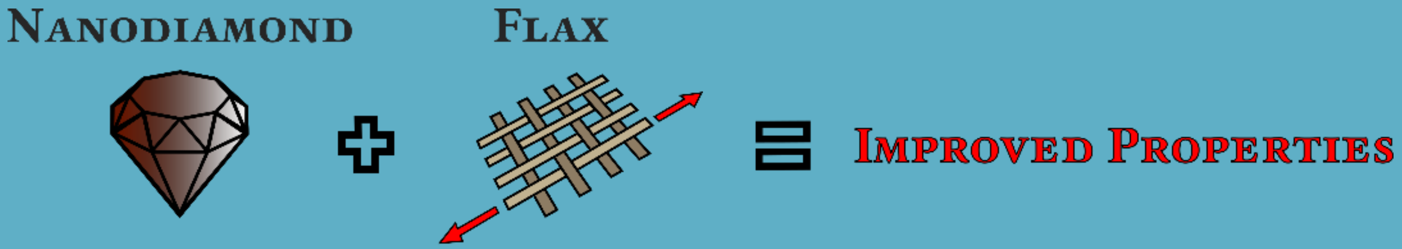
Nanodiamond-treated Flax: Improving Properties of Natural Fibers

C. Hinzmann[1], D. F. Parsons[2], J. Fiedler[1], J. Zalieckas[1], and B.Holst[1]
[1] Department of Physics and Technology, University of Bergen, Bergen, Norway,
[2] Department of Chemical and Geological Sciences, University of Cagliari, Cagliari, Italy



Carsten Hinzmann
carsten.hinzmann@uib.no

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Talk outline

Motivation	Results	Modeling	Outlook	Q&A
• Natural fibers • Nanodiamonds	• Nanodiamond treatment • Mechanical properties • Comparison between flax and cotton	• Explanation of experimental findings	• New application	

Why natural fibers?

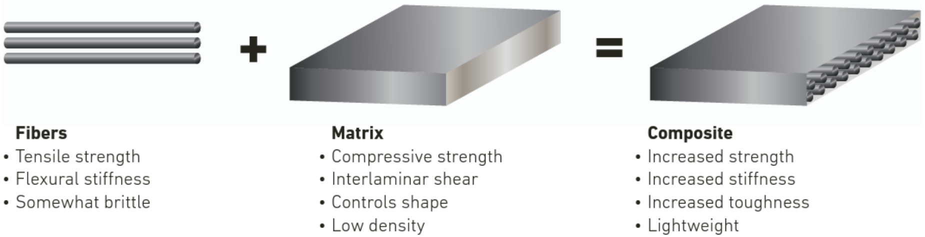


Fig. 1: Fiber reinforced composite material [1]

Advantages:

- More sustainable (biodegradable, less energy consumption, less costs) [2]
- Competitive specific mechanical properties (strength to density ratio) [2]
- Excellent damping properties

Disadvantages:

- Lower ultimate strength than synthetic fibers
- Variability in properties
- Hydrophilic (poor compatibility with matrix)

[1] L.C. Droworth, Essentials of Advanced Composite Fabrication and repair, 2019

[2] L. Yan et al., Composites Part B: Engineering, 2014

Where are natural fibers used?

Cost and weight saving:

Fig. 2: Components of Mercedes E-Class from late 1990s using natural fiber composites [1]

Utilizing special properties:

Fig. 3: Guitar made from flax fiber for acoustic reasons [2]

[1] Chauhan et al., Journal of Thermoplastic Composite Materials, 2022

[2] Black Bird Guitars

Reducing the gap to glass fibers

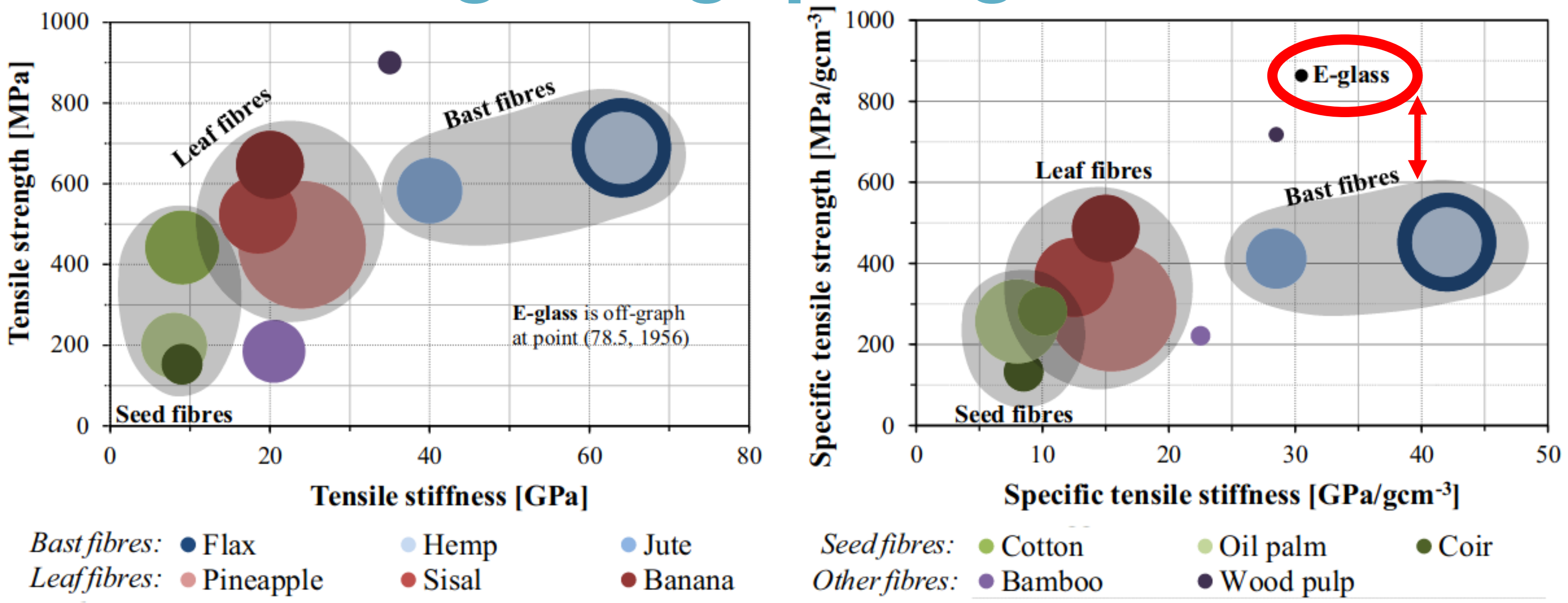


Fig. 4: Comparison of typical strength and stiffness performance of various plant fibers [1]

[1] Chauhan et al., Journal of Thermoplastic Composite Materials, 2022

How can nanodiamonds help?

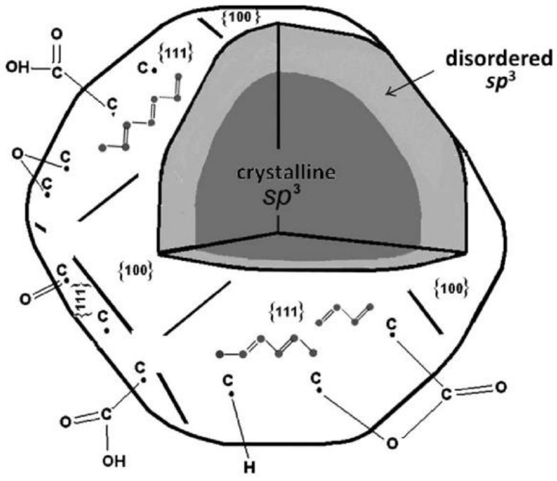


Fig. 5: ND of 3-5nm size [1]

Treatments:

- Chemicals change the composition of fibers
- Nano-particles (CNT, graphene) bond to and cover fibers

Nanodiamonds (NDs):

- Exceptional mechanical resistance (hardness, tensile strength…)
- **Tunable surface properties:**
  - Surface groups (compatible to organic natural fibers)
  - Hydrophobic ↔ Hydrophilic
  - Zeta potential
- Bio-compatible, **non-toxic** (unlike CNT, graphene ...) [2]

[1] Oliver A Williams, ed. Nanodiamond, The Royal Society of Chemistry, 2014

[2] V. N. Mochalin et al., Nature Nanotechnology, 2012

Nanodiamond treatment

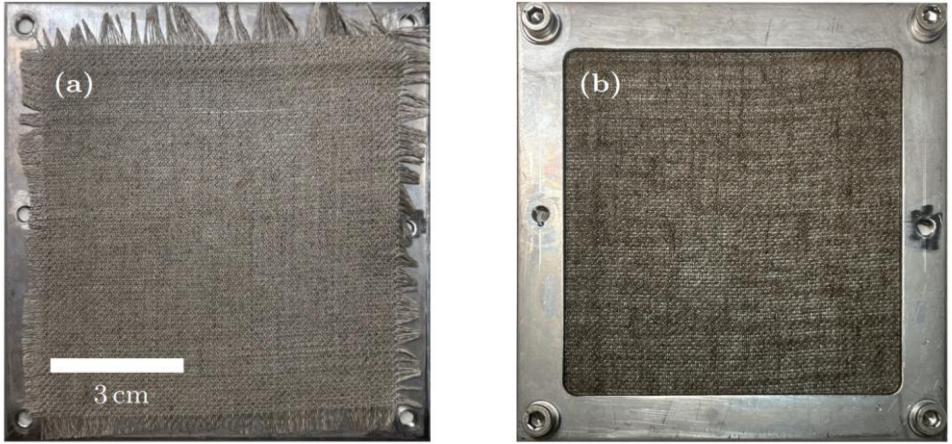


Fig. 6: Picture of dry flax fabric on base plate (a) and wet flax fabric mounted for treatment (b) [1]

Materials:

- Standard off the shelf flax fabric for composites
- 150g/m^2 2/2 twill woven flax fabric (Libeco NV, Belgium)
- Hydrogen-terminated nanodiamonds (Carbodeon Ltd Oy, Finland)

Cleaning of flax:

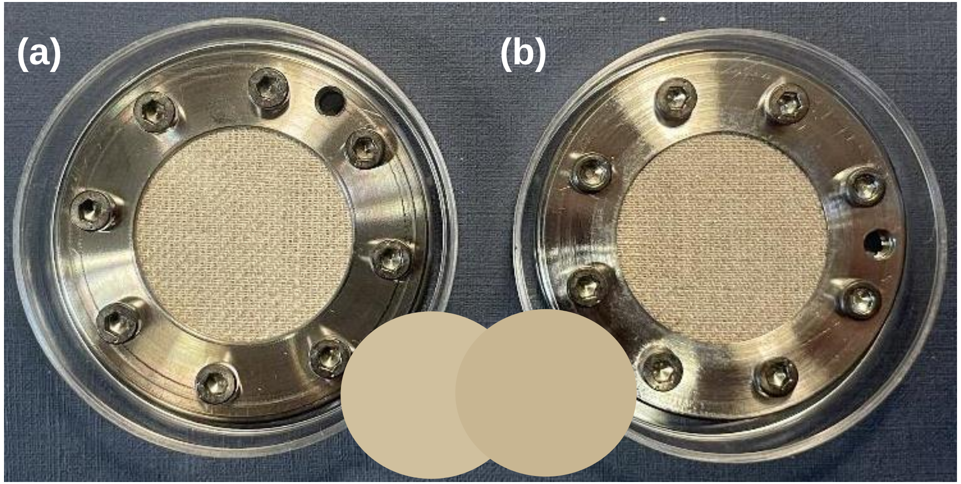
- Sonication in isopropanol (3 min) and deionized water (20 min)

ND treatment:

- ND dispersion of 0.3%
- Sonication for 30 min
- Drying on hot plate at 60 °C [2]

[1] C. Hinzmann et al., Cellulose, 2023 (under review)   [2] Van de Velde and Baetens, Macromolecular Materials and Engineering, 2001

Nanodiamond density



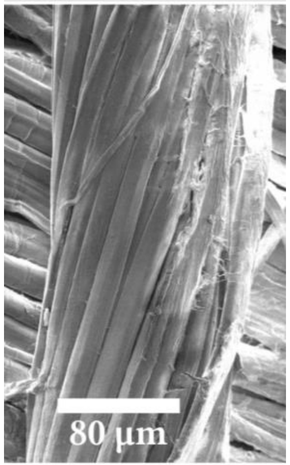


Fig. 7: White light image of untreated (a) and nanodiamond treated flax (b) [1]

Fig. 8: SEM image of flax yarn [1]

Density estimation:

- Weight based → ~35 mg ND on 260 mm × 450 mm fabric

⇨ **All elementary fibers are fully covered with NDs**

[1] C. Hinzmann et al., Cellulose, 2023 (under review)
[2] Mandal, RSC Adv., 2021

Mechanical properties

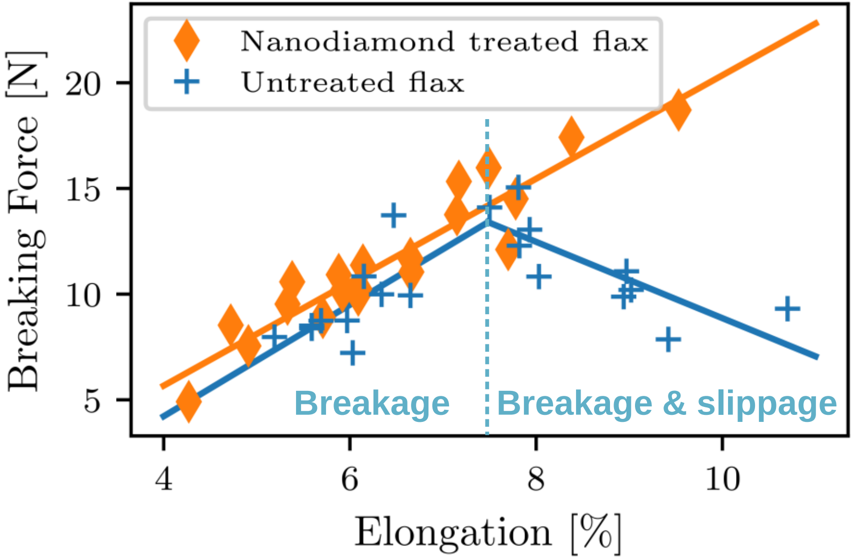


Fig. 9: Ultimate tensile strength (UTS) as a function of elongation [1]

Tensile strength of single threads:

- Based on ISO13934-1:2013
- Increase in UTS by **~ 24 %** with decrease in strain by **~ 11 %**

⇨ **Almost all tested ND-treated flax threads are stronger than untreated flax threads at the same elongation**

[1] C. Hinzmann et al., Cellulose, 2023 (under review)

Yarn structure and clamping

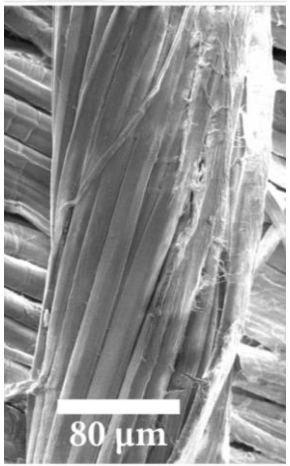


Fig. 10: SEM image of flax yarn [1]

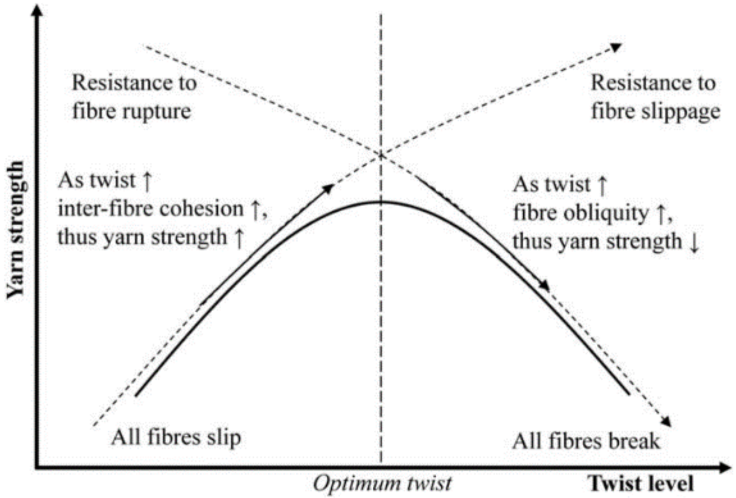


Fig. 11: Overlapping effects influencing the correlation between yarn strength and twist angle [2]

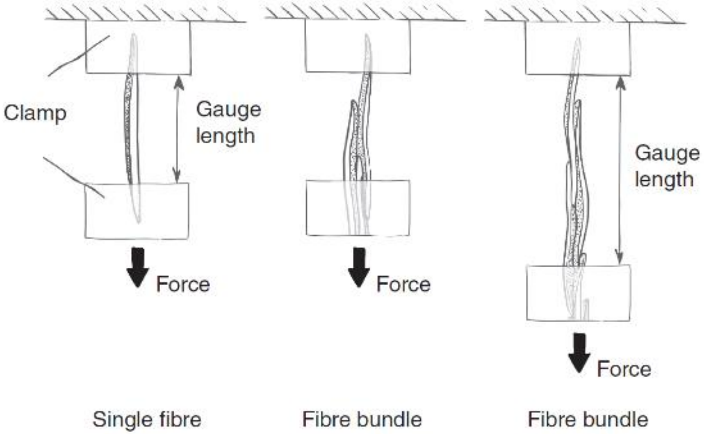


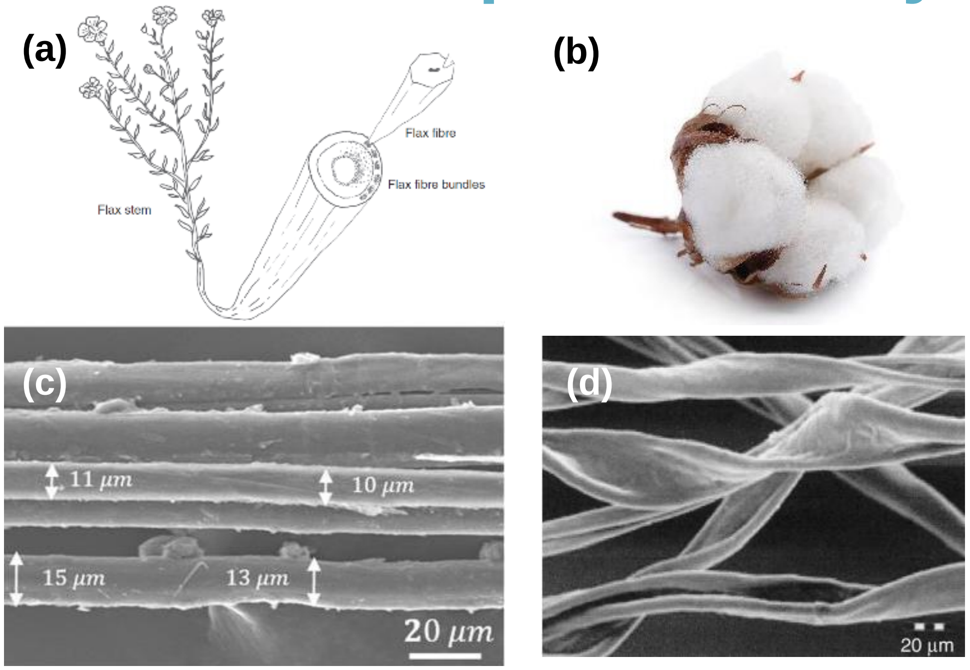
Fig. 12: Different clamping conditions [3]

⇨ **NDs increase cohesion between elementary fibers, which makes the yarn stronger**

[1] C. Hinzmann et al., Cellulose, 2023 (under review) [2] D. U. Shah et al., Journal of Composite Materials, 2013 [3] J. Müssig and K. Haag, Biofiber Reinforcements in Composite Materials, 2015

[4] M. Dochia et al., Handbook of Natural Fibres, 2012
[5] S. Houshyar et al., Cellulose, 2019

Cotton experiments by S. Houshyar et al.



Tensile strength improvement with nanodiamond treatment:

Flax:	Cotton:
+ 24% [1]	+ 40% [2]

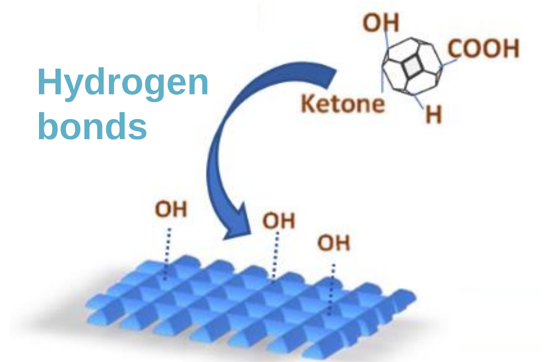


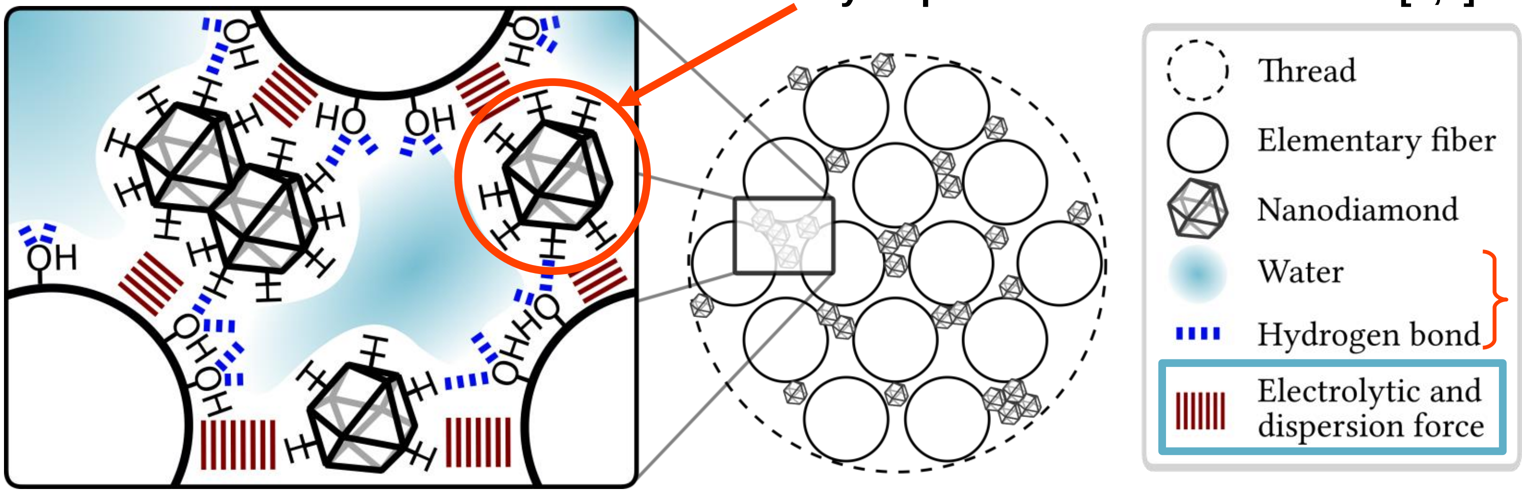
Fig. 13: (a) Flax plant drawing [1]; (b) Cotton boll image [2]; (c) SEM image of single flax fibers [3]; (d) SEM image of cotton fibers [4]

Fig. 14: Schematic of the nanodiamond interacting with cotton [5]

[1] J. Müssig and K. Haag, Biofiber Reinforcements in Composite Materials, 2015
[2] Image by Racool_studio on freepik.com
[3] S. Ahmed et al., Fibers, 2018

Proposed explanation for tensile strength increase

Hydrophobic and confines water [2,3]



- Important in cellulosic materials [4]
- 3x stronger hydrogen bonding in cellulose in wet conditions [5]

Fig. 15: Schematic (not to scale) of a thread's cross-section; Nanodiamonds bond between elementary fibers, increasing the adhesion between the elementary fibers and strengthening the thread; Additional water is confined by the hydrophobic nanodiamonds to further increase the adhesion between the elementary fibers [1]

[1] C. Hinzmann et al., Cellulose, 2023 (under review) [2] S. Stehlik et al., Diamond and related Materials, 2016 [3] A. M. Vervald et al., Journal of Colloid and Interface Science, 2019

[1] C. Hinzmann et al., Cellulose, 2023 (under review) [2] S. Houshyar et al., Cellulose, 2019

Nanodiamond induced force

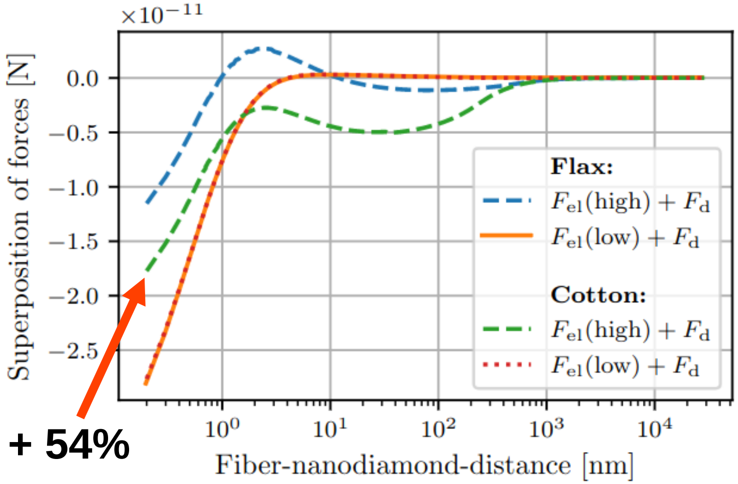


Fig. 16: Superposition of electrolytic force and dispersion force as a function of fiber-nanodiamond-distance [1]

Zeta potential difference:

Flax:	Cotton:
– 5 mV in 1mMol KCl (pH 7) [3]	– 15 mV in 1mMol KCl (pH 7) [4]

Tensile strength improvement with nanodiamond treatment:

Flax:	Cotton:
+ 24% [1]	+ 40% [2]

+ 67%

Chemical composition; Cellulose ratio [5]:

Flax:	Cotton:
70%	90%

[3] A. Bismarck et al., Polymer Composites, 2002 [4] T. Pusić et al., Coloration Technology, 1999 [5] J. Müssig and K. Haag, Biofiber Reinforcements in Composite Materials, 2015

Conclusion

Non-toxic nanodiamond treatment of flax:

- Increased UTS by + 24%

⇨ Decreases performance gap to glass fibers

Modeling of interaction between ND and natural fibers:

- Introduction of electrolytic and dispersion forces
- Stronger interaction with cotton than with flax

⇨ Higher strength improvements for ND-treated cotton

⇨ Presumably because of cotton's lower zeta potentials

Future work

Improving properties of natural fibers:

- Testing the zeta potential hypophysis by tuning the zeta potential of flax
- Combining ND-treatment with chemical treatments

⇨ Increase strength of natural fibers

Testing ND-treated flax in composite applications:

- Performing standard composite performance tests (tensile test, compression, bending …)
- Testing interface (pull-out tests)

⇨ **Finding beneficial applications for natural fibers**

Impact fatigue test for wind turbine blade erosion:

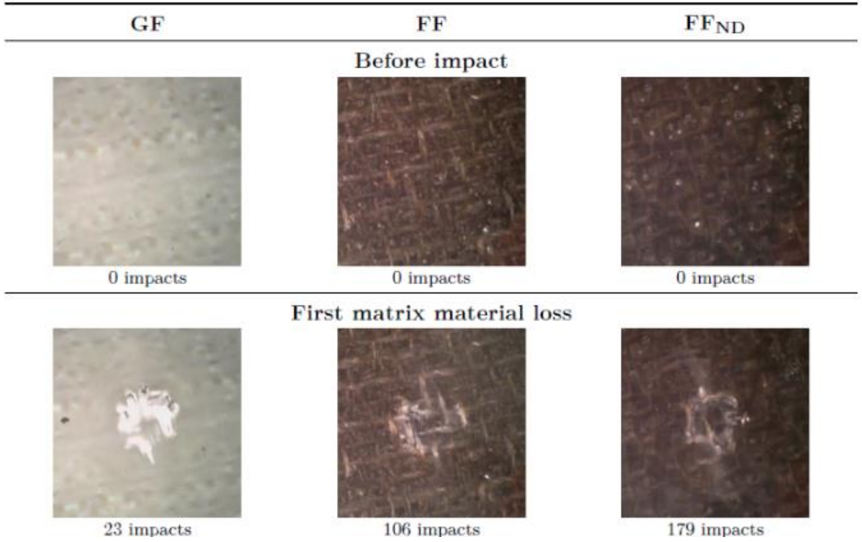


Fig. 17: Impact number to reach first matrix material loss (v = 160m/s)

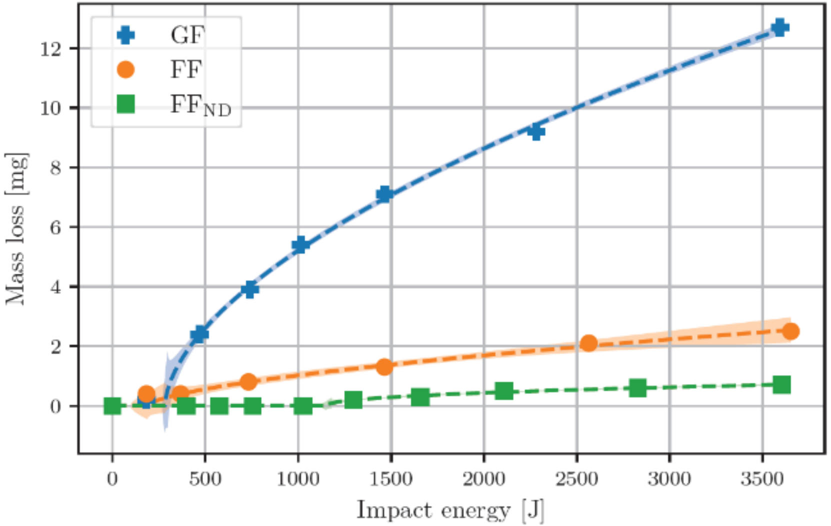


Fig. 18: Mass loss as a function of accumulated impact energy for impact velocities of 160m/s

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- Mentor: **Charlotte Hasager** (Danish Technical University)
- **Nanophysics group** at University of Bergen

Q & A

Would you like to collaborate on a related topic?

Please contact me in the coffee break or by e-mail:
carsten.hinzmann@uib.no

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