THE EFFECT OF POROSITY AND PORE STRUCTURE ON THE ACCUMULATION OF PARTICLES INTO CELLULOSIC FIBROUS FILTERS

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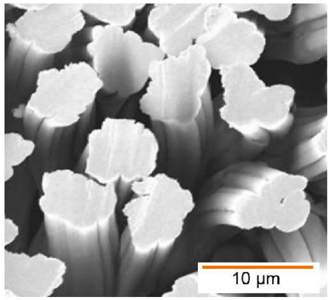
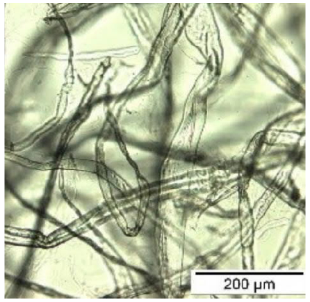
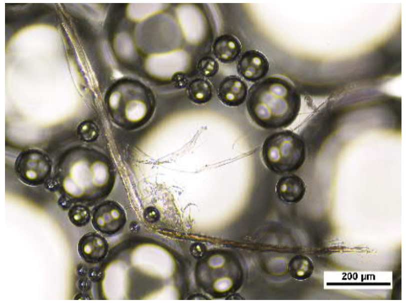
InterPore2022 Hybrid

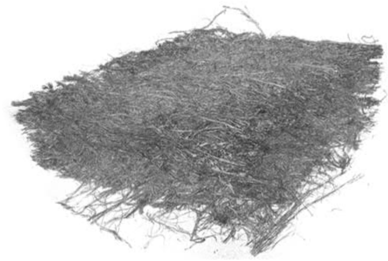
Approach for this study

1. Make test filters from bio-based fibres with foam forming







Viscose fibers + Pulp fibers + Foam = Fiber-laden foam → Final sample

remove foam, press and dry, or dry and press

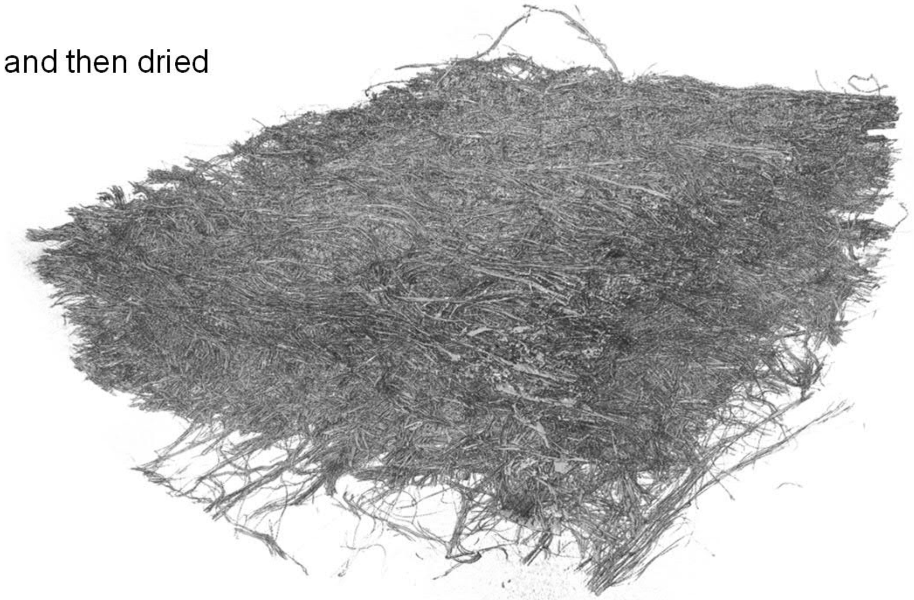
2. Measure pressure loss
3. Measure filtration efficiency with DEHS oil droplets (ISO16890)
4. Load samples with fine test dust particles (ISO 12103-1 A2)
5. Take X-ray tomographic images of clean and loaded filters
6. Analyse the structure of filters and deposition of dust
7. Simulate 3D fluid flow in tomographic images and filtration of particles

Foam formed samples

- Viscose fibers 70% - BSKP pulp 30%
- Foam removed with a vacuum
- Most samples were first dried in an oven, then re-wetted to 70% solids content, and pressed to different density levels
- KP9 and KP10 were pressed right after forming (3 bar, 6 bar) and then dried

Trial point	Basis weight [g/m^2]	Thickness [µm]	Density [kg/m^3]
V1	268	2742	98
V2	259	2357	110
KP2	203	1780	114
KP3	199	1560	128
KP5	194	1100	176
KP6	197	1380	143
KP7	198	1220	163
KP8	199	1042	191
KP9, 3 bar	207	1840	113
KP10, 6 bar	205	1580	130

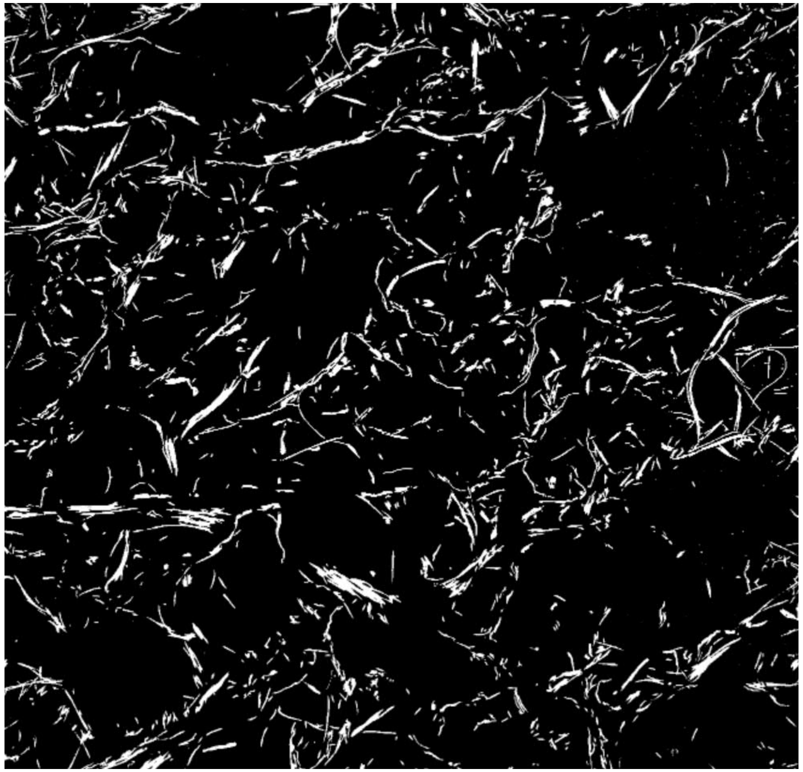
- Lowest density was ca. 100 kg/m^3
- Viscose fibre is rather rigid → highest density was ca. 200 kg/m^3



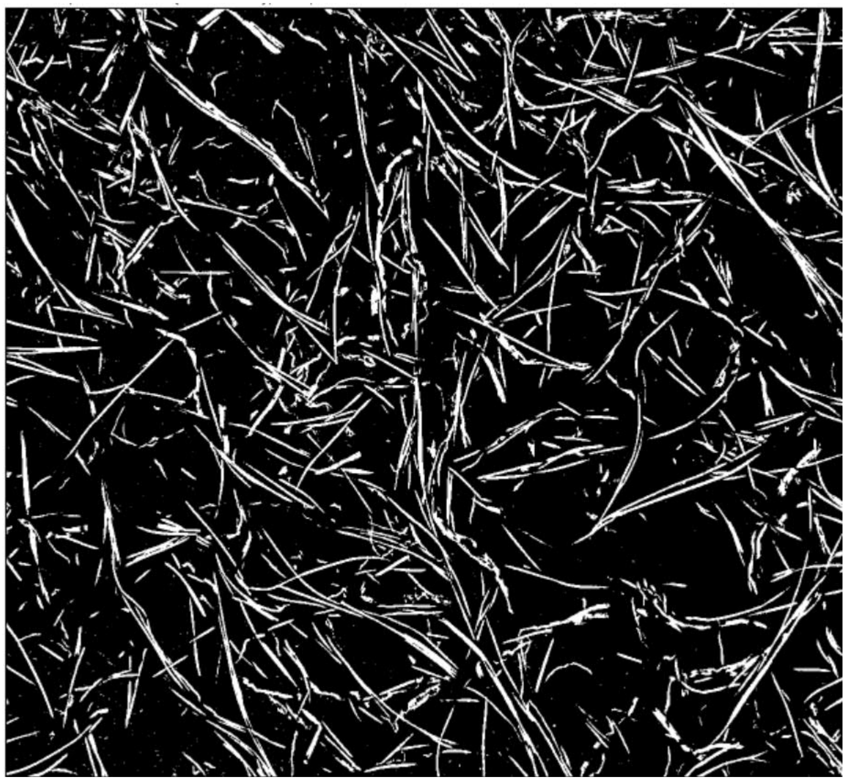
- X-ray tomographic image of sample V1 (6.4 mm × 6.4 mm × 3 mm)
- Resolution 4 µm
- Taken with Desktom CT from RX-solutions

Cross-sectional X-ray images of clean V2 and KP8 in the middle of the sample

1 mm

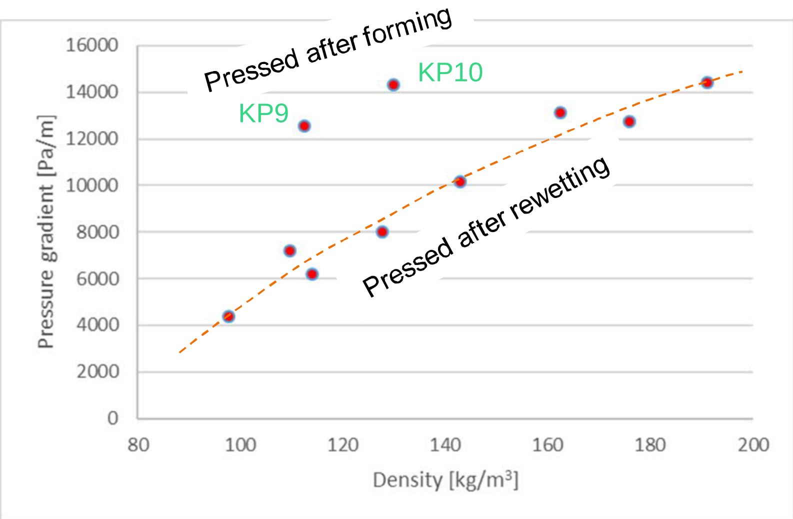


V2, density 110 kg/m^3



KP8, density 191 kg/m^3

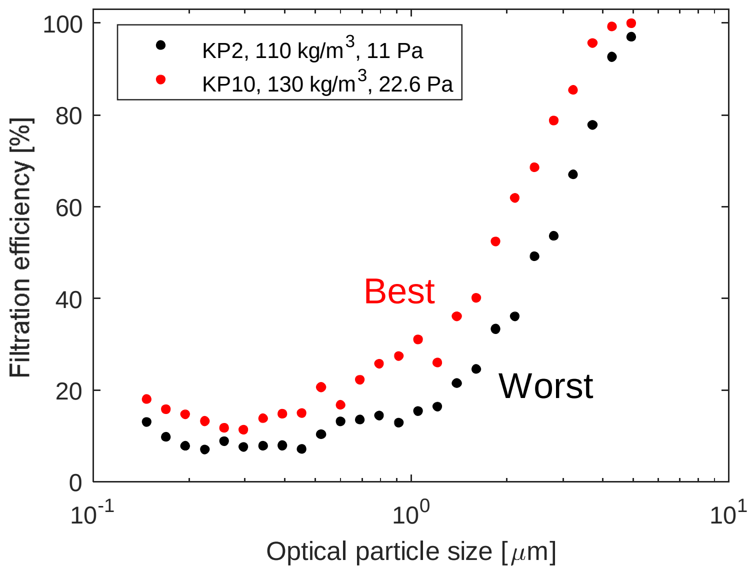
Pressure loss



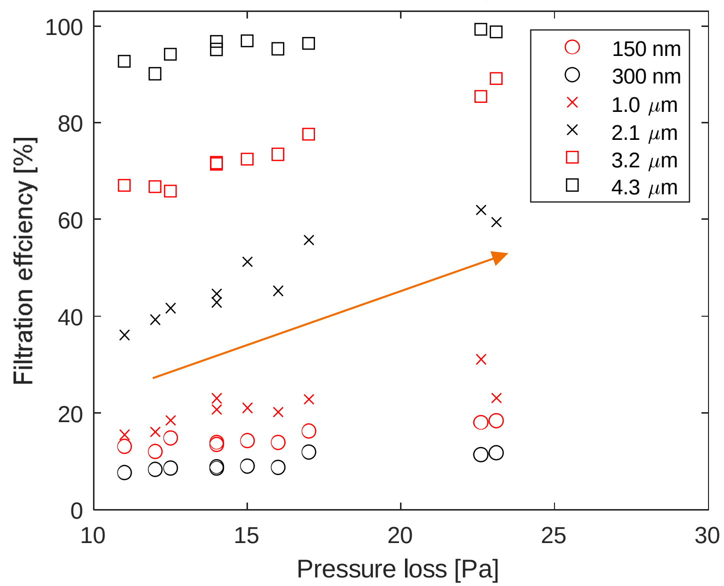
Trial point	Thickness [µm]	Density [kg/m^3]	Pressure loss [Pa]	dP/dx [Pa/m]
V1	2742	98	12	4376
V2	2357	110	17	7212
KP2	1780	114	11	6180
KP3	1560	128	12.5	8013
KP5	1100	176	14	12727
KP6	1380	143	14	10145
KP7	1220	163	16	13115
KP8	1042	191	15	14395
KP9, 3 bar	1840	113	23.1	12554
KP10, 6 bar	1580	130	22.6	14304

- The measurement was performed with the velocity of 5.3 cm/s
- Pressure gradient increases with increasing density, as expected
- Samples KP9 and KP10 have a higher pressure gradient (→ qualitatively different structure)

Filtration efficiency (ISO16890)



Best samples



Filterclass	0.1 microns	0.3 microns	0.5 microns	1 microns
F5 (EU 5)	0-10	5-15	15-30	30-50
F6 (EU 6)	5-15	10-25	20-40	50-65
F7 (EU 7)	25-35	45-60	60-75	85-95
F8 (EU 8)	35-45	65-75	80-90	95-98
F9 (EU 9)	45-60	75-85	90-95	>98

- Measurement with DEHS oil droplets (density 0.9 g/cm^3)
- Filtration efficiency is proportional to pressure loss

- The filtration efficiency of the best sample KP10 is comparable to EU5 filter
- “Effective against pollen and finer atmospheric dust, considerable effect against smoke.”

Porosity and pore size profiles of clean samples (V2, KP8, KP10)

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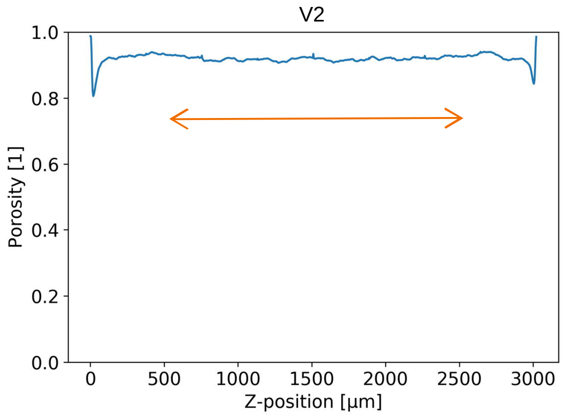
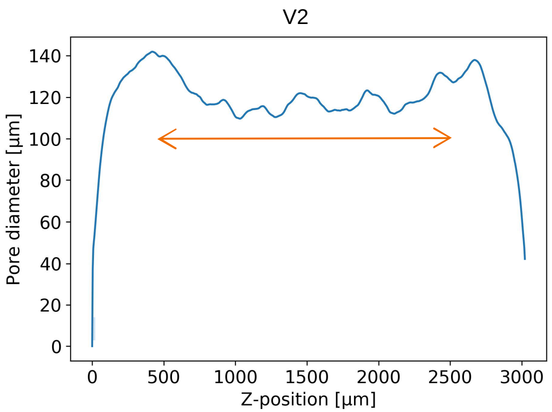
V2: Gently pressed after rewetting

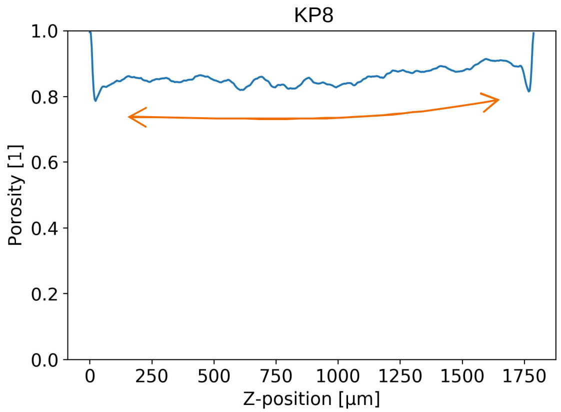
110 kg/m^3

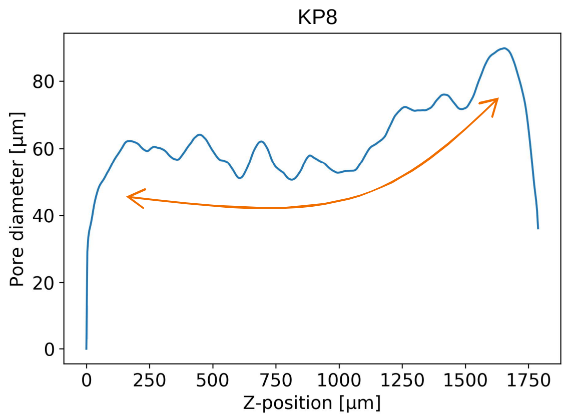




KP8: Strongly pressed after rewetting

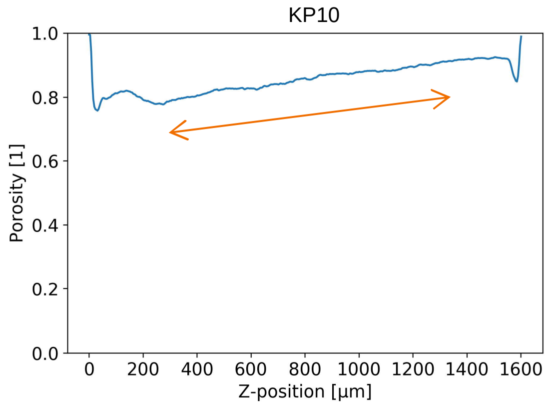
191 kg/m^3

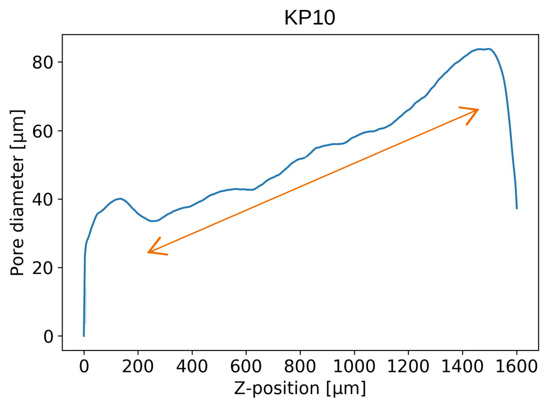




KP10: Strongly pressed after forming

130 kg/m^3



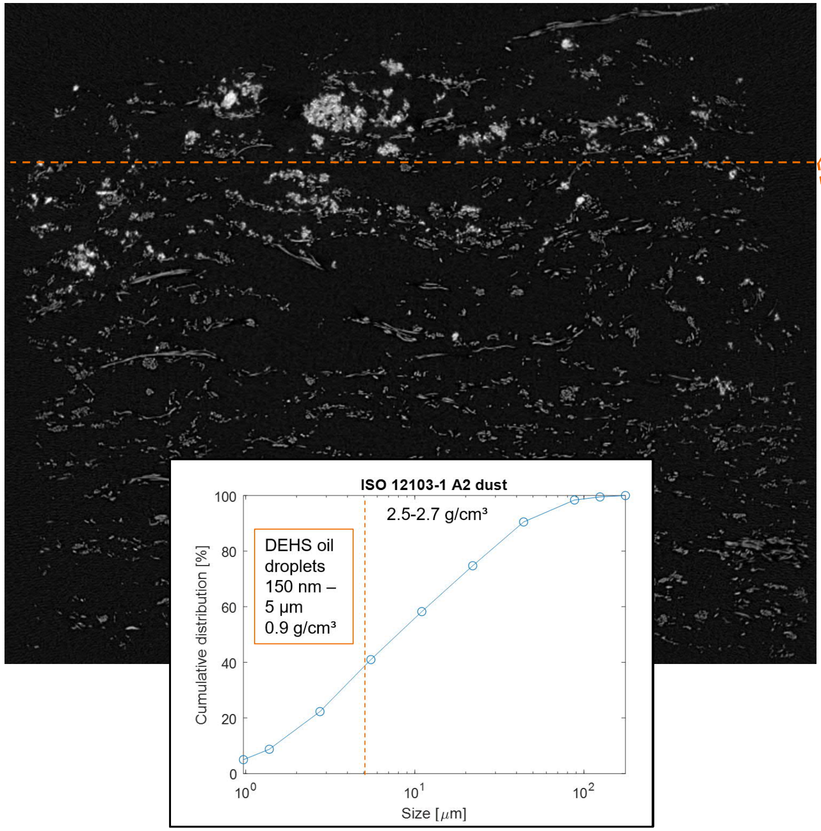


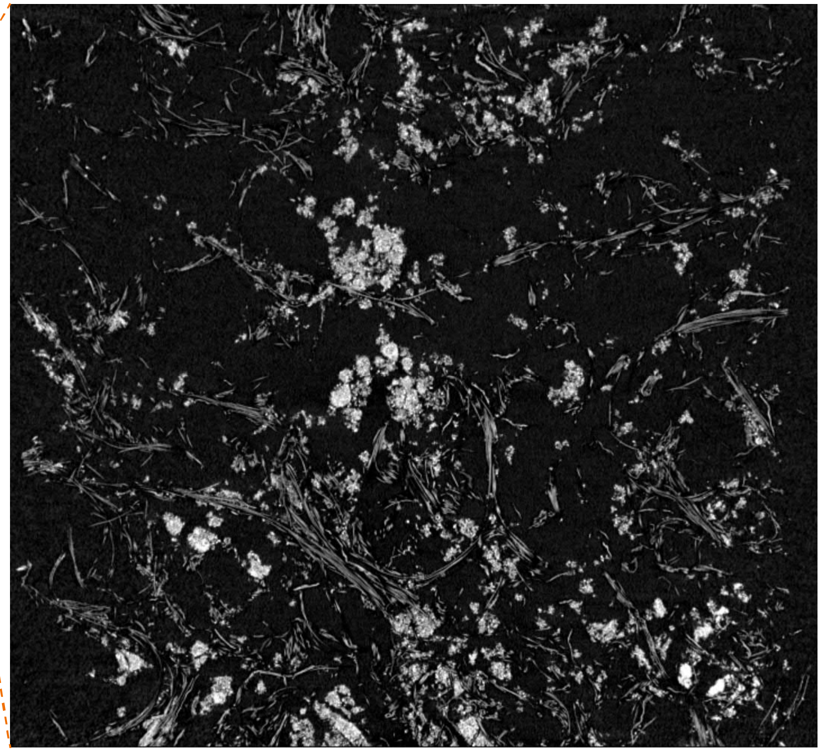
Loading samples with fine test dust

V1: 98 kg/m^3

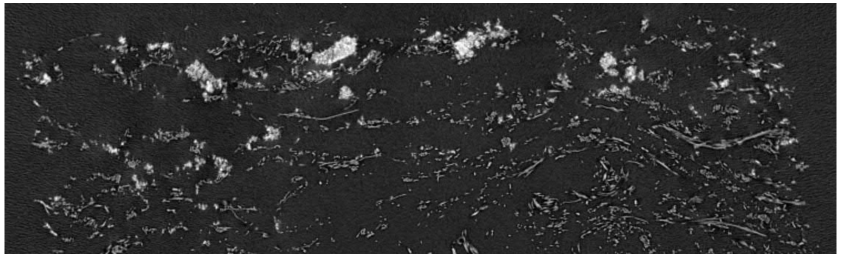
flow direction

1 mm



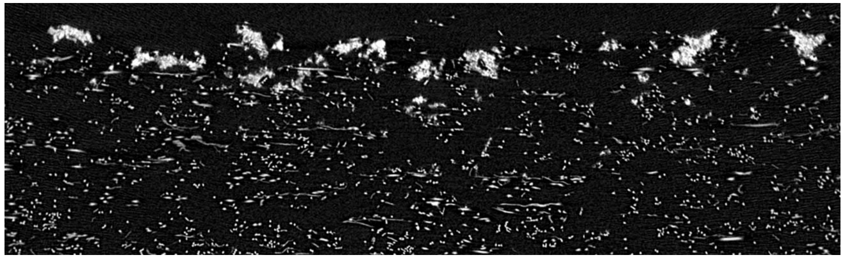


Porosity profiles of loaded samples (V1 and KP8)

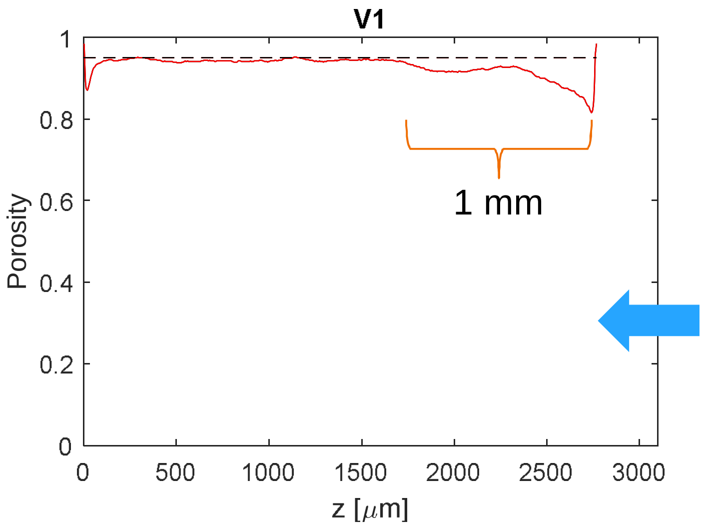


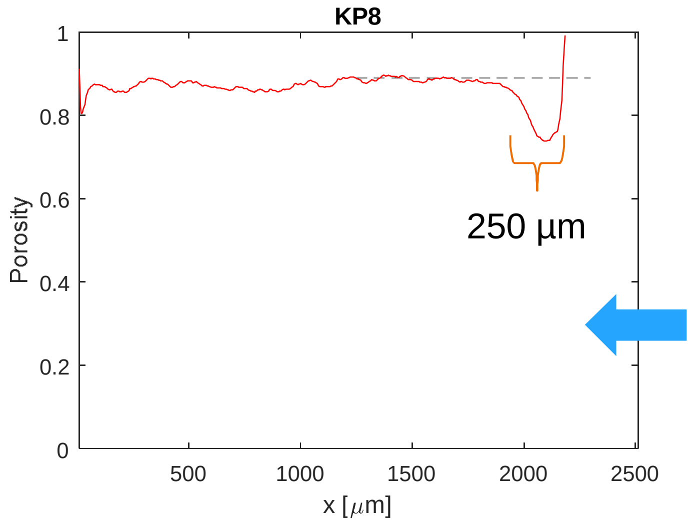
V1: 98 kg/m^3, loading: 56 g/m^2

flow direction



KP8: 191 kg/m^3, loading: 32 g/m^2

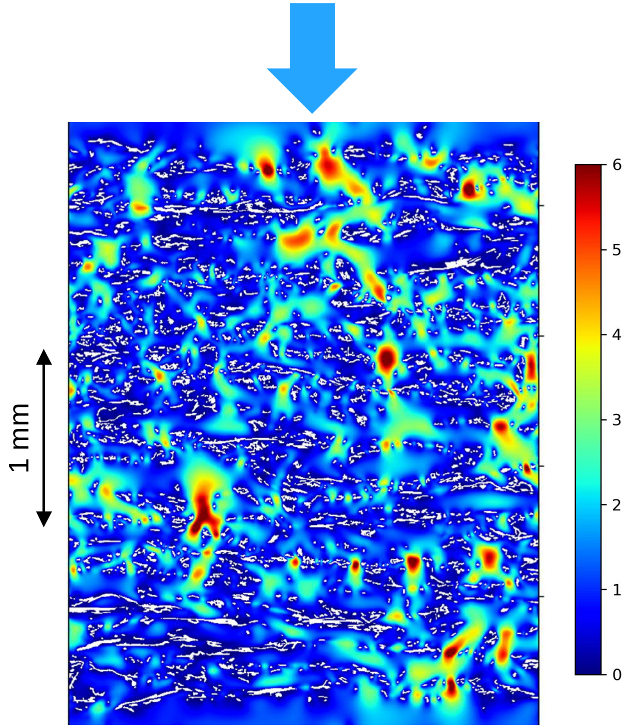




- Particles are deposited deep into the structure
- Low density → clogs later

- Particles are deposited mainly at the surface
- High density → clogs earlier

3D flow and filtering simulations

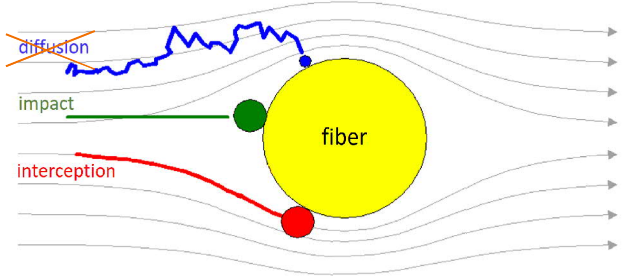


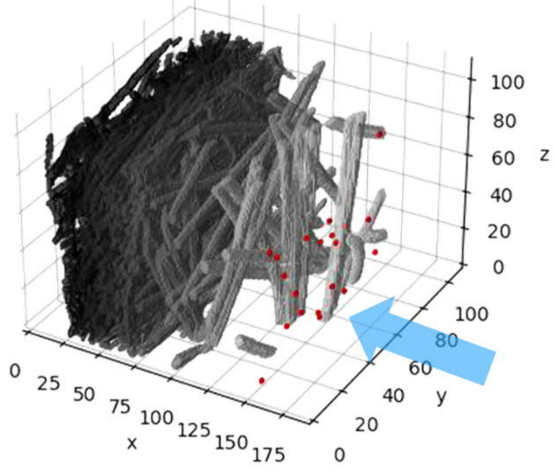
Sample V2
System size 2.8 mm × 2.8 mm × 4 mm

- Lattice-Boltzmann method (Walberla)
- Simulation predicts the pressure loss with a good accuracy

ΔP_{sim} [Pa]	ΔP_{exp} [Pa]	diff. [%]
18.3	17.0	8

- Non-Brownian particles (D > 1 µm)



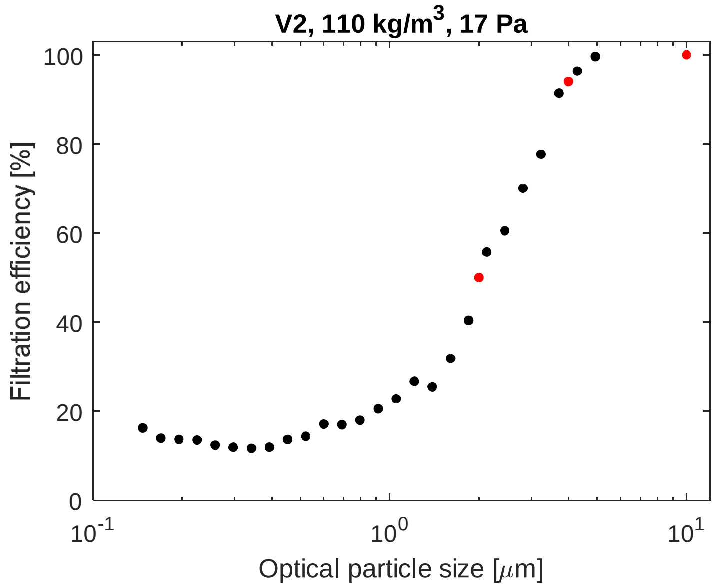


$$m_p \frac{d\boldsymbol{v}}{dt} = 6\pi\, r_p \mu_a (\boldsymbol{u} - \boldsymbol{v})$$

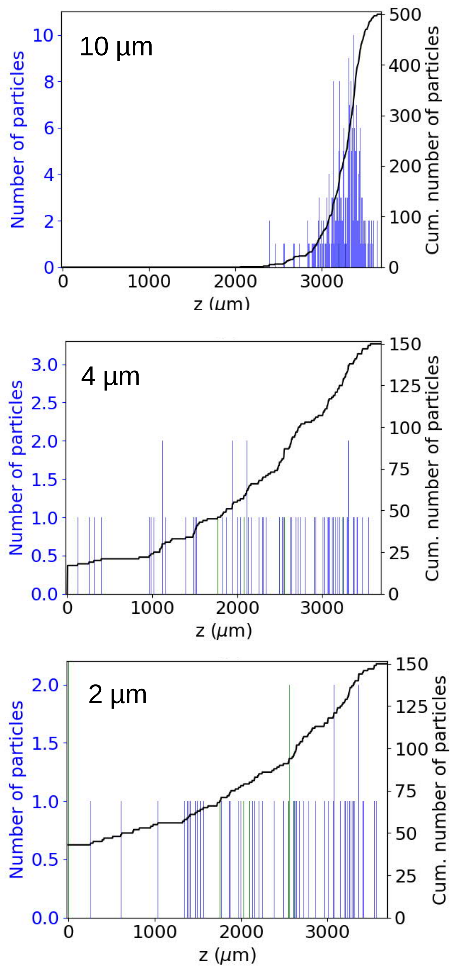
- Particle equation of motion is solved by using a modified velocity Verlet algorithm
- Clogging due to particles is omitted

Filtering simulations for sample V2 (110 kg/m^3, 17 Pa)

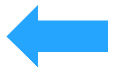
- Partice density 0.9 g/cm^3 (DEHS droplets)
- Diameter 2 µm, 4 µm or 10 µm



Diameter [µm]	2	4	10
eff. measured [%]	50	94	100
eff. simulated [%]	69	88	100



flow direction



Conclusions

- Foam forming can be used to make porous samples from biobased fibrous materials
- Porosity and pore size profiles can be modified by varying the pressing conditions

- Filtering efficiency (DEHS droplets) is proportional to pressure loss
- High-porosity filter is good for fine test dust (clogging takes place later)

- Fluid flow simulations with the lattice-Boltzmann method worked well
- Filtering simulation with non-Brownian particles worked reasonably well (still work to do)

- The filtering efficiency of the best sample is similar to an EU5 filter
- Filtering efficiency could be improved by
  - Decreasing the fibre width
  - Nanofibrillated cellulose
  - Electrospinning on the bottom side

Ongoing work at VTT

beyond

the obvious

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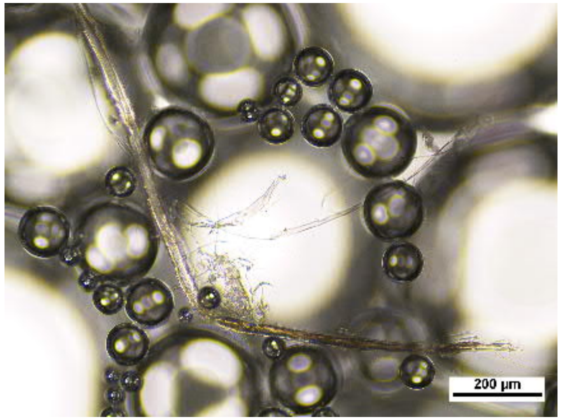
Background and motivation

- Foam forming is a promising way of making e.g. thermal insulation materials, sound insulation materials, packaging materials, and nonwovens



- Excellent uniformity, high forming consistency, highly porous structures, raw materials of all sizes and shapes, layered structures

In this work we study the possibility of making bio-based air filtering materials with foam forming

Lab scale

Pilot scale

Hjelt et al., Foam forming of fiber products: a review, Journal of Dispersion Science and Technology (2021)

X-ray microtomography

An imaging method to obtain a 3-dimensional digital representation of virtually any kind of a sample at resolution of few micrometers.

Tomography at VTT

- RX-solutions desktom
- Sample sizes from few millimeters to ~20 cm
- Best spatial resolution 4 µm

Image analysis and visualization

From the obtained 3D images we can analyse for example following:

- Volume / thickness / dimensions
- Pore size distributions
- z-profile of density/porosity/pore size/material distribution
- Fibre orientation
- Penetration of (labeled) particles

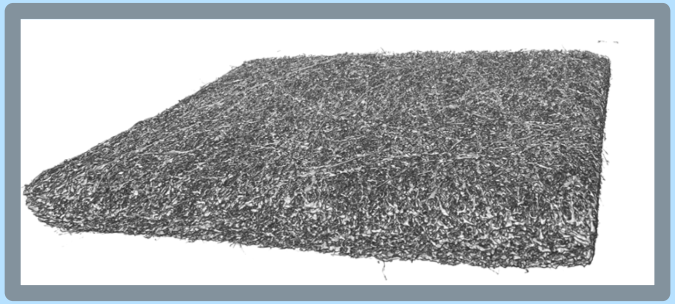


Fig 1: A 3D visualization of a cardboard sample

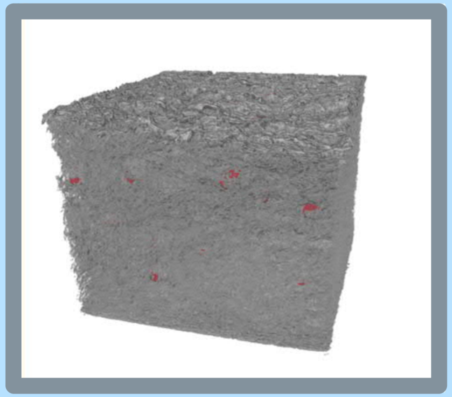
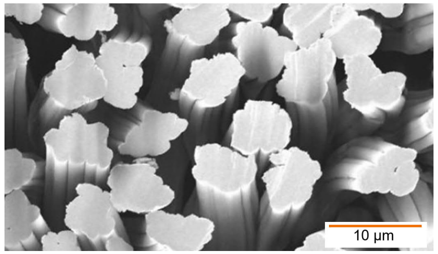


Fig 2: A 3D video of porosity inside a cellulose material

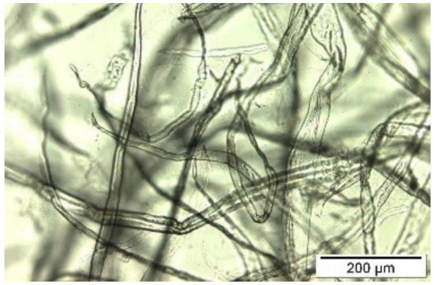
Foam formed samples

- viscose 70% - BSKP pulp 30%
- BSKP fibres bind the fibres together
- viscose fibres*: length 5 mm, width 6.5 µm
- BSKP fibres: length 2 mm, width 30 µm
- basis weight 200 g/m^2 or 260 g/m^2

- surfactants: SDS + tween20 (0.48 g/l+0.51 g/l)
- air content 60%, consistency 0.77%
- foam removed by vacuum



viscose



BSKP

*0.5 dtex, Danufil 5

a)

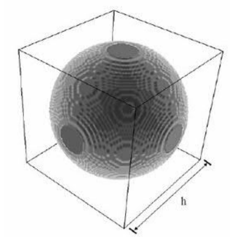
b)

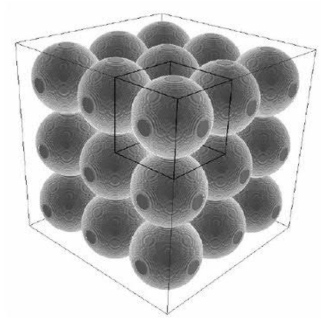
The working procedure for the foam-laid handsheets: a) Fiber foam is poured into the handsheet mold. b) Foam-forming handsheet mold before foam removal by vacuum.

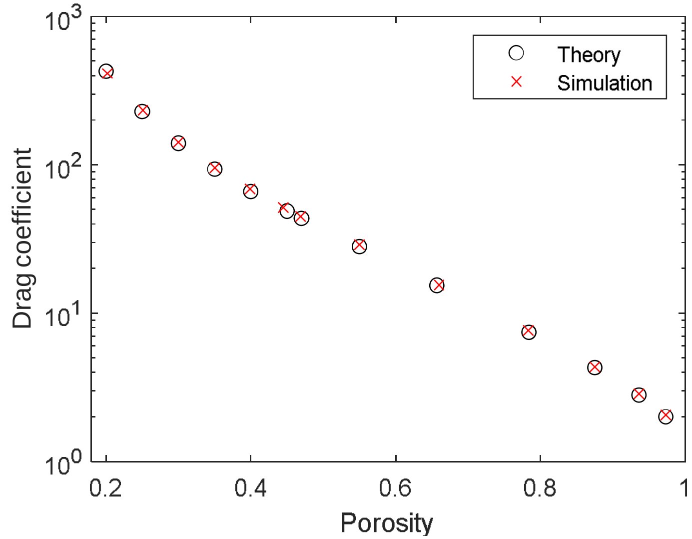
Flow simulations in X-ray tomographic images

- Lattice-Boltzmann method
- Simulations performed with Walberla
  https://www.walberla.net/
- two relaxation time (TRT) model
- TRT relaxation parameters: $\omega_1 = 1.5$,
  $\omega_2 = 0.6154$ from the "magic formula"
- body force 10^{-8} in lattice units
- periodic boundary conditions
- simulations on a high-performance Linux-workstation with two (AMD EPYC 7452) processors and 256 GB of RAM
- lattice update speed 1.41×10^8 per second.

- test case: periodic bed of spheres with a simple cubic structure







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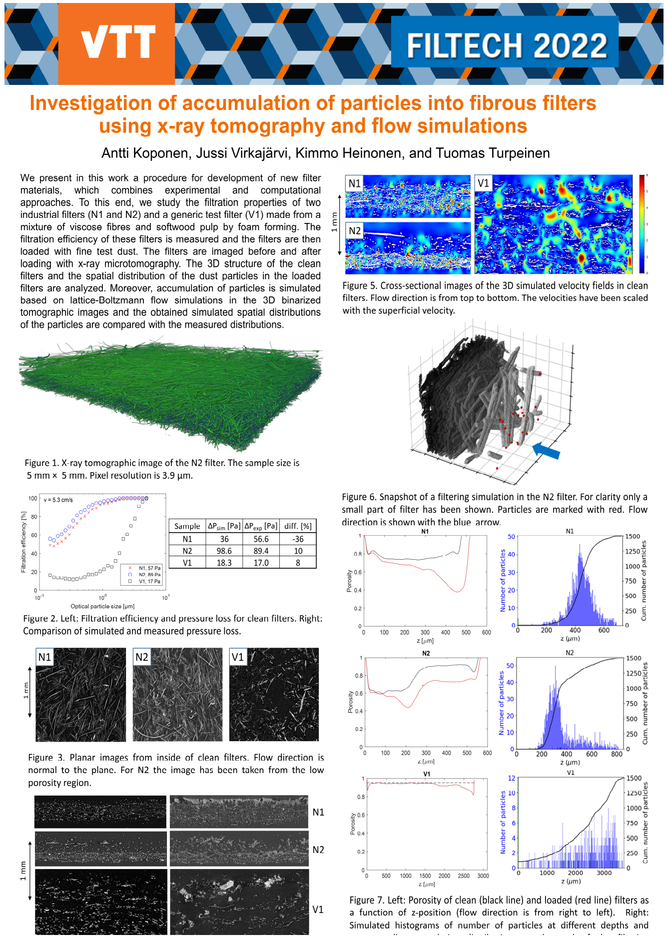

INVESTIGATION OF ACCUMULATION OF PARTICLES INTO FIBROUS FILTERS USING X-RAY TOMOGRAPHY AND FLOW SIMULATIONS

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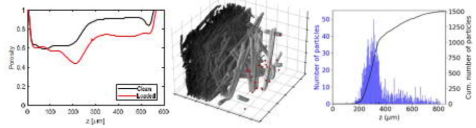
ABSTRACT

Filtration mechanisms have been studied for decades with direct filtration experiments, theoretical analysis and more recently by computer simulations. Moreover, modern imaging techniques like X-ray microtomography enable microscopic structural analysis of clean and dirty filters, and the obtained 3D images can be used after binarization for realistic filtration simulations. As the underlying physical mechanisms in filtering are very complicated, the development of new types of filters is hardly possible without combining these different approaches.



Left: Porosity profile of a clean and loaded filter. Middle: Snapshot of a fouling simulation in an X-ray tomographic image of the filter. Right: Histogram and cumulative distribution of filtered particles at different depths of the filter at the end of the simulation.

In this work, we combine filtration experiments, X-ray microtomographic imaging and realistic filtration simulations for the analysis of filters and filtering. To this end, we study the filtration properties of two industrial filters and a generic test filter made from a mixture of viscose fibres and softwood pulp by foam forming. The filtration efficiency of these filters is measured and the filters are then loaded with fine test dust. The filters are imaged before and after loading with X-ray microtomography. The 3D structure of the clean filters and the spatial distribution of the dust particles in the loaded filters is analyzed. Moreover, accumulation of particles is simulated based on lattice-Boltzmann flow simulations, and the obtained simulated spatial distributions of the particles are compared with the measured distributions.

KEYWORDS

filtering efficiency, filter loading, X-ray microtomography, structural analysis, filtering simulation

Antti Koponen, Jussi Virkajärvi, Kimmo Heinonen, and Tuomas Turpeinen, Investigation of accumulation of particles into fibrous filters using x-ray tomography and flow simulations, FILTECH 2022, 8-10.3.2022, Cologne – Germany, Conference Proceedings, ISBN: 978-3-941655-19-5.