

A Resin Infiltration Model to Optimize Transparent Wood Production

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11/09/2025 VTT – beyond the obvious

Transparent wood

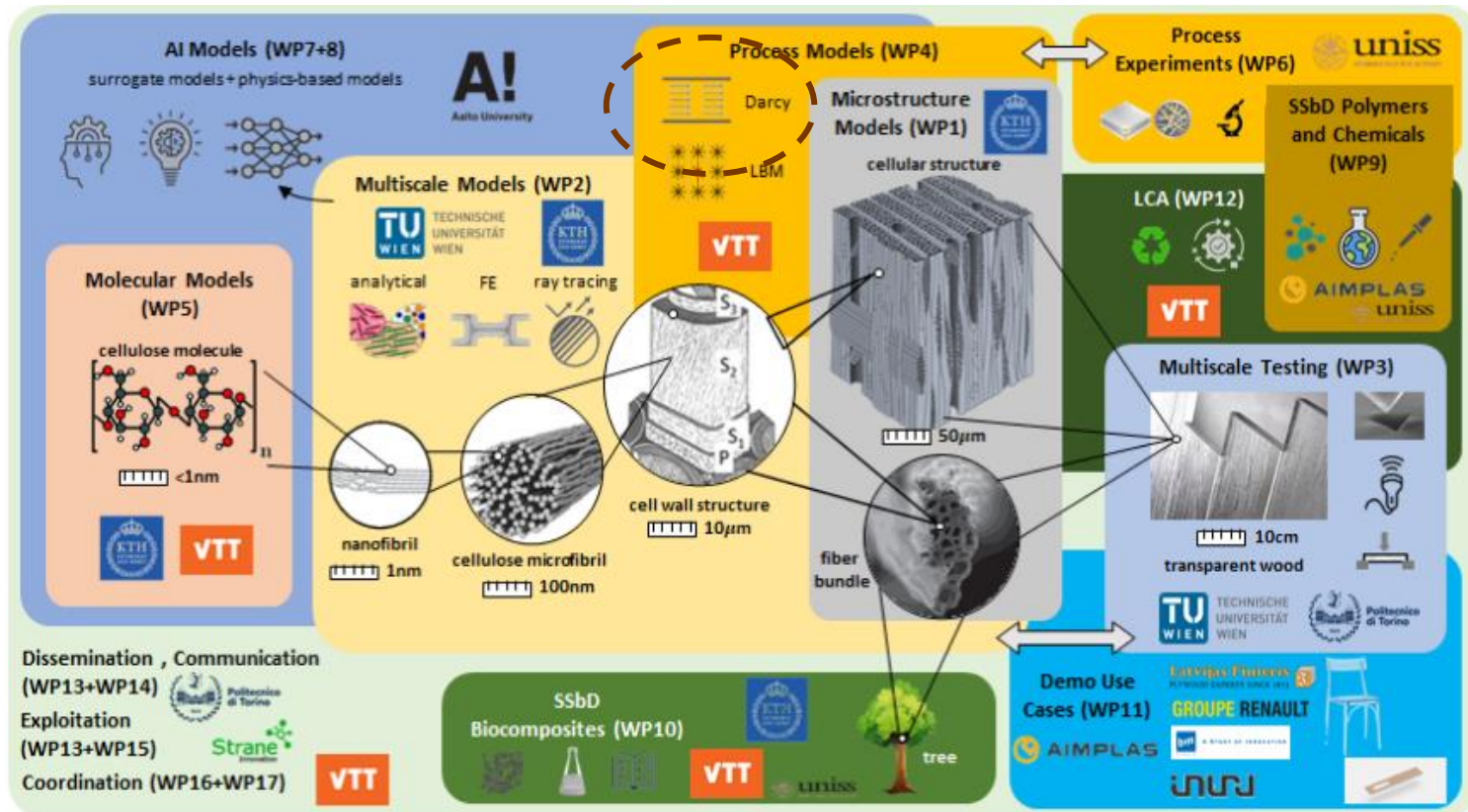
- Wood is not transparent because of
 - Scattering at interfaces
 - Absorption by chromophores (mainly in lignin)
- Transparent wood prepared by
 - Removing chromophores (delignification)
 - Filling pores with polymer with matching refractive index
- Potential uses
 - Optically functionalized material for smart buildings
 - Structural optics
 - Photonics
- Al-TranspWood project
 - Multiscale simulations
 - AI-driven approach to scalability and optimization



AI-TranspWood project

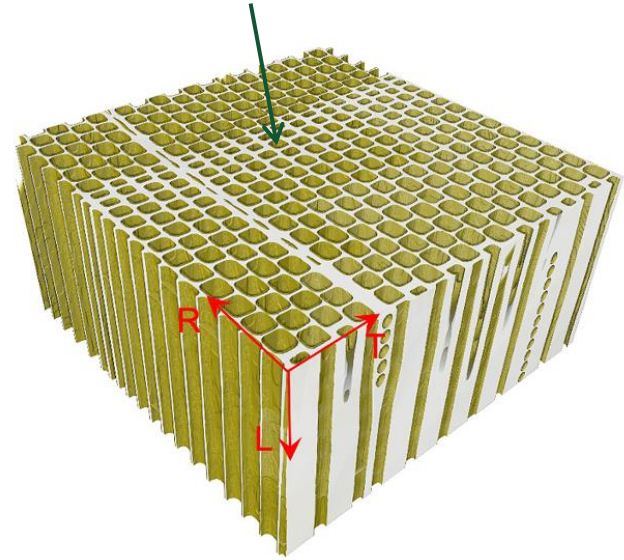
AI-TW
AI-TRANSPWOOD

VTT

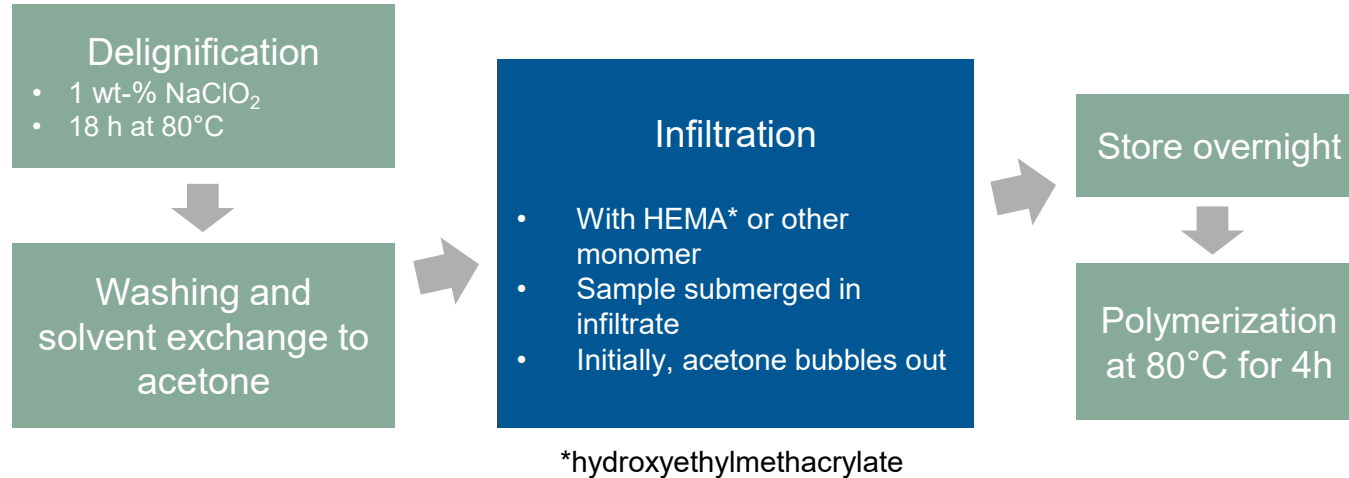


Microstructure

- The centers of the wood cells are hollow (lumens)
- Infiltration by monomer and polymerizing leads to filling the lumens with polymer
- Cell walls have high stiffness and strength
- Result is a composite with soft fibers in stiff matrix



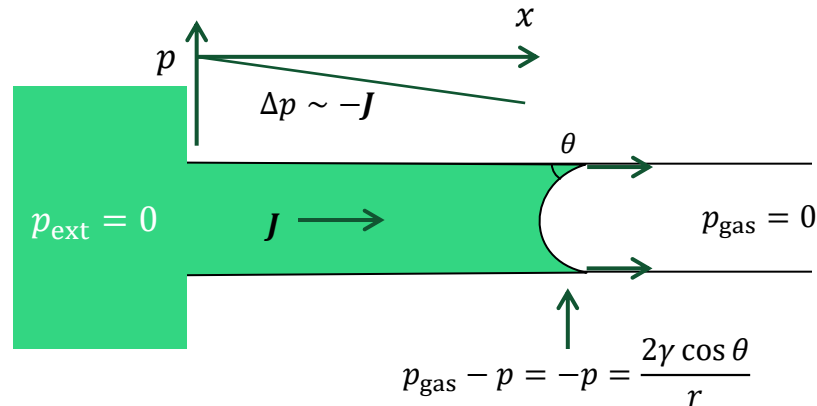
Experimental procedure



- Performed by University of Sassari

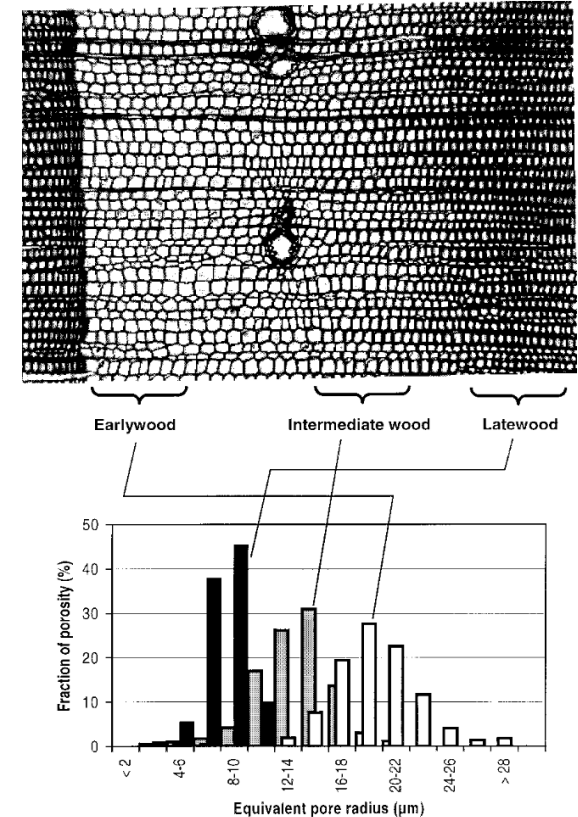
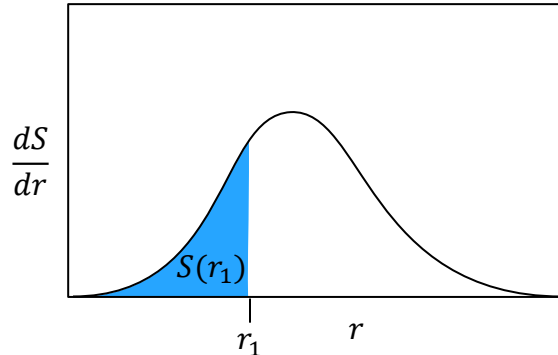
Infiltration mechanism

- Unforced infiltration in vacuum driven by capillary forces
- Pressure of the fluid at the front is negative
 - Pressure loss due to dissipation (Darcy's law)



Pore size distribution

- With saturation $0 < S < 1$, small pores are locally filled but largest pores remain empty
- At pressure p , the radius of the largest filled pore is given by the Young-Laplace equation as $r = \frac{2\gamma \cos \theta}{p}$
- The cumulative pore size distribution is given by $S(r)$
 - Also gives saturation as a function of r



Model

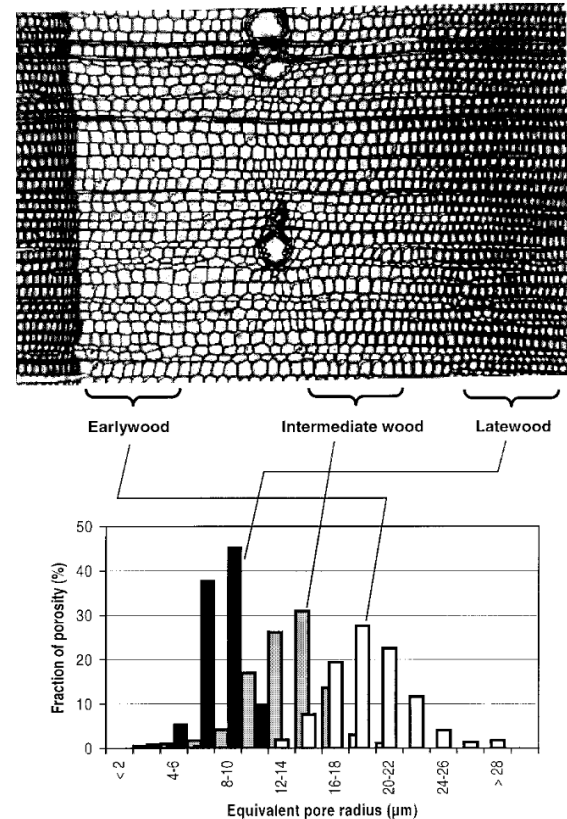
- Mass balance $\phi \frac{dS}{dt} = -\nabla J$
 - ϕ is the porosity
- Flux (Darcy's law) $J = -\frac{K'}{\mu} \nabla p$
 - μ is viscosity
 - $K' = k_s(S)K$ is the anisotropic permeability
 - $k_s(S) = S$ specifies the saturation dependency (steepness of infiltration front)
- $S = S(r)$ and $r = r(p) = \frac{2\gamma \cos \theta}{p}$
 - Pore sizes are taken to follow a truncated normal distribution ($S(r)$ is the CDF)
 - $S(r_{cut}) = 0$ where r_{cut} is a cutoff radius (minimum pore radius)
- Separation of scales is assumed
 - Pores are small
 - Liquid moves in a microscopic network of pores of various sizes

Implementation

- Using FEniCSx
- Weak form: $\int_{\Omega} \left[\delta p \phi \frac{S(p_{n+1}) - S(p_n)}{\Delta t} - \nabla(\delta p) \cdot \mathbf{J}(p_{n+1}) \right] d\mathbf{x} = 0$
- Boundary condition: $p = 0$ Pa
- Adaptive timestepping to speed up solution as infiltration rate decreases

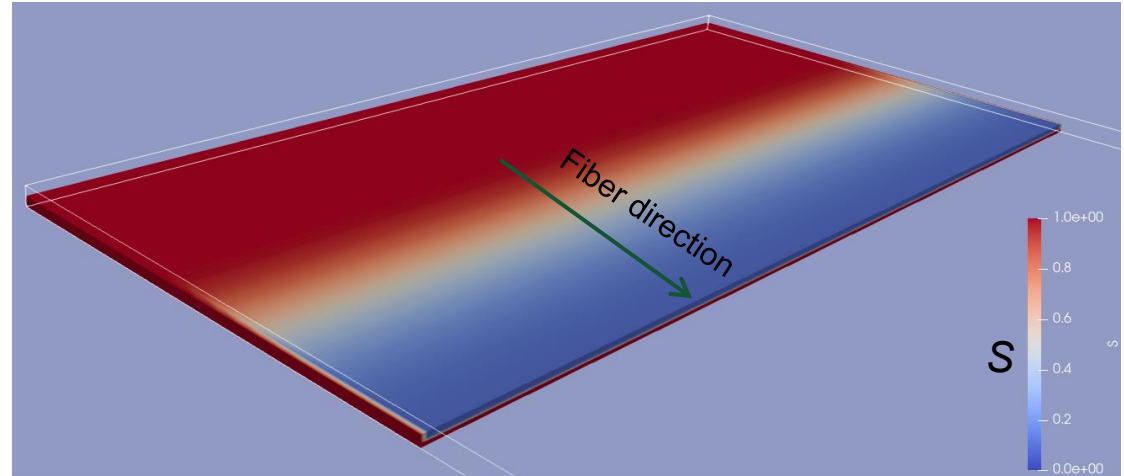
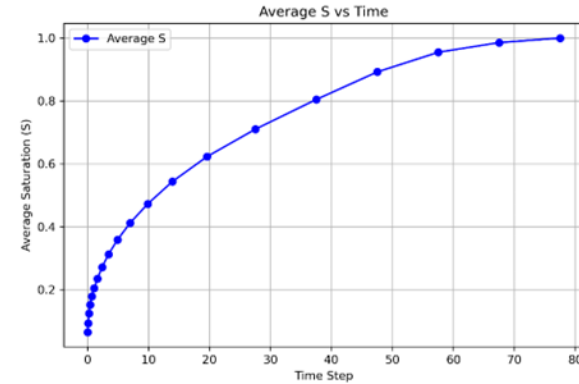
Parameters

- Lack of studies on delignified wood
- Perre & Turner, Holzforschung (2001) gives some estimates for untreated softwood
- Permeability: $k_{\parallel} \approx 10^{-12} \text{ m}^2$, $k_{\perp} \approx 10^{-16} \text{ m}^2$
- Mean pore radius: 10 – 20 μm , relative standard deviation: 20%
- Porosity: $\phi \approx 0.6$
- HEMA
 - Viscosity: 0.07 Pa s
 - Surface tension: 20 – 30 mN/m
 - Contact angle (assumed): $0^\circ - 50^\circ$



Simulation example

- Sample thickness: 5 mm
- 50 mm x 50 mm
- Typically, one direction dominates
 - Fiber direction or z direction
 - $S \sim t^{\frac{1}{2}}$ (cf. Washburn equation)
- Typical infiltration time: within 2 minutes



Reduced units

- We note that by changing the variable to $u = \frac{p}{2\gamma \cos \theta}$ we have
 - Young-Laplace equation: $r = \frac{1}{u}$
 - Darcy's law: $J = \frac{2\gamma \cos \theta}{\mu} \mathbf{K}' \cdot \nabla u = \eta \mathbf{K}' \cdot \nabla u$
- Therefore, the monomer-related effects can be combined into $\eta = \frac{2\gamma \cos \theta}{\mu}$
- The infiltration time will be inversely proportional to η

Experimental results with short infiltration times

0.6 mm thick birch

1 min



5 min

10 min

20 min

1.4 mm thick birch (much slower infiltration!)

1h



2h

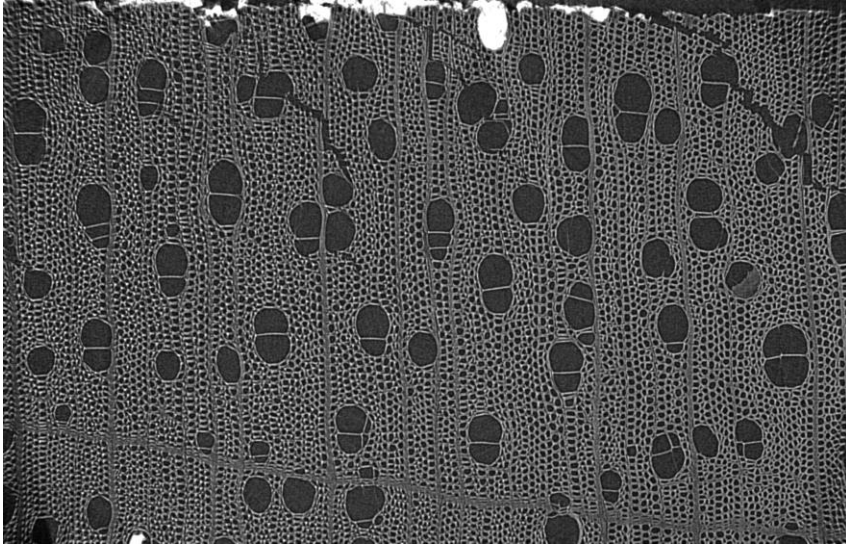


3h

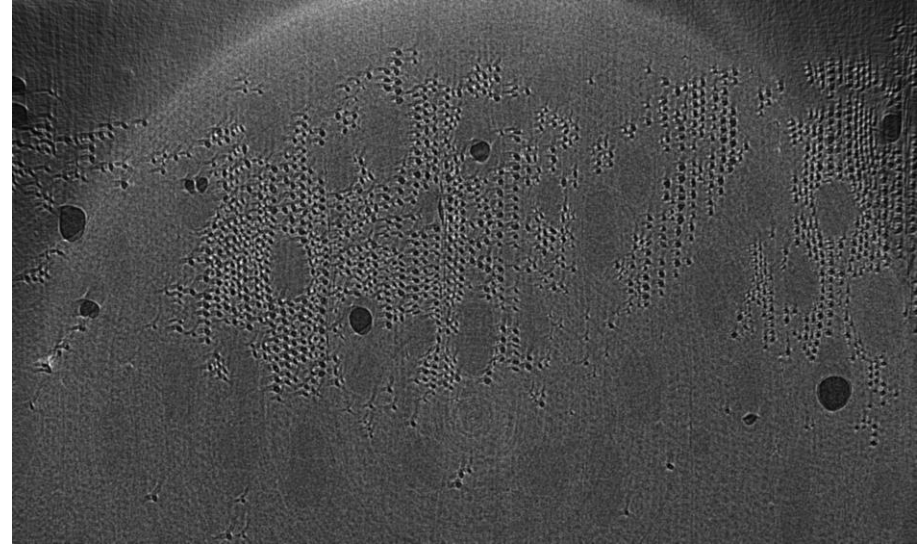


X-ray μ CT

Untreated 1.4 mm thick birch



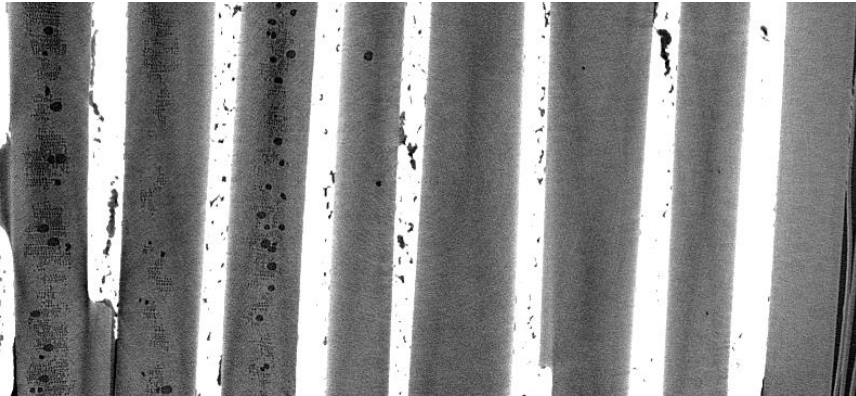
Infiltrated for 60 min



0.6 mm and 1.4 mm comparison

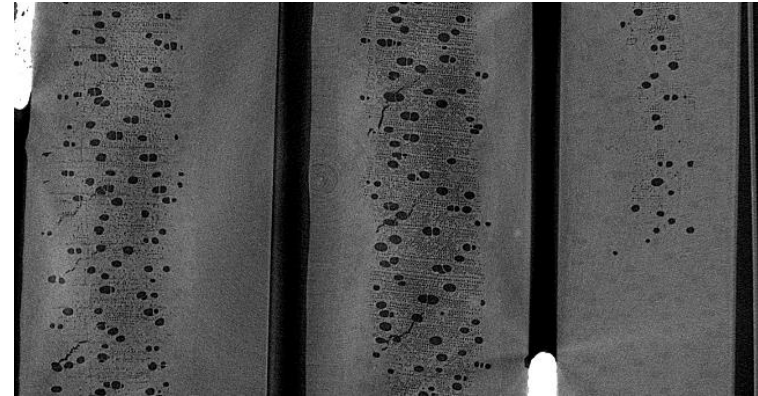
Birch 0.6 mm

1 min 5 min 10 min 20 min 30 min 1 h 2 h 3 h



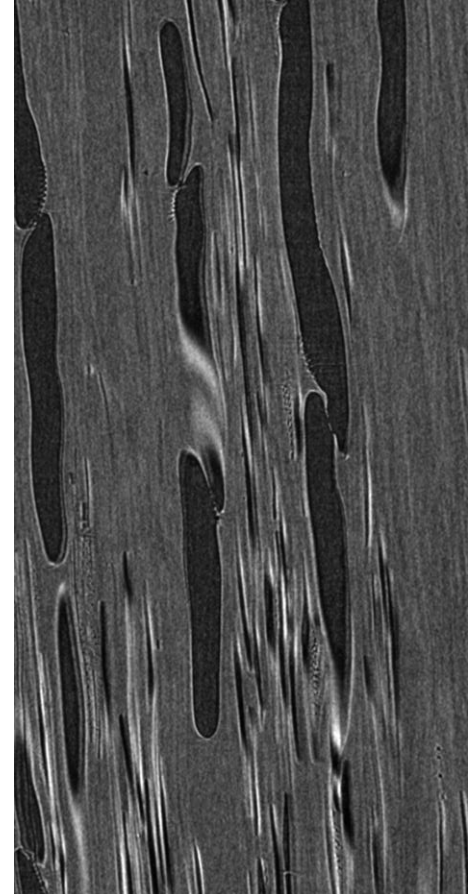
Birch 1.4 mm

1 h 2 h 3 h



Observations

- Infiltration not locally homogeneous
 - Model assumption violated
- Saturation quickly reaches certain level across the sample but then slows down
- Unfilled pores remain in both vessels (large channels) and fibers (small channels)
- Sample thickness seems to strongly affect the infiltration time



Possible explanations for slowdown in infiltration

- Gas trapped inside the pores?
 - Seems unlikely given the applied vacuum
- Poor wettability of the delignified cell wall?
 - The nanoporosity could create a pinning effect (large advancing contact angle)
 - Nanopores saturate first, then micropores?

Conclusions

- Model describes an idealized infiltration process
- Real structure doesn't obey separation of scales
 - Channels are macroscopically long
 - Modelling work will continue at a more microscopic level (lattice Boltzmann)
- Unknown effect slows down the infiltration
 - Experimental investigations will continue



Chen, B., Montanari, C., Popov, S., & Berglund, L. A. (2023). *Composites Science and Technology*, 244, 110262

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Thank you!

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