Cellulose filaments (CF) for light-weight composites and high performance concretes

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Vice President, Research and Development
Kruger Inc.

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Kruger Inc.: Four Generations

- Founded in 1904, Kruger Inc. has over 100 years of history as a privately held, fourth-generation family company
- Montréal-based private conglomerate that operates businesses across 10 industries:
  - Over 5,000 employees
  - 19 manufacturing and production operations
  - 38 renewable energy power plants

JOSEPH **KRUGER**

GENE H. **KRUGER**

JOSEPH **KRUGER II**

SARAH **KRUGER**

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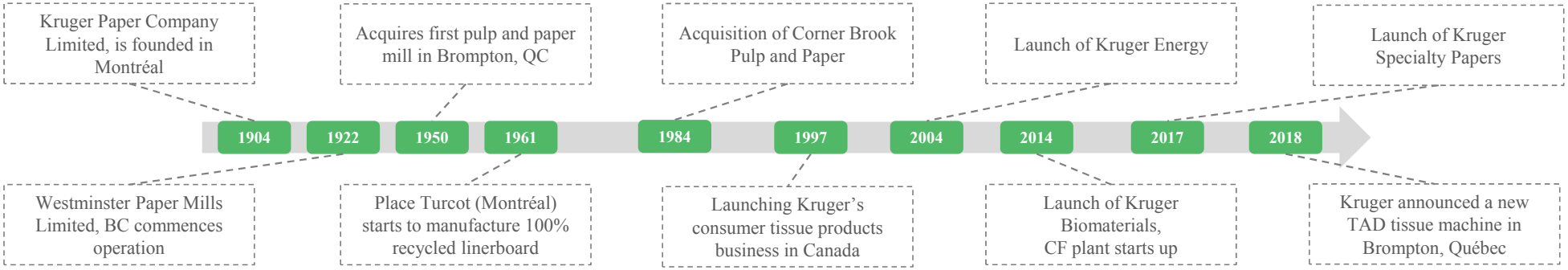

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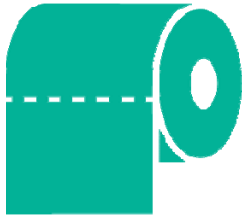
Our Sectors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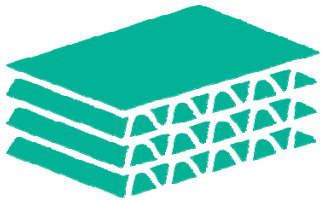
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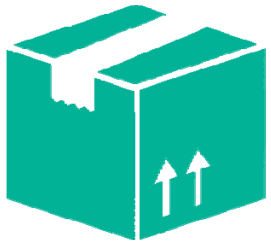
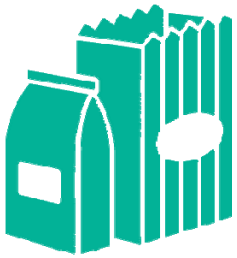
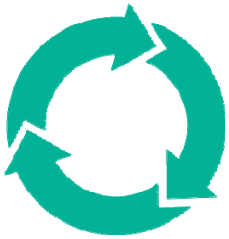

Packaging

Energy

Publication Papers

Biomaterials


Specialty Papers


Recycling

Real Estate

Wines and Spirits

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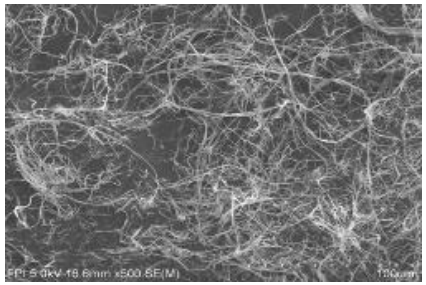
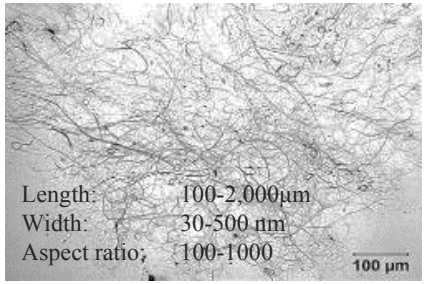
FiloCell® – Cellulose Filaments

- Produced in Trois-Rivières, QC, Canada
- 6,000T/y capacity
- Mechanical process, 100% yield
- No chemicals, no enzymes, zero effluent
- Made from FSC® pulp using renewable electric power
- Robust on-line quality control
- Available forms:
  - Water suspension (2-4% solids)
  - Wet pulp (~30% solids)
  - Dry fluff
  - Dry film





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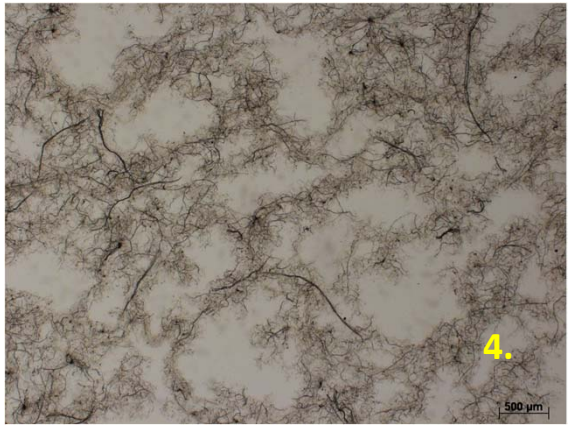
CF development in the production process



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Cellulose Filaments applications

Pulp and Paper

Polymer composites

Light weighting

Higher strength

Enhanced rheology

Concrete and cement products

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Cellulose Filaments in pulp and paper applications

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Pulp and Paper Application

- 70 industrial scale trials
- Reinforcement pulp grades
- Publication paper grades
- Specialty paper grades
- Tissue products
- Several commercial grades

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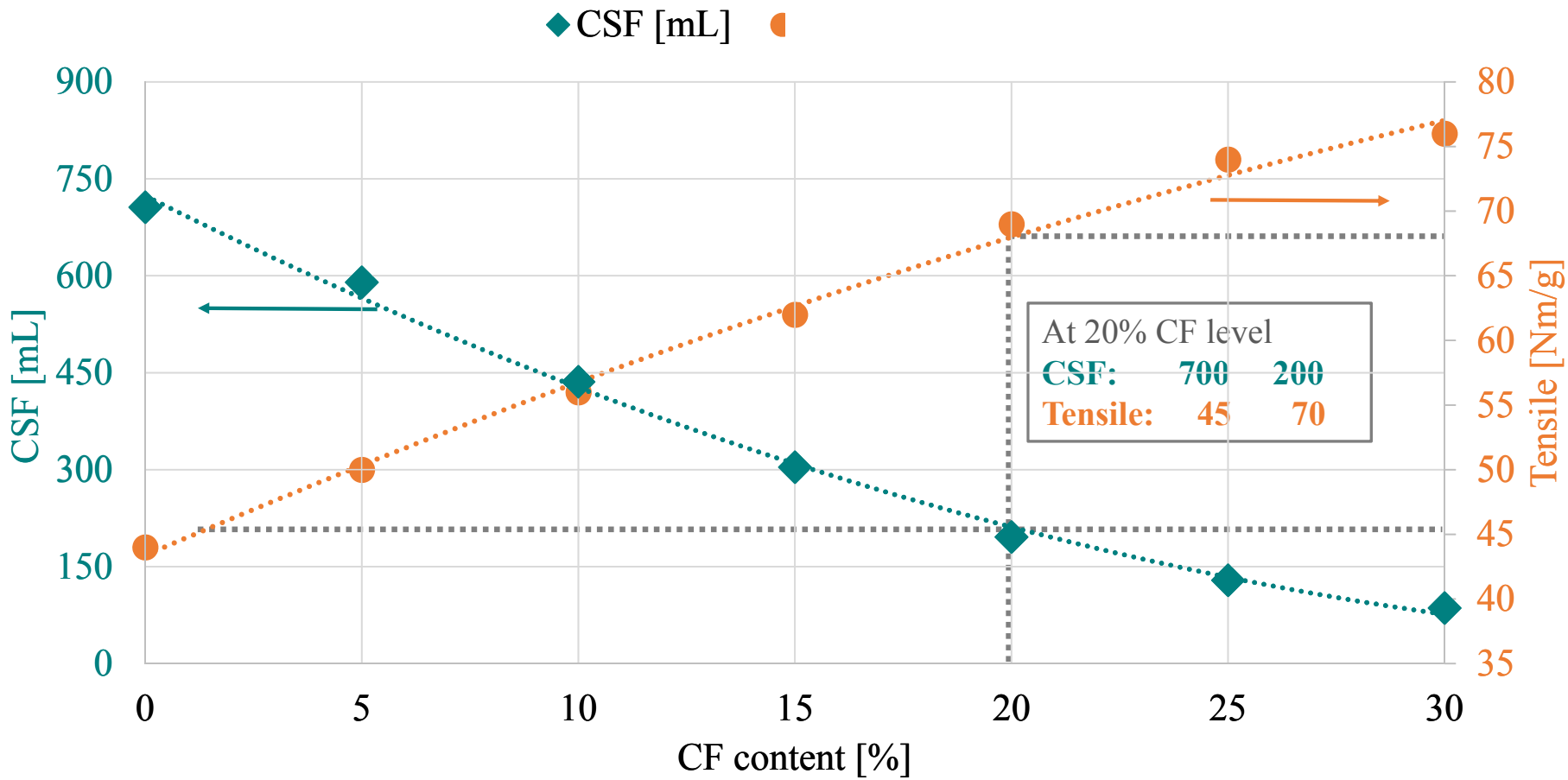
Reinforcement pulp grades (NBSK)



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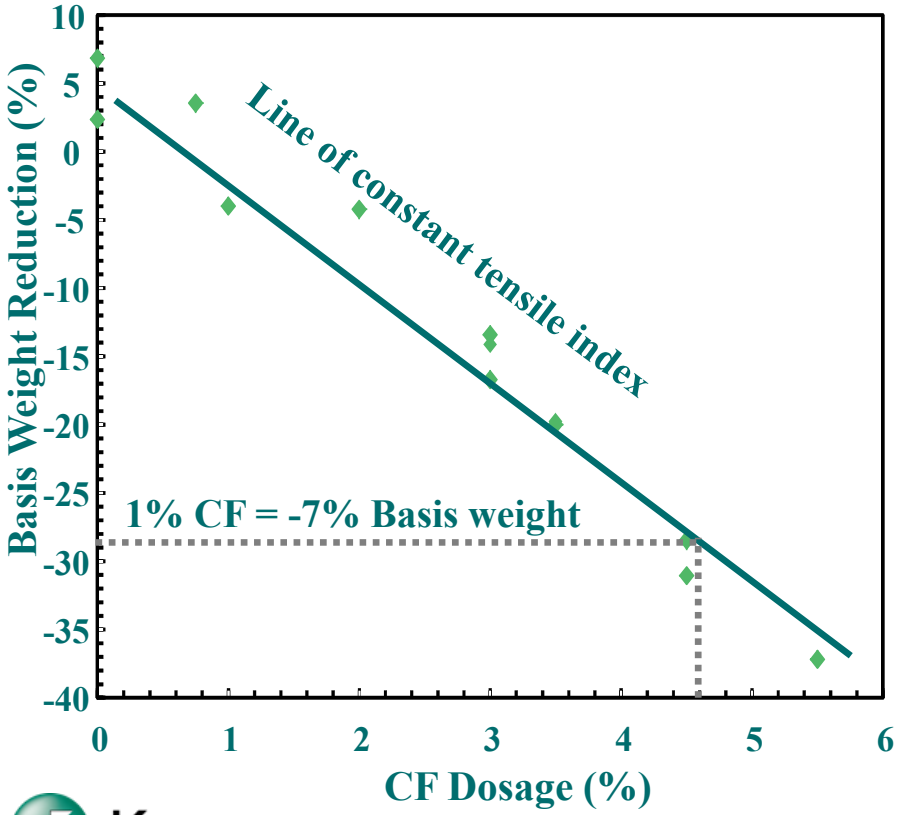
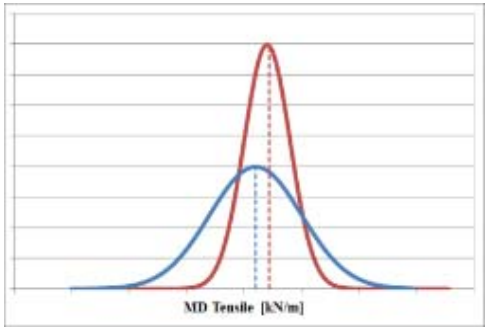
Unique publication paper grades

Light-weighting of uncoated printing paper



High Bulk / High Opacity LWC grade

- 20% reduction in basis weight
- Identical caliper, opacity and strength
- Increased wet-web strength
- Improved strength uniformity
- Break rate of LWC paper:
  - With CF: 1.3%
  - Without CF: 3.3%.



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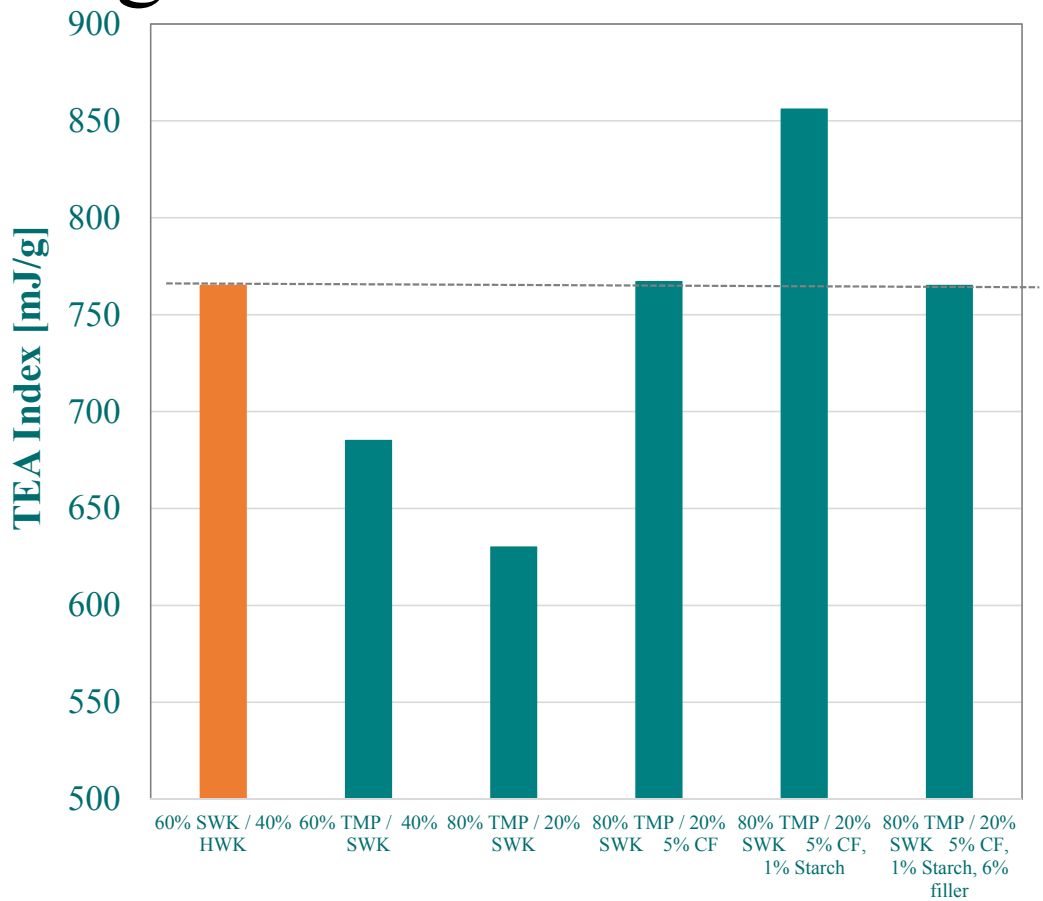
CF use in specialty Paper grades

- Furnish optimization
- Use of TMP pulp at identical strength properties
- Addition of filler for improved opacity and surface finish
- More uniform sheet, no impact on converting performance.



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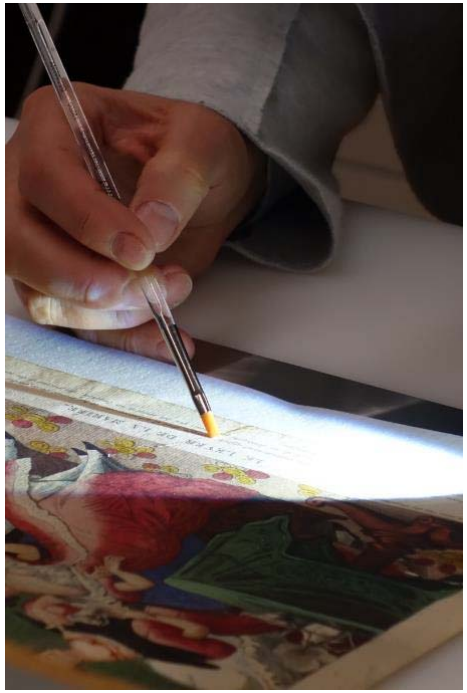
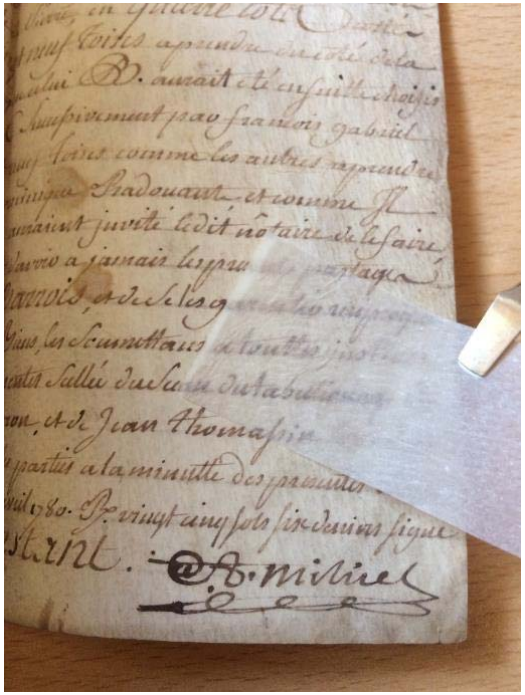
Dry and Redispersible CF Film

- Low basis produced on a paper machine with a conventional drying section
- Since 2014, paper conservator Rémy Dreyfuss-Deseigne works on the introduction of CF films in art conservation
- CF films transmit light and can be as transparent as a polyester film like mylar.
- Transparency does not change after aging

CF film in art restoration - Workshop





March 19-22, 2019: Albertina Museum in Vienna, Austria
June 2019: The Indiana Historical Society, Indianapolis, USA
July 2019: The Tokyo National Research Institute for Cultural Properties, Tokyo, JAPAN

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CF in concrete

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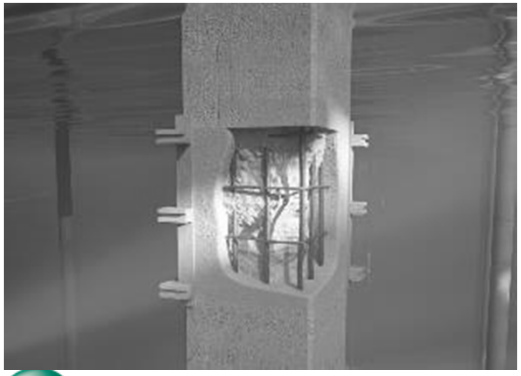
Specific applications in concrete

Self-Consolidating

High & Ultra-High Performance

Underwater



Floors & Roads

Shotcrete

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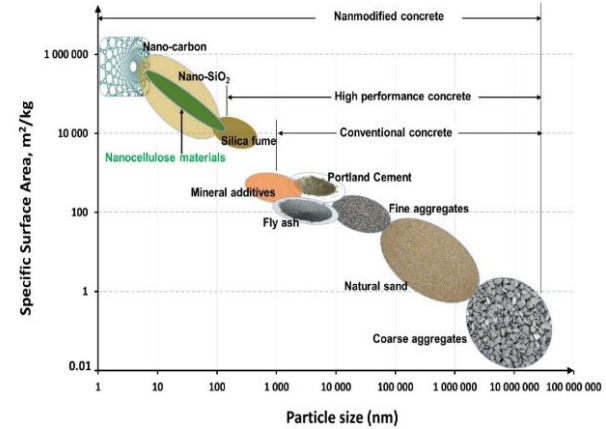
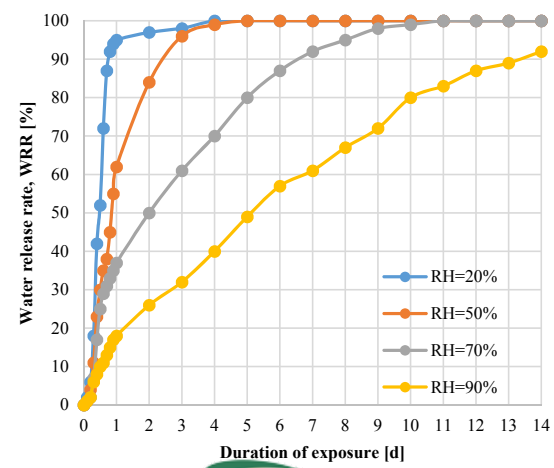
What makes CF unique in concrete applications?

1. High surface area
   - Nanomodification of concrete at the scale of hydrates
2. High surface reactivity (presence of OH^- on surface)
   - Intimate adherence with the cementitious matrix
3. Highest aspect ratio among nanocellulose materials
   - Significant reinforcing ability as well as a viscosity modifying effect
4. Hydrophilic and hygroscopic features
   - Water retention capacity of CF (WRC): up to 350%
   - Water release rate of CF (WRR) positively impacts internal curing and degree of hydration



Sobolev K. et al. Am. Ceram. Soc. Bull. 2005;84(10):14-14



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CF ENHANCES CONCRETE PROPERTIES IN ITS THREE MAJOR PHASES

1 **Fresh concrete**

2 **Hardening concrete**

3 **Hardened concrete**

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1 EFFECT OF CF ON THE PROPERTIES OF FRESH CONCRETE

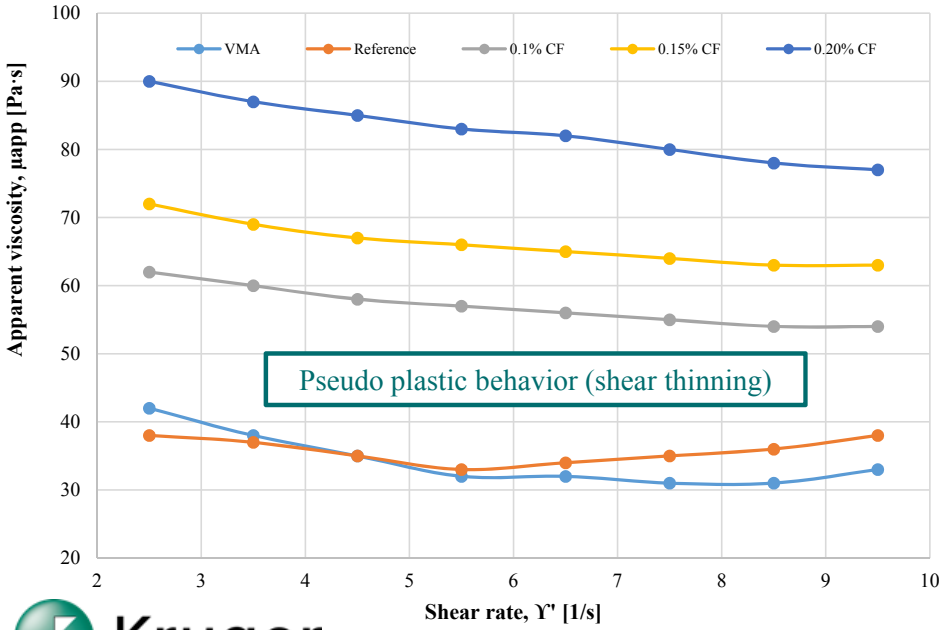
CF serves as a viscosity modifying agent (VMA) in flowable concrete

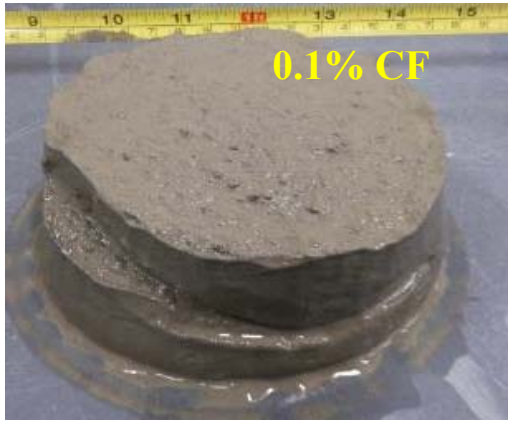
TYPICAL APPLICATION: SELF-CONSOLIDATING CONCRETE (SCC)

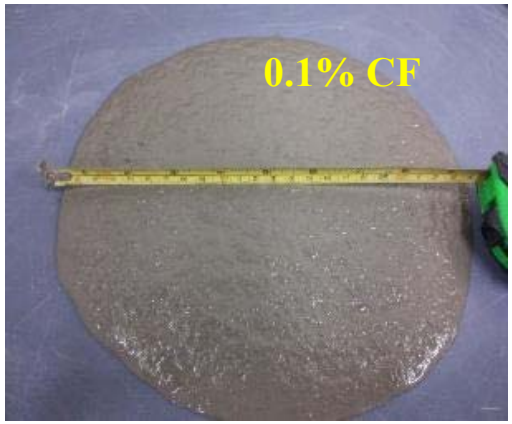
- SCC is highly flowable, non-segregating (stable) concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation
- The balance between flowability and stability is highly delicate and requires the use of VMA

CF effect on Rheology

- CF alters mixture rheology and workability, improves stability







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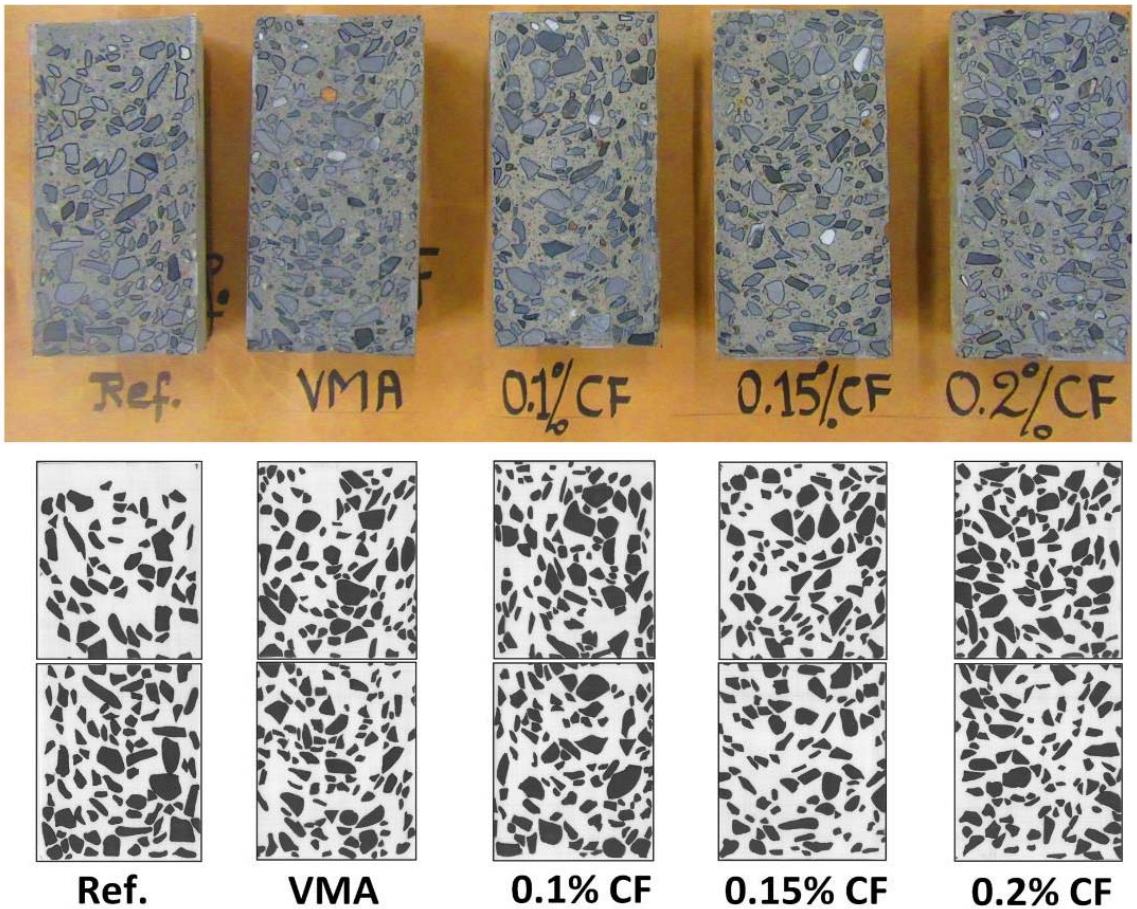
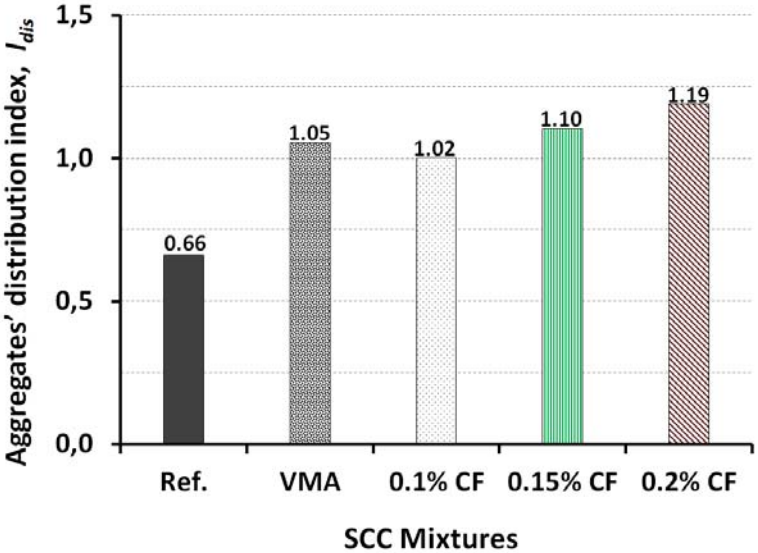
CF in SCC - matrix skeleton structure



CF can be used as VMA to improve mixture homogeneity



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2 EFFECT OF CF ON THE PROPERTIES OF HARDENING CONCRETE

CF serves as a shrinkage reducing admixture in low water-to-cement ratio systems

TYPICAL APPLICATION: ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

- UHPC is a cementitious, concrete material that has a minimum specified compressive strength of 120MPa with specified durability, tensile ductility and toughness requirements

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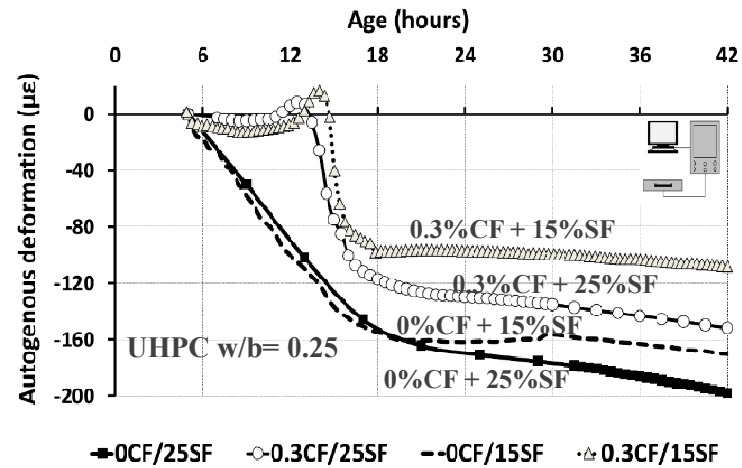
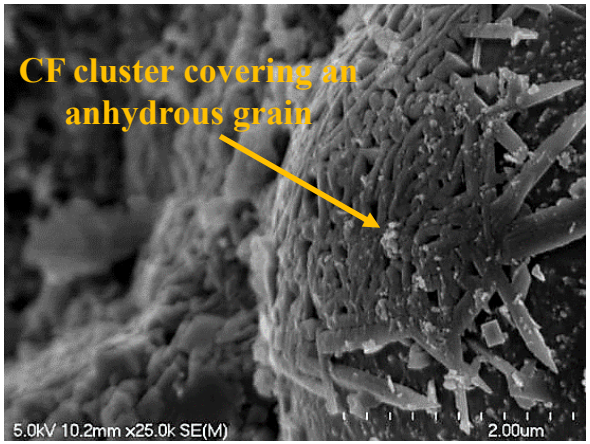
Reduction of autogenous shrinkage driven by internal curing

- CF reduces early-age autogenous shrinkage by releasing adsorbed water within the concrete, resulting in reduces cracking

- CF does not affect the air-void network and improves mechanical behavior





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O. Hisseine et al. 2018, Cement and Concrete Research, Submitted for review

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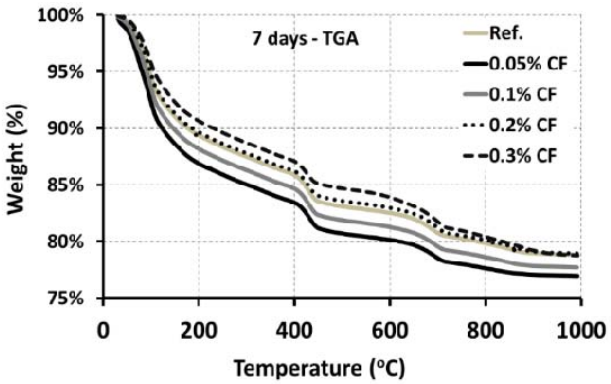
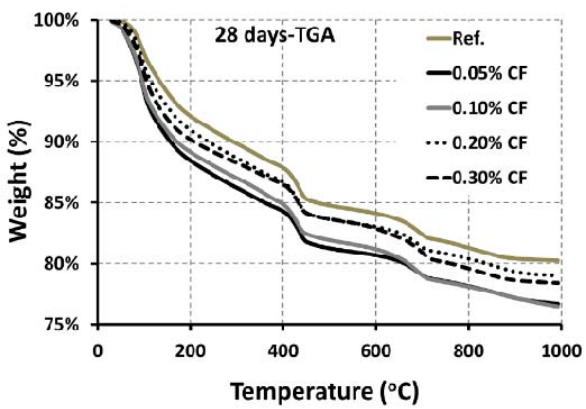
3 EFFECT OF CF ON THE PROPERTIES OF HARDENED CONCRETE

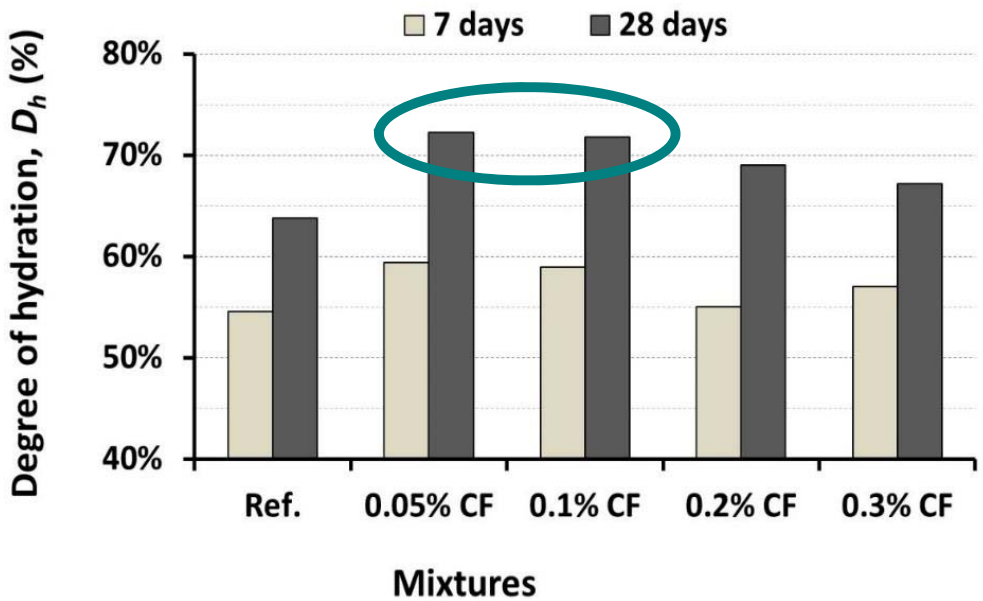
CF serves as a nano-reinforcing agent leading to higher mechanical properties due to:

1) **Higher degree of hydration**
2) **Stronger Calcium-Silicate-Hydrate (C-S-H) matrix**
3) **Stiffer matrix due to crack bridging**

3.1. A higher degree of hydration







Higher degrees of hydration (+15%) with CF → internal curing effect

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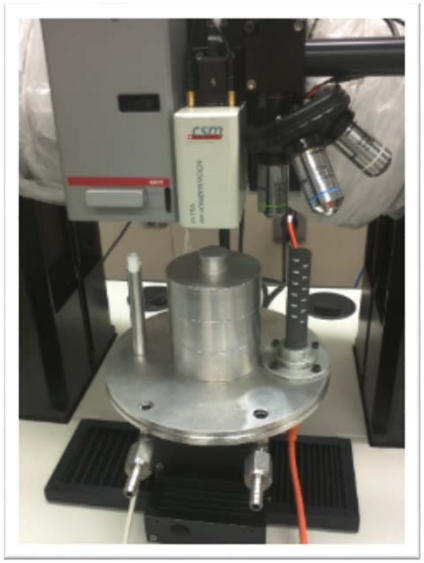
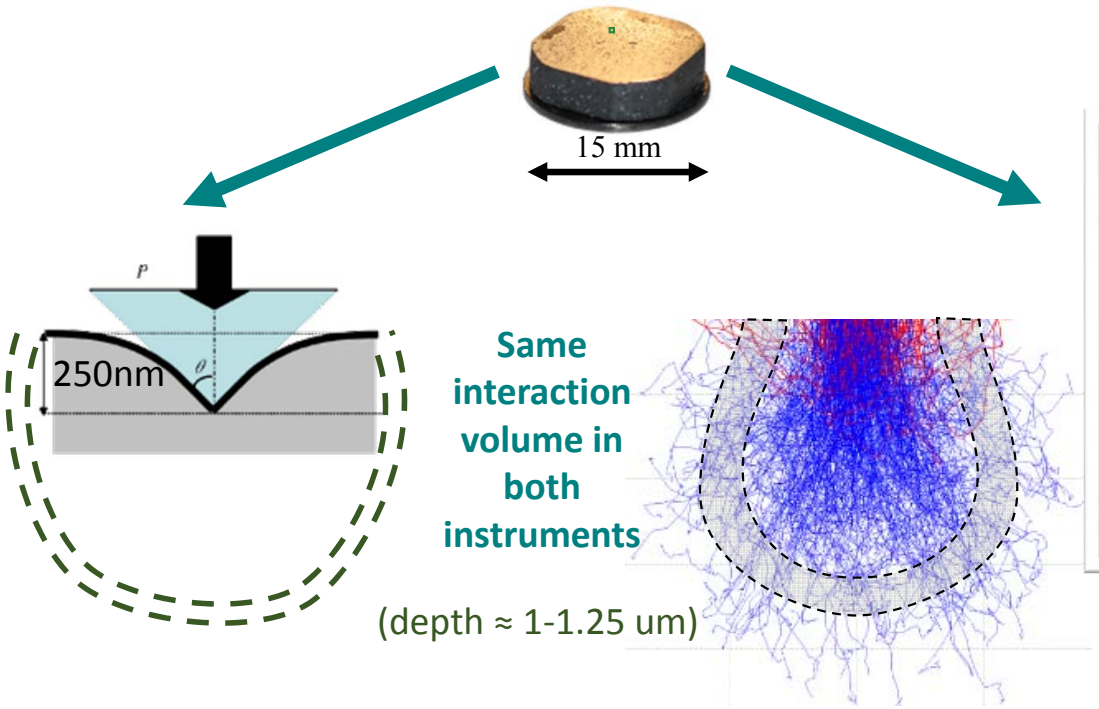
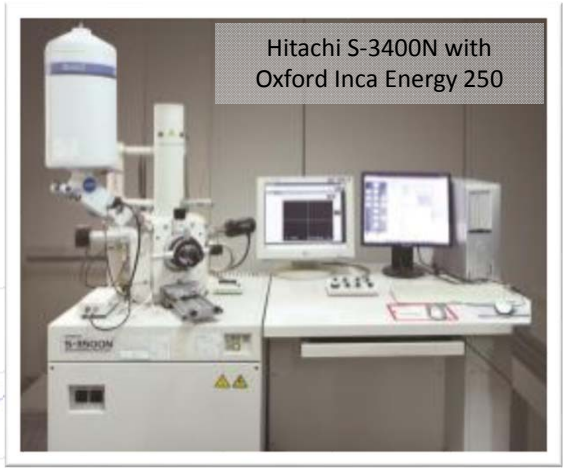
3.2. Stronger Calcium-Silicate-Hydrate (C-S-H) matrix





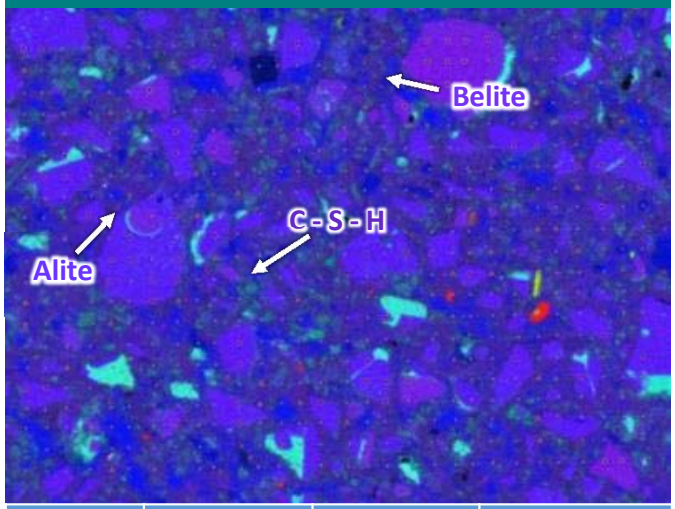


Nanoindentation coupled with quantitative energy-dispersive spectroscopy (NI-QEDS)

Hisseine et al. 2019, Construction and Building Materials, 206 (2019) 84–96.

3.2. Stronger Calcium-Silicate-Hydrate (C-S-H) matrix

100% Cement, w/c = 0.30, 28d



	M (GPa)	H (GPa)	C (GPa)
Alite	108±17	10.4±1.6	8800±3000
Belite	117±13	8.8±1.0	5000±3300
C-S-H	26.1±3.4	0.78±0.17	146±34

Nanoindentation showed enhancement of the microstructure, by increasing C-S-H mechanical properties at the micro scale

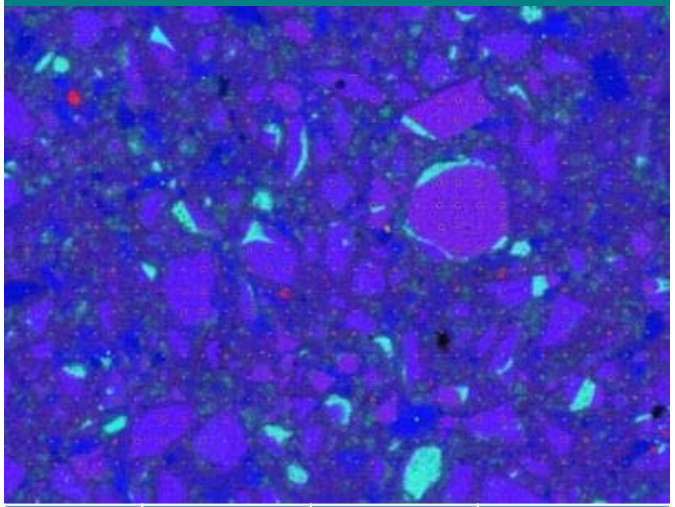
CSH: Calcium-Silicate-Hydrate (the glue of concrete)

M=Indentation modulus

H=Indentation hardness

C=Contact Creep

0.05% CF, w/c = 0.30, 28 d



	M (GPa)	H (GPa)	C (GPa)
Alite	107±17	10.7±1.6	7700±1400
Belite	111±19	9.2±2.0	4900±2800
C-S-H	**29.2±3.5**	**0.98±0.20**	**175±31**

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Hisseine et al. 2019, Construction and Building Materials, 206 (2019) 84–96.

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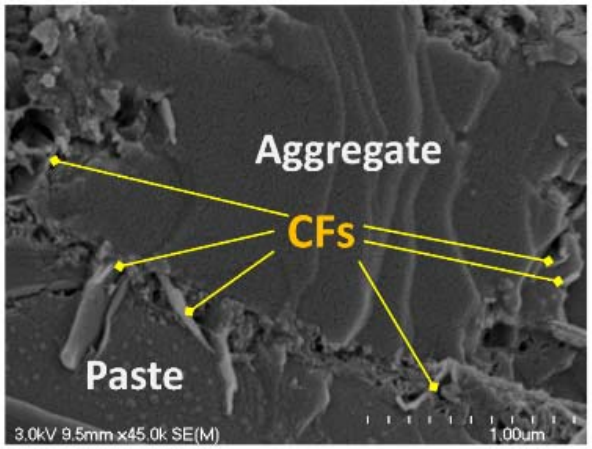
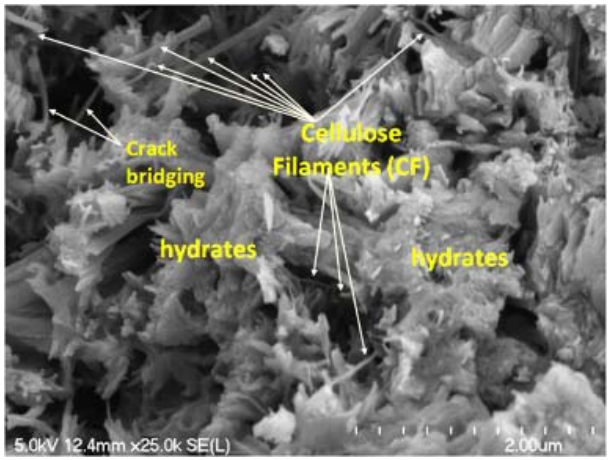
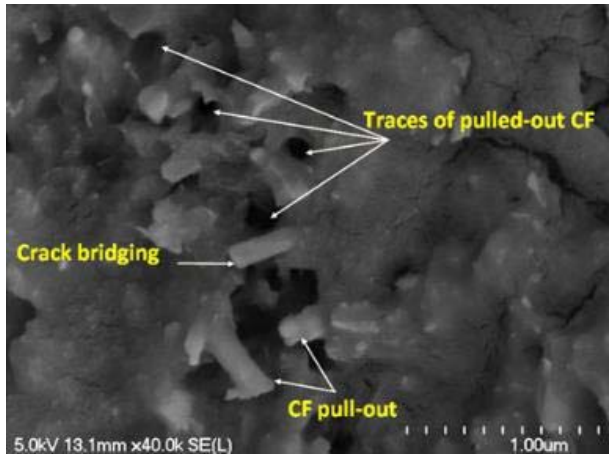
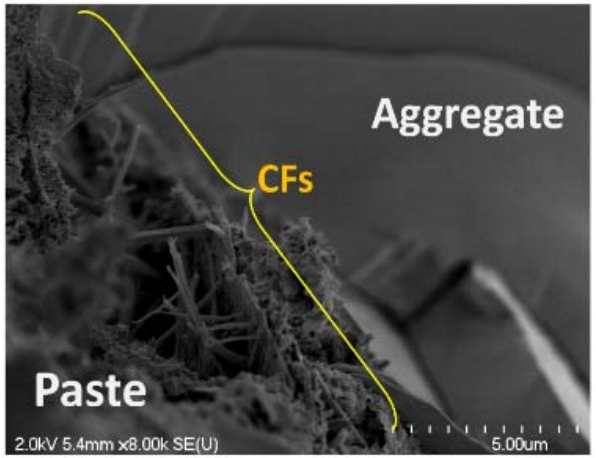
3.3. Stiffer matrices due to crack bridging

- CF provides matrix reinforcement of the interfacial transition zone (ITZ)
  - At fresh state: CF around aggregates limits bleeding and segregation (higher stability)
  - At hardened state: CF in the ITZ reinforces concrete by crack bridging resulting in improved fracture behavior and toughness









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O. Hisseine et al 2018, J. Mater. Civ. Eng., 30(6): 04018109

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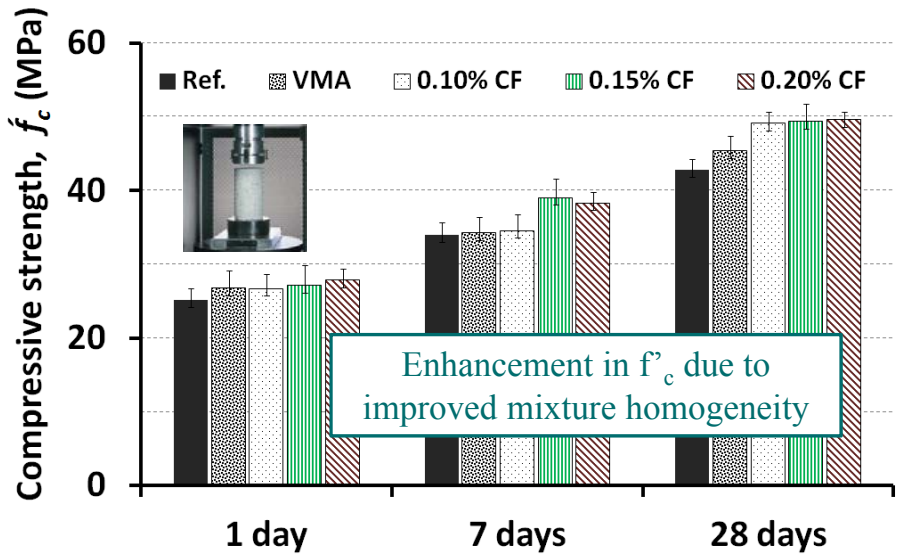
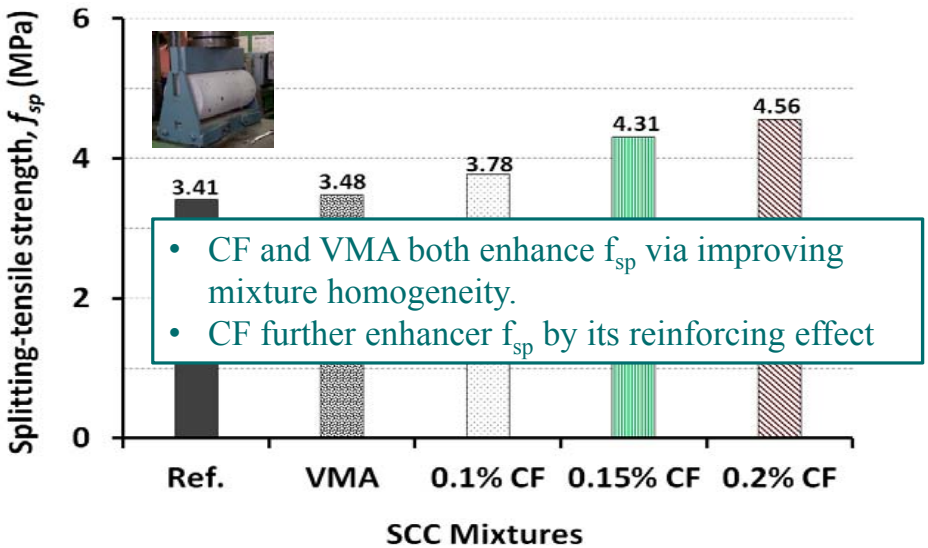
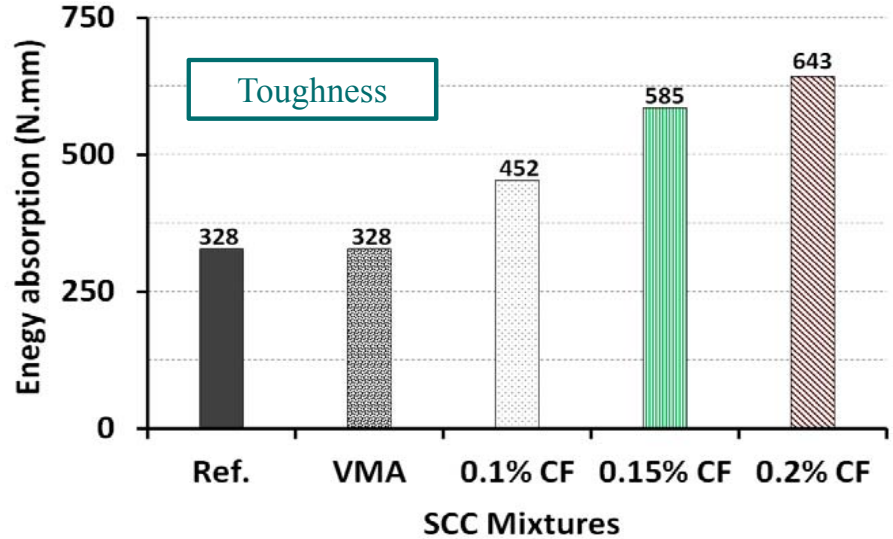
3.3. Mechanical properties

- Improved mechanical performance
- Mixtures with CF have increased toughness







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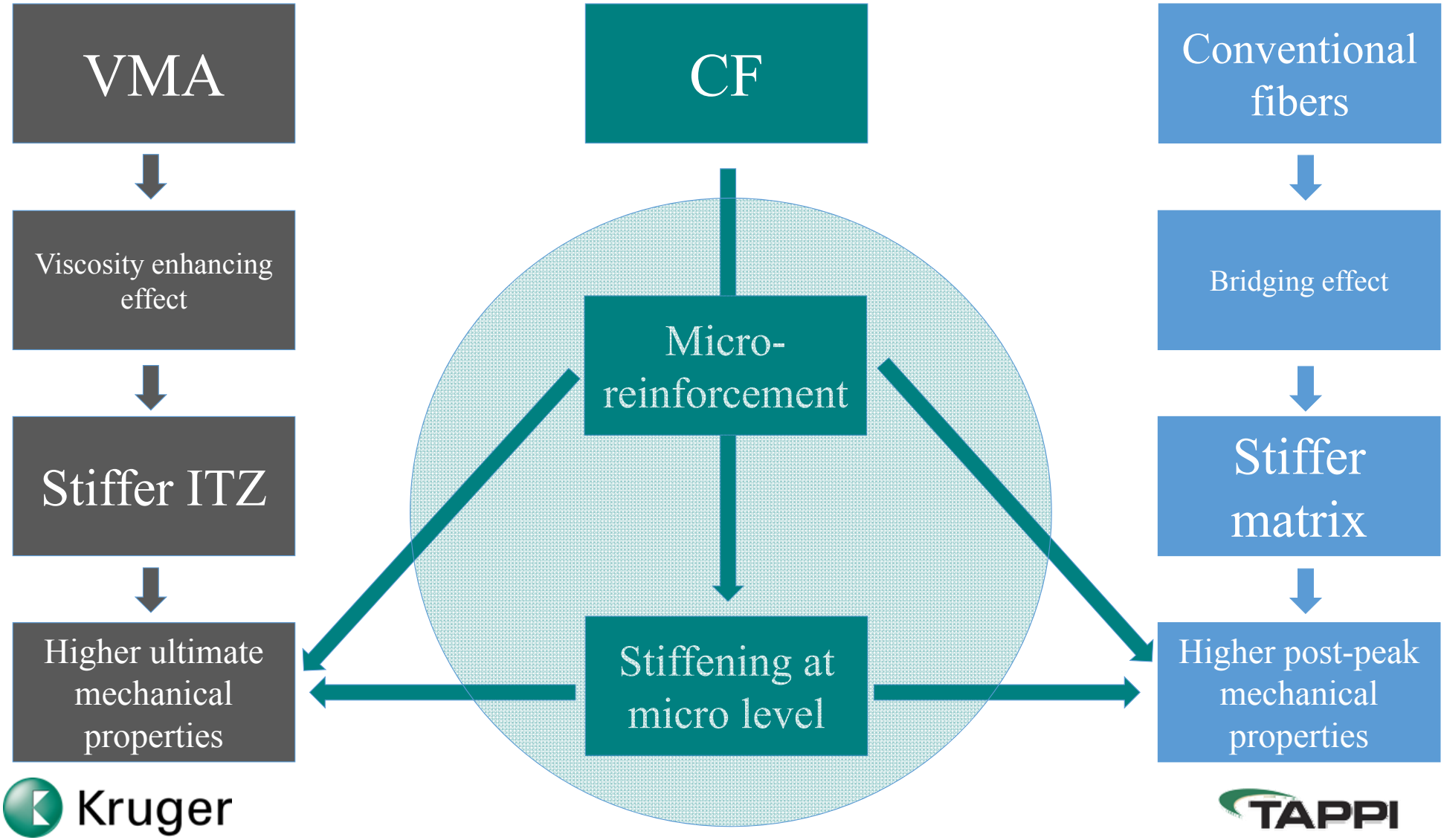
Impact of CF on various concretes

	Regular	Self-consolidating	Ultra-high performance
Segregation & bleeding	+	+++	+
Mixture stability	+	++	+
Shrinkage	++	+++	+++
Flexural strength	+	++	+
Toughness (flex. capacity)	+	+++	+++
Tensile-splitting strength		++	
Elastic modulus			+
Compressive strength		+	



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CF in concrete summary

- Modifies the viscosity and reduces slump flow
- Improves the cohesiveness and reduces segregation
- Reduces autogenous shrinkage, internal curing without the drawbacks related to the use of lightweight aggregates
- Increases compressive strength and elastic modulus
- Increases flexural strength and flexural toughness

CF in lightweight composites

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CF-Composite applications

Automotive

Consumer goods

Aerospace

Construction

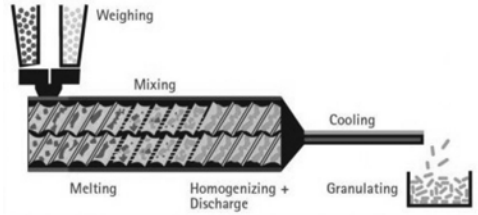
Mass transportation

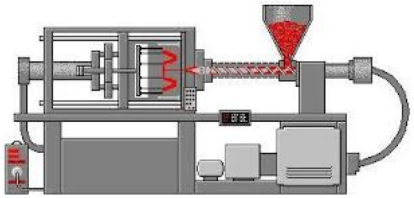
From CF to Injection Molded Parts

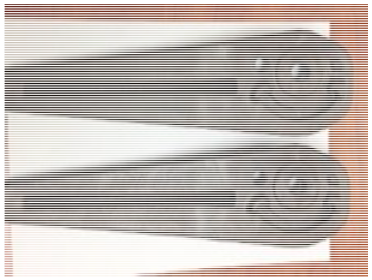
Production of FiloCell cellulose filaments → Conditioning into dried & dispersed form → Compounding with thermoplastic resin → Injection molding of compound

30% solids

99% solids

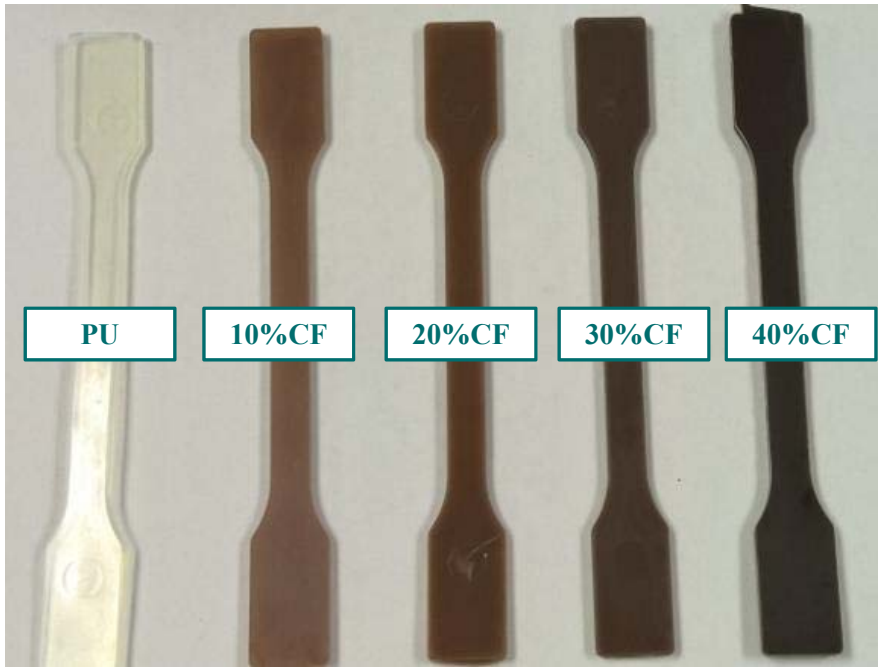






CF successfully mixed with polymers

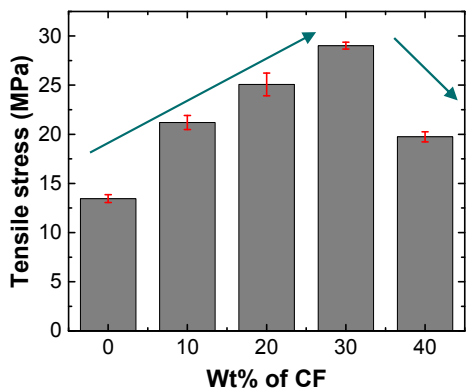
- Up to 40% CF
- Bioplastics (PHA, PLA, Bio-HDPE)
- Ethylene-vinyl acetate (EVA)
- Polyamides (Nylons)
- Polyethylene (HDPE, LDPE, LLDPE)
- Polypropylene (PP)
- Polyurethane (TPU)
- Polyester (PE)
- Polyethylene Terephthalate Glycol (PEG)



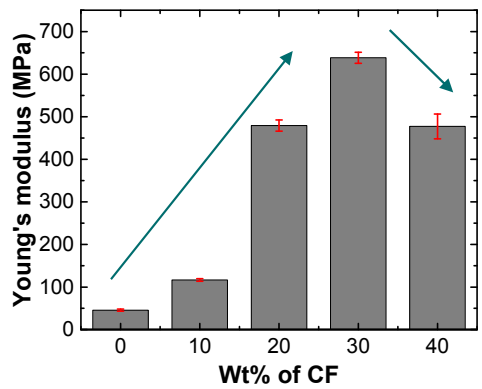
Polyurethane-CF composites

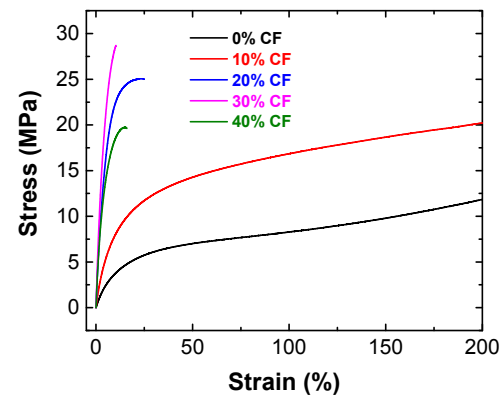
- Significant improvement in strength
- Increased material stiffness, expected loss of ductility

100% improvement at 30% CF level

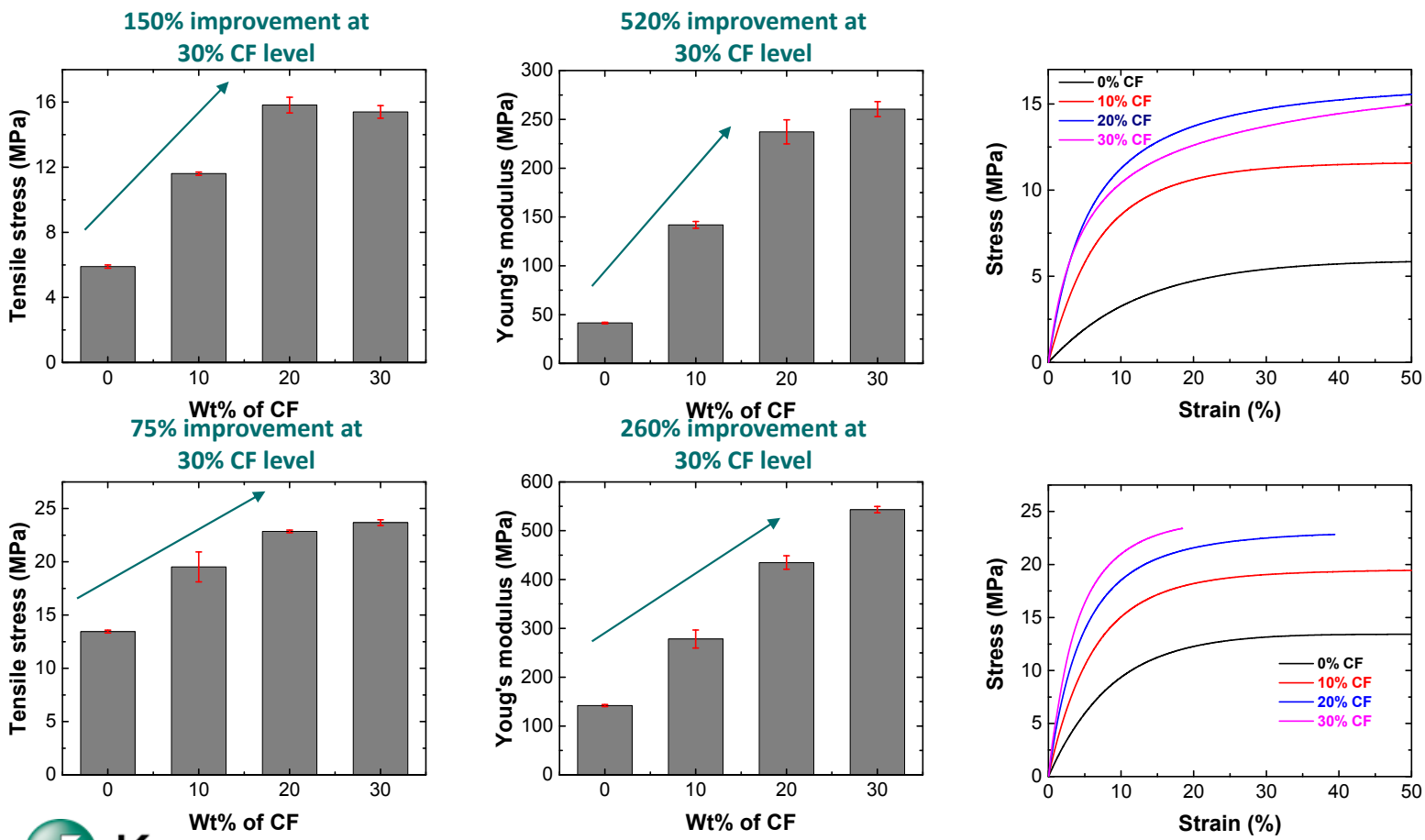


1,100% improvement at 30% CF level





Polyester-CF composites



Polyester elastomer HYTREL® 4056 with low modulus

Polyester elastomer HYTREL® 5556 with medium modulus

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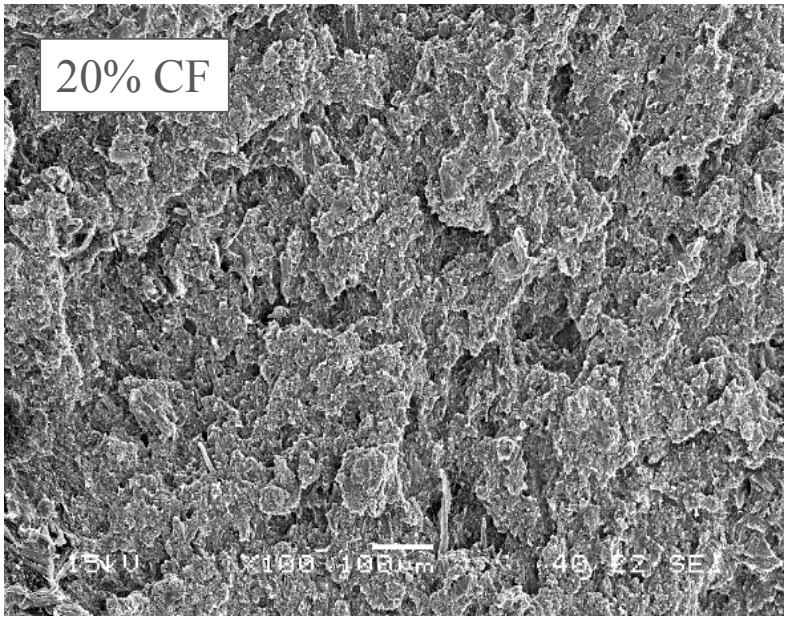
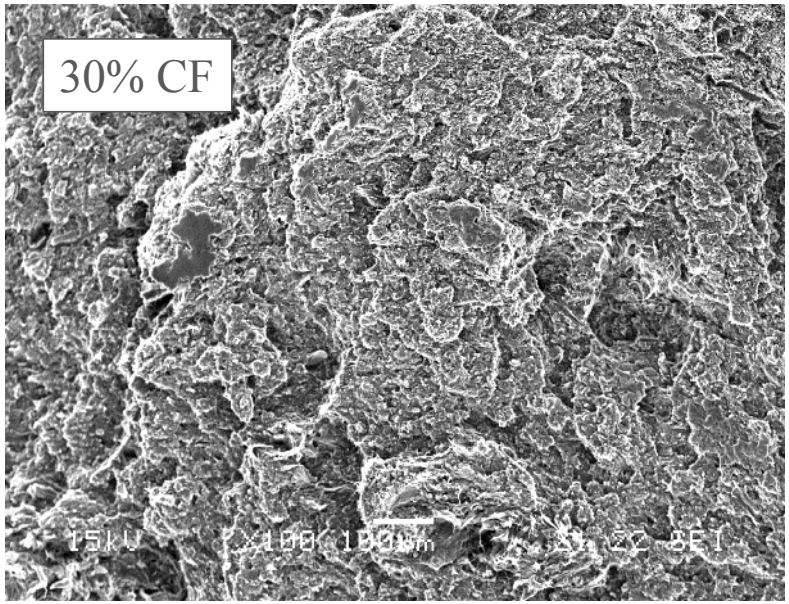
LLDPE-CF COMPOSITES

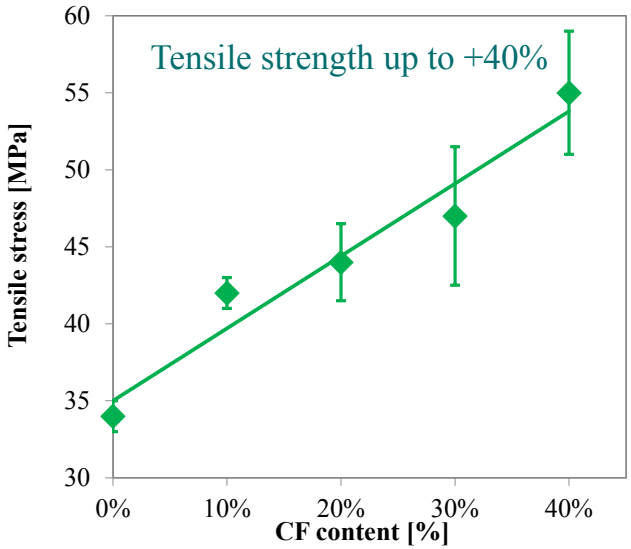
- Excellent dispersion and interfacial interaction
- Compatibility without coupling agents

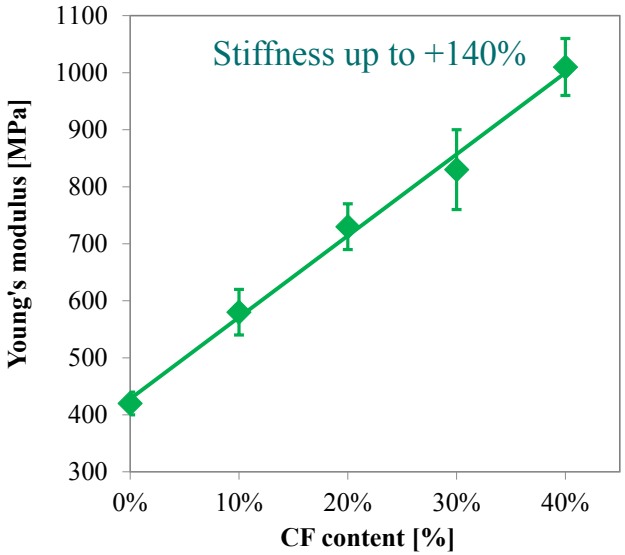


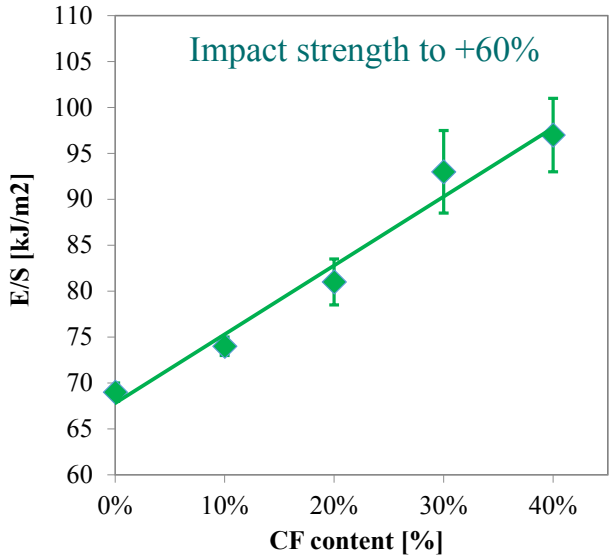


LLDPE-CF composites

- Composites with up to 40% CF
- Improved the mechanical properties







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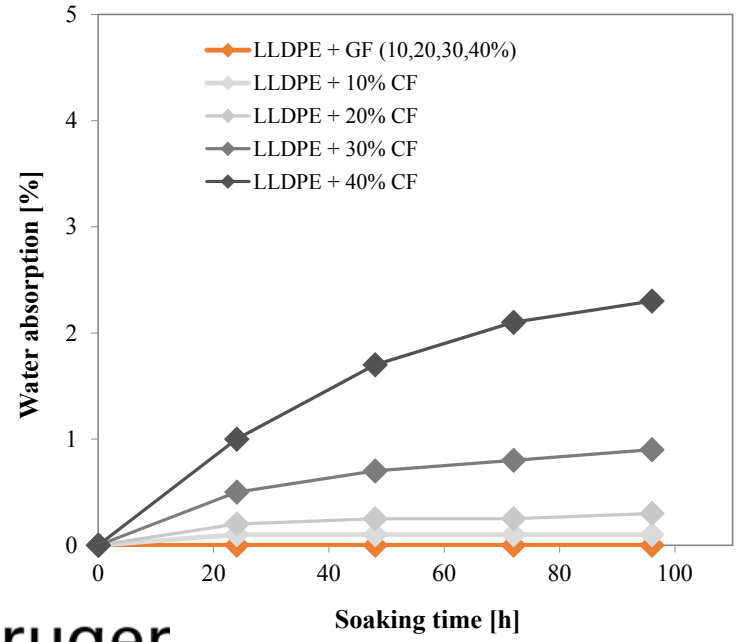
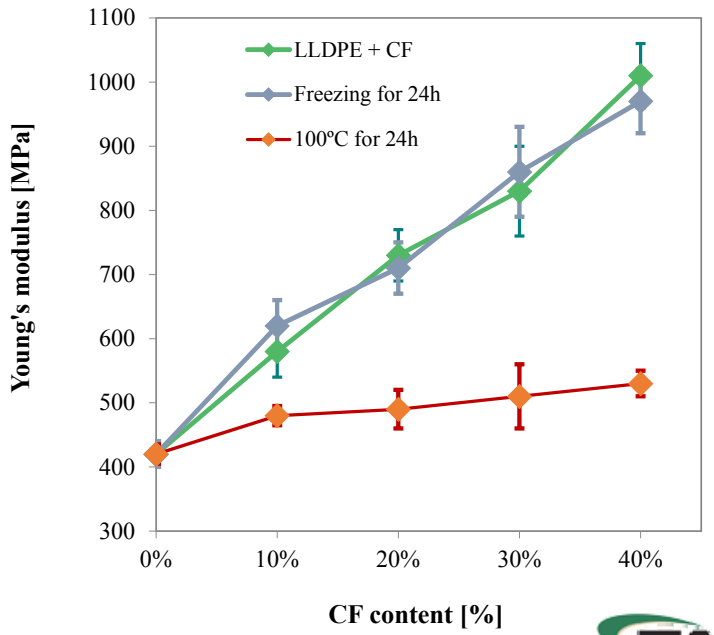
LLDPE-CF composites

- Low water absorption
- No effect of freezing, negative impact of heat





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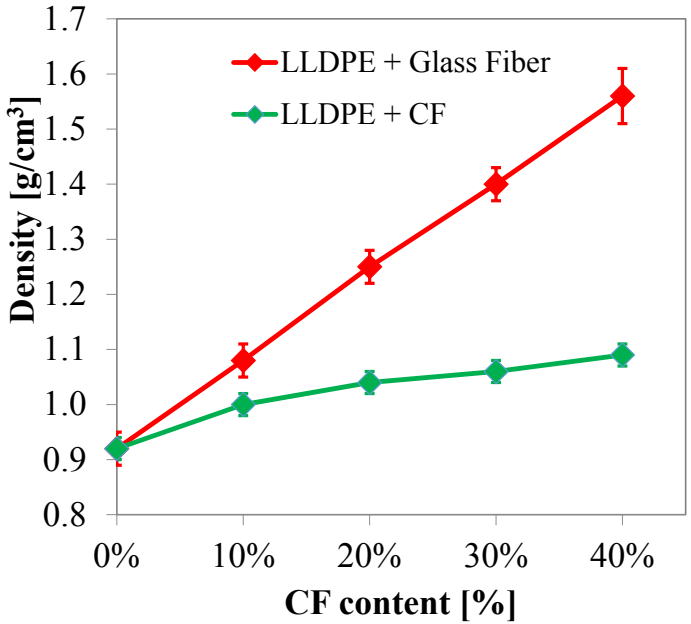
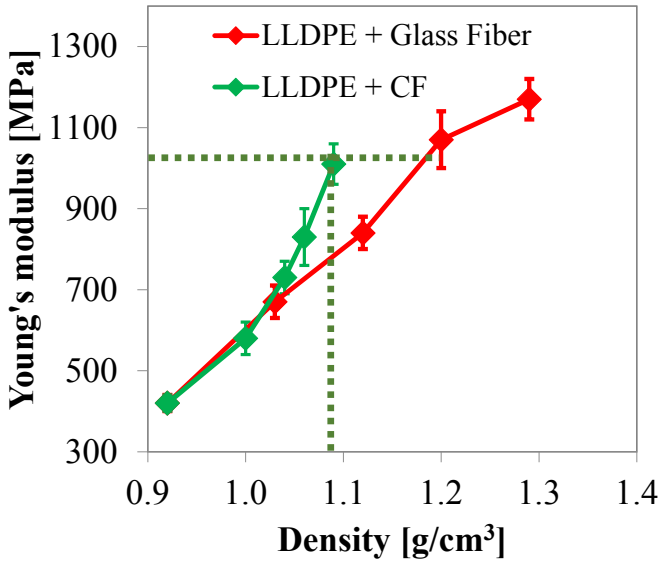
LLDPE-CF vs. LLDPE-Glass fiber

- CF composites had lower density than glass fiber composites
- At equal density CF composites had higher Young's modulus





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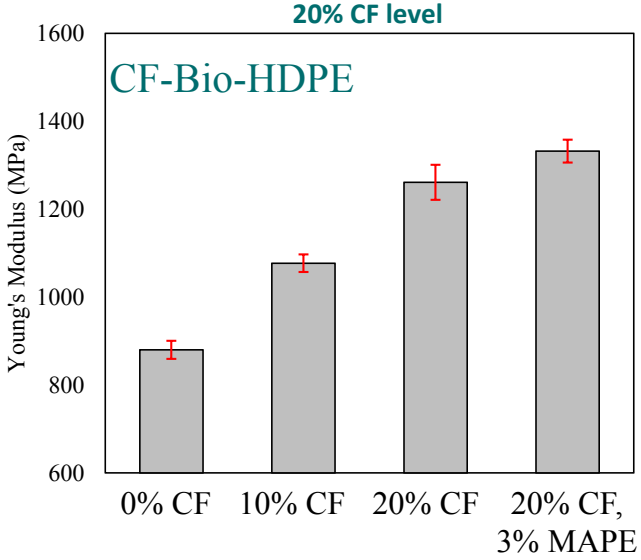
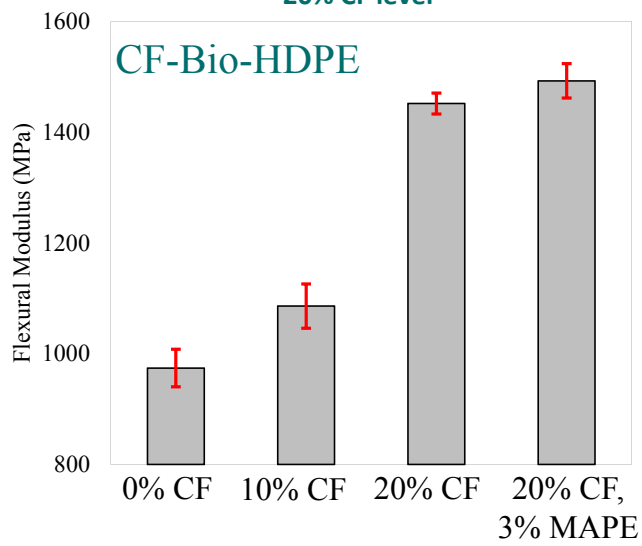
Biocomposites: CF-PLA and CF-Bio-HDPE

- Significant improvement in strength
- Good compatibility with PLA, PHA and Bio-HDPE

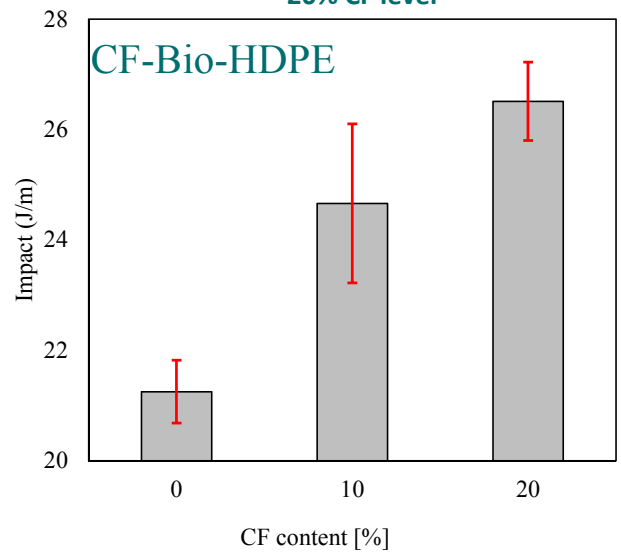
47% improvement at 20% CF level



65% improvement at 20% CF level



25% improvement at 20% CF level



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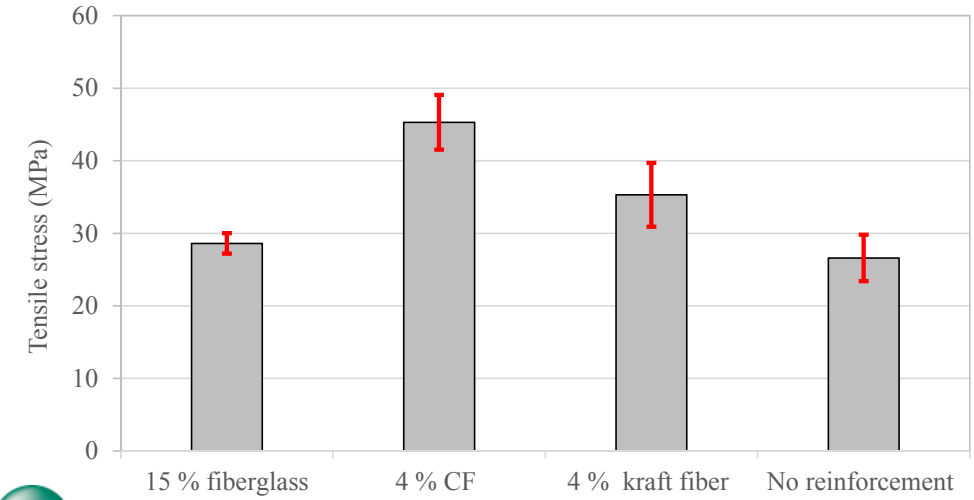
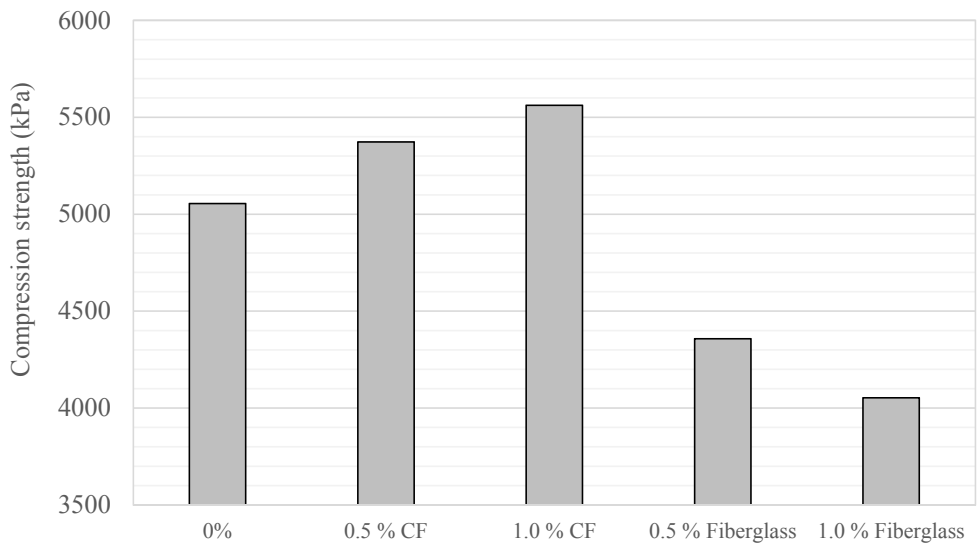
CF-reinforced Bulk Molding Compounds (BMC)

- Generally a fiberglass-reinforced thermoset resin
- Replacing fiberglass with cellulose filaments resulted in:
  - 5% weight reduction
  - Significant improvement of tensile stress (72%) and the tensile modulus (11%)



CF-reinforced biopolymer foams

- High strength bio-based insulating rigid polyester foam composite from glycerol polyol and citric acid and cellulose filaments



CF polymer composites summary

- Technology to produce dry and dispersed CF
- Composites with up to 40% CF loading
- Good dispersion and interfacial interaction
- No need for coupling agent
- Improved strength and stiffness
- Low water uptake
- Suitable for fiber glass replacement
- Applications for biocomposites

Conclusion

- CF is a unique cellulosic biomaterial
- Continuous CF production of 6,000 T/y
- Adaptive manufacturing, strict quality control
- Dedicated team for new business
- Focused product and application development, partnerships between industry and academia
- Several commercial paper grades
- Various concrete and compisite applications

Thank you

PRESENTED BY

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