibers, fines, impurities)**
- **Cheaper than Virgin Fibers**
- Examples: SOP (Sorted Office Paper)
  OCC (Old Corrugated Containers)

Nanko *et al.* (2005), The World of Market Pulp.

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Woody, Non-woody and Recycled Pulps

- Morphology (Fiber Quality Analyzer - OpTest)

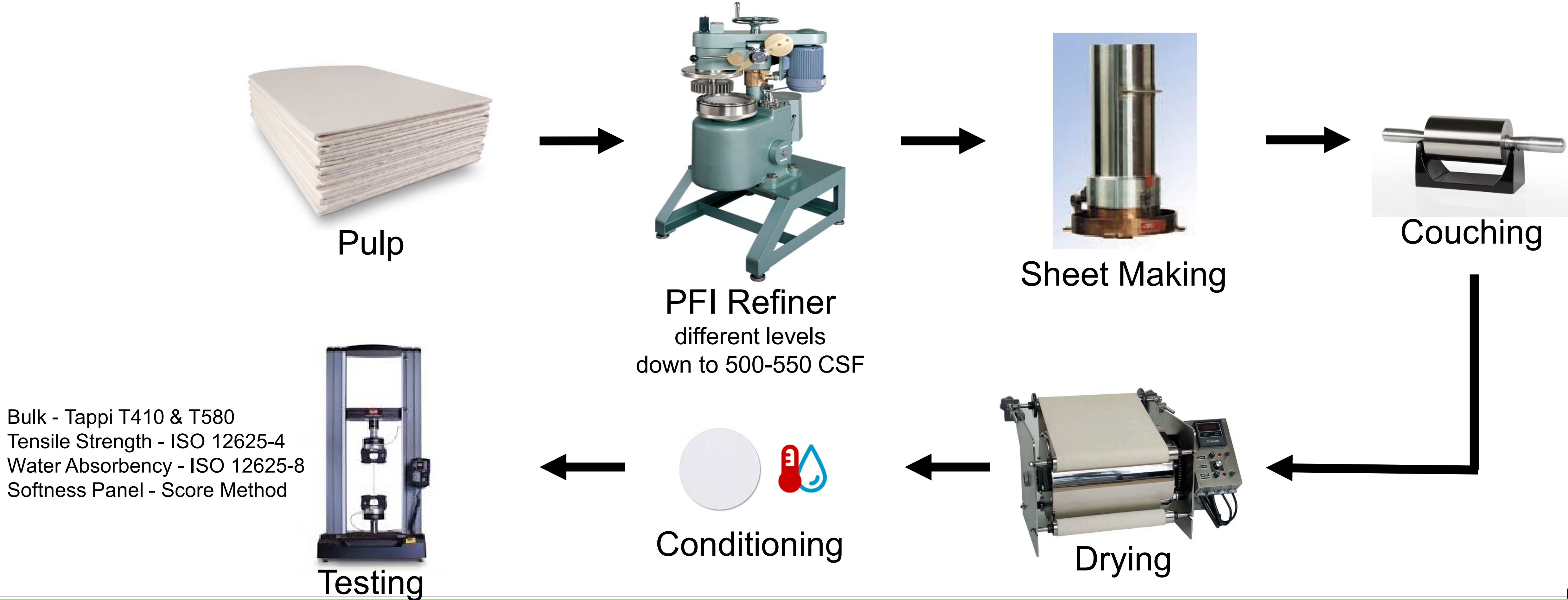
	BEK	Acacia	SBHK	NBHK	SBSK	NBSK	DIP	BWS	SBWS	Bamboo
Width (µm)	16.4	17.0	18.5	16.6	28.1	28.4	18.1	14.8	16.5	15.4
Coarseness (mg/km)	73	62	110	72	216	135	98	84	88	92
Length Weighted Fines (%)	4.5	5.0	14.9	9.5	5.0	3.8	10.4	18.3	14.3	12.8
Population (million fibers/g)	18.8	23.5	10.4	22.9	2.7	4.3	13.5	19.3	16.6	9.6
Length Weighted Fiber Length (mm)	0.82	0.78	1.11	0.70	2.58	2.34	1.17	0.91	0.93	1.72

10 Fibers Evaluated

Hardwoods	Softwoods	Recycled	Non-wood
BEK = Bleached Eucalyptus Kraft	SBSK = Southern Bleached Softwood Kraft	DIP = Deinked Pulp	BWS = Bleached Wheat Straw Soda
Acacia = Bleached Acacia Kraft	NBSK = Northern Bleached Softwood Kraft		SBWS = Semi-bleached Wheat Straw Soda
SBHK = Southern Bleached Hardwood Kraft			Bamboo = Bleached Bamboo Soda
NBHK = Northern Bleached Hardwood Kraft			

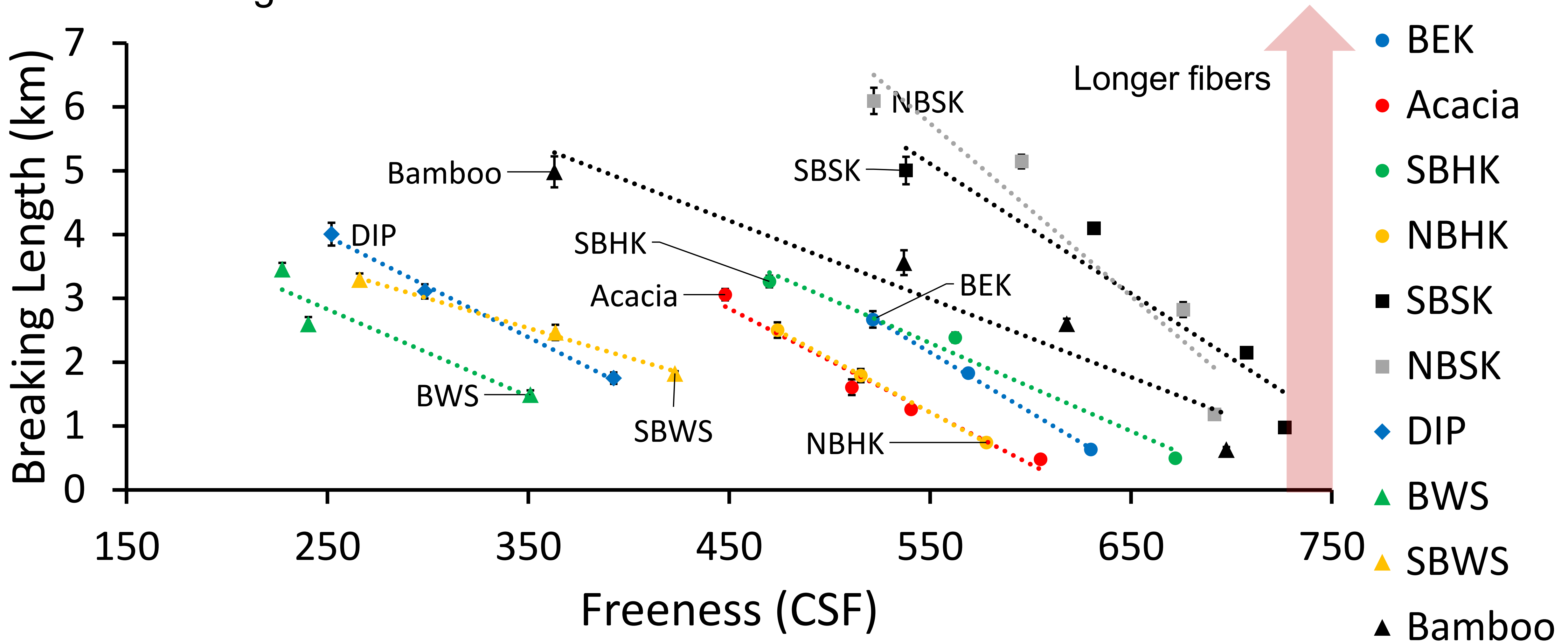
Handsheet Making

- Modified TAPPI handsheet making procedure (30 g/m^2, uncreped)



Tensile Strength

- Tensile Strength vs Freeness



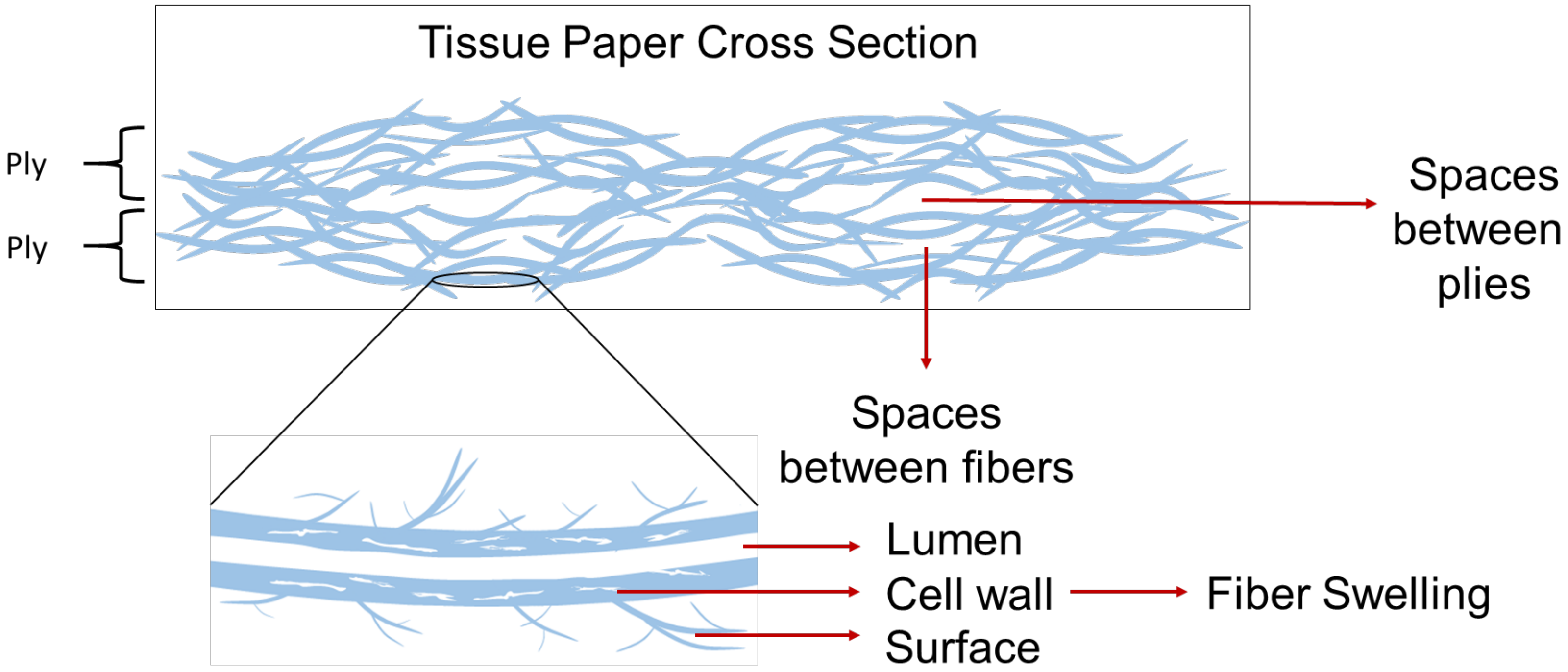
Fibers/Sheet Structure and Water Absorbency

- **Water Absorbtion in Tissue Paper**

✓ Ability to absorb and retain water
✓ Essential property for toweling products

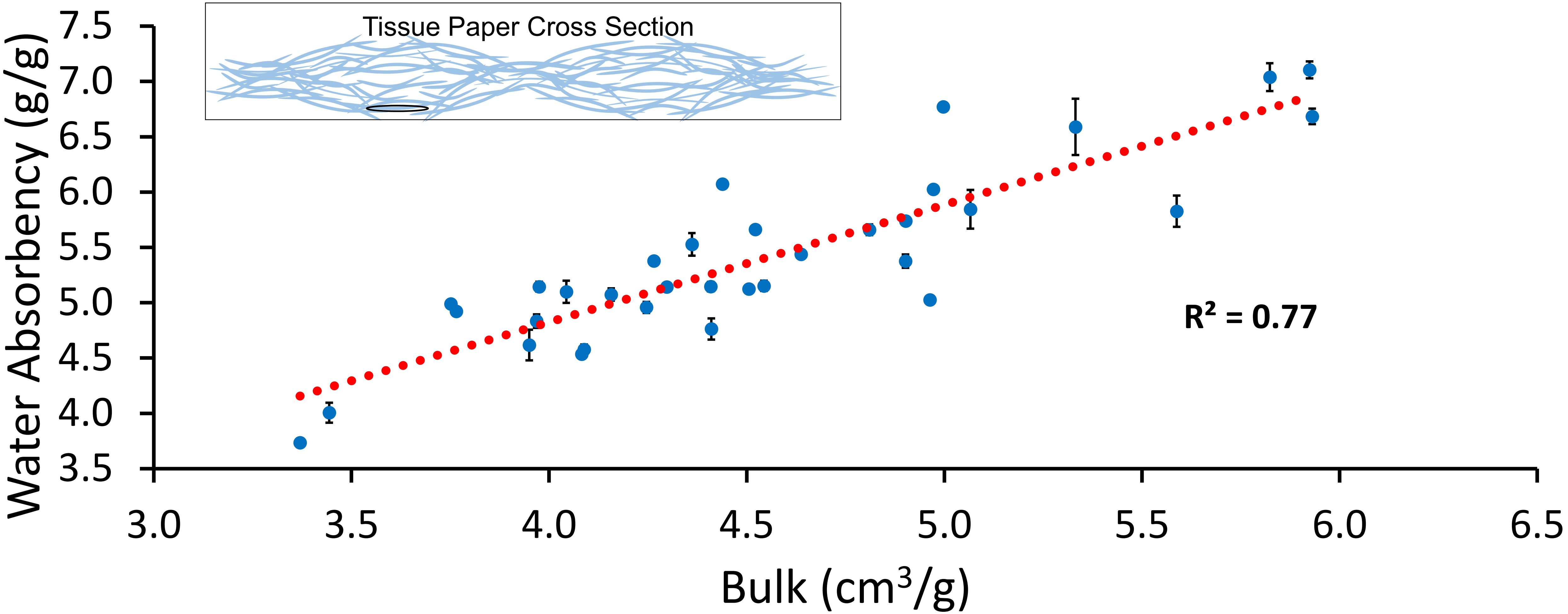
✓ Absorbency rate: how fast
✓ Absorbency capacity: how much

✓ **High absorbency → hydrophilic fibers** forming a **porous** and **stable fiber web** structure

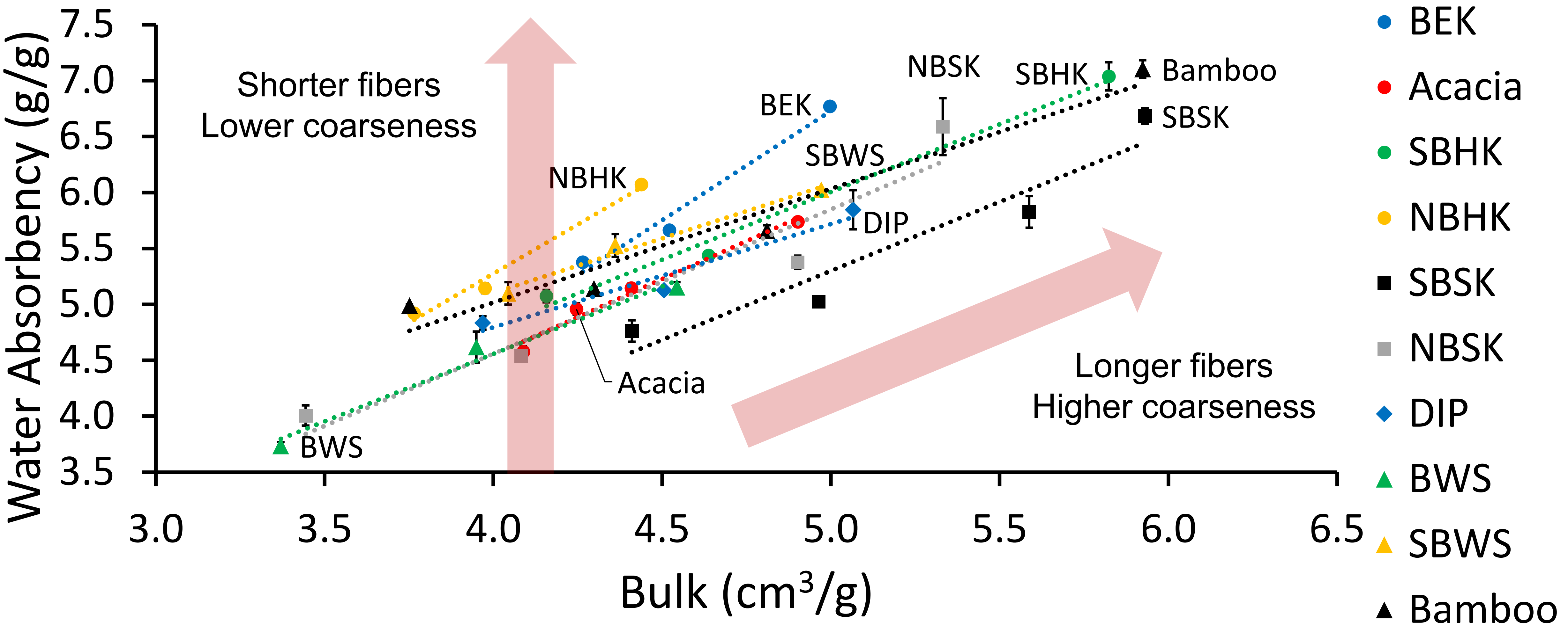


[1] Ko *et al.* (2016), J. of Korea Tappi 48(5);
[2] Hollmark (1984), Handbook of Phys. & Mech. Testing of Paper & Pbd. Volume 2, Chapter 20.

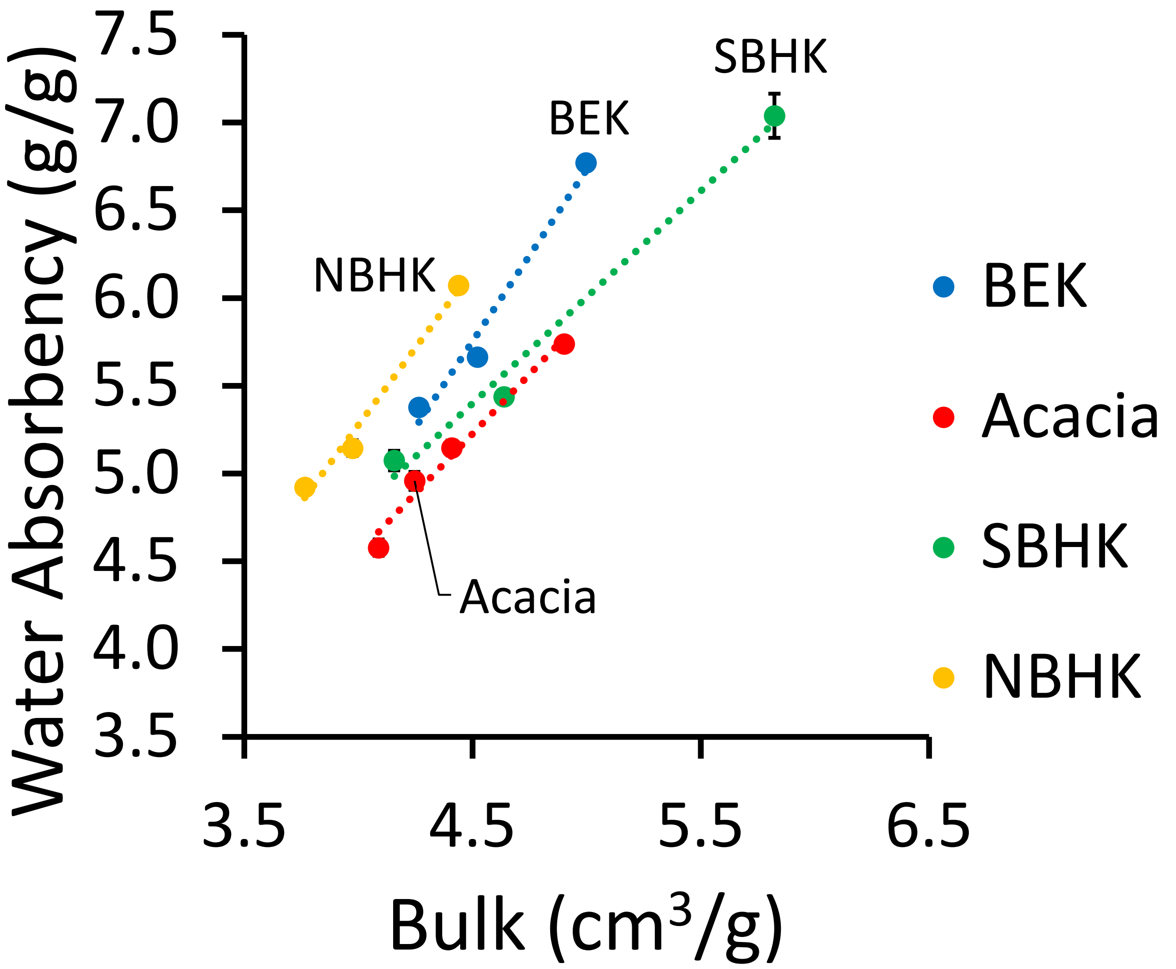
Water Absorbency and Bulk



Water Absorbency vs Bulk



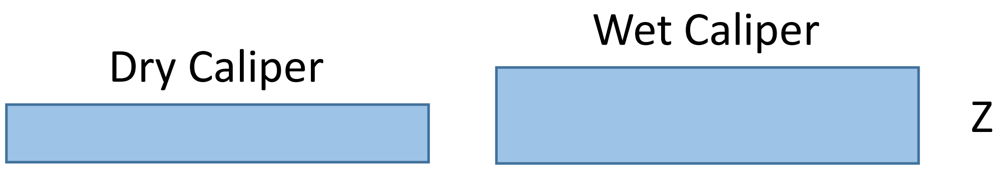
Water Absorbency vs Fiber Dimensions



	BEK	Acacia	SBHK	NBHK
Width (µm)	16.4	17.0	18.5	16.6
Coarseness (mg/km)	73	62	110	72
Length Weighted Fines (%)	4.5	5.0	14.9	9.5
Population (million fibers/g)	18.8	23.5	10.4	22.9
Length Weighted Fiber Length (mm)	0.82	0.78	1.11	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

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

$$ABS_{\text{swelling}}\left(\frac{g\ \text{water}}{g\ \text{fiber}}\right) = \frac{m\ \text{water}}{m\ \text{sheet}} = \frac{\rho\ \text{water}}{\rho\ \text{sheet wet}} - \frac{\rho\ \text{water}}{\rho\ \text{sheet dry}}$$

Sheet Swelling and Water Absorbency

- ✓ Factors affecting fiber swelling

  Hemicellulose, carboxyl groups, cell wall porosity and amorphous cellulose (positive effect)

  Lignin and extractives (negative effect)

XPS (X-ray Photoelectron Spectroscopy) – Surface Composition					
Market Pulp	O/C Ratio	C – C or C – H	C – O	C = O or O – C – O	O = C – O
BEK	0.78	21	59	20	< 1
Acacia	0.75	28	51	20	< 1
SBHK	0.84	19	60	21	< 1
NBHK	0.80	23	55	22	< 1

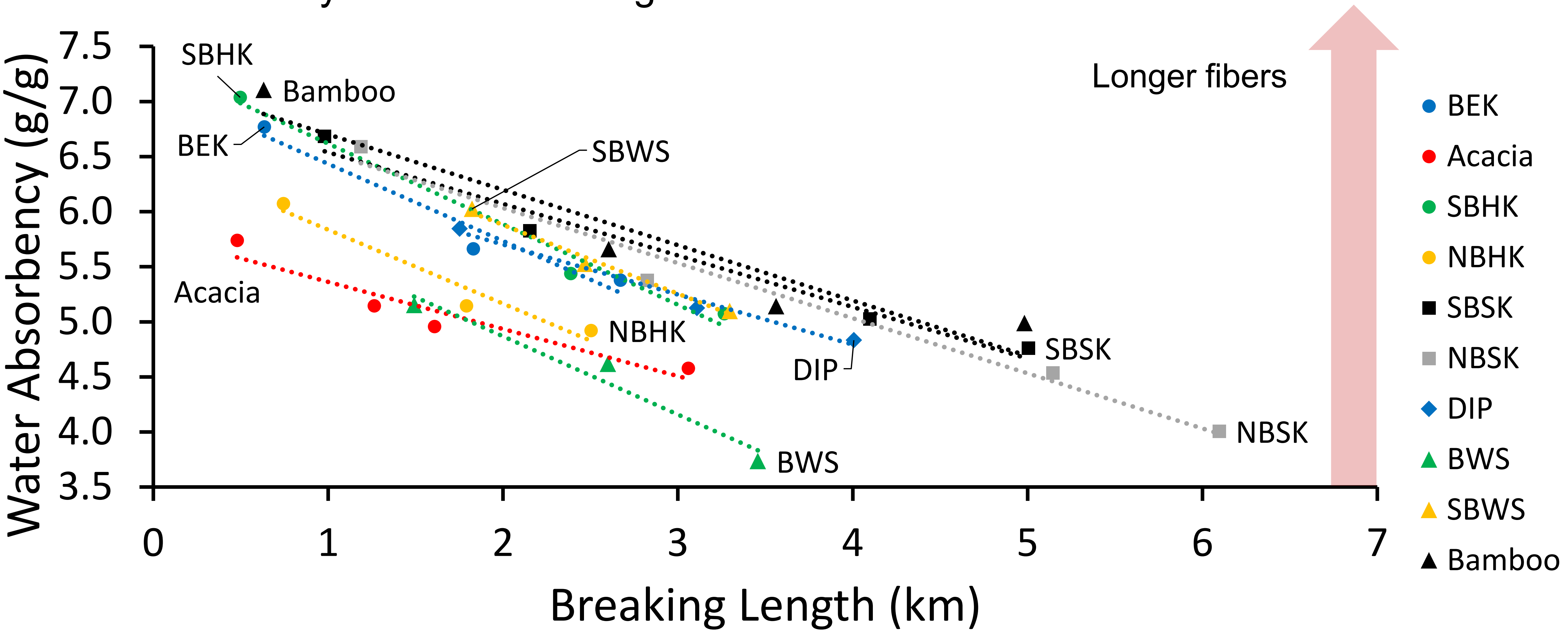
Market Pulp	$ABS_{swelling}$ (g/g)
BEK	1.0
Acacia	0.6
SBHK	1.0
NBHK	1.1

Concentration of hydrophobic material on fiber surface [1, 2]

[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



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

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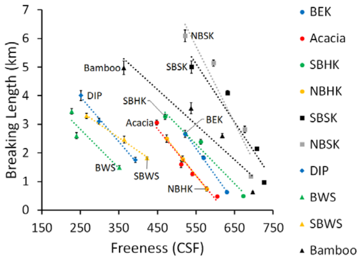
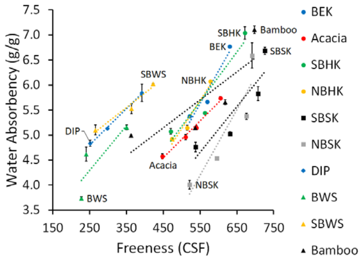
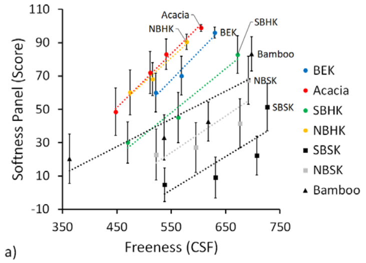
Fibers and Tissue Paper Performance

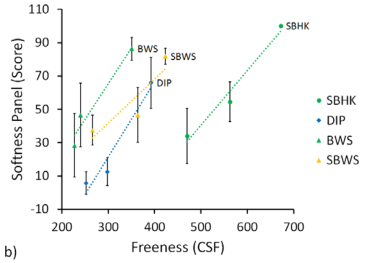
- Fiber Blending Optimization Models
  - ✓ Database (10 different fibers + different refining levels + major tissue properties)







a)



b)

  - ✓ 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)

ABS_n = f (Tensile $Strength_n$)

ABS_n = f (Canadian Standard $Freeness_n$)

ABS_n = f (PFI $revolutions_n$) → indirect measure of refining energy

✓ Assumption - Properties of fiber blend follows a linear mixing rule [1, 2, 3]

$P_{Fiber\ Blend} = P_1*X_1 + P_2*X_2 + ... + P_n*X_n$; P_n = property of pulp n; X_n = mass fraction of pulp n

✓ Nonlinear Optimization

[1] Kullander *et al.* (2012), Nordic P&P Res. J.; [2] Tutuş *et al.* (2017), Drvna Industrija (68)4;
[3] Perng *et al.* (2018), Pan Pacific Fibre Value Chain Conference.

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Fibers and Tissue Paper Performance

- **Model 1: Maximize water absorbency @ required tensile strength**

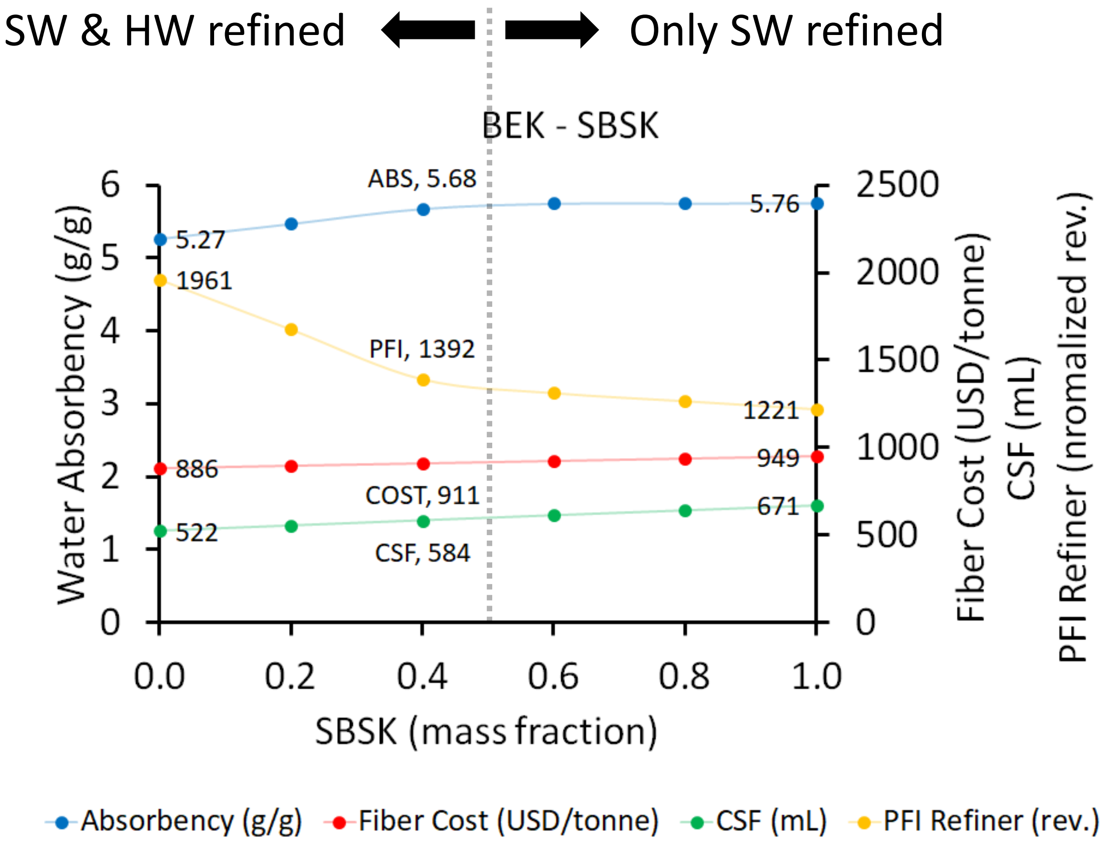
✓ Variables: $\mathbf{X_n}$ **= mass fraction of fiber n**
$\mathbf{T_n}$ **= tensile strength of fiber n**
n = 2 (pairs of HW and SW)

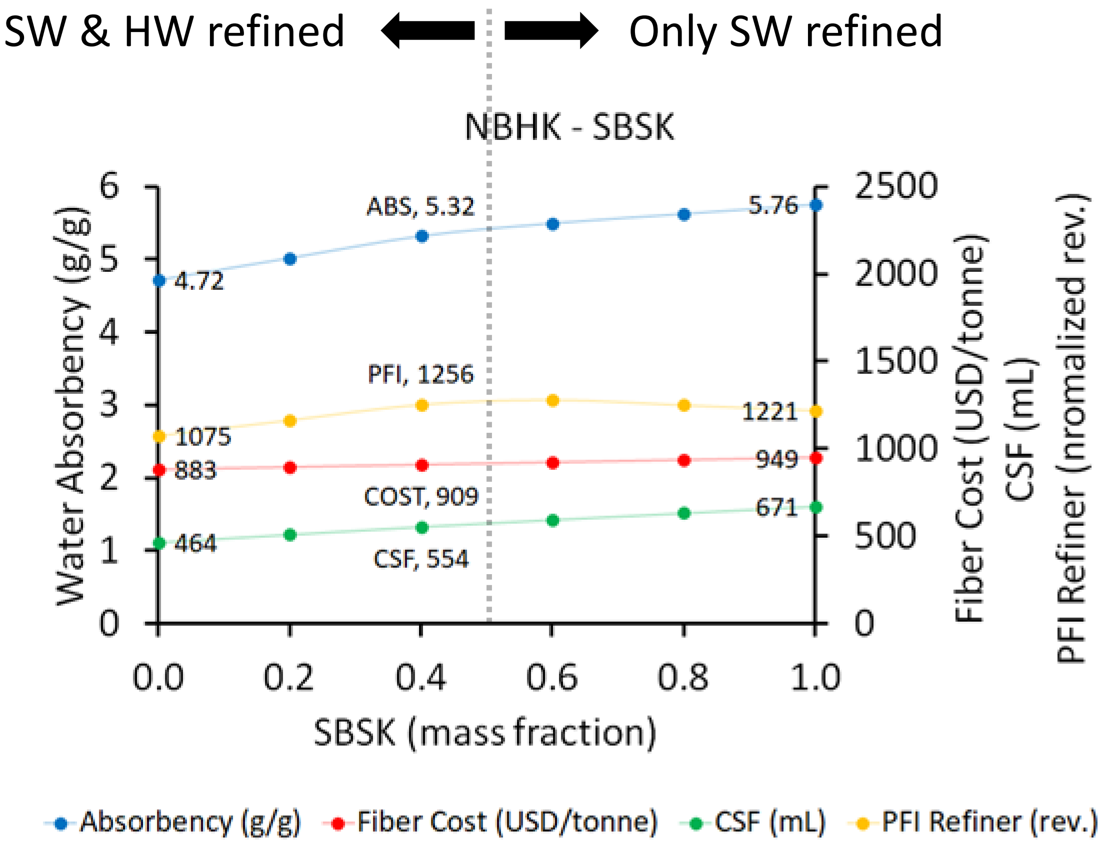
✓ Objective function: **MAX (ABS =** $\mathbf{ABS_1{*}X_1 + ABS_2{*}X_2}$**)**
$ABS_n = (a_n{*}T_n + b_n)$ (linear regression)
MAX { $ABS = (a_1{*}T_1 + b_1){*}X_1 + (a_2{*}T_2 + b_2){*}X_2$ }

✓ Constrains: $\mathbf{T_1{*}X_1 + T_2{*}X_2 >= T_{min}}$; $\mathbf{T_{min}}$ **= 2.67 km (kitchen towel)**
$T_{n\,MIN} <= T_n <= T_{n\,MAX}$ (values are within the refining levels evaluated)

Fibers and Tissue Paper Performance

Maximize water absorbency @ required tensile strength





- ✓ 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 = mass fraction of fiber n**
T_n = tensile strength of fiber n
P_n = price of fiber n

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

✓ Constrains: **$T_1 * X_1 + T_2 * X_2 + \ldots + T_n * X_n >= T_{min}$;** **Tmin = 2.67 km (kitchen towel)**
$ABS_1 * X_1 + ABS_2 * X_2 + \ldots + ABS_n * X_n >= ABS_{min}$; **$ABS_{min}$ = 5.8 g/g**
$T_{n\,MIN} <= T_n <= T_{n\,MAX}$ (values are within the refining levels evaluated)
$X_1 + X_2 + \ldots + X_n = 1$; $0 <= X_n <= 1$

Fibers and Tissue Paper Performance

- Minimize fiber cost @ required strength and absorbency

RISI - Q2 2019 - Delivered List Price @ 20% Discount - US East	
Market Pulp	**USD/tonne**
BEK	885.60
SBHK	**883.20**
NBHK	883.20
SBSK	**948.80**
NBSK	1036.00
DIP	**712.00**

Market Pulp	X (mass fraction)	Fiber Cost (USD/tonne)
SBHK (unrefined)	0.48	883.20
SBSK (refined)	0.35	948.80
DIP (refined)	0.17	712.00
Fiber Blend	**1.00**	**875.93**

Fisher Solve - Q1 2019 - Delivered Price - US Southeast	
Market Pulp	**USD/tonne**
BEK	**843.91**
SBHK	**853.99**
NBHK	849.62
SBSK	**847.19**
NBSK	919.48
DIP	835.56

Market Pulp	X (mass fraction)	Fiber Cost (USD/tonne)
BEK (unrefined)	0.30	843.91
SBHK (unrefined)	0.22	853.99
SBSK (refined)	0.47	847.19
Fiber Blend	**1.00**	**847.71**

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

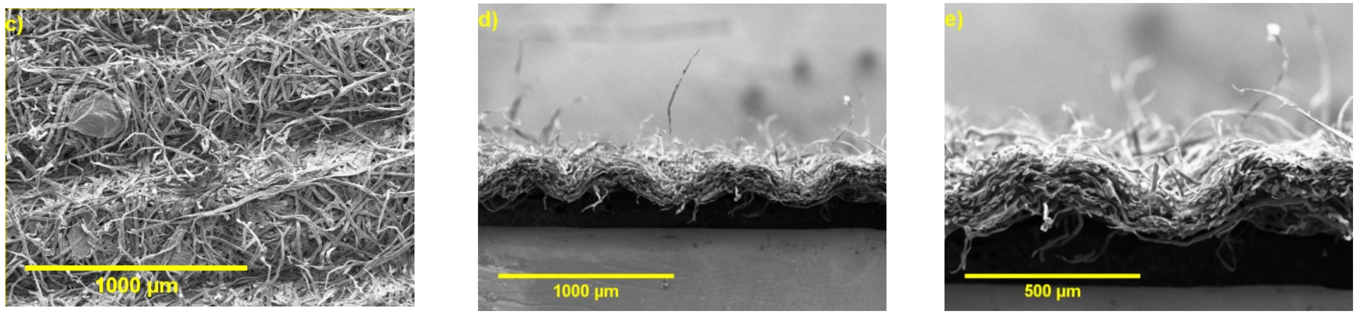
Fiber Blending Optimization Models and Tissue Paper Performance

- 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

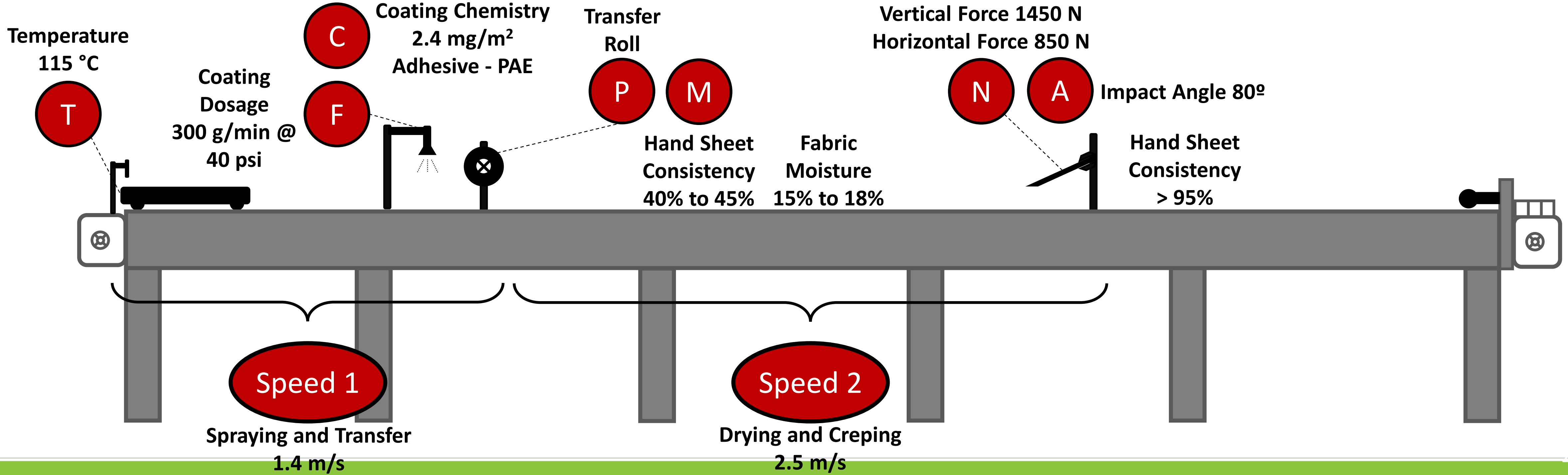
- Models can be specifically developed according to the goals and constrains of a given mill

Creping Process and Tissue Paper Performance



Creping Process and Tissue Performance

- Methodology
  - ✓ Creping Simulator Unit **Kemira**



Creped Handsheets vs Commercial Products

Tissue Product	Creped Hand Sheets (BEK 850 PFI rev.)	Consumer Bath Tissue		Professional Bath Tissue
Technology	Creping Simulator	Advanced*	Conventional**	Conventional**
Tensile Strength Index (Nm/g)	4.7	5.5 ± 1.8	6.2 ± 2.9	5.2 ± 1.9
Apparent Density (kg/m^3)	144	92 ± 24	124 ± 24	128 ± 32
Water Absorbency (g/g)	8.1	9.8 ± 0.8	7.7 ± 1.0	7.5 ± 0.5
TSA Softness (TS7 - dB)	11.6	10.1 ± 1.9	14.0 ± 3.0	19.2 ± 4.0

*Advanced Technology: CTAD (Creped Through-Air Drying) or UCTAD (Uncreped Through-Air Drying)
**Conventional Technology LDC (Light Cry Crepe)

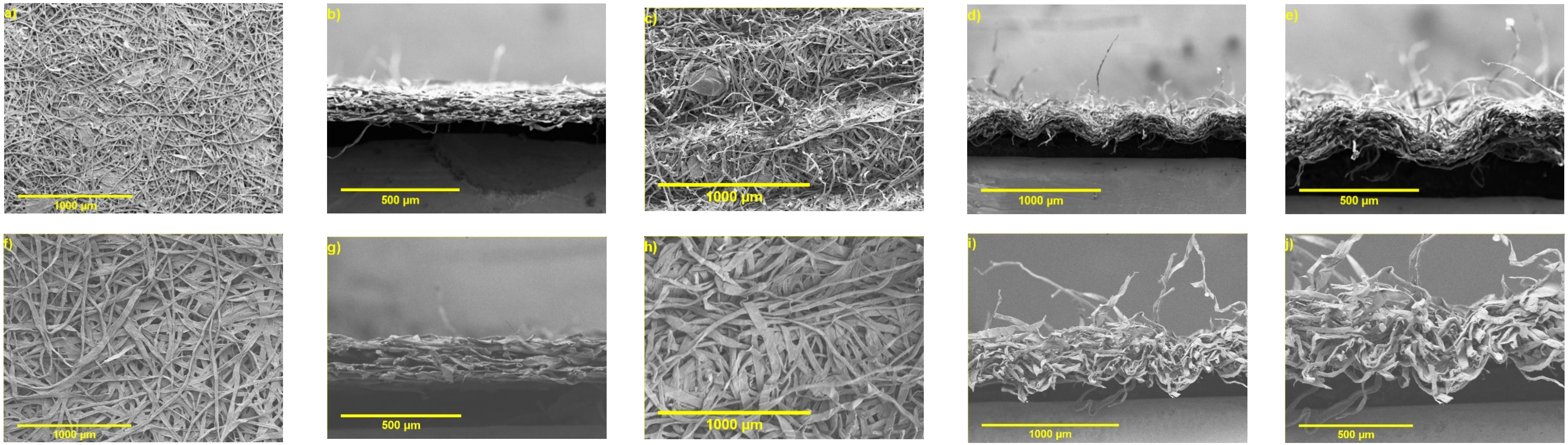
Creping Process and Tissue Performance

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

Uncreped Handsheets | Creped Handsheets

BEK

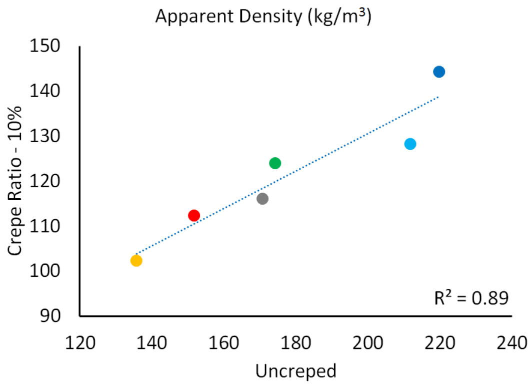
SBSK

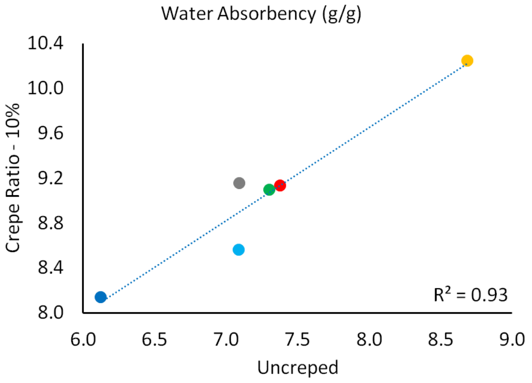


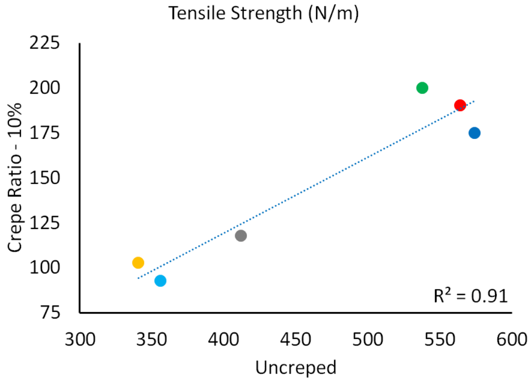
- ✓ Crepe folds
- ✓ Buckling and distortion of fibers
- ✓ Delamination of fiber web (surface)
- ✓ Free fiber ends

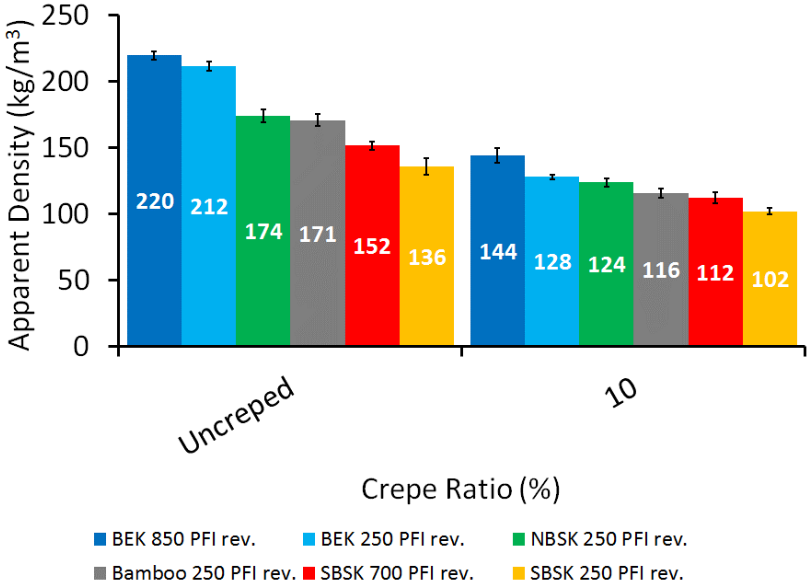
Creping Process and Tissue Performance

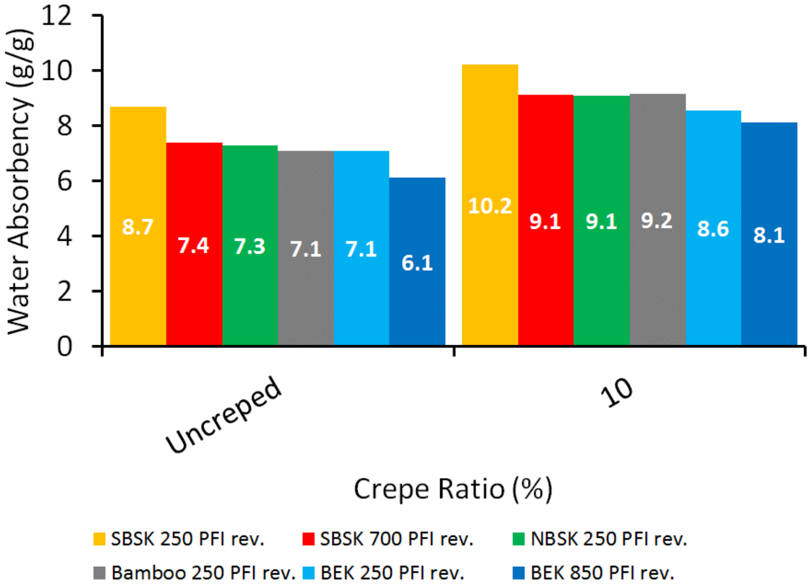
- Uncreped vs Creped Handsheets (BEK, SBSK, NBSK, Bamboo → different refining levels)

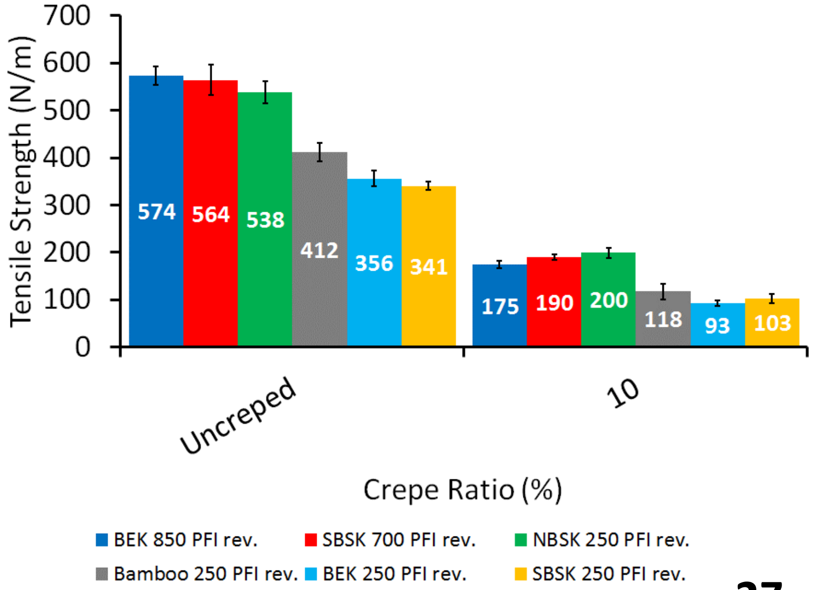










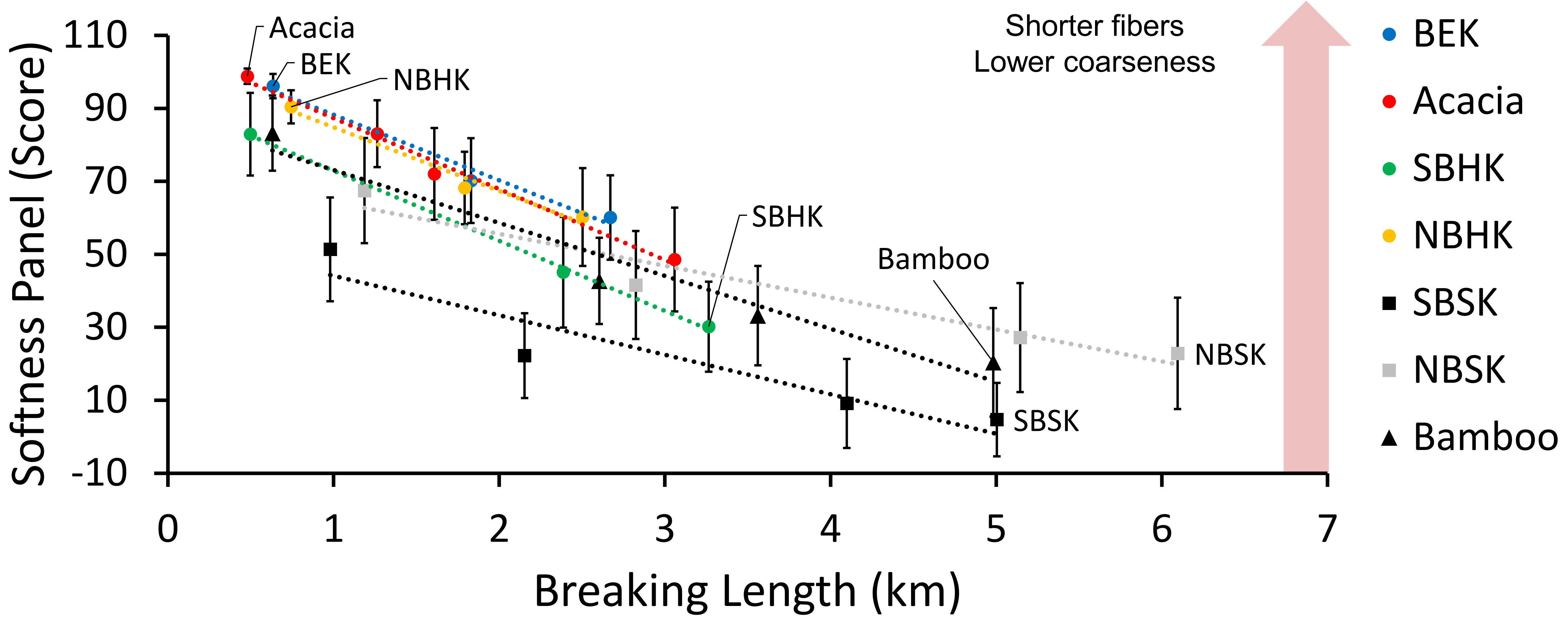


Creping Process and Tissue Performance

- ✓ 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)



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

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Thank you !

de Assis *et al.* (2019). Comparison of Wood and Non-Wood Pulps for Tissue Paper. BioResources14(3).

Contact:

Hasan Jameel – jameel@ncsu.edu

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 [1]

Agriculture based Market Pulp [2]

"Sustainable" Fibers [3, 4]

Unbleached Eucalyptus Pulp [5]

[1] https://columbiapulp.com/; [2] https://generaenergy.com; [3] https://www.seventhgeneration.com/home; [4] http://truegreenpaper.com/; [5] https://www.tissueworld.com