Title	Aqueous foam as the carrier medium for producing tailored fiber materials
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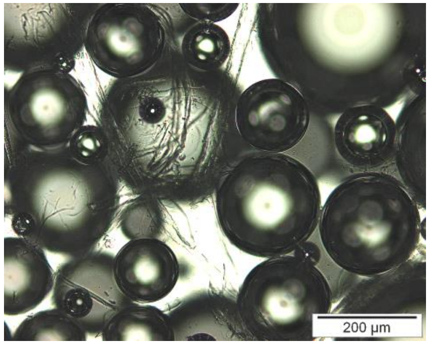

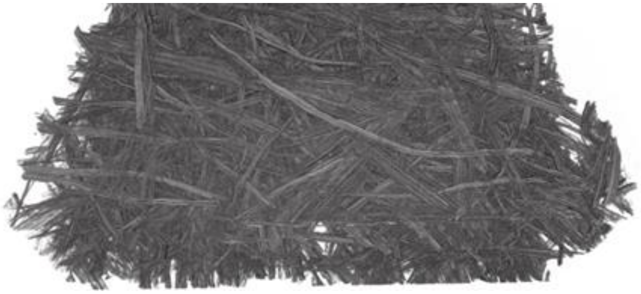

Aqueous foam as the carrier medium for producing tailored fiber materials

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ACADEMY OF FINLAND
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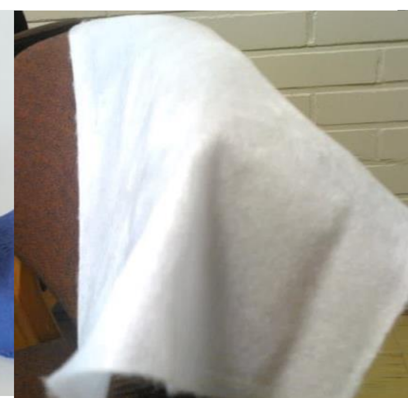
Outline

1. Foam forming technology
2. Micro-structure vs. foam properties
3. Fiber-foam interaction
   - factors affecting air-liquid interface breaking

Foam forming – versatile technology

- Use of a wide variety of raw materials
- High product homogeneity
- Tailored micro-structure
- Light-weight or dense products
- Layered products, 3D forms
- Resource savings (raw material, water, energy)



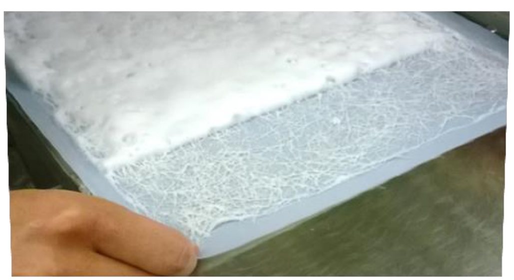



How does it work?

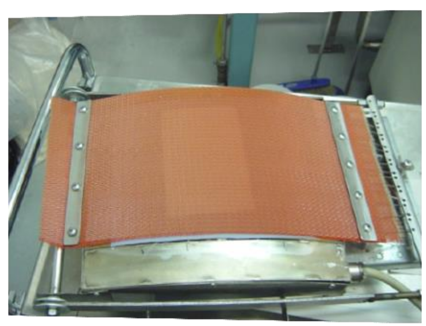
1. *Making foam & mixing raw materials*

2. *Forming on a fabric*

3. *Removing foam with vacuum*



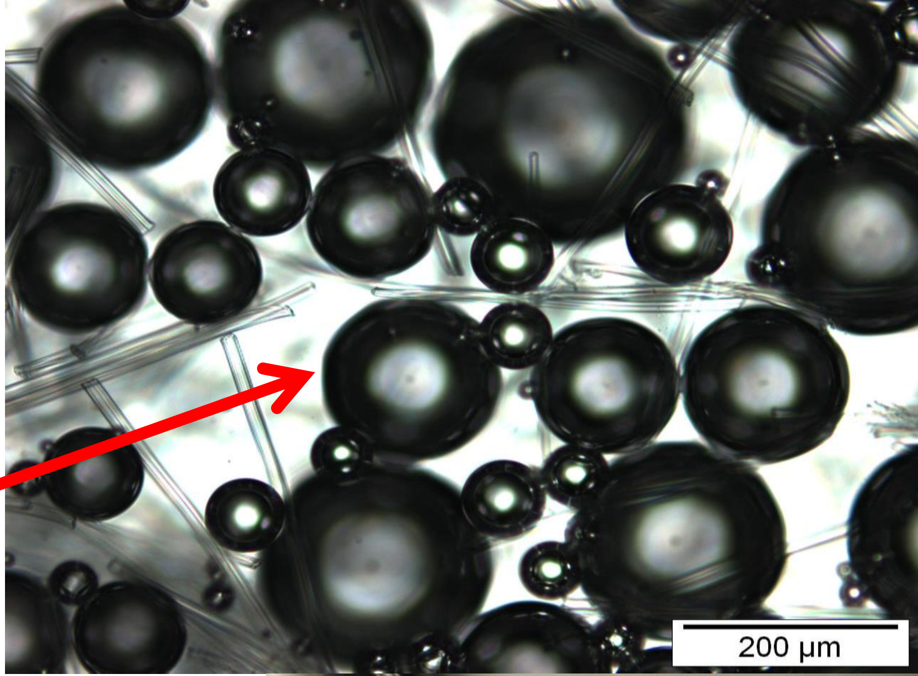
4. *Drying*



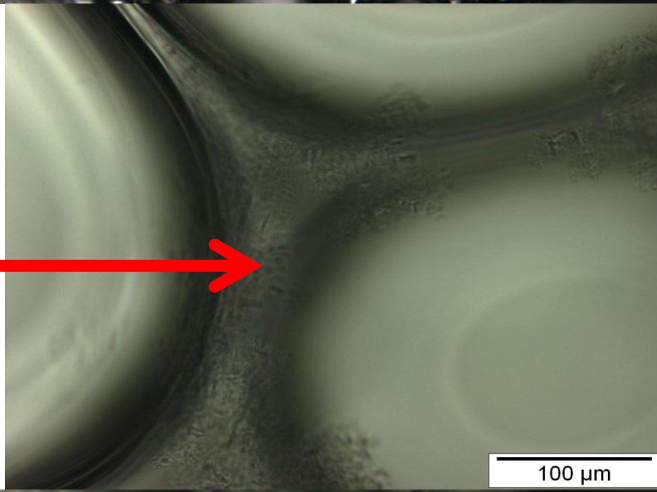
…or all that in a pilot

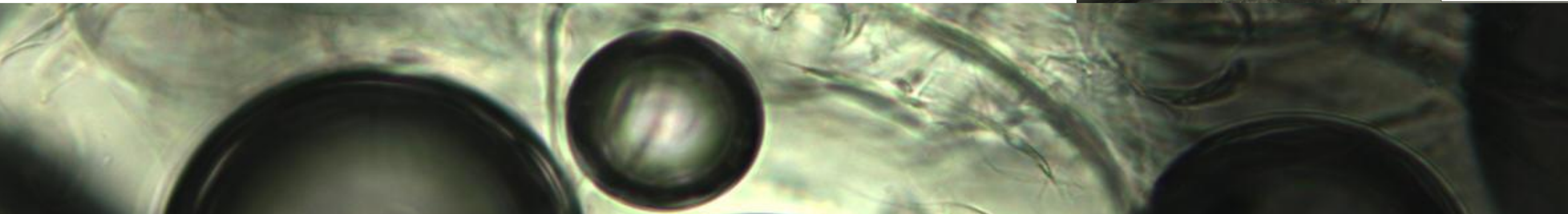
Why does it work?

- Bubbles prevent fiber flocculation and help in achieving structural homogeneity and desired pore structure
  - **Turbulence not required**



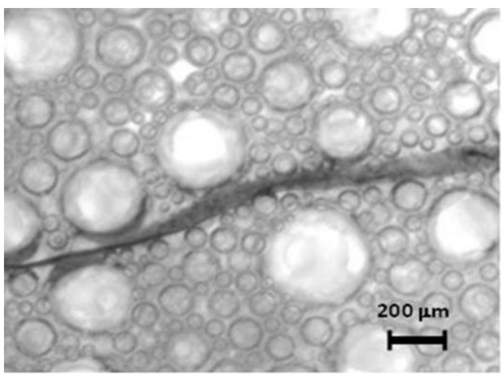
- Nanomaterials and fine particles are carried in bubble vertices and at interfaces

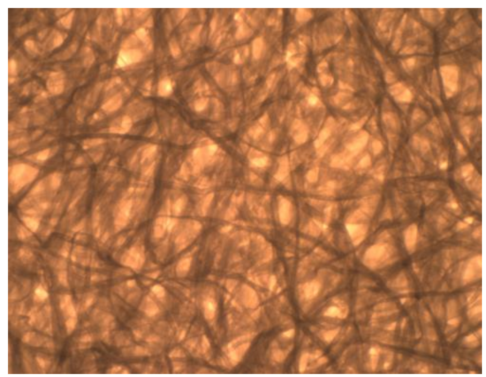


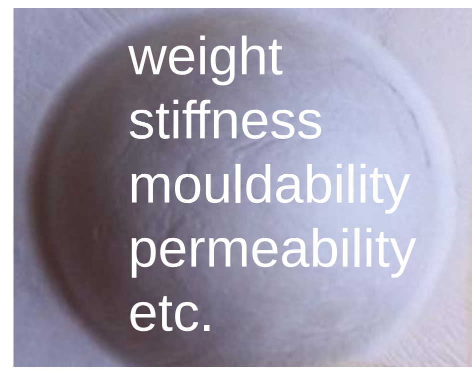


Foam-fiber interaction provides means to tailor…

- Structural homogeneity (”formation”)
- Material density (10-1400 kg/m^3 for cellulose)
- Micro-porous structure
- Material layers



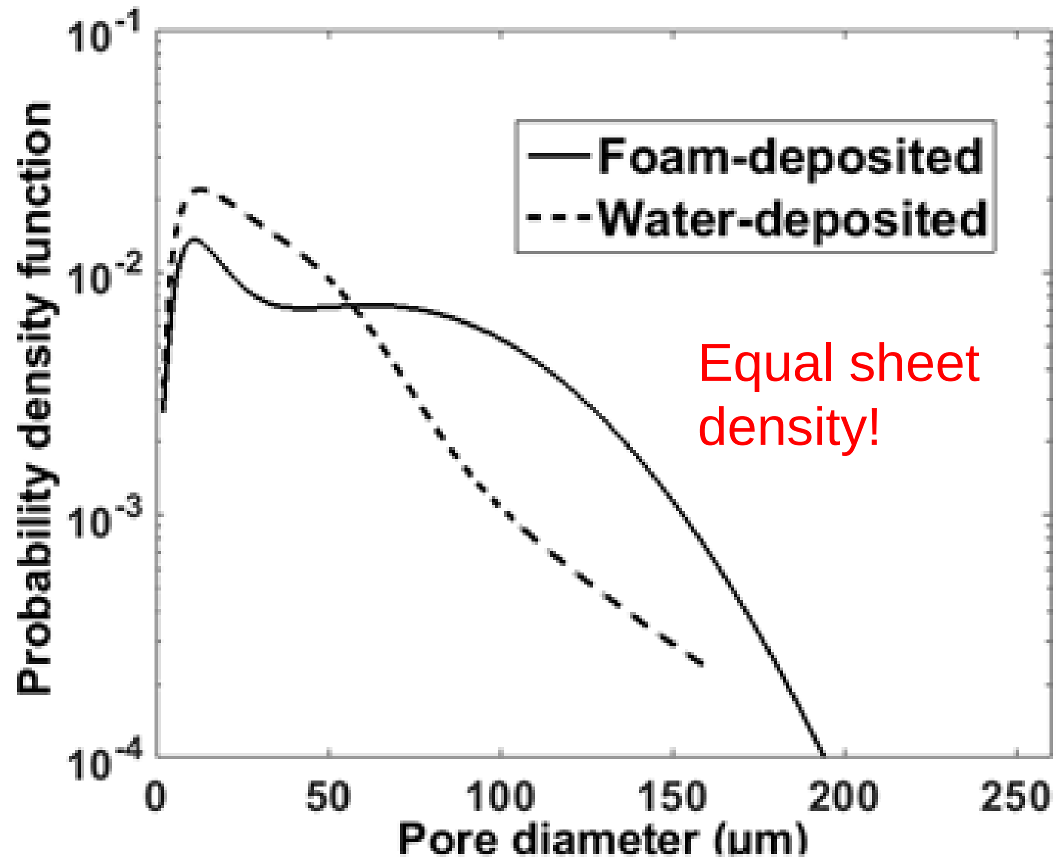




FOAM PROPERTIES → ***FIBER NETWORK STRUCTURE*** → ***MATERIAL PERFORMANCE***

Pore size vs. carrier medium

CTMP



A. M. Al-Qararah et al., Colloids and Surfaces A: Physicochem. Eng. Aspects 482, 544 (2015)

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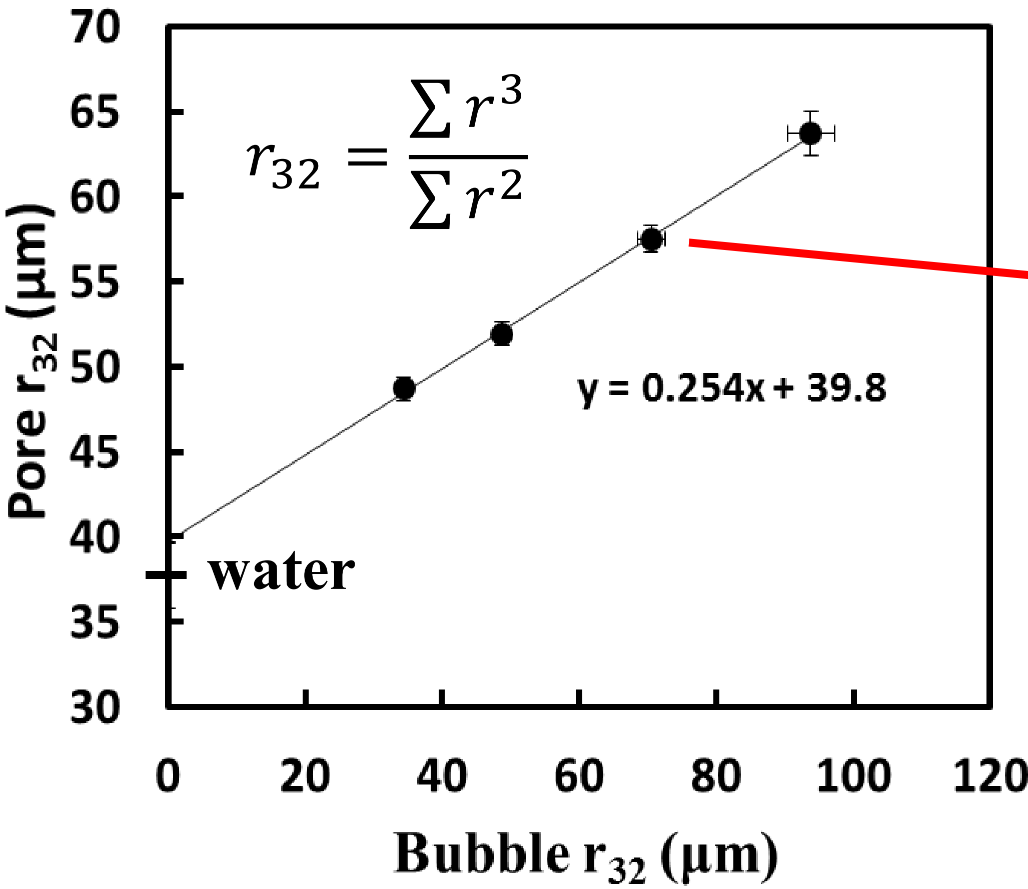
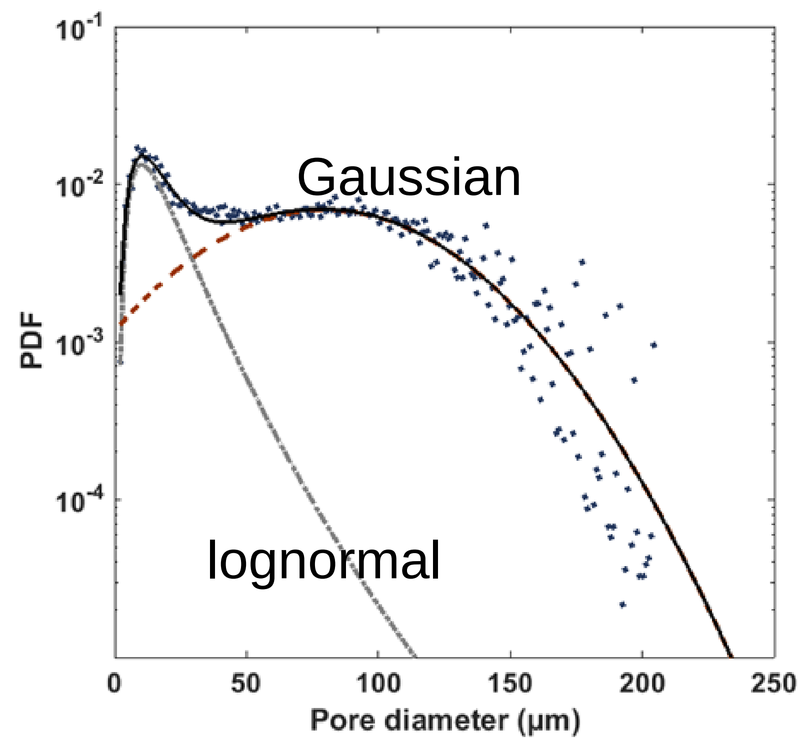
Pore size vs. bubble size

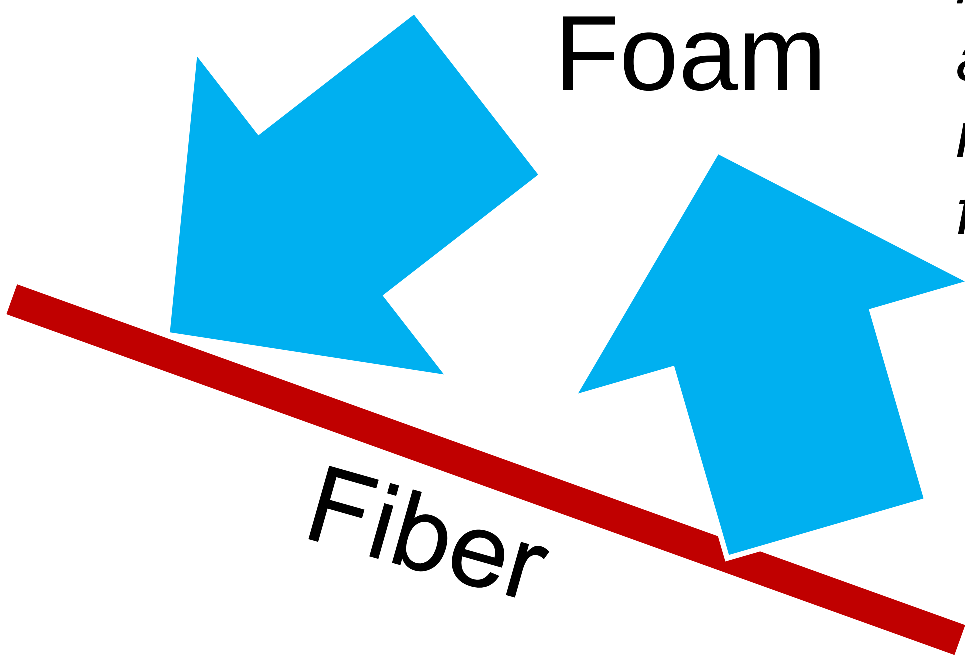


CTMP, sheet density 100 kg/m^3



Mutual interactions

bubble size
air content
rheology
foam stability



flocculation
orientation
deposition
network structure

Fiber-foam interaction in mixing

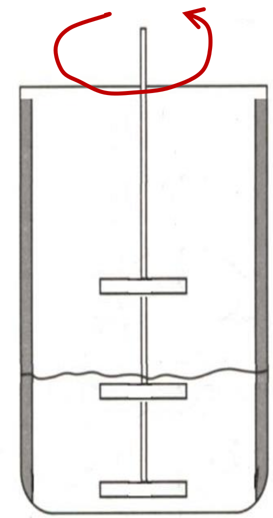
Life of a bubble characterized by **capillary number**
(shear stress/interface strength)

viscosity, shear rate, bubble radius

$$Ca = \frac{\mu \dot{\gamma} r}{\sigma}$$

surface tension

N rev/min



$$\langle \dot{\gamma} \rangle = kN$$

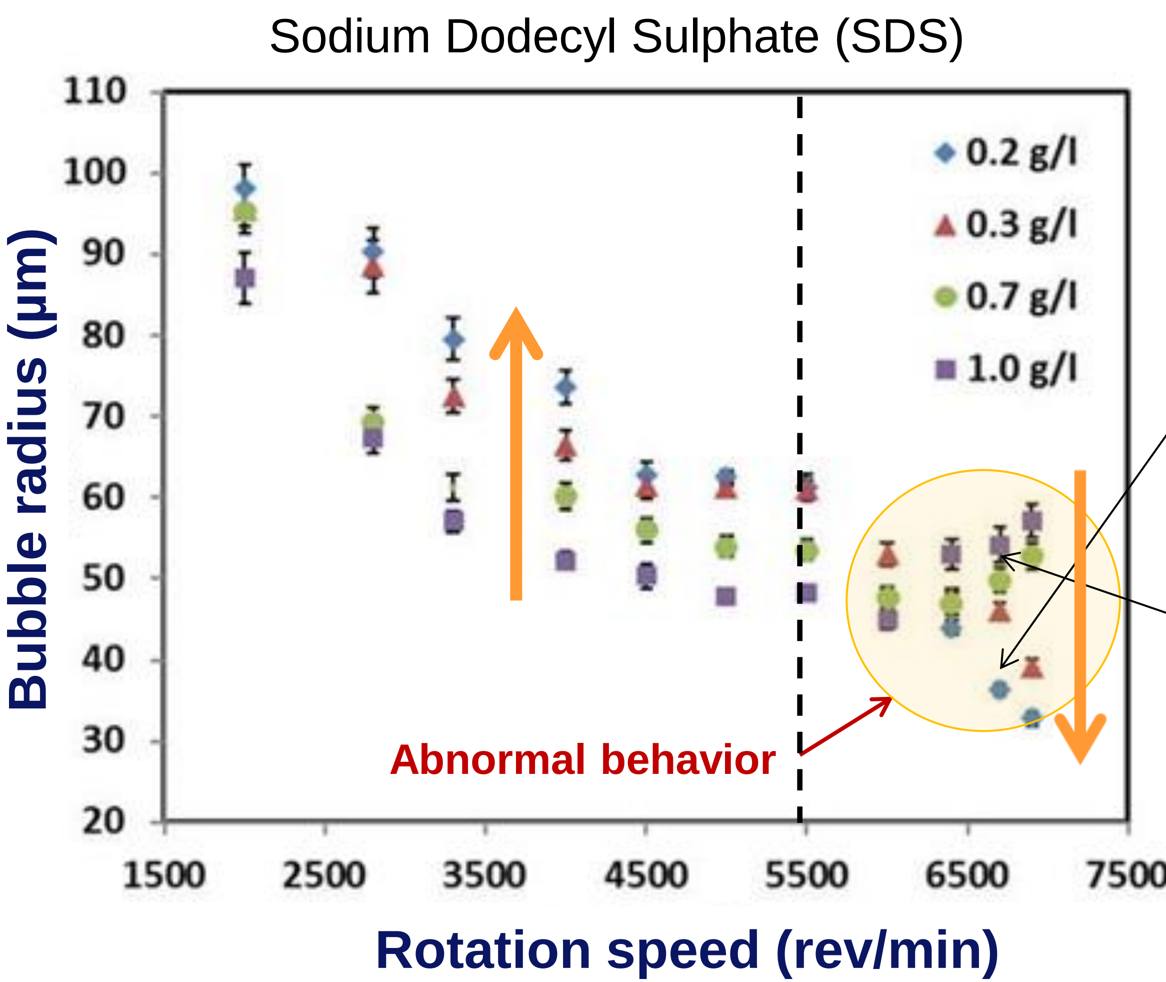
$$r_{max} \sim \frac{Ca_{crit}\sigma}{\mu\dot{\gamma}} \sim \sigma$$

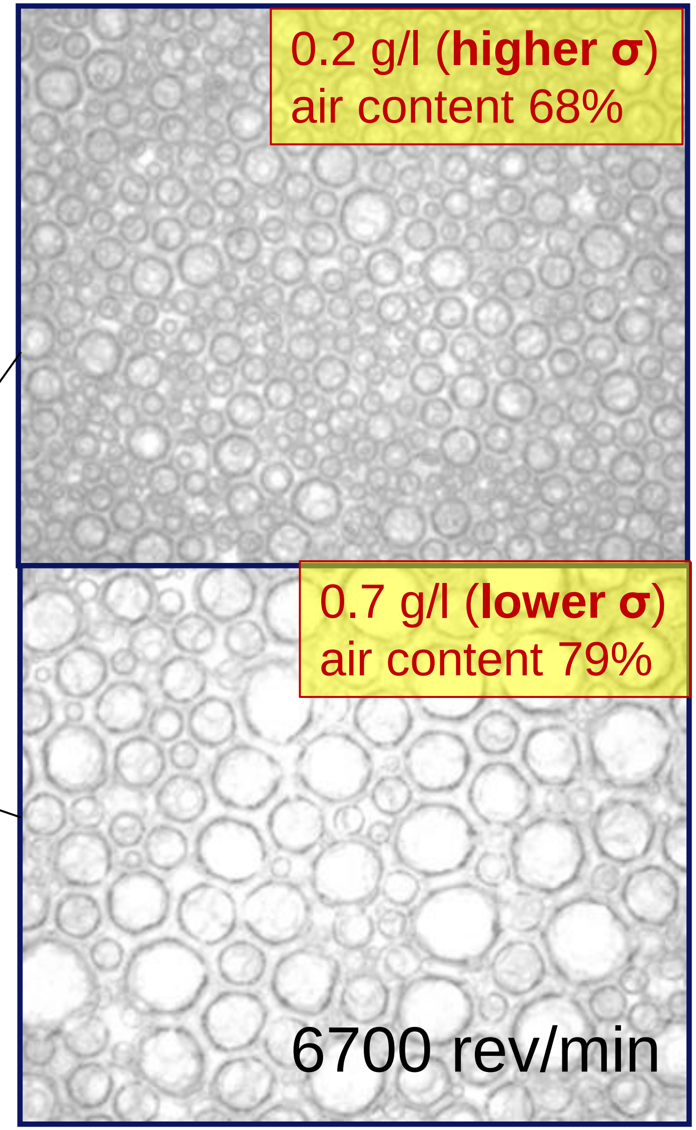
Bubble size increases with surface tension

Abnormal response due to <u>surfactant depletion</u>

J. Boos et al., Langmuir 28, 9303 (2012)

Bubble size <u>decreases</u> with surface tension for high rotation speeds





Air content correction

$$r_{32} = \frac{\sum r^3}{\sum r^2} \sim \frac{\phi V_T}{A_I}$$

V_T ← total volume

A_I ← total interface area of bubbles

Mass balance for surfactant:

$$c_s(1-\phi)V_T = \Gamma A_I + \underbrace{c_f(1-\phi)V_T}_{\text{foam lamella}}$$

$$r_{32} \sim \frac{c_f K_L \Gamma_m \phi}{(c_s - c_f)(1-\phi)}$$

$$r_{max} \sim \frac{Ca_{crit}\sigma}{\mu \dot{\gamma}}$$

$$\langle \dot{\gamma} \rangle = kN$$

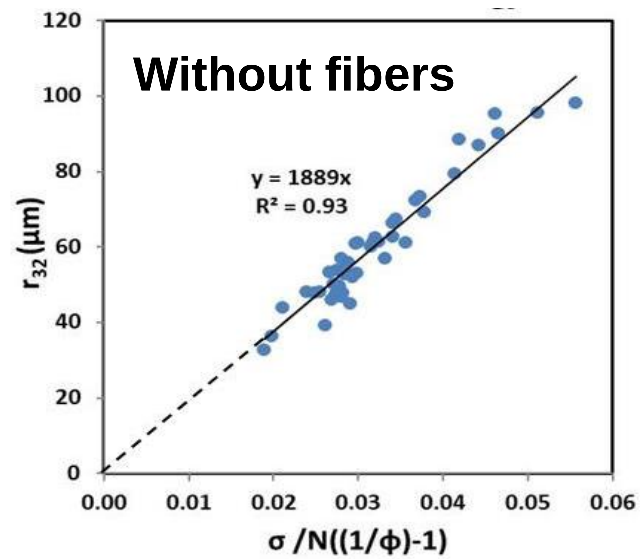
Merge

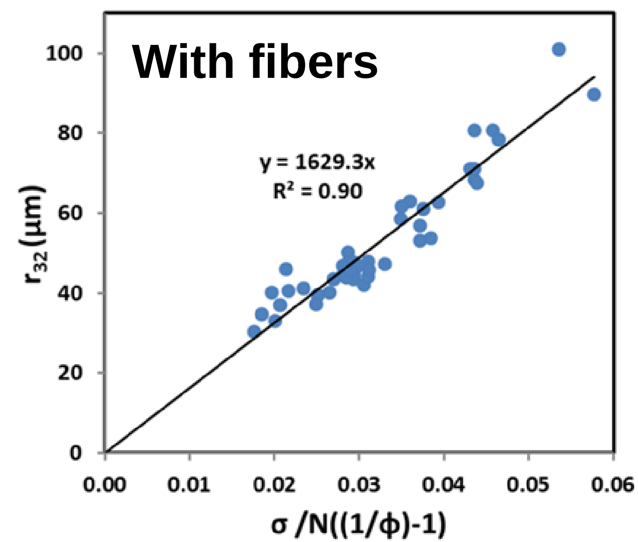
$$r_{32} \sim \frac{\sigma}{N(\frac{1}{\phi} - 1)}$$

N rotation number

σ surface tension

ϕ air content

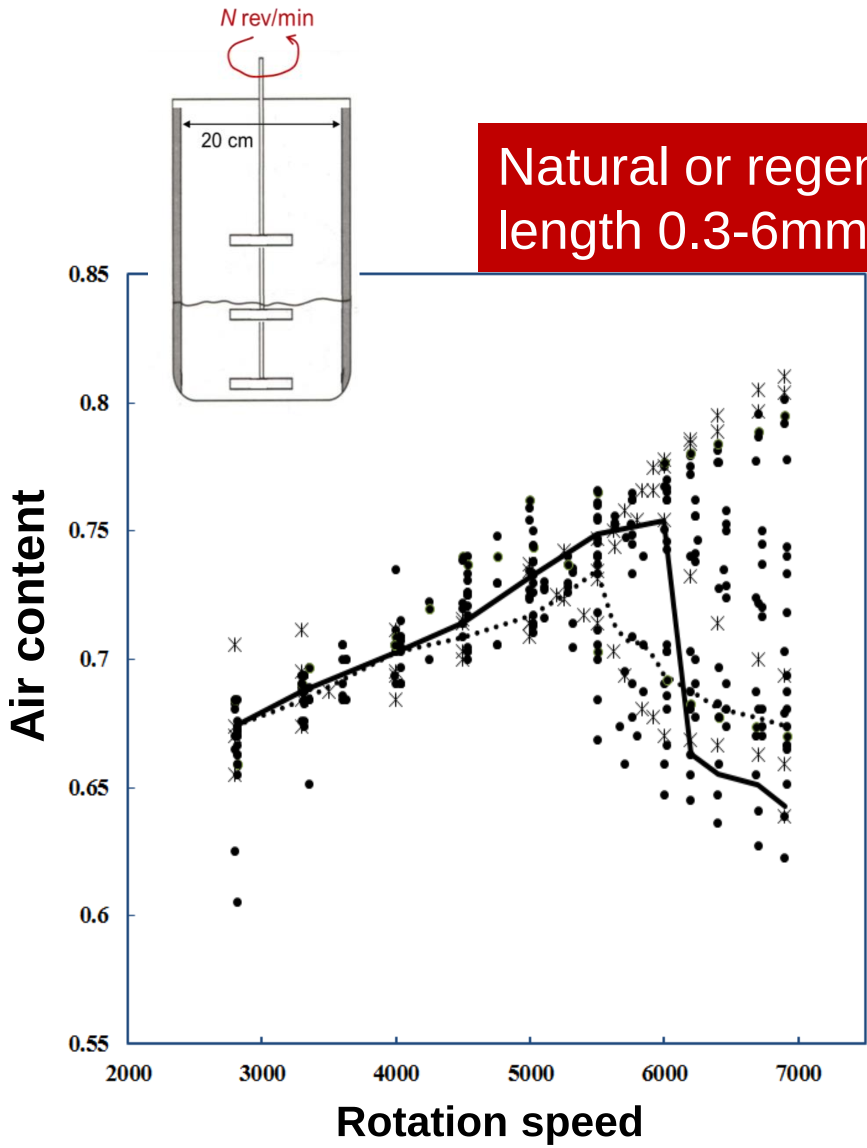


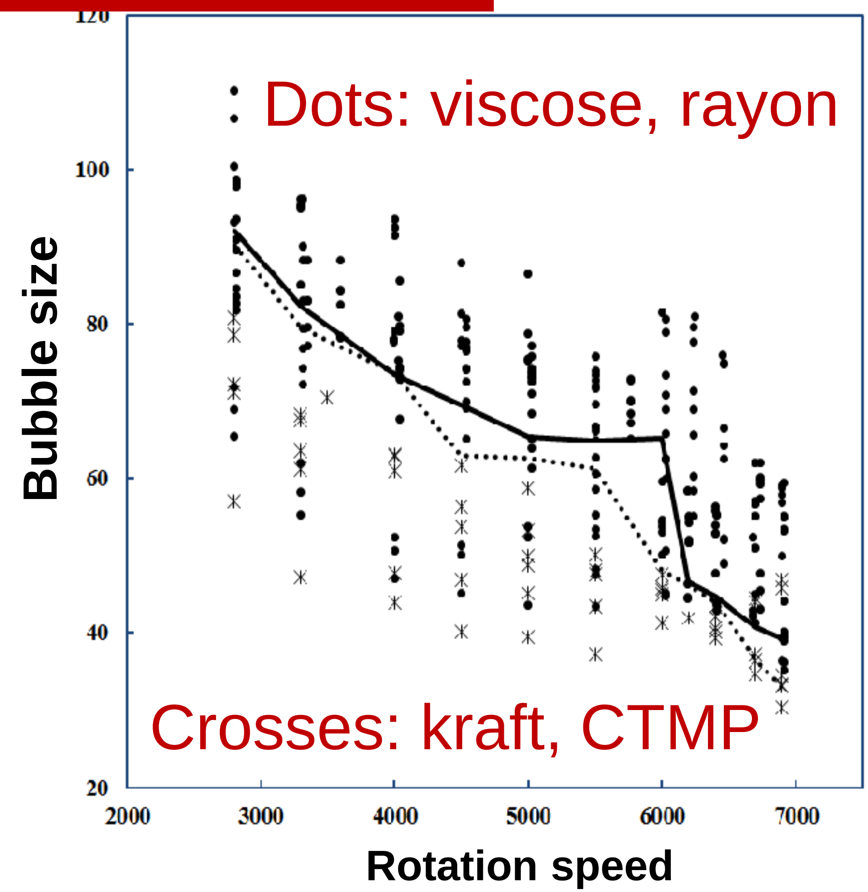


…after many experiments

A.M. Al-Qararah et al., Colloids and Surfaces A: Physicochem. Eng. Aspects 467, 97 (2015)

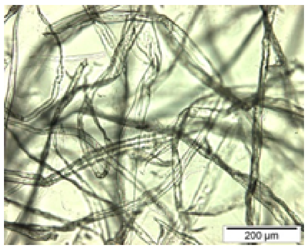
Natural or regenerated cellulose fibers, length 0.3-6mm, diameter 10-30 μm



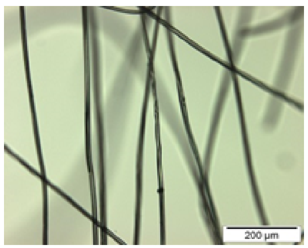


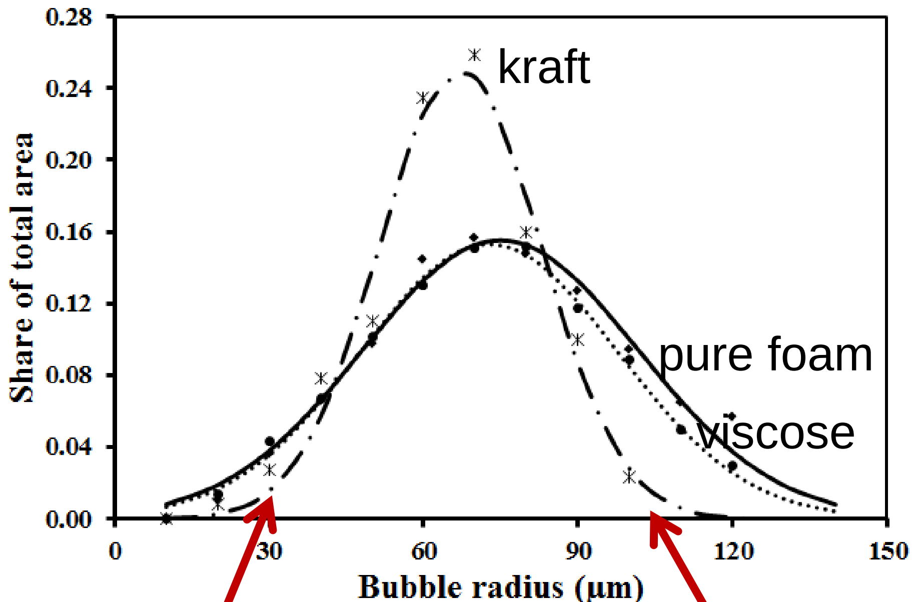
Interface breaking mechanisms

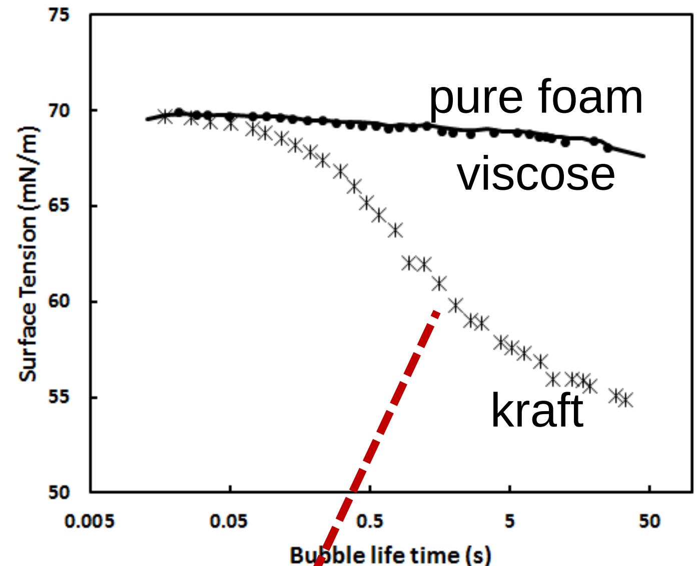
Kraft fibres



Viscose fibres





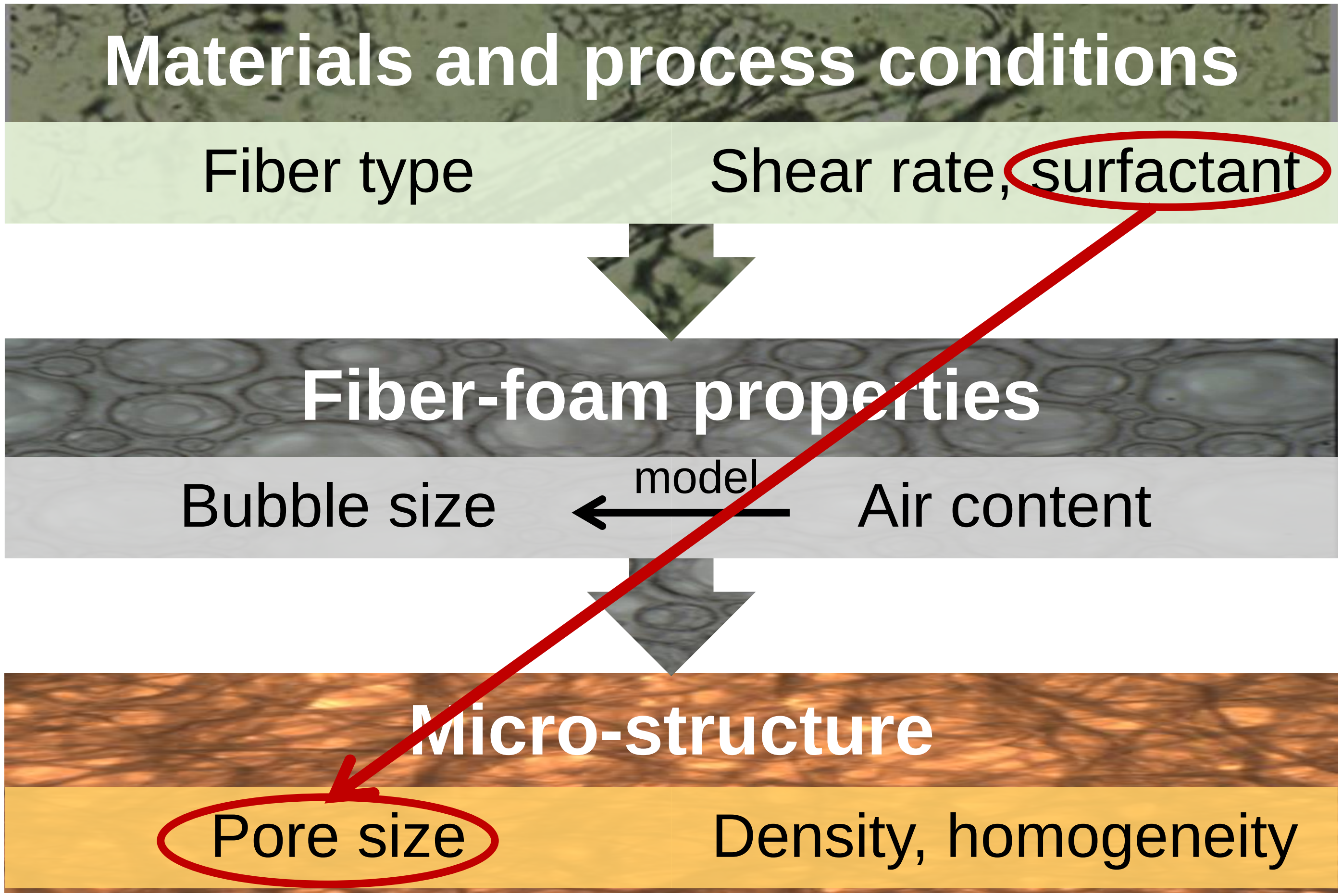


- Rough fiber surfaces capture air and **speed up bubble growth**

Natural fibers

- Fines accumulate at air-water interfaces and **reduce the surface tension** without stabilizing the interfaces
- **Viscosity** and shear forces **increase**

Summary


Materials and process conditions
Fiber type
Shear rate, surfactant
Fiber-foam properties
Bubble size
model
Air content
Micro-structure
Pore size
Density, homogeneity