

Effect of inter-tow spacing on dual-scale flow patterns in LCM preforms



OUTLINE

Introduction

Motivation

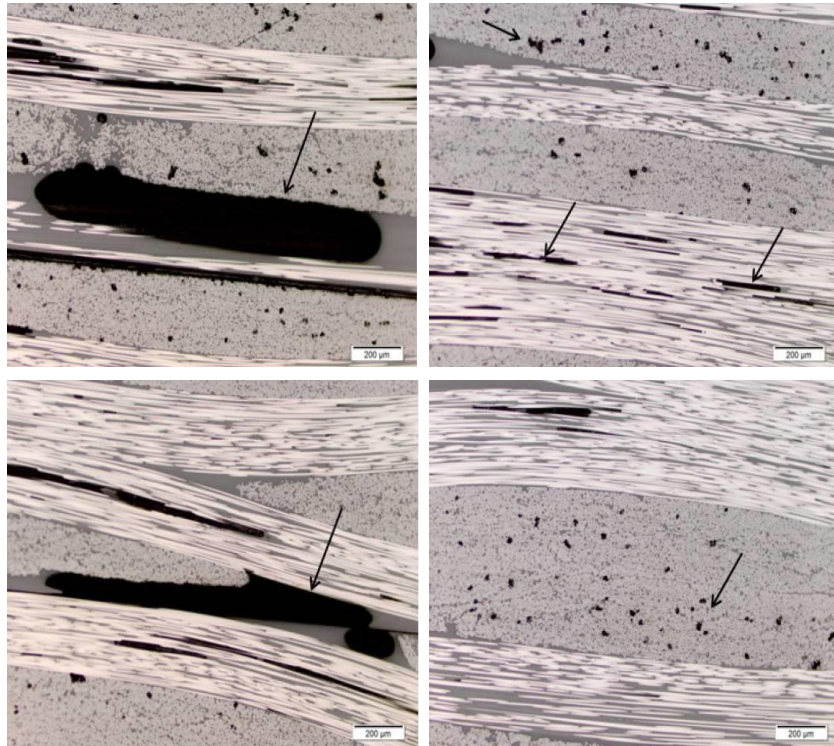
Materials and Methods

Results

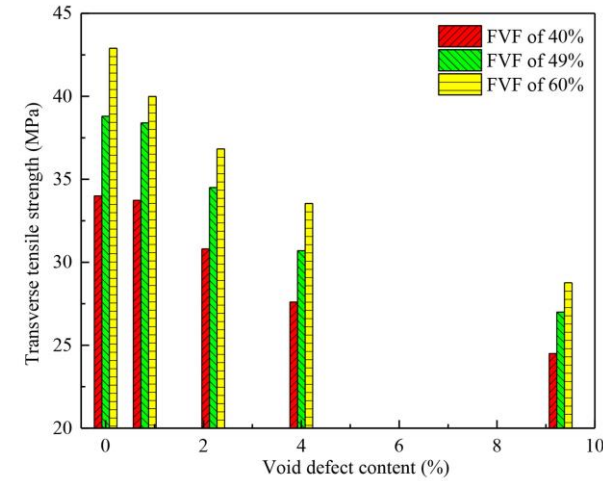
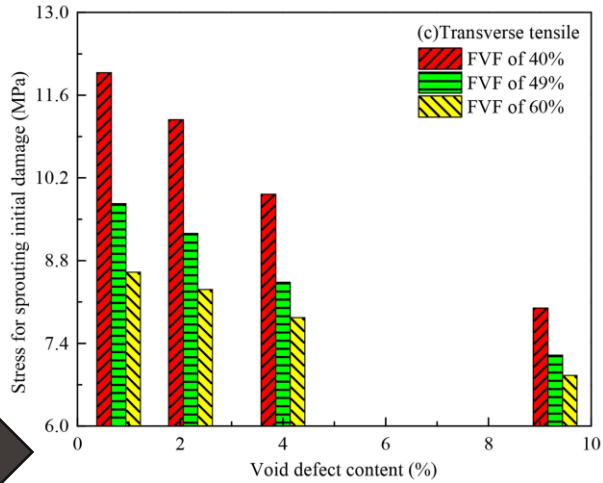
Conclusion



Quality of LCM parts



Arnaud (PhD thesis, 2013)



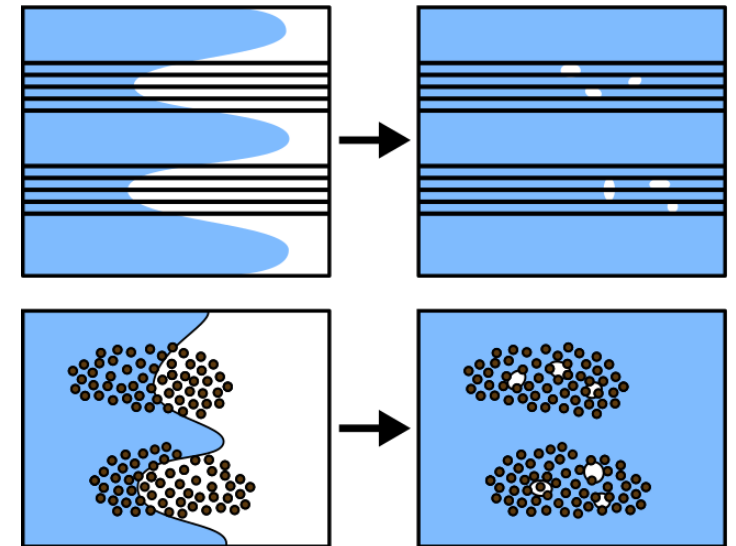
Bai et al., 2024

✓ Void content and typology has dramatic effects on mechanical performance

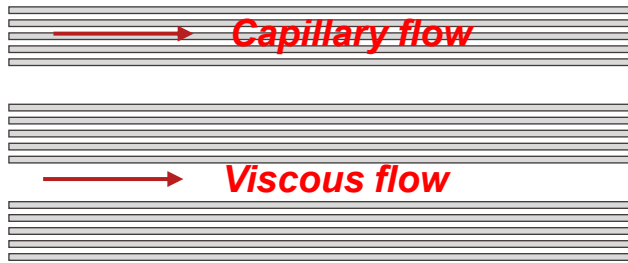
! How are they formed?

↓
Imbalanced impregnation generates bubbles, leading to residual voids

↓
Dry fibrous preforms act as dual-scale porous media



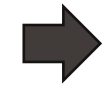
Flow pattern and void typology both depend on Ca



Mechanisms: capillary number

$$Ca = \frac{\eta V}{\gamma} = \frac{\text{viscous forces}}{\text{capillary forces}}$$

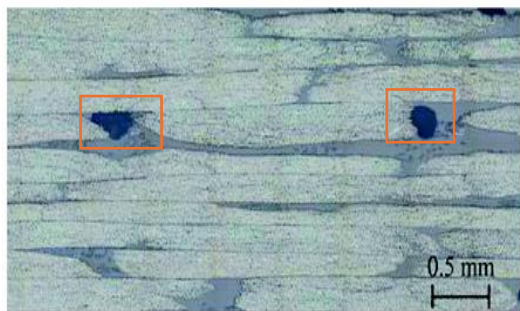
- ✓ η : viscosity
- ✓ γ : surface tension
- ✓ V : flow front velocity



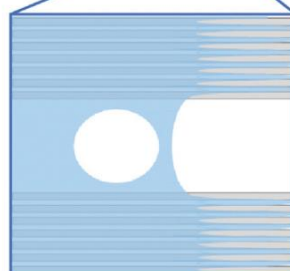
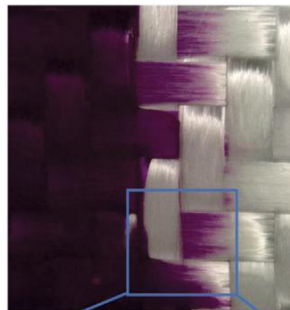
Aim find and predict Ca_{opt}

- Capillary-dominated flow
- ✓ Low pressure/velocity
- ✓ Inter-tow porosity

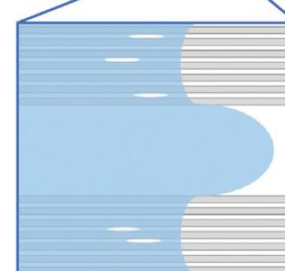
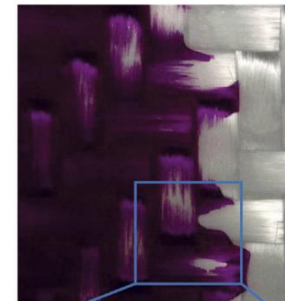
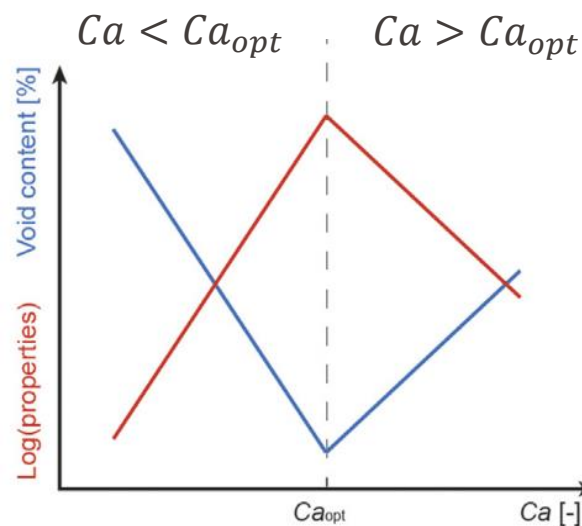
Macro-voids



Zhou et al., 2022

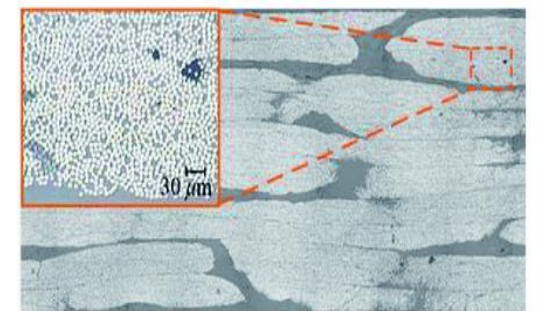


Teixido et al., 2022



- Viscous-dominated flow
- ✓ High pressure/velocity
- ✓ Intra-tow porosity

Micro-voids



Capillarity

Origin: curved soft interfaces

- Liquid flow front in LCM

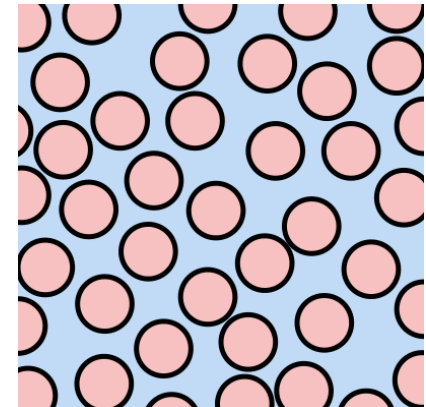
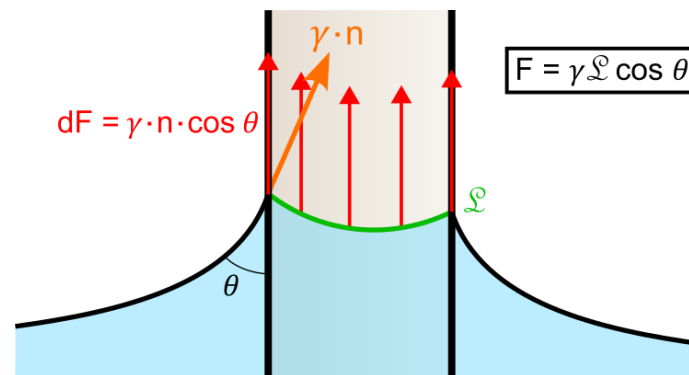
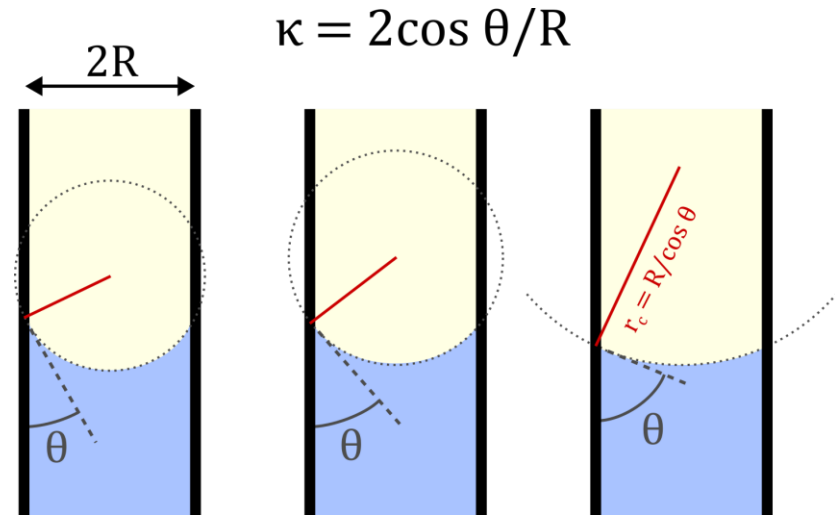
Upscaling: capillary pressure

- Laplace law: $P_c = \gamma \kappa$
- 3 phases: $\kappa = f(\theta)$

P_c can also be viewed as a force per unit surface

- Force: surface tension and length of contact line
- Surface: pore areal fraction

$$\Rightarrow P_c = -S_f \gamma \cos \theta$$



Contact angle dynamics

θ depends on Ca!

- Increasing with CL velocity
- Several existing models

$$\theta^3 = \theta_\mu^3 + 9\Gamma Ca$$

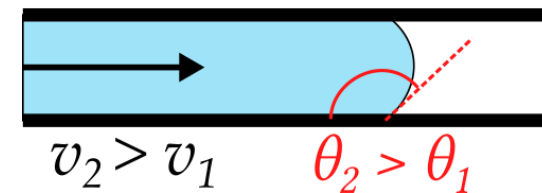
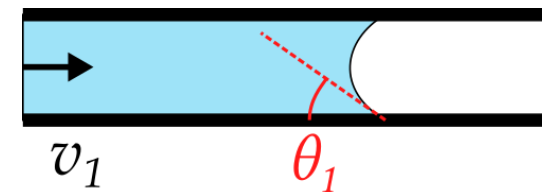
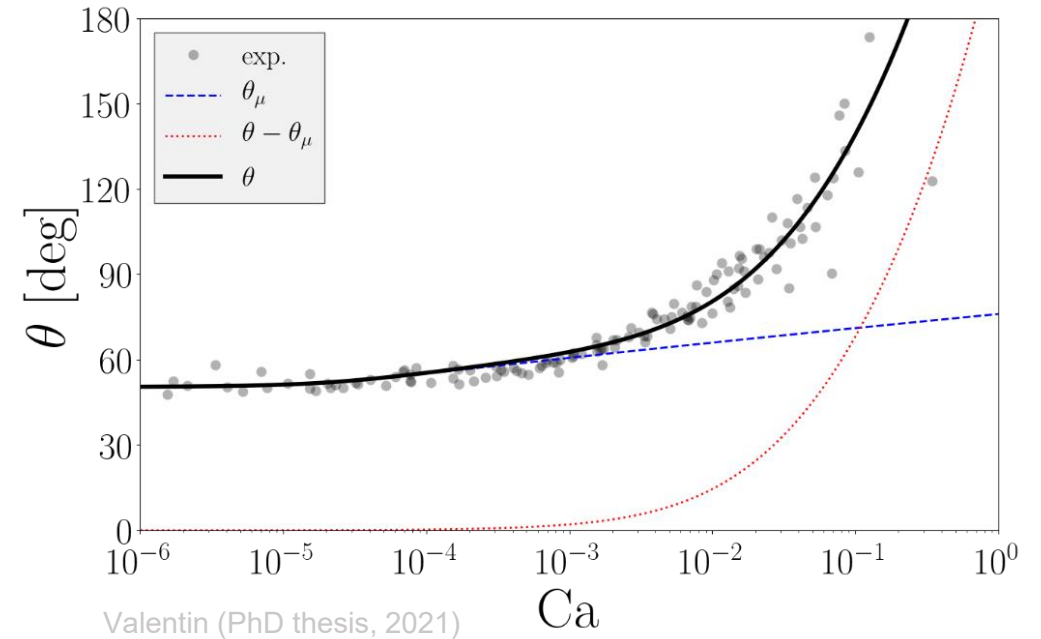
$$\cos \theta = \cos \theta_e - \Lambda \sinh^{-1} \left(\frac{Ca}{C_B} \right)$$

Petrov et al., 2003

- P_c is also velocity-dependent!

$$P_c = S_f \gamma \cos \theta$$

- Reduces impregnation kinetics at higher Ca ($\cos \theta < 0$)



Viscous phenomena

Darcy's law
$$\frac{Q}{A} = -\frac{K}{\eta} \frac{dp}{dx}$$

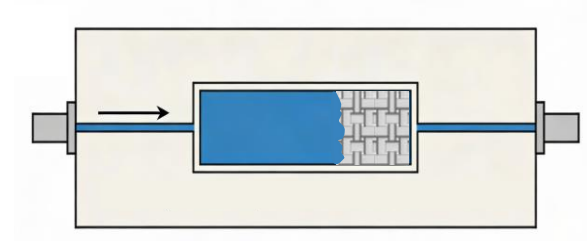
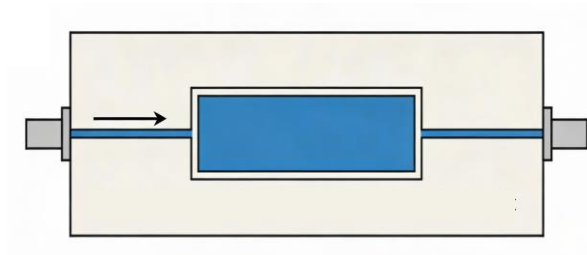
- Saturated permeability

$$K_{sat} = -\frac{Q_{out}\eta L}{A\Delta P}$$

- Unsaturated permeability

- ✓ Constant flow rate
- ✓ Constant pressure

$$\frac{dL}{dt} = -\frac{K}{\eta(1 - V_f)} \frac{dP}{dx}$$



! $R_s = \frac{K_{unsat}}{K_{sat}} \rightarrow \text{Capillarity}$

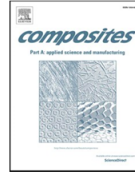
Previous work

Composites: Part A 149 (2021) 106560

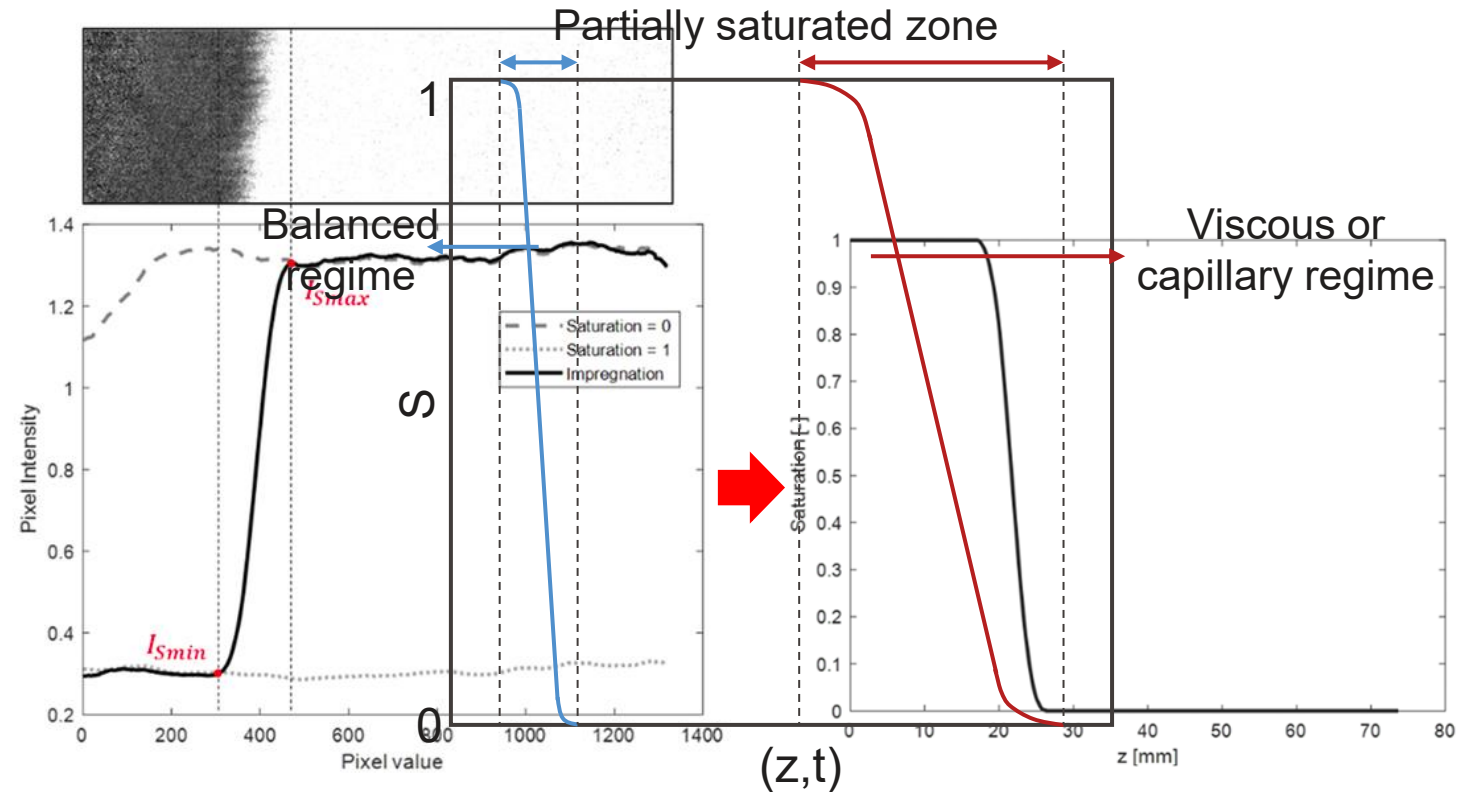
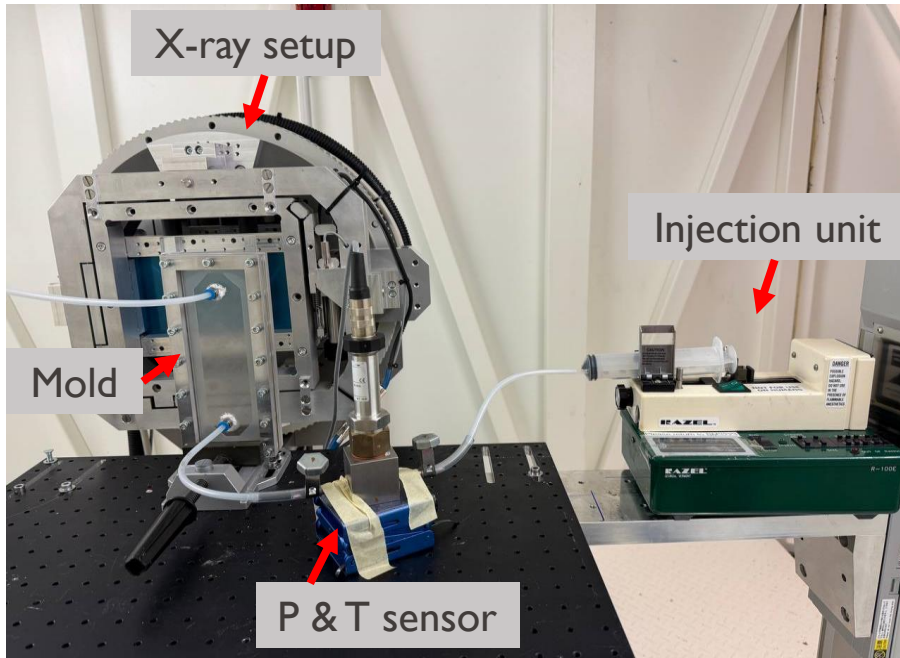
Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa



In-operando dynamic visualization of flow through porous preforms based on X-ray phase contrast imaging

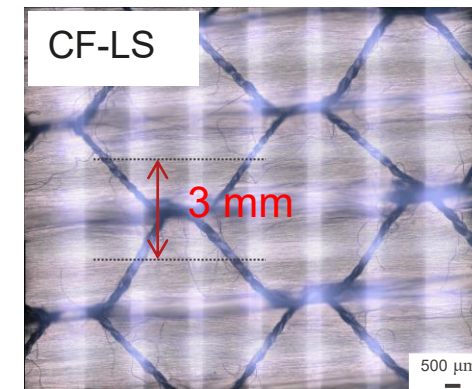
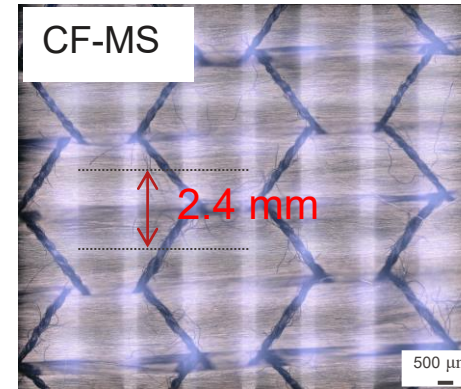
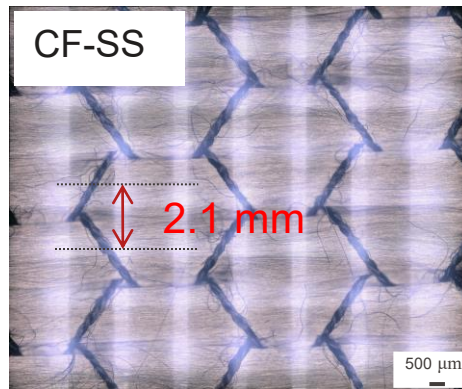
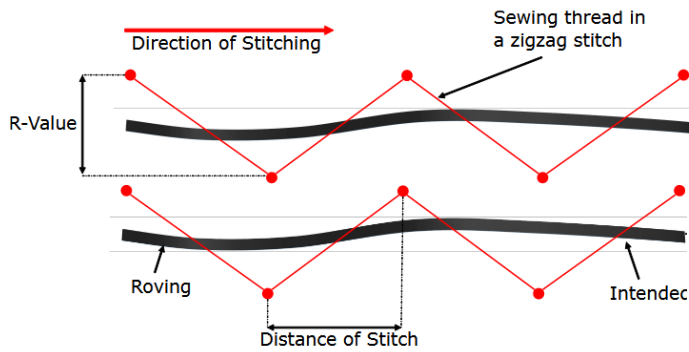
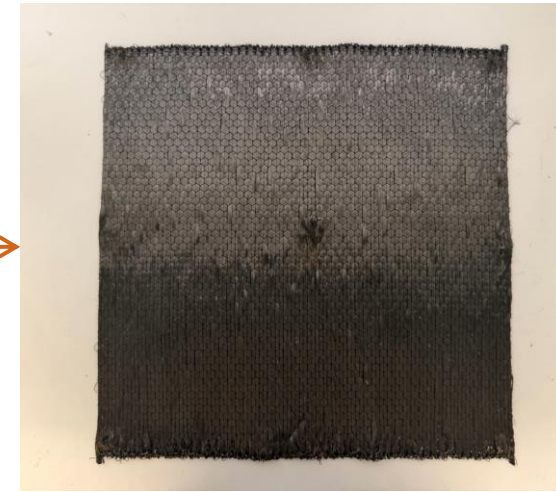
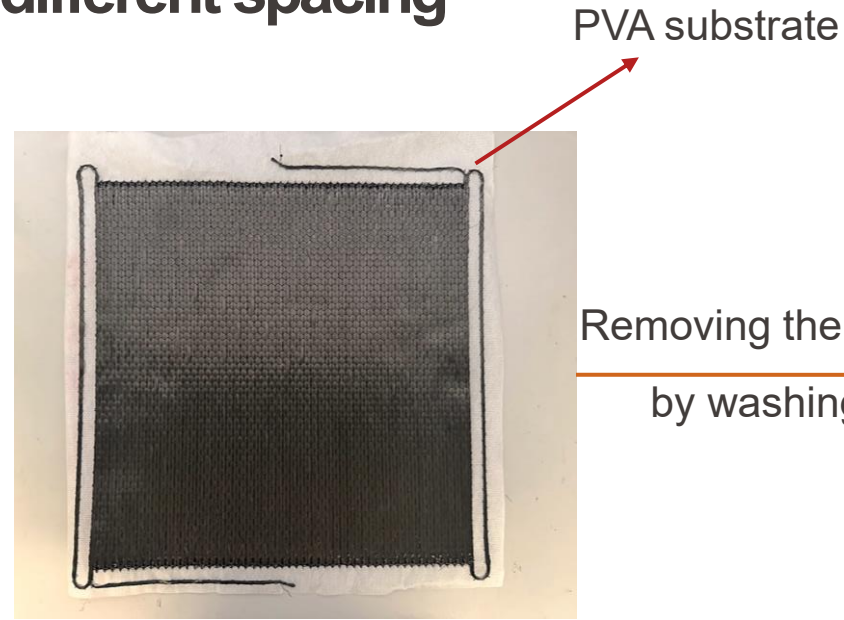
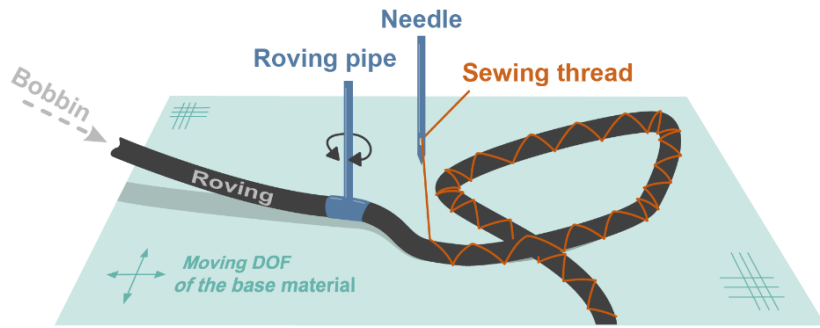


Motivation

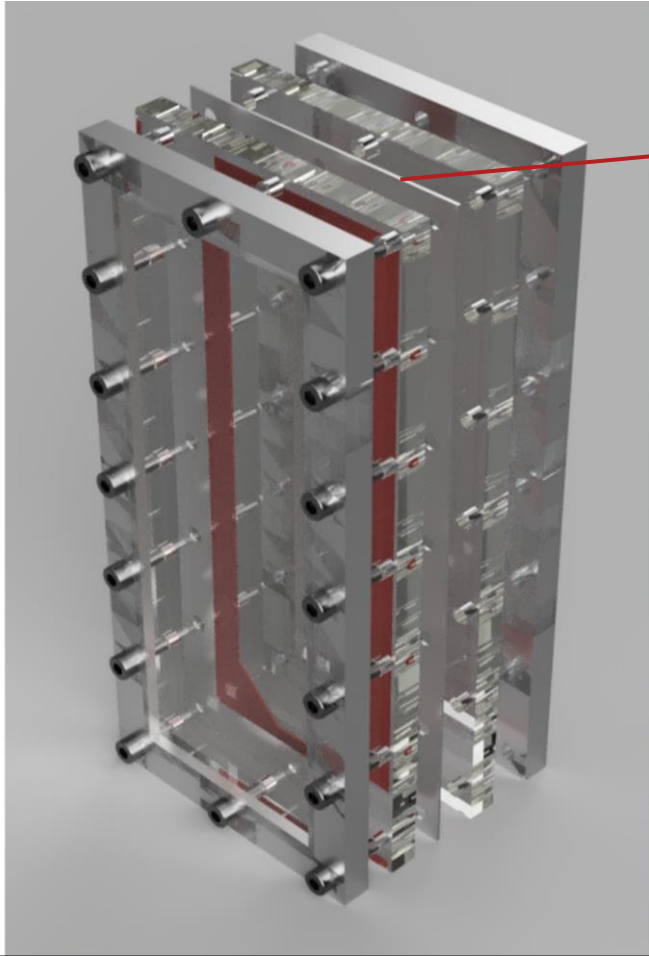
- Develop a better understanding of flow-regime transitions during LCM impregnation.
- Identify how processing and material parameters shift the optimal capillary-number window.
- Focus on the role of fabric spacing in promoting a balanced flow front.
- Support future prediction and modeling of void formation in dual-scale fibrous media.

Materials and Methods: Fabrics with different spacing

- Tailored placement technique (TFP)



Materials and Methods: Mold for flow visualization

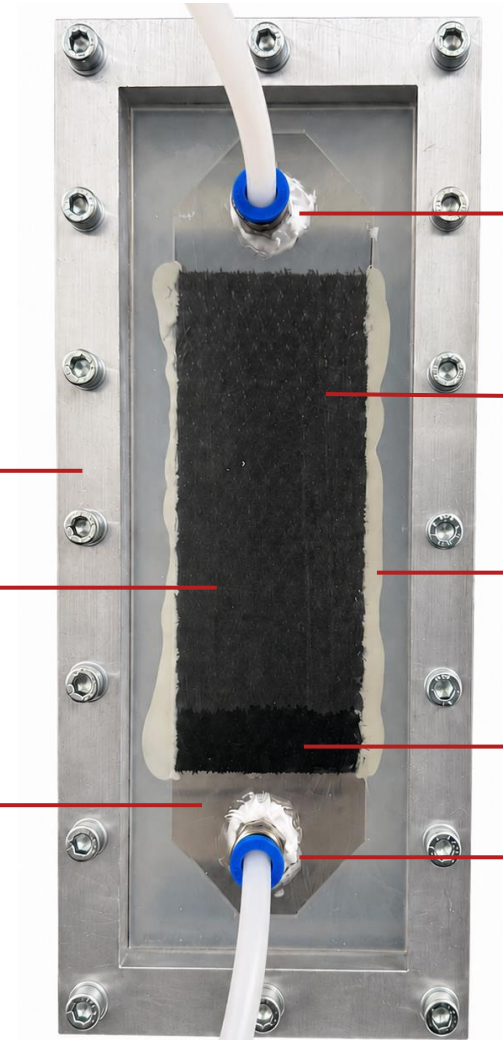


Metallic spacer with different thicknesses to keep the volume fraction constant at 45%

Metallic frame

Carbon fabric

Transparent PMMA windows



Outlet


Silicon joint

Flexible sealant

Fluid

Inlet

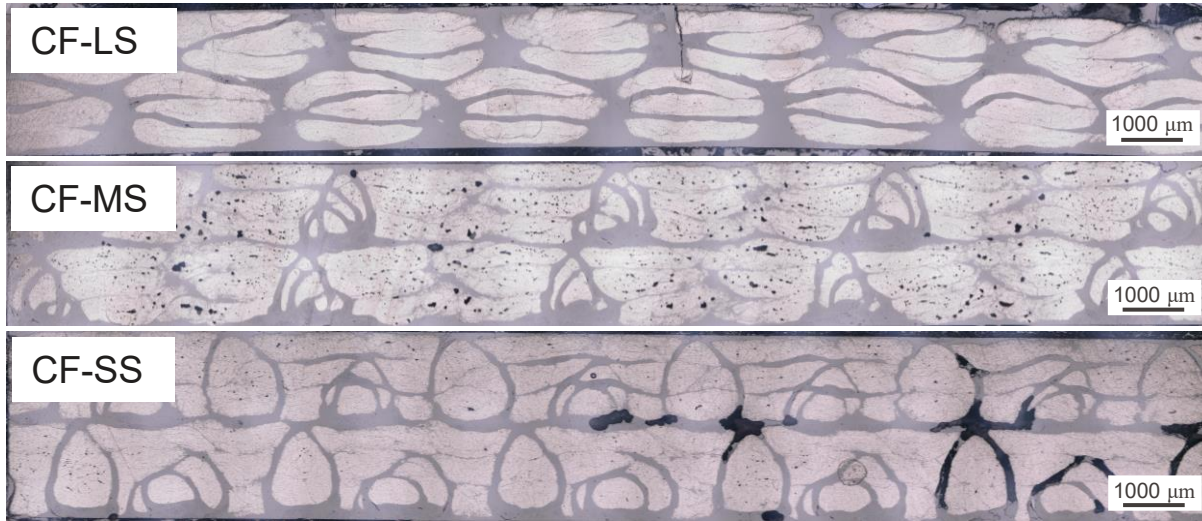
Materials and Methods: Liquids

 Liquid	Viscosity (Pa . s)	Density (g / ml)	Surface tension (mN / m)	application
PEG 16.7 wt. %	0.103	1.026	56.5	X-ray phase-contrast imaging
PEG + Znl 2	0.087	1.276	32.7	X-ray phase-contrast imaging and micro-tomography
RIMR 135 epoxy resin +	0.7-1.1	1.13 – 1.17	-	Preparation of composite sheets
RIMH 137 hardener	0.01-0.05	0.93 – 0.98	-	

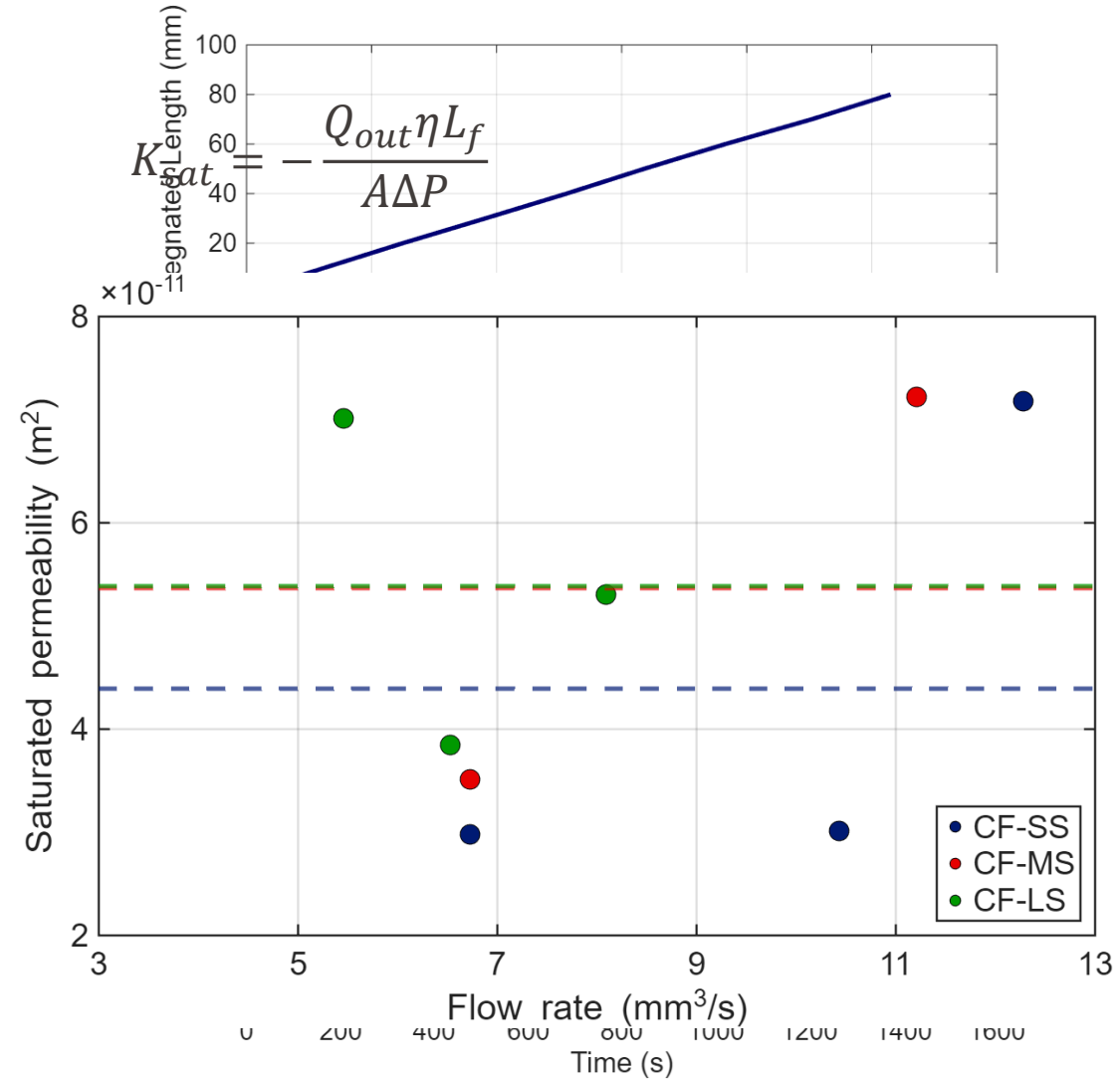
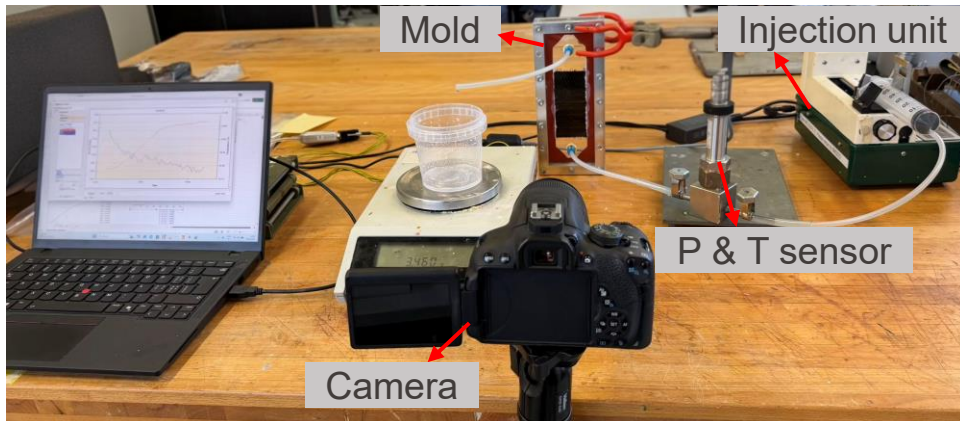
* Values at 25 °C

Fabric Characteristics and Permeability Measurement

- Cross-section view of samples

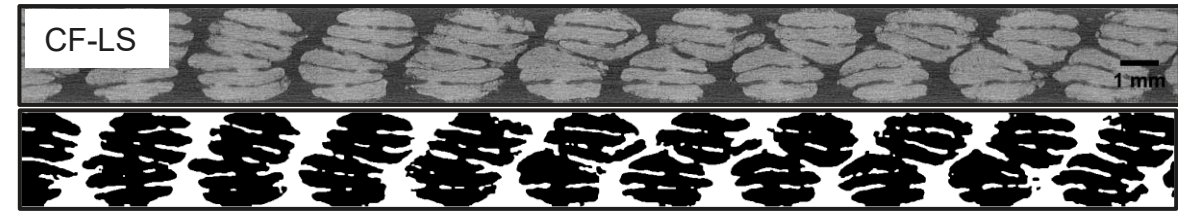
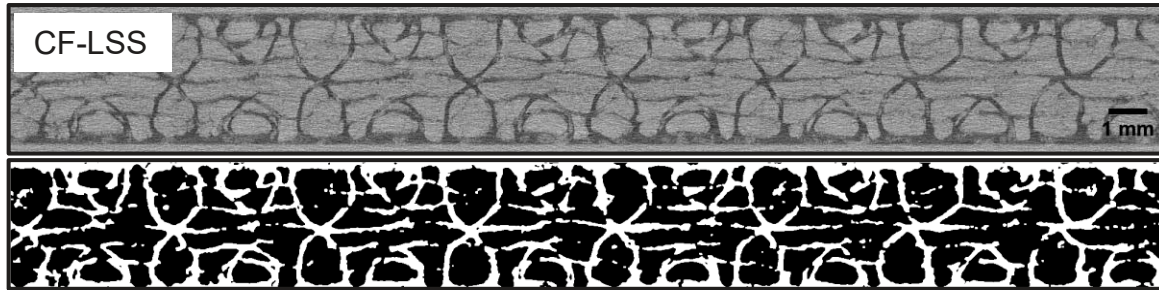


- Permeability measurement setup at constant flow rate



Granulometric Analysis of Fabric after compaction

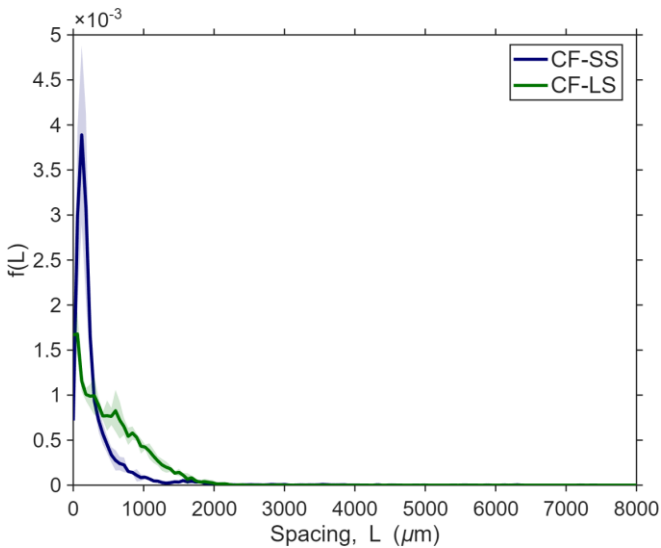
Binarized micro-CT images were used to quantify the actual spacing distribution between fabric regions after compaction to $V_f = 45\%$.



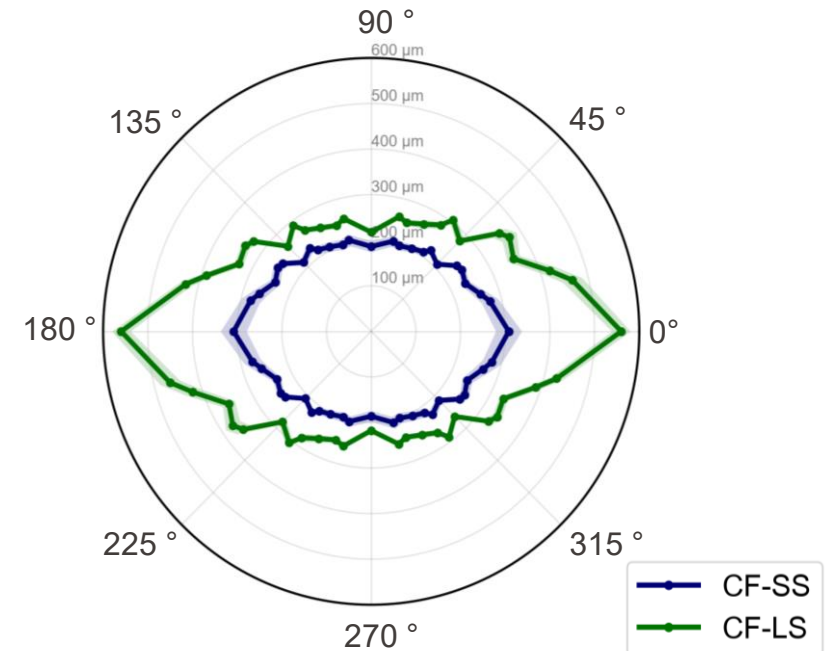
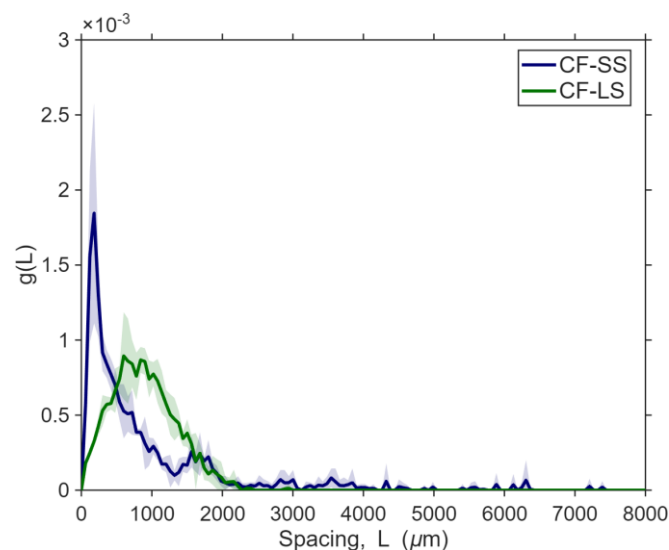
Granulometric analysis of the samples along the 0° direction

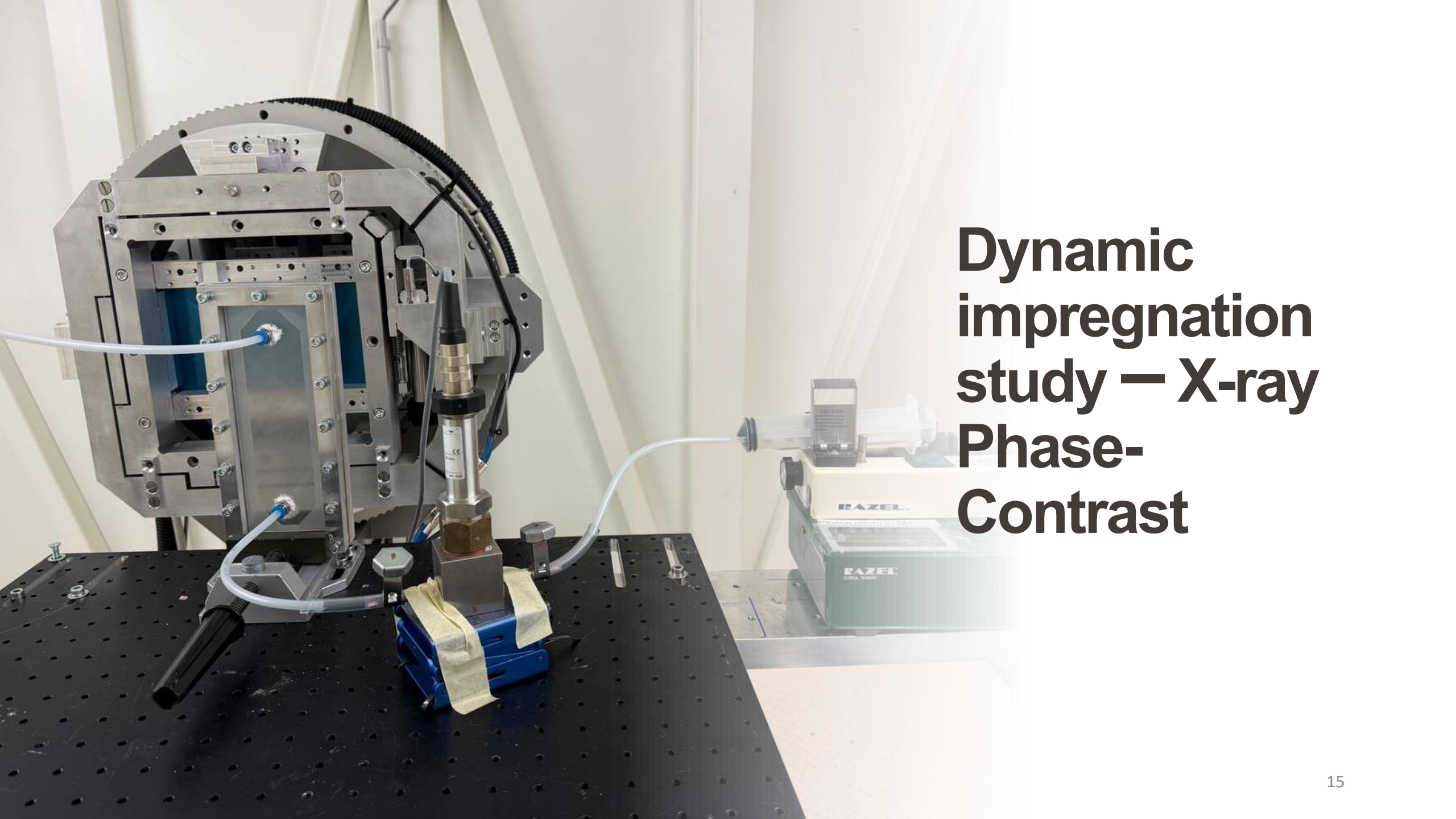
Results are averaged over four micro-CT slices for each sample

Number-based spacing distribution



Measure-based spacing distribution



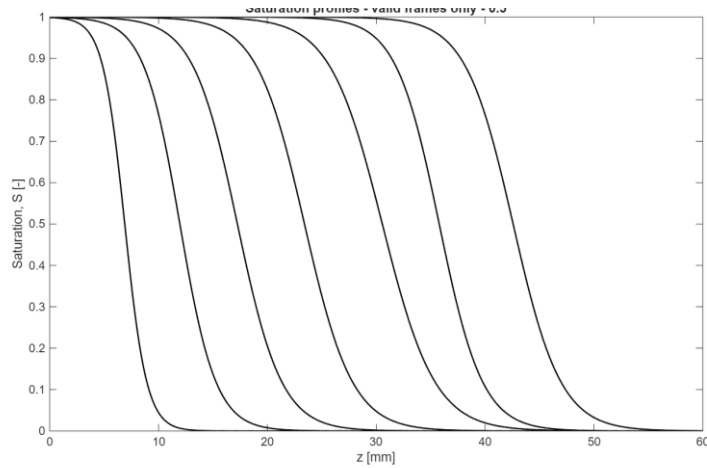
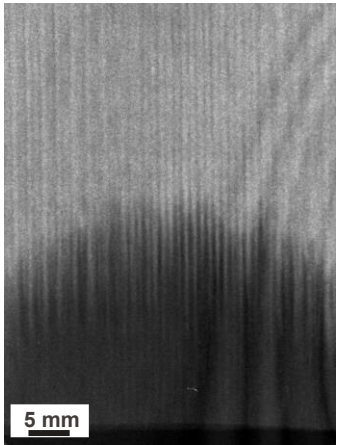


Dynamic impregnation study — X-ray Phase- Contrast

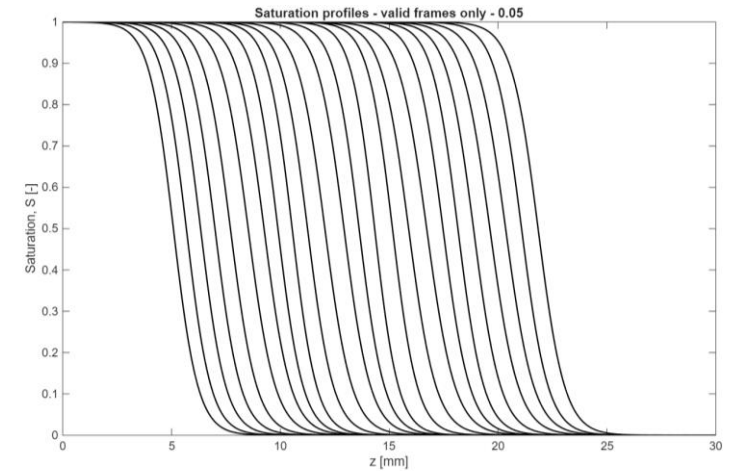
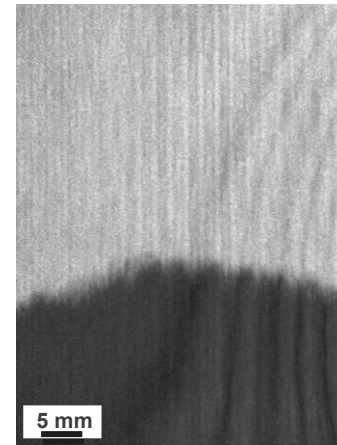
- Time-Resolved X-ray Phase-Contrast and Scattering Images of Impregnation

- ✓ Fabric → CF-SS
- ✓ Liquid → PEG 16.7 wt.%

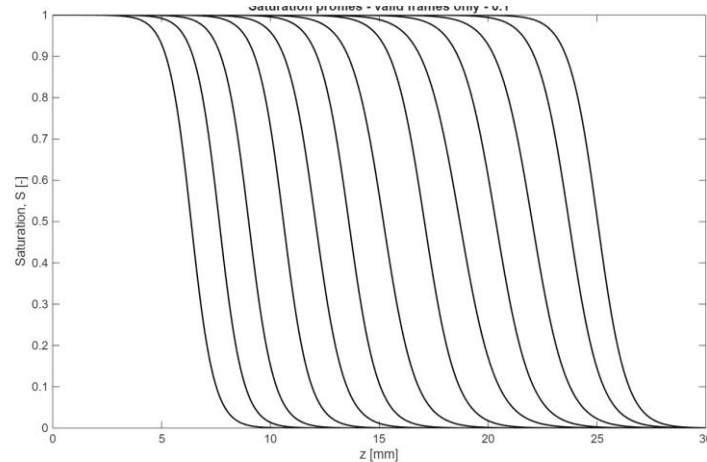
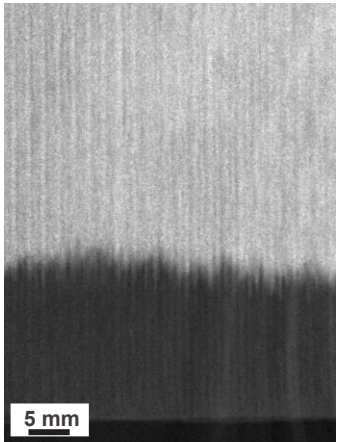
$$Ca = 1 \cdot 10^{-3}$$



$$Ca = 8 \cdot 10^{-5}$$



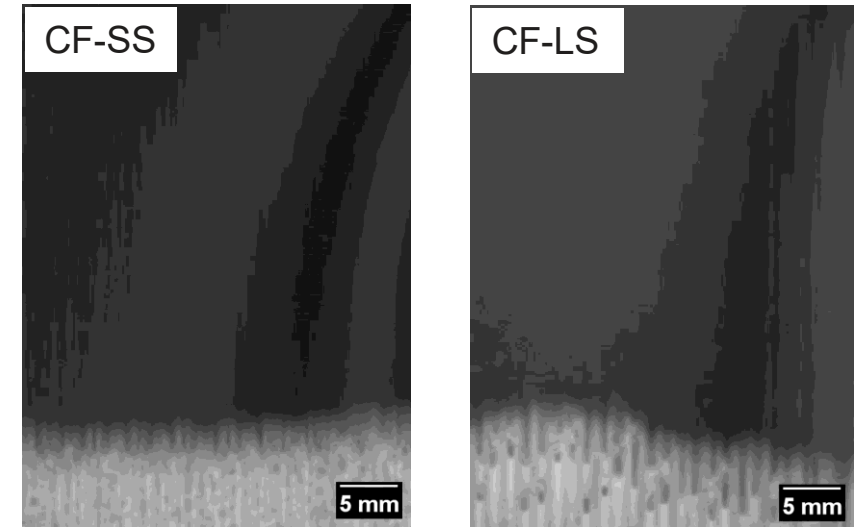
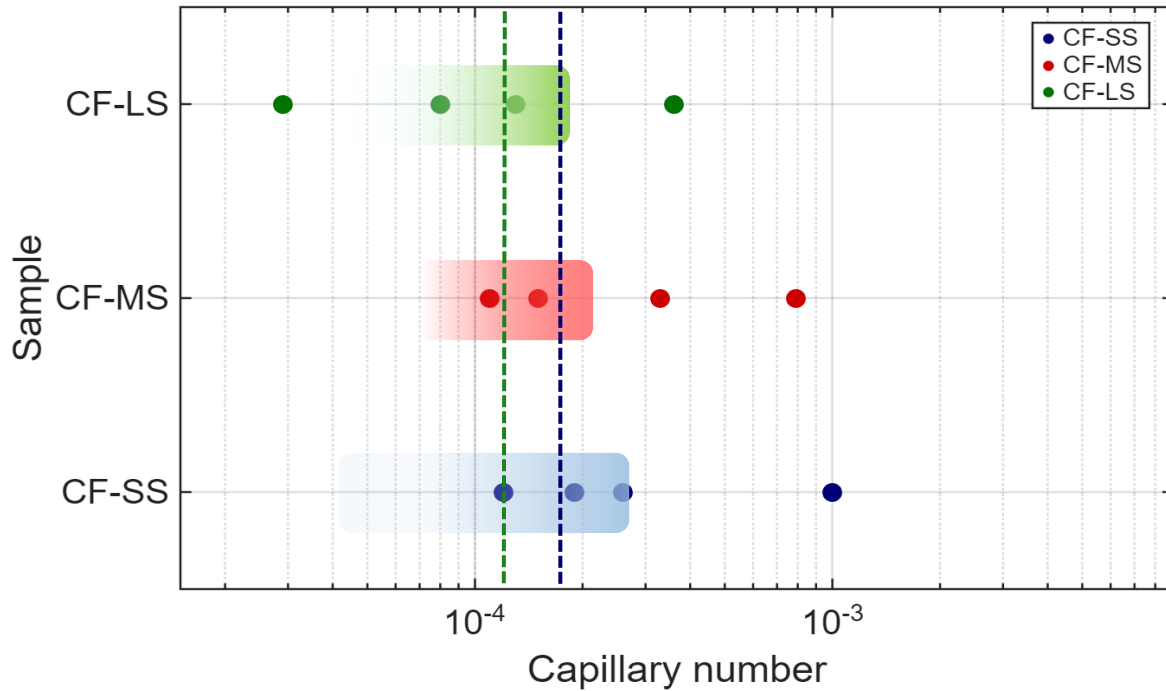
$$Ca = 2.6 \cdot 10^{-4}$$



- ✓ Limitation:

At low capillary numbers, scattering images are less effective for identifying the capillary regime

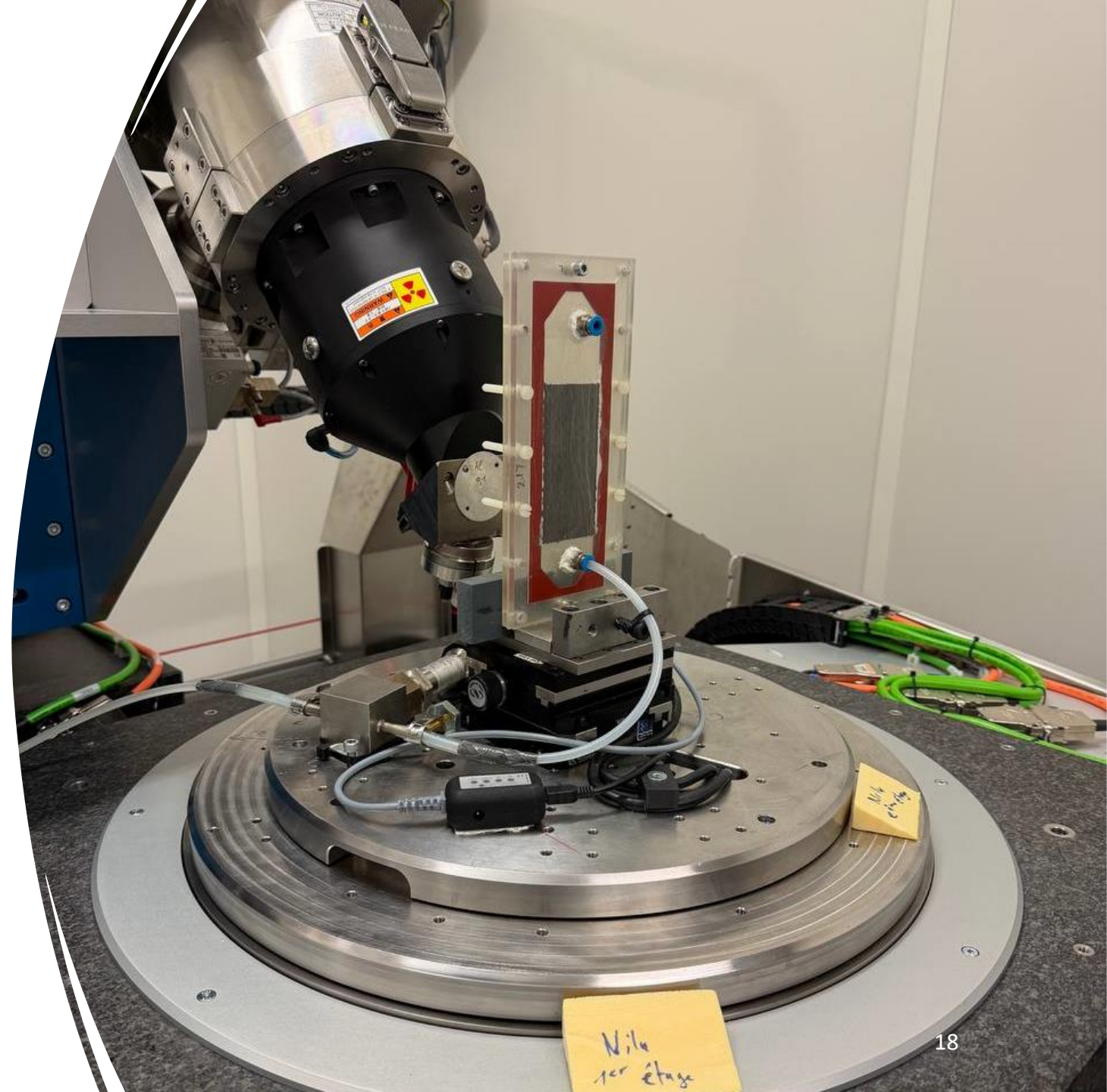
Scattering images provide an approximate window for identifying the possible balanced flow regime.



Sample	CF-SS	CF-LS
T (°C)	24.08	22.11
v (mm / s)	0.065	0.057
Ca (-)	$1.8 \cdot 10^{-4}$	$1.67 \cdot 10^{-4}$

- ✓ The analysis was narrowed to the two representative samples with the smallest and largest spacings.
- ✓ PEG + ZnI₂ absorption contrast improves void visibility and shows potential for resolving the capillary-dominated regime.

Dynamic impregnation study — micro- tomography

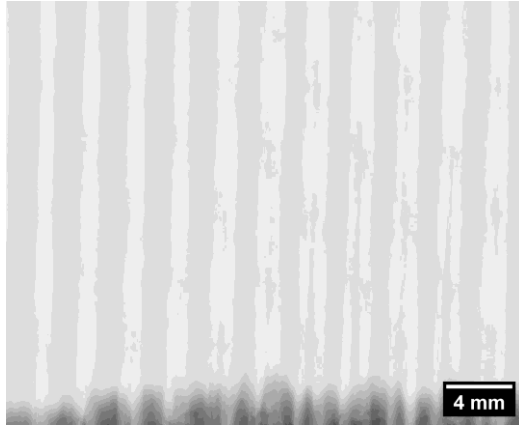


Micro-Tomography and High-Resolution Impregnation Imaging

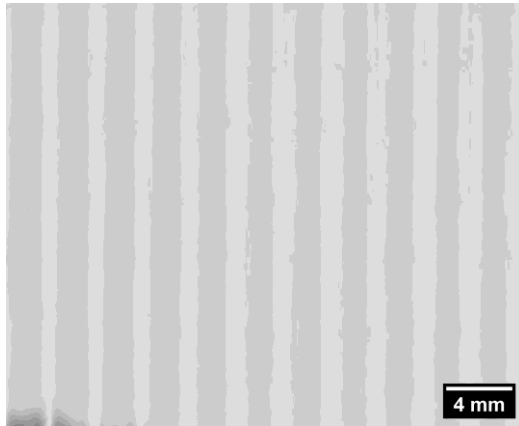
- ✓ High-resolution 2D impregnation images capture the flow-front evolution during mold filling.

CF-LS

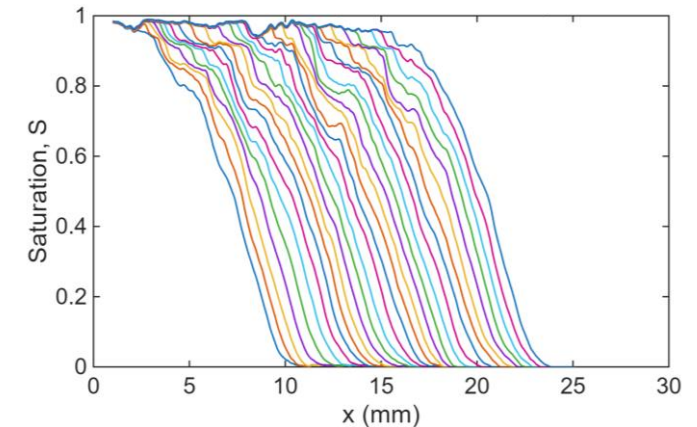
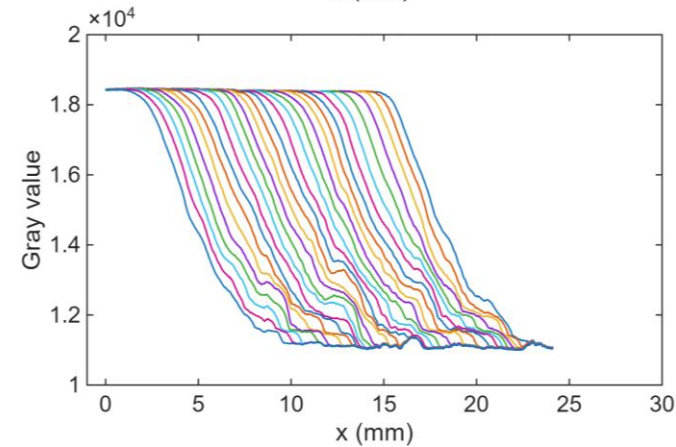
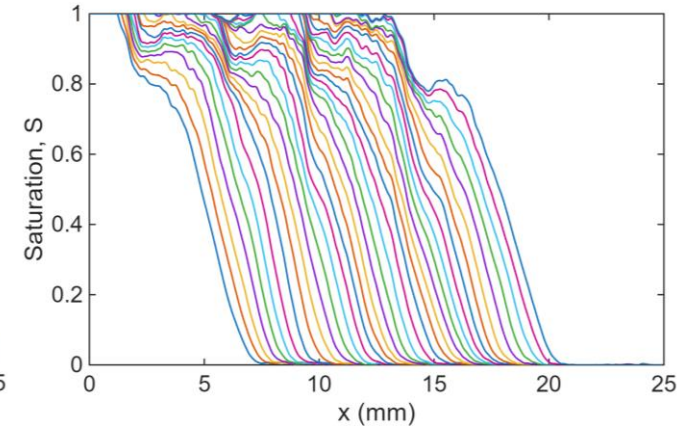
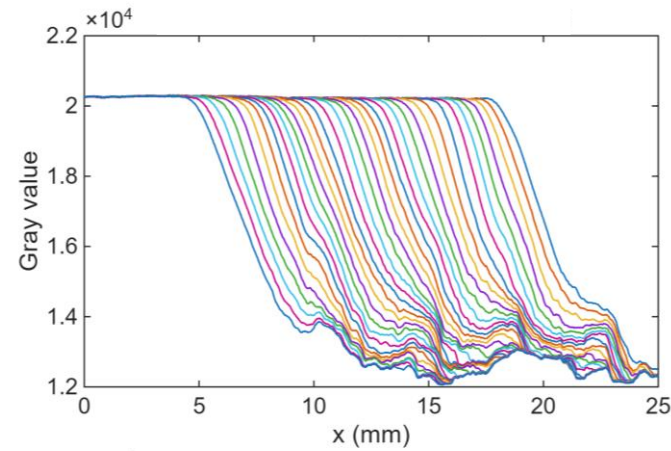
$$Ca = 1.51 \cdot 10^{-4}$$



$$Ca = 1.93 \cdot 10^{-4}$$



Velocity-Dependent Saturation Profiles during Fabric Impregnation

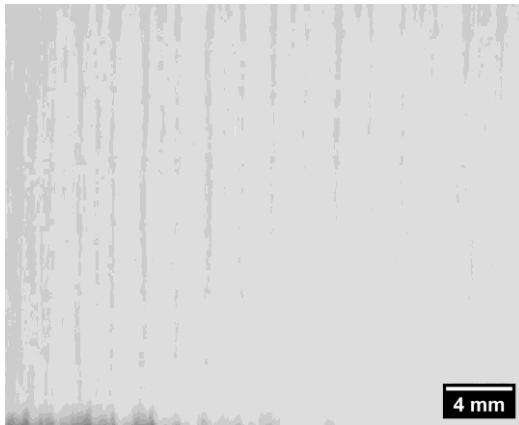


CF-LS

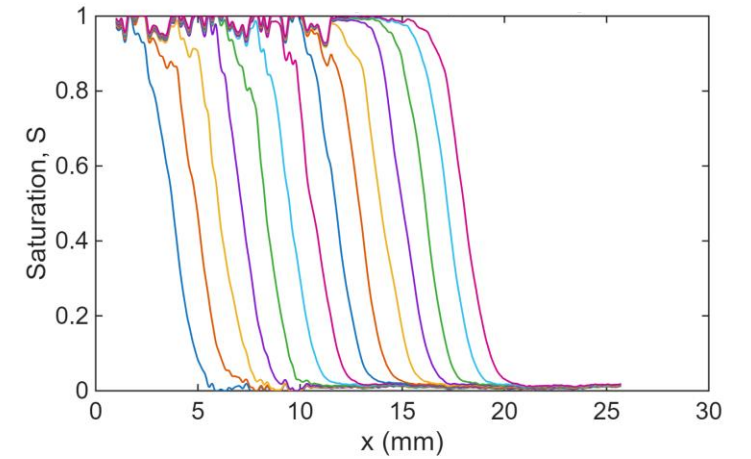
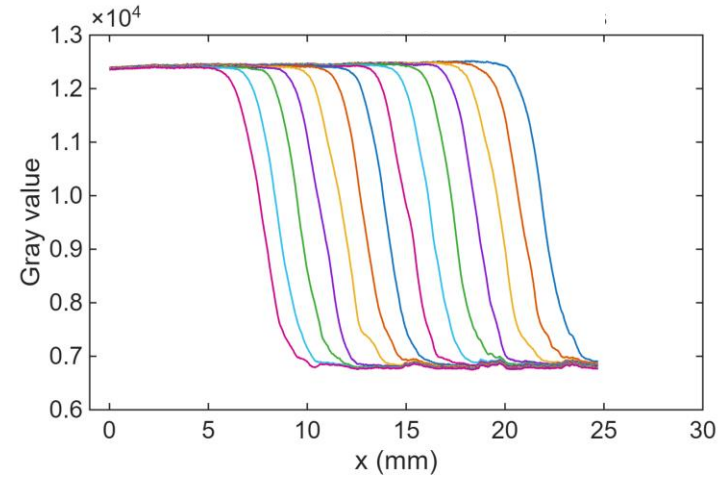
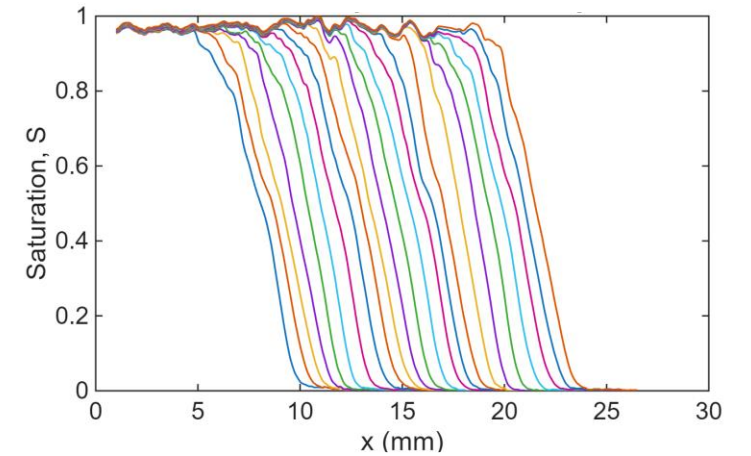
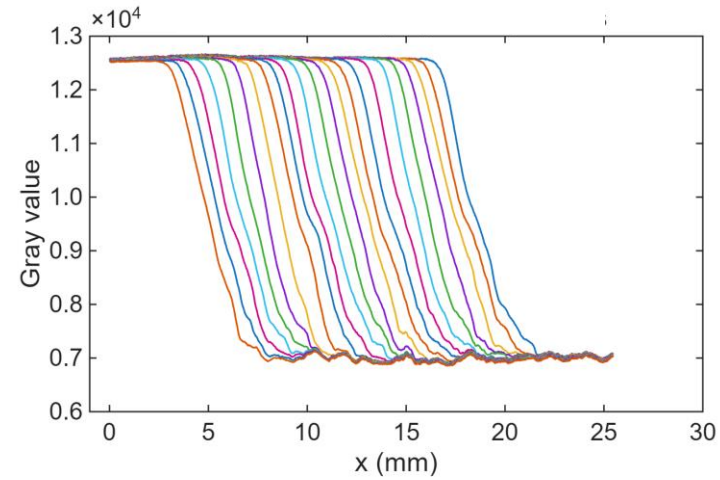
$$Ca = 2.46 \cdot 10^{-4}$$

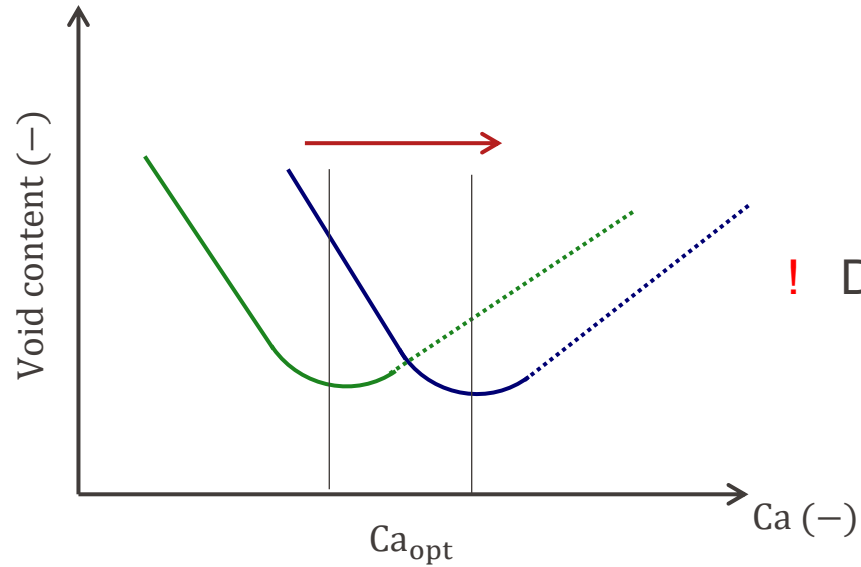


$$Ca = 4.26 \cdot 10^{-4}$$



Velocity-Dependent Saturation Profiles during Fabric Impregnation





! Decreasing the inter-tow spacing shifts the optimal capillary number toward higher values.

- ✓ Wet CT datasets enable 3D void analysis, including void location, number, and distribution.

$$Ca = 1.51 \cdot 10^{-4}$$

CF-LS wet state 3D view

$$Ca = 1.93 \cdot 10^{-4}$$



Conclusion

- At constant fiber volume fraction, changing the inter-tow spacing did not lead to a major variation in saturated permeability.
- Scattering-based phase-contrast images were effective for identifying viscous-dominated impregnation regimes.
- Absorption imaging revealed that decreasing inter-tow spacing shifts the balanced-flow regime toward higher capillary numbers.

The EPFL logo is displayed in a bold, red, sans-serif font in the top left corner of the slide. The background of the slide is a photograph of the EPFL campus at dusk, featuring a large, three-dimensional red sculpture of the letters 'EPFL' on a grey base, with a modern building and trees in the background under a twilight sky.

EPFL

17th International Conference on Flow Processes in Composite
Materials (FPCM-17)

Thank you for your attention !

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