

Potential Utilizations of 3D Printed Fracture Network Model

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Application of 3D printing to geological research

3D printed rocks



Moon rock
(Holloway, 2012)



Coal rock
(Ju et al., 2014)



Sandstone
(Ishutov et al., 2015)

Controllable

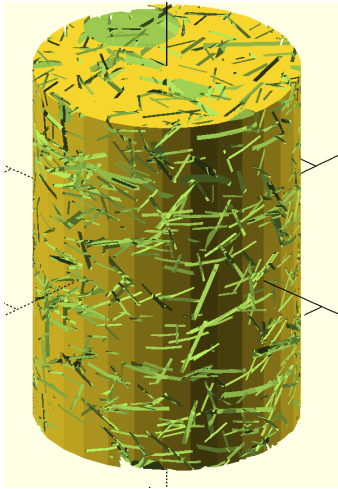
Duplicable

Visible

- Use the same materials as real rocks
- Help validate existing flow modeling and numerical methods
- Provide physical, chemical, thermal, mechanical aspects of fluid dynamics in rock

Suzuki et al. (2016)

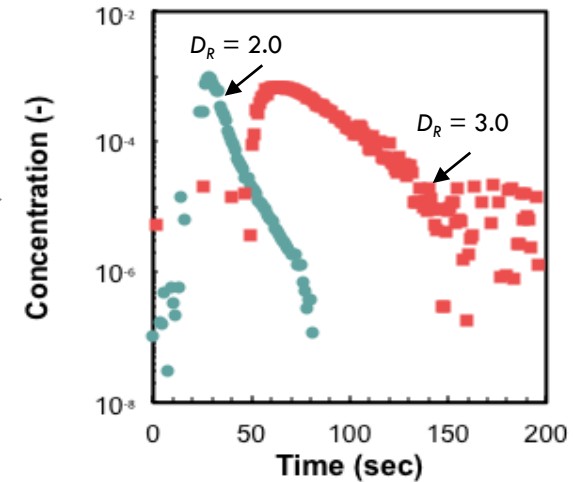
Fracture network



3D printing



Flow experiment

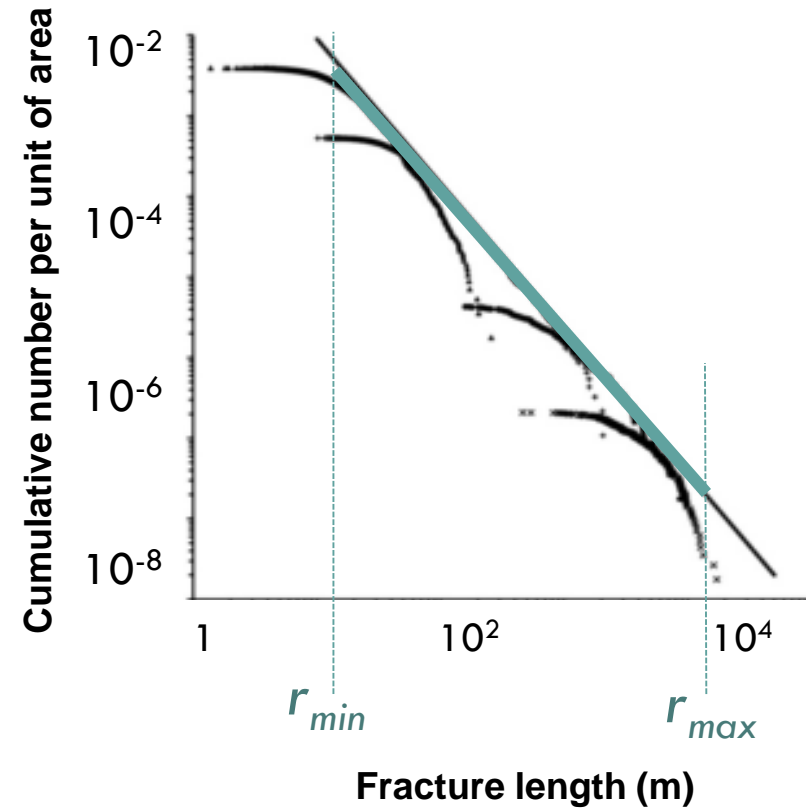


Today's talk:

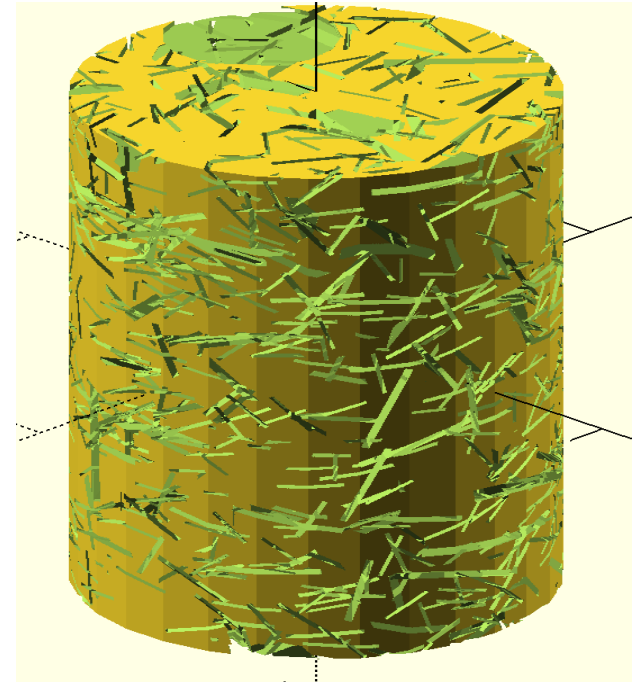
- Improve post-treatment for printing fractures
- Verify the accuracy of making samples by micro CT scan
- Compare with numerical simulation

Scaling of fracture systems

(Suzuki et al., 2016)



(Castaing et al., 1996; Odling et al., 1999)



Min aperture / radius
0.2 / 1.6 mm

Max aperture / radius
1 / 8 mm

3D printer

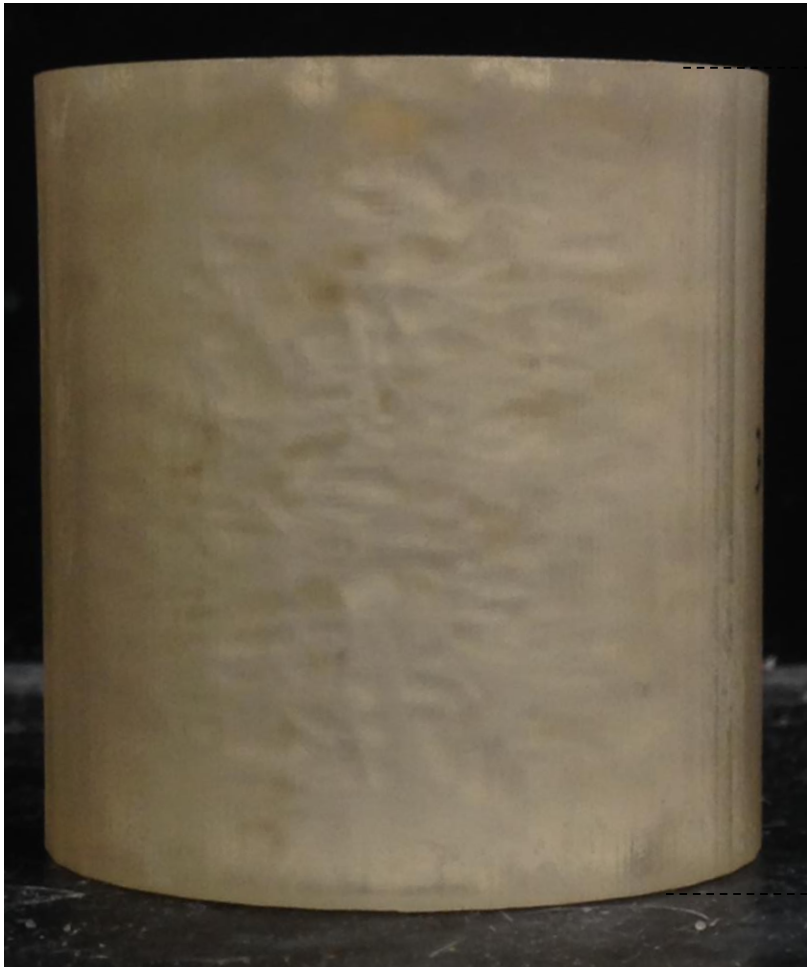


VisiJet ® EX200 Plastic Material for 3-D Modeling,
3D Systems @Stanford 3-Dimensional Printing Facility (3D)

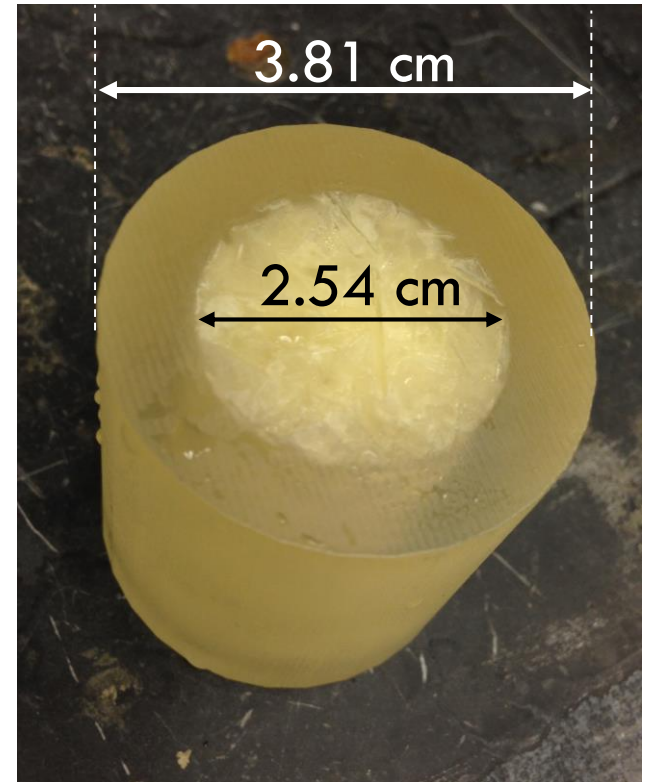
16 micron accuracy

Base material: UV curable acrylic plastic

Printed sample



4 cm



Post-treatment

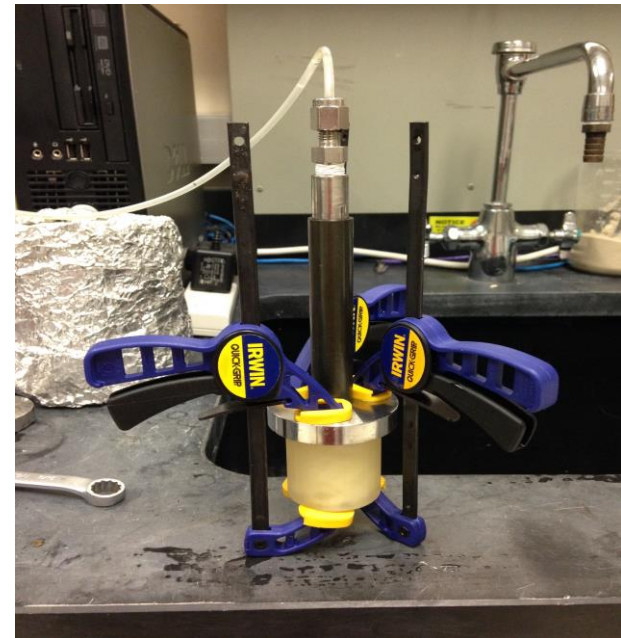
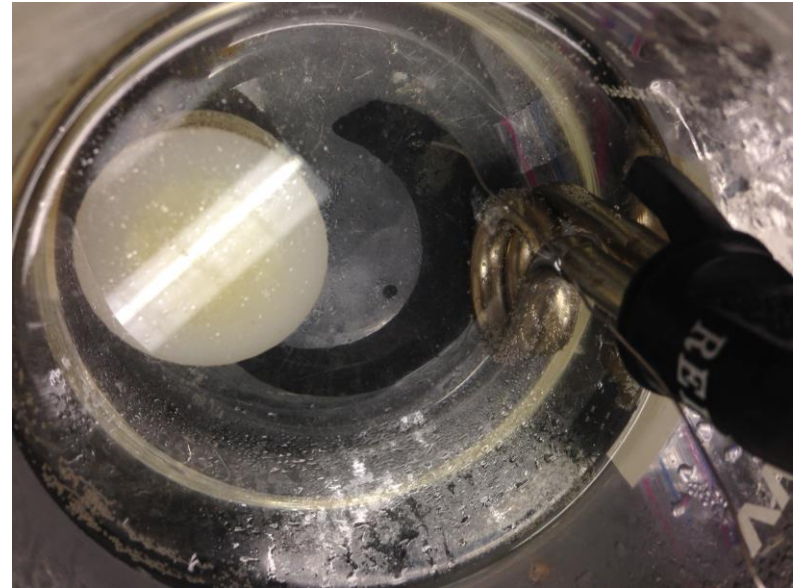
- (1) Immerse in an ultrasonic oil bath
- (2) Submerge in hot water at 60 °C

- (3) Dissolve the wax using ethanol (Suzuki et al., 2016)



hexane (This study)

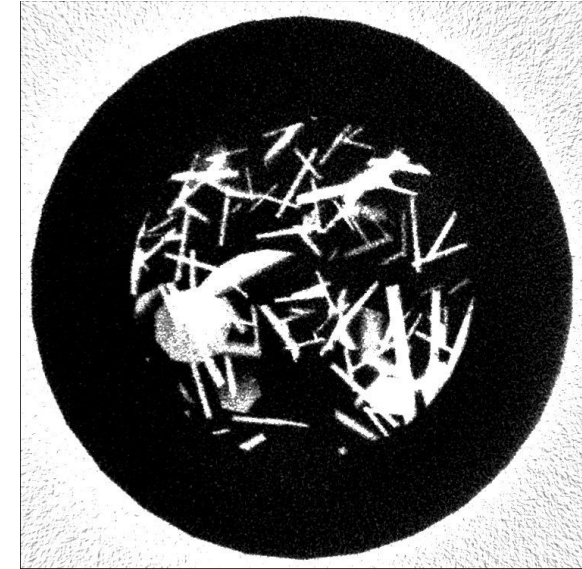
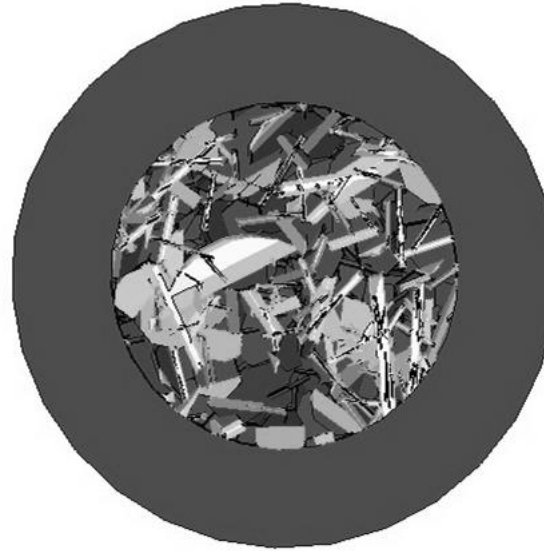
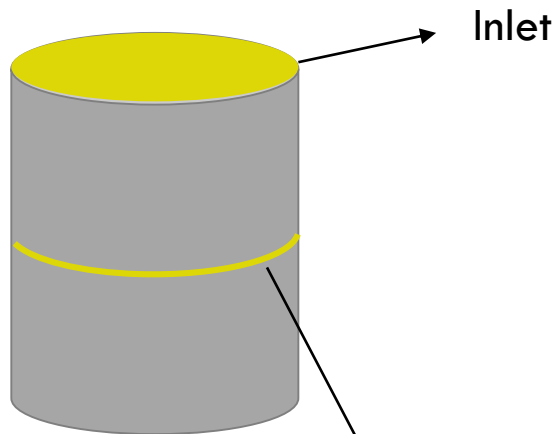
- (4) Flush using isopropyl alcohol to dissolve the hexane



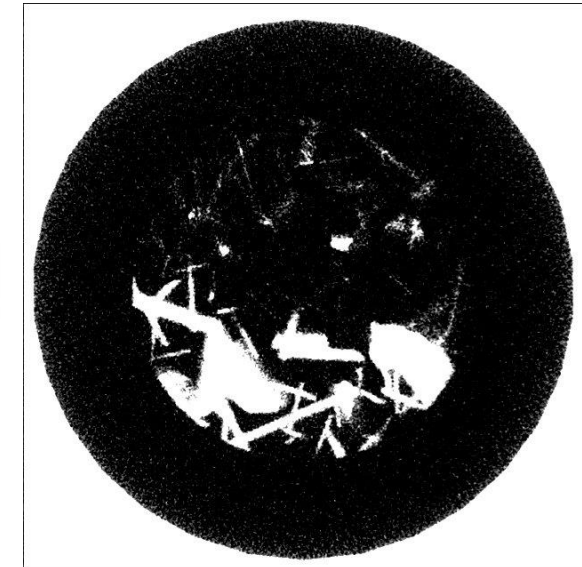
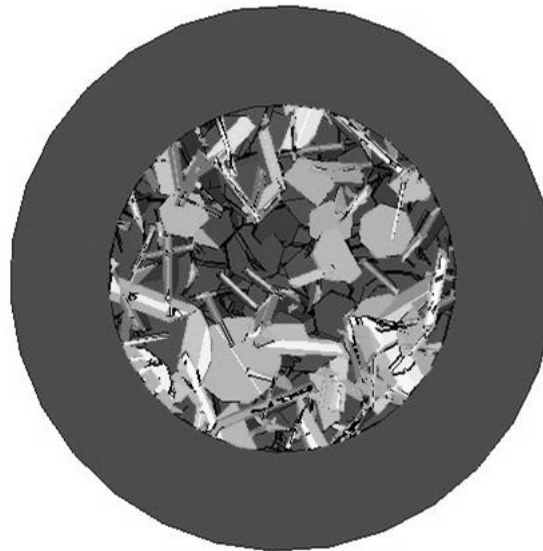
Treating with ethanol

Computational design

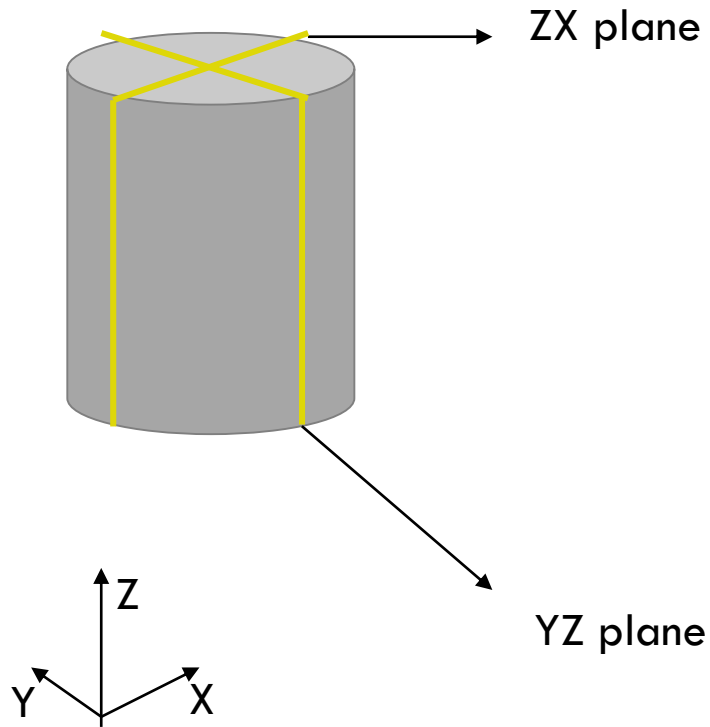
CT image



Center



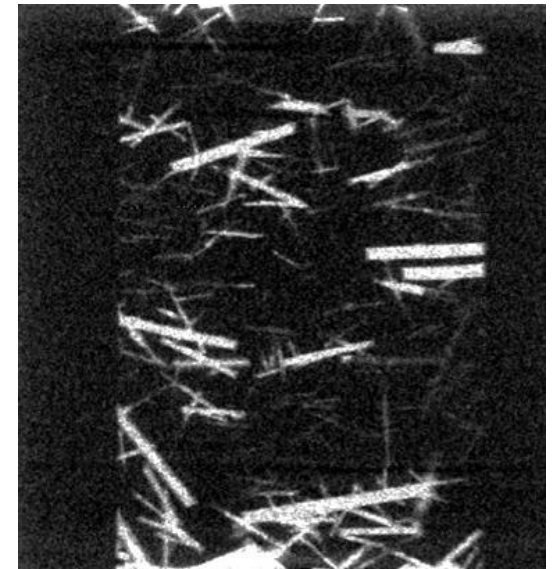
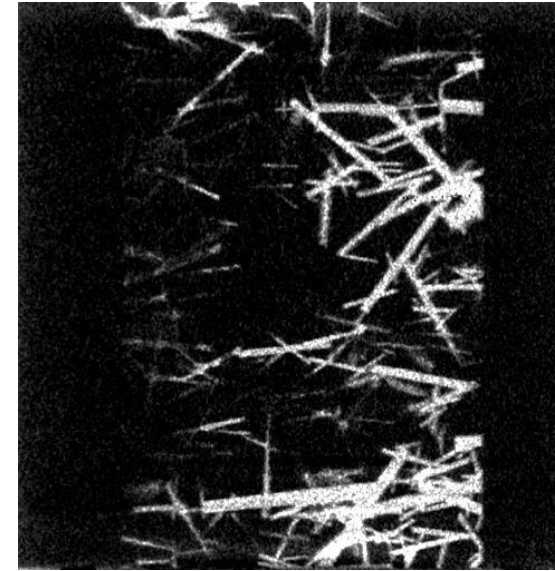
Treating with ethanol



Computational design



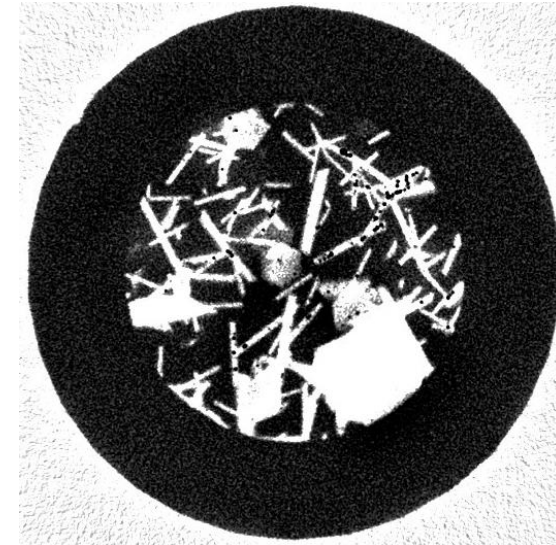
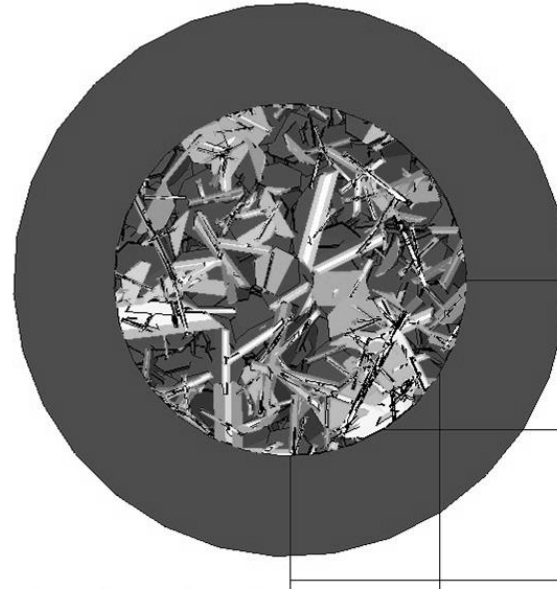
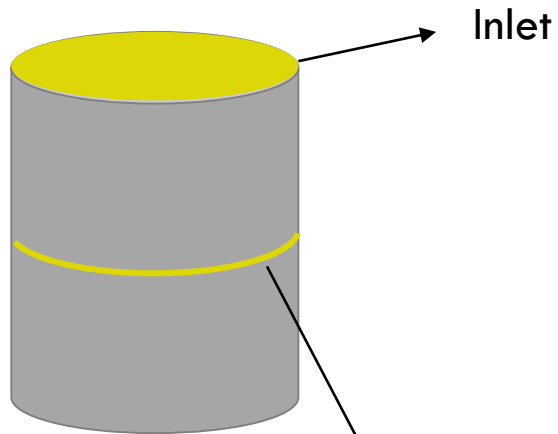
CT image



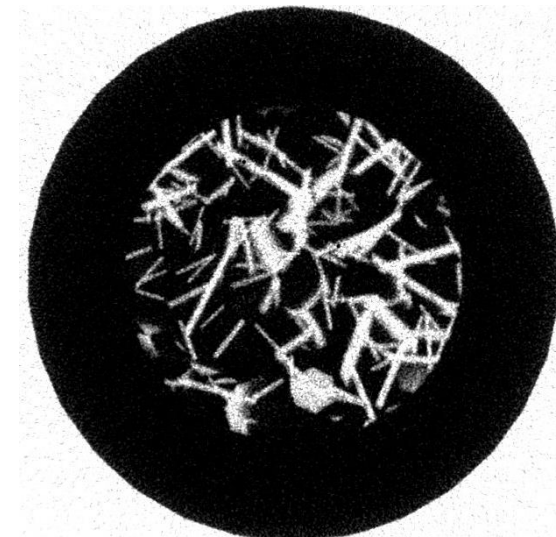
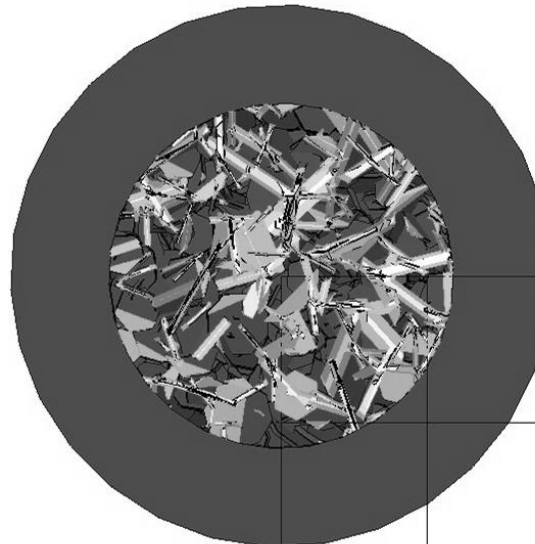
Treating with hexane

Computational design

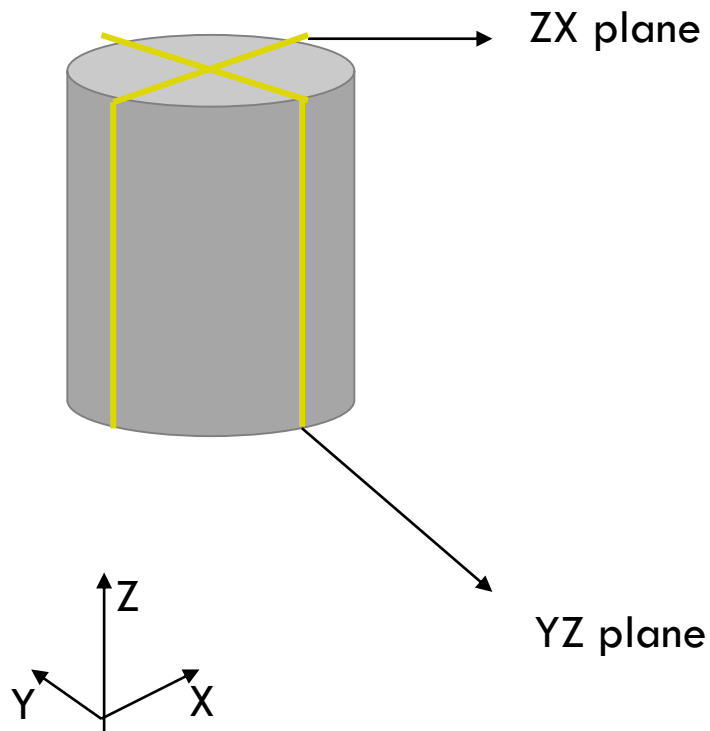
CT image



Center



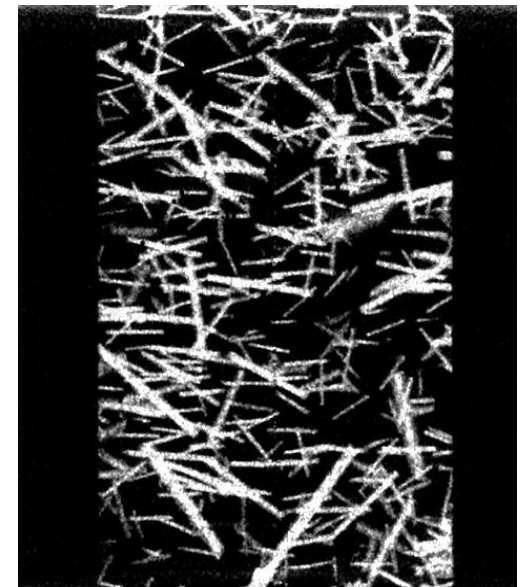
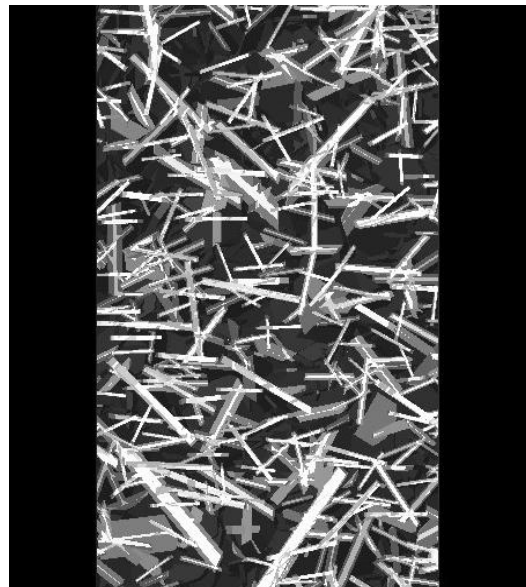
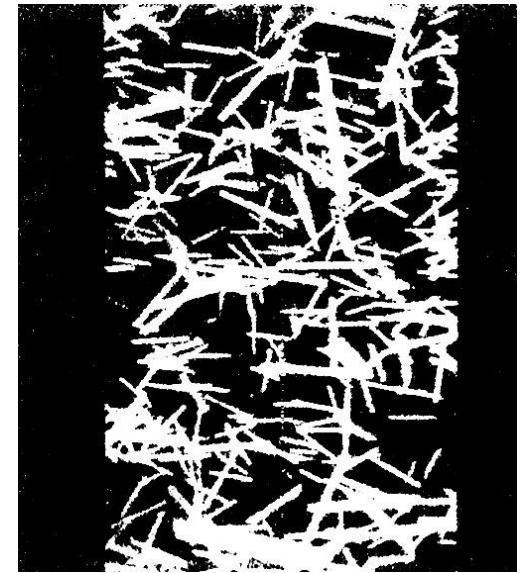
Treating with hexane



Computational design

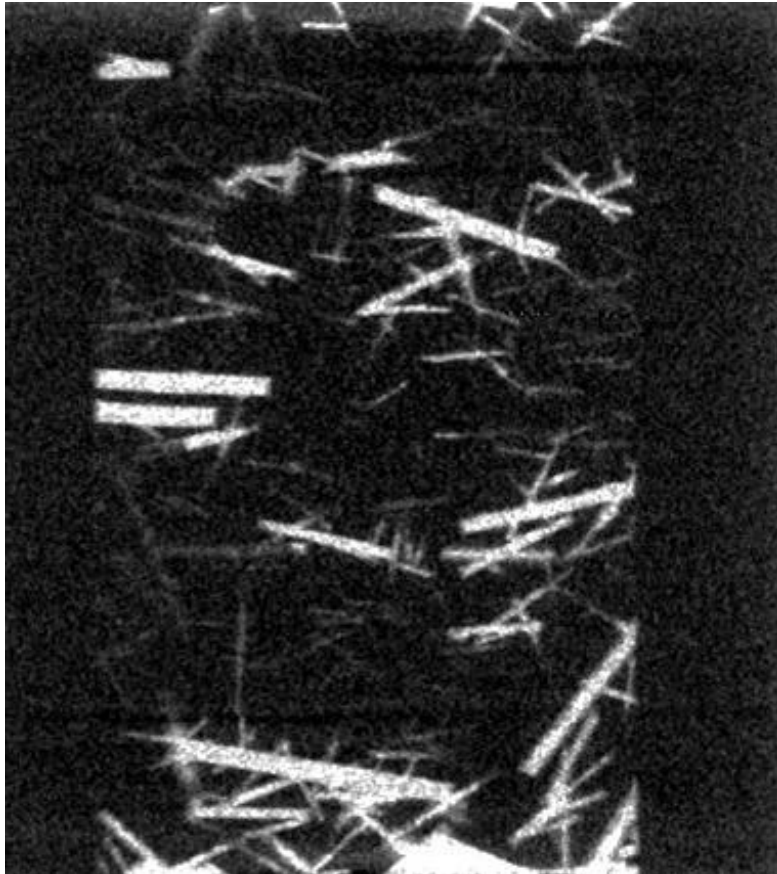


CT image

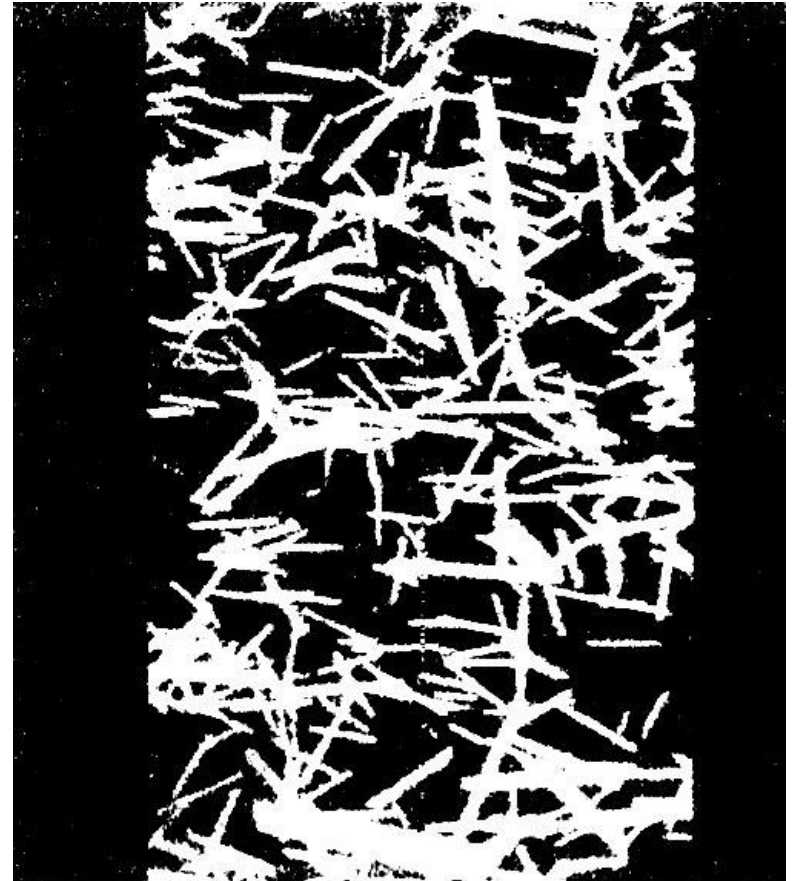


CT image

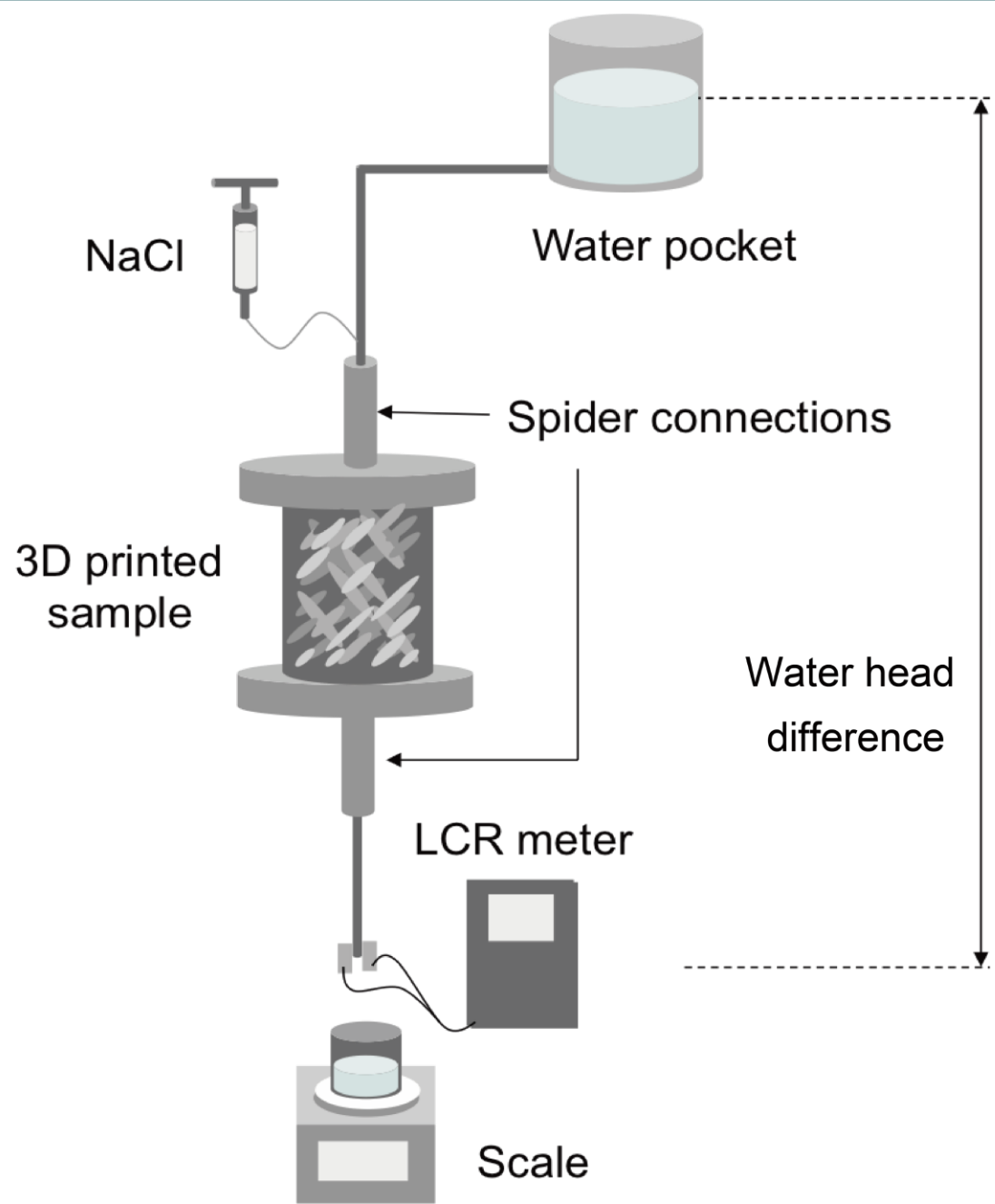
ethanol



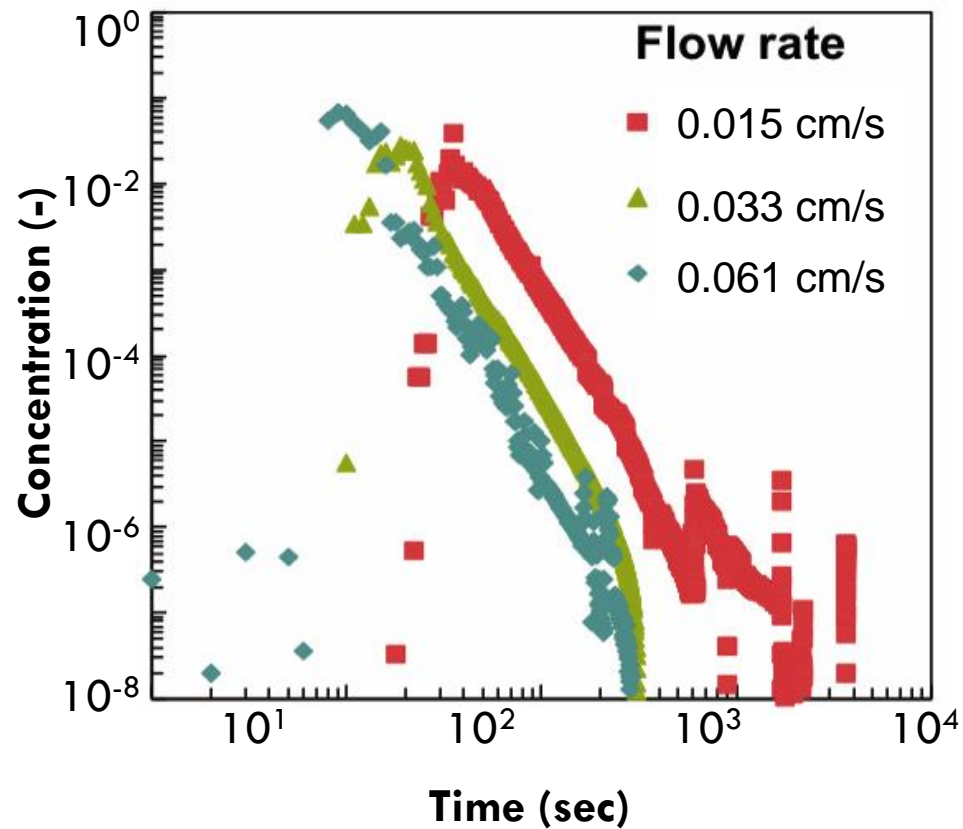
hexane



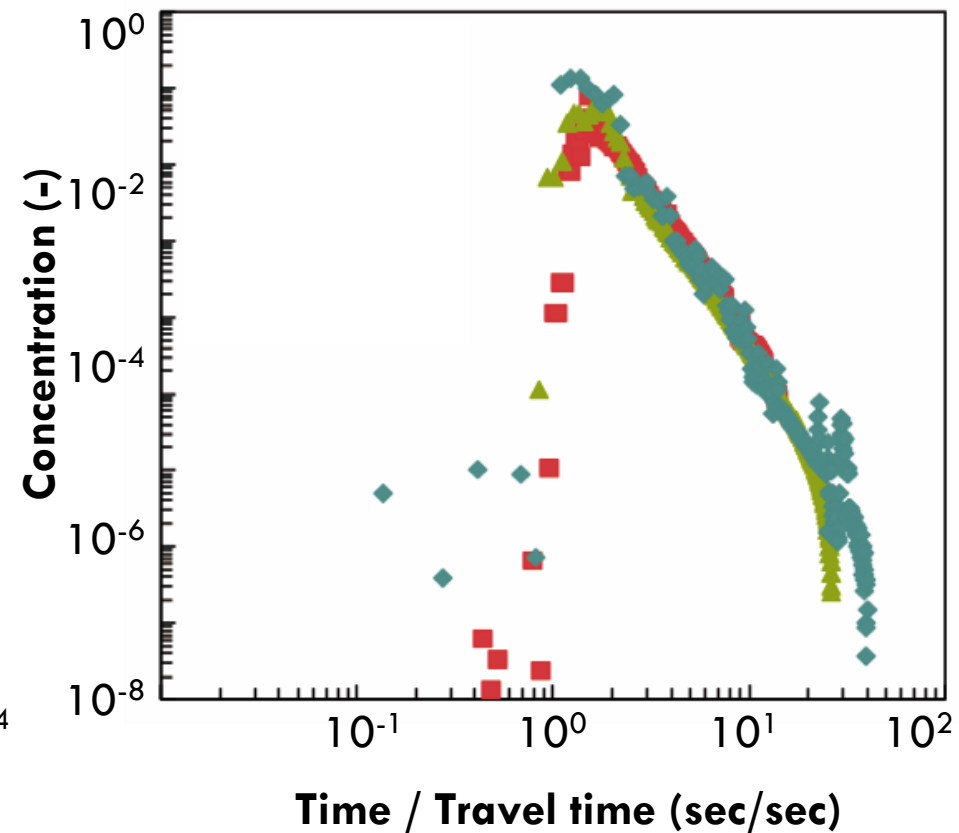
Improvement!



Tracer response

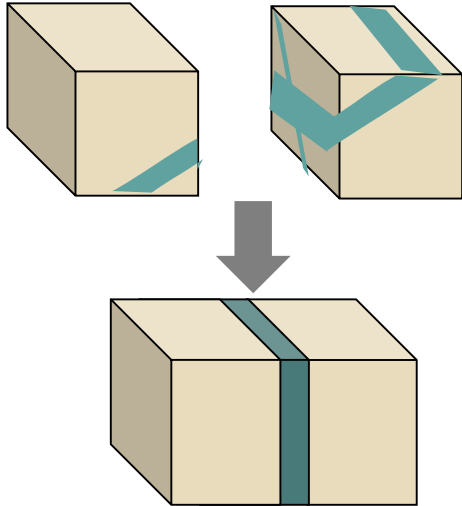


Normalized results



(Watanabe & Takahashi, 1995; Jing et al., 2000; Suzuki et al., 2015)

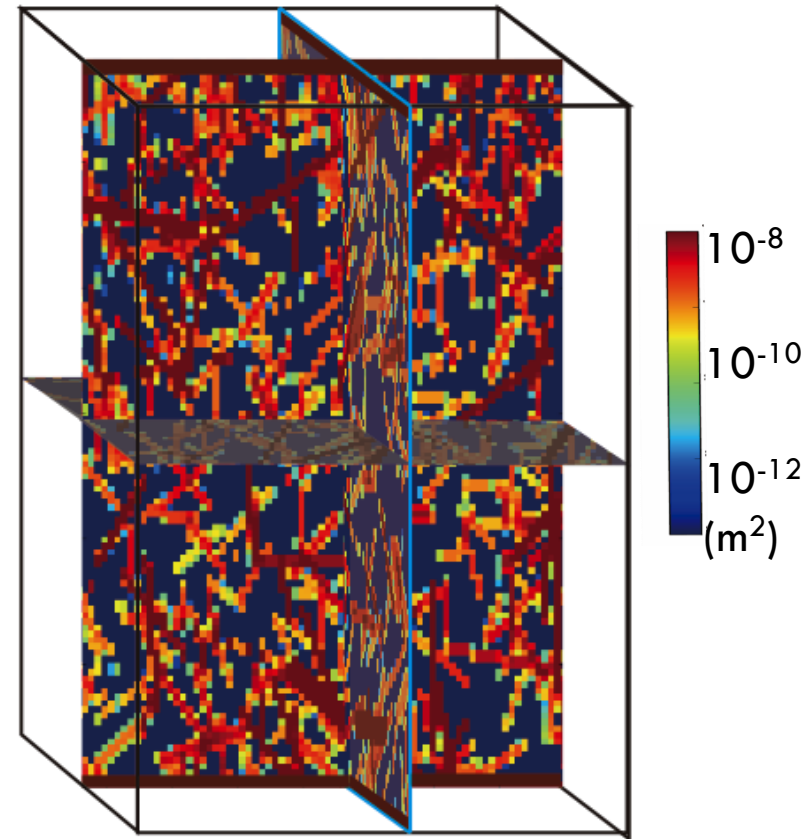
Local permeability on grid surface



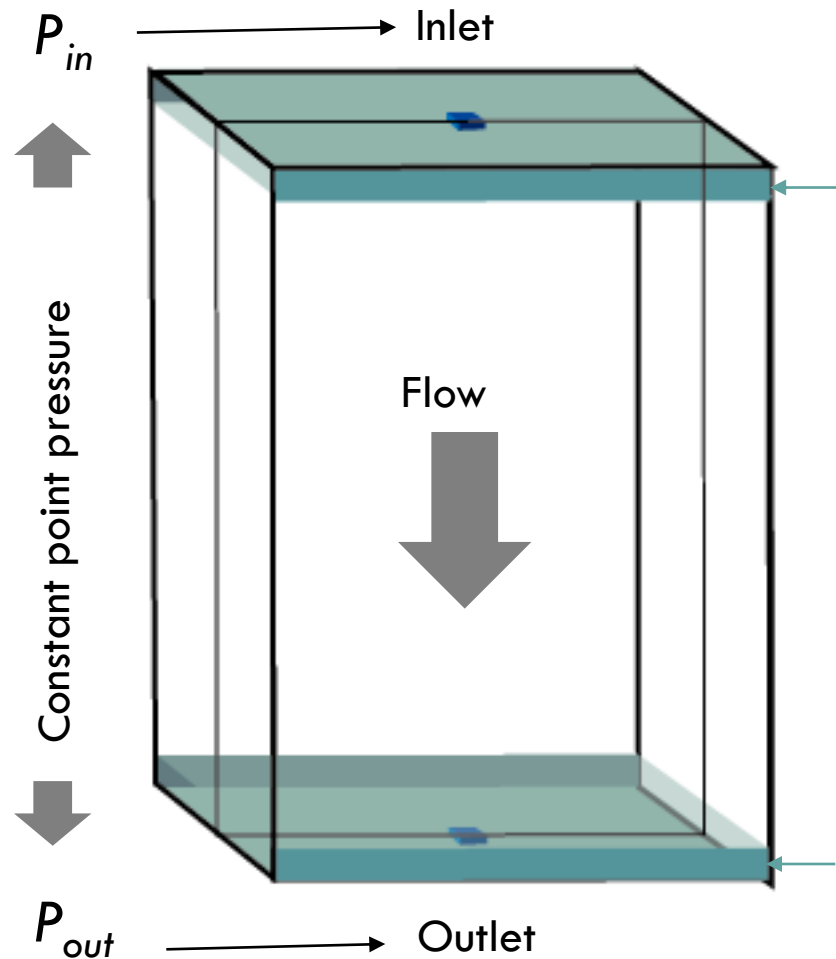
Permeability: Cubic law (Snow, 1968)

$$K_i = \frac{h^3 L}{12 A_i} \quad i = x, y, z$$

- η : aperture
- L : crossing length
- A : grid surface area



(Watanabe & Takahashi, 1995; Jing et al., 2000; Suzuki et al., 2015)



Spider connection
 $K_{spider} = 1 \times 10^{-5} \text{ m}^2$

Steady state flow

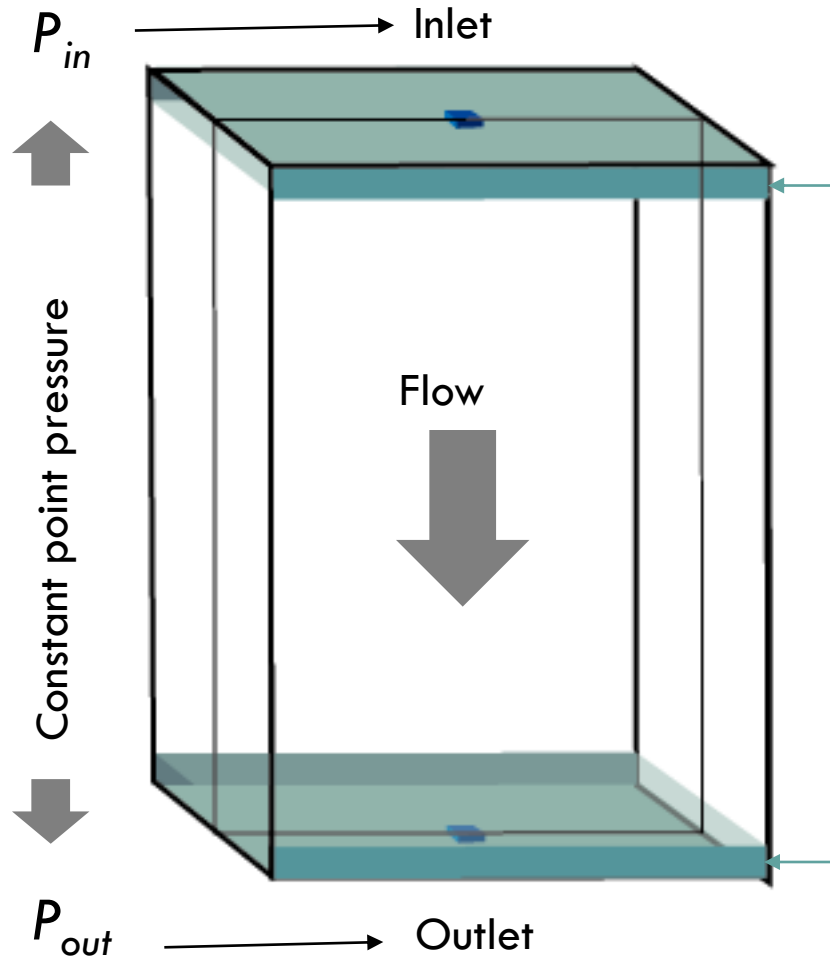
$$\dot{a}Q_i = 0 \quad i = x\pm, y\pm, z\pm$$

Flow rate: Darcy's law (Bear, 1972)

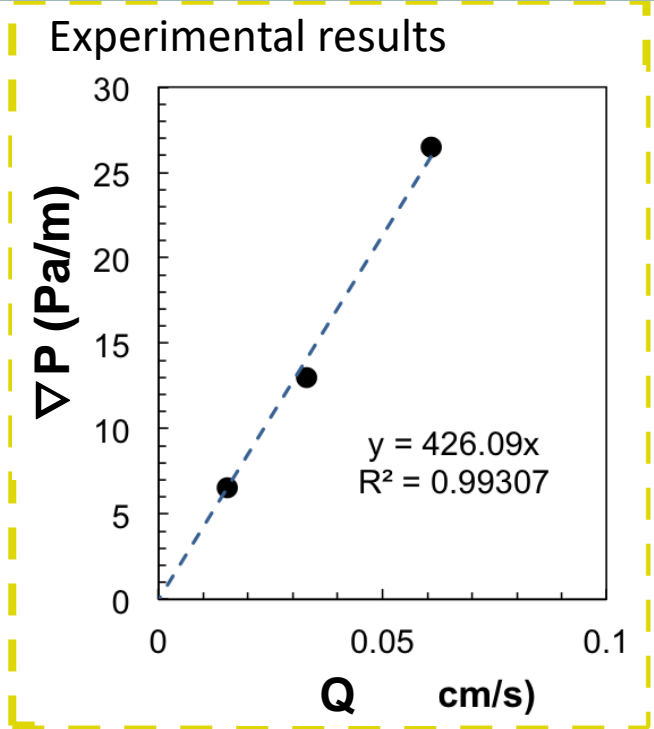
$$Q_i = \frac{K_i}{m} \nabla P_i \quad i = x\pm, y\pm, z\pm$$

- A : grid surface area
- K : local permeability
- μ : water viscosity
- ∇P : pressure difference

(Watanabe & Takahashi, 1995; Jing et al., 2000; Suzuki et al., 2015)



Spider connection
 $K_{spider} = 1 \times 10^{-5} \text{ m}^2$

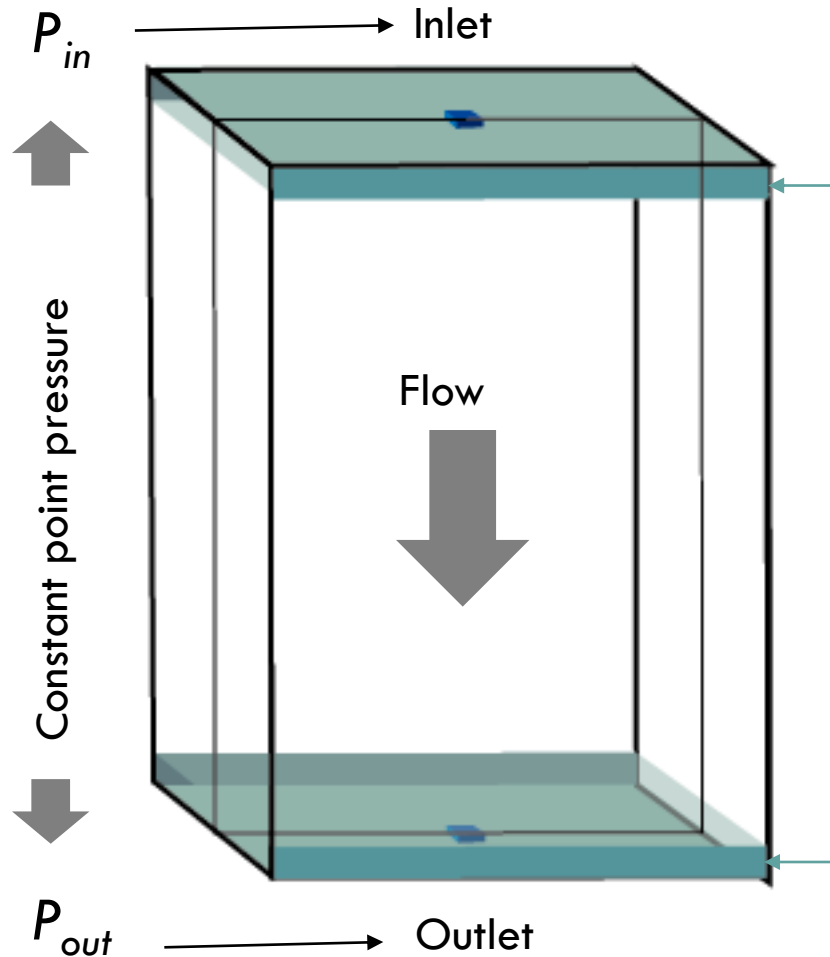


Flow rate: Darcy's law (Bear, 1972)

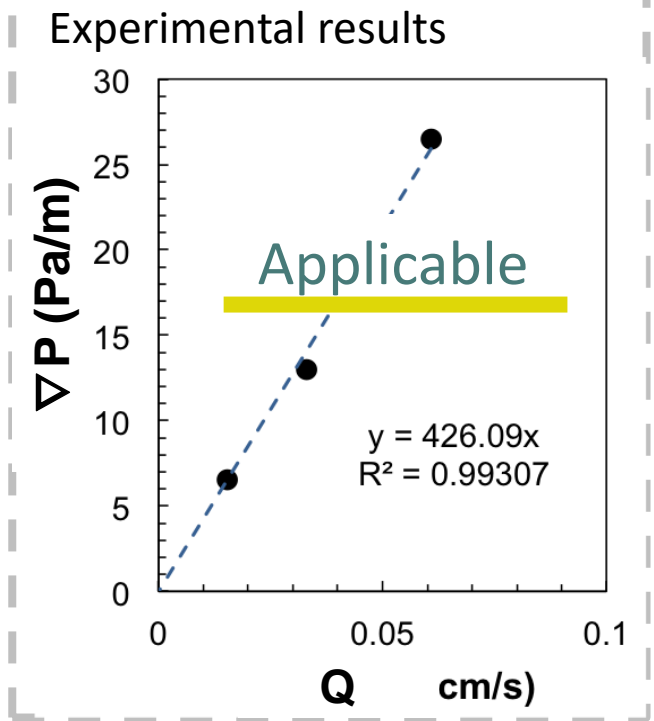
$$Q_i = \frac{K_i}{m} \nabla P_i \quad i = x \pm, y \pm, z \pm$$

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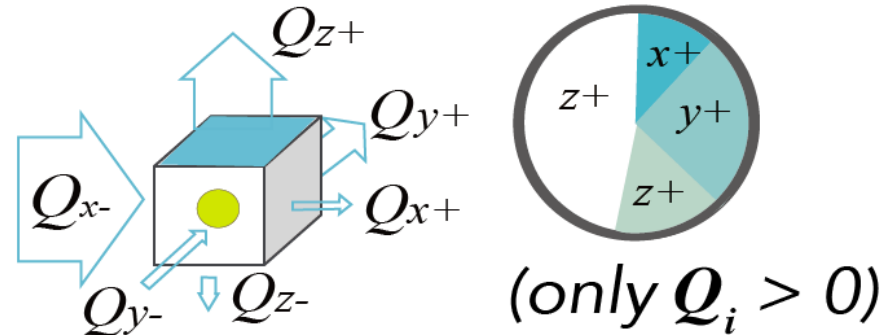
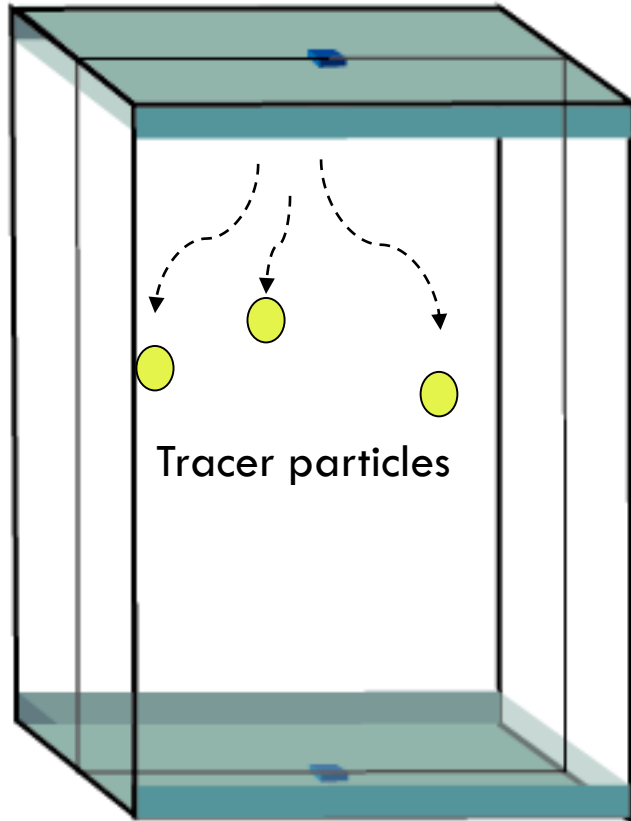
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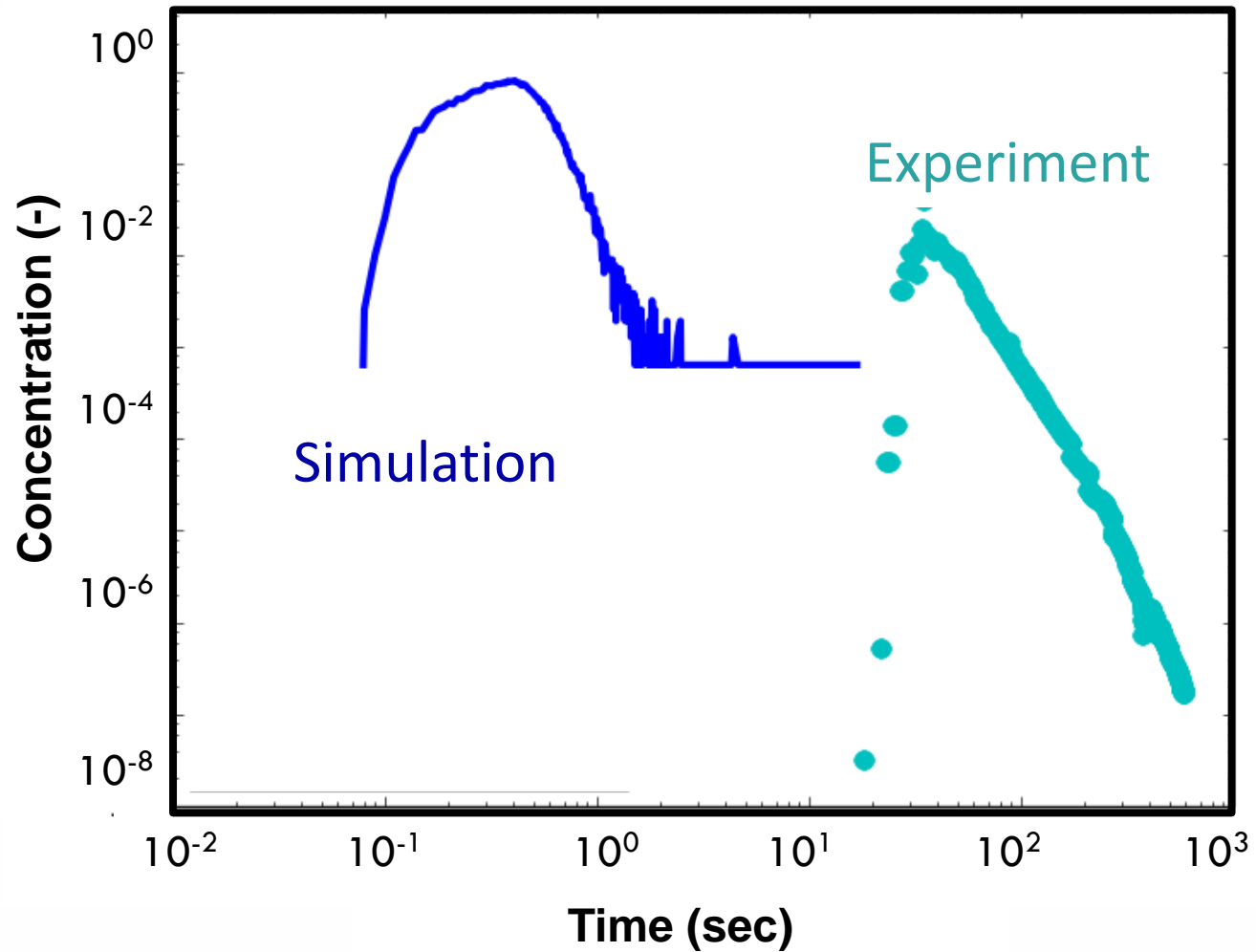
Probability of direction



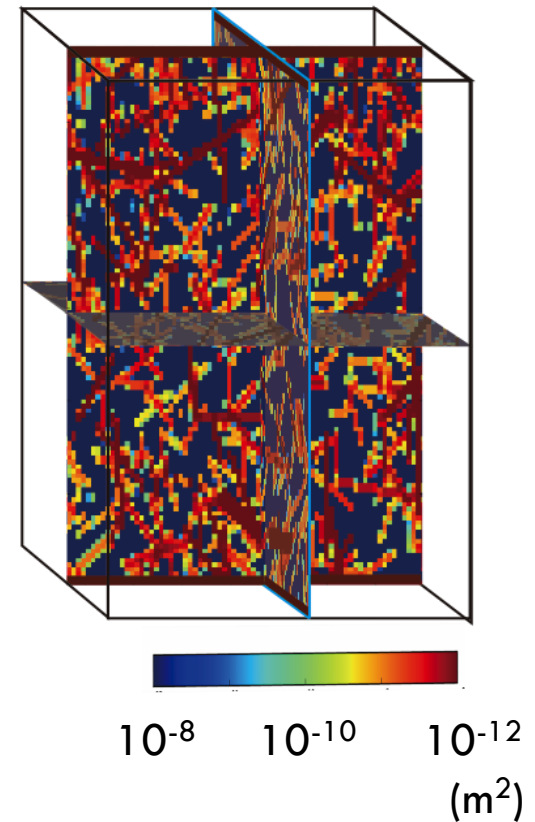
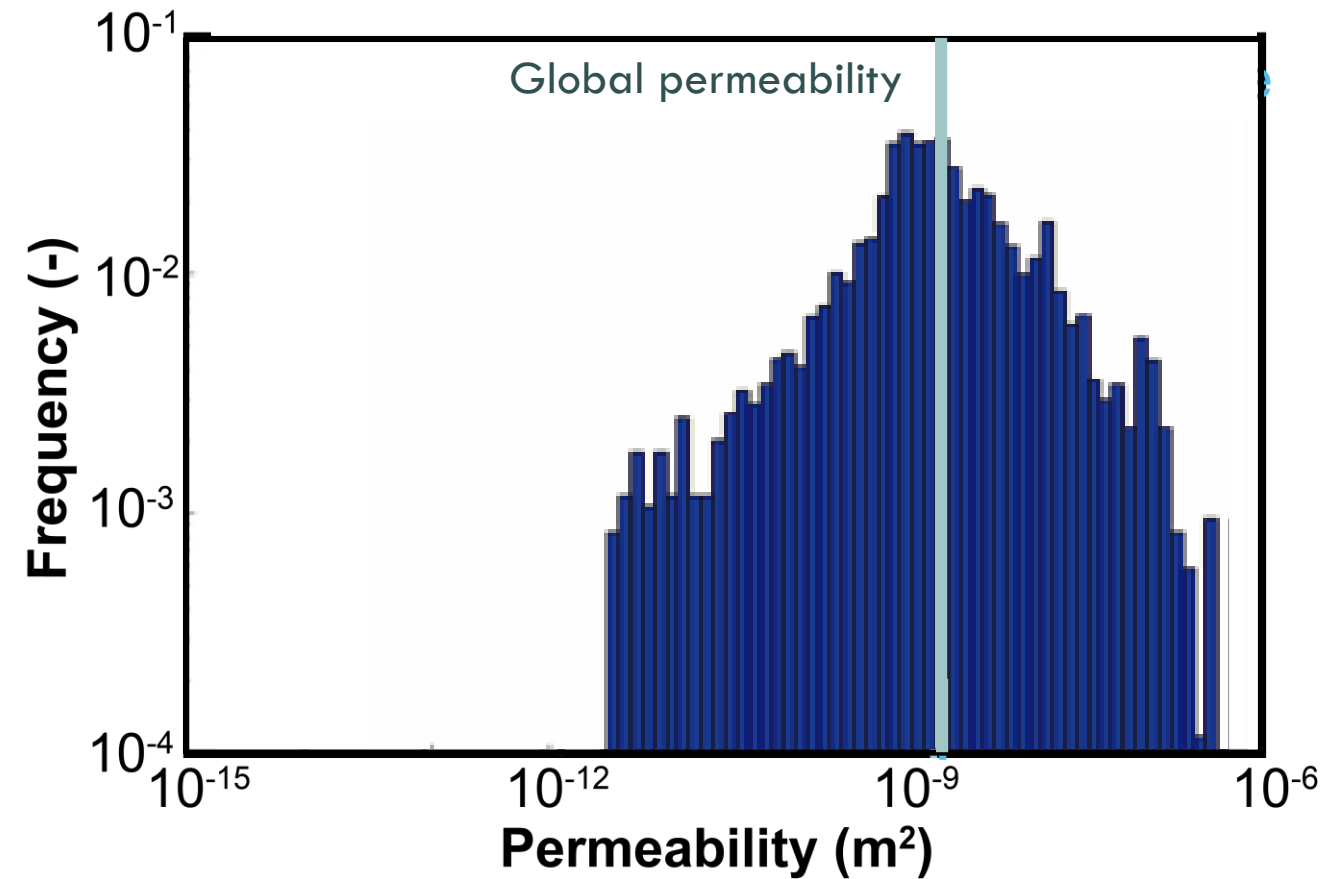
Simulation condition

Parameter	Value
Domain [m ³]	0.042 × 0.025 × 0.025
Number of grid cells [grids]	126 × 75 × 75
Pressure difference between the inlet (P_{in}) and the outlet (P_{out}) [Pa]	2800
Viscosity of water [Pa · s] at 23°C	9.321 × 10 ⁻⁴
Density of water [g/cm ³] at 23°C	0.9975
Number of tracer particles [Particles]	50000

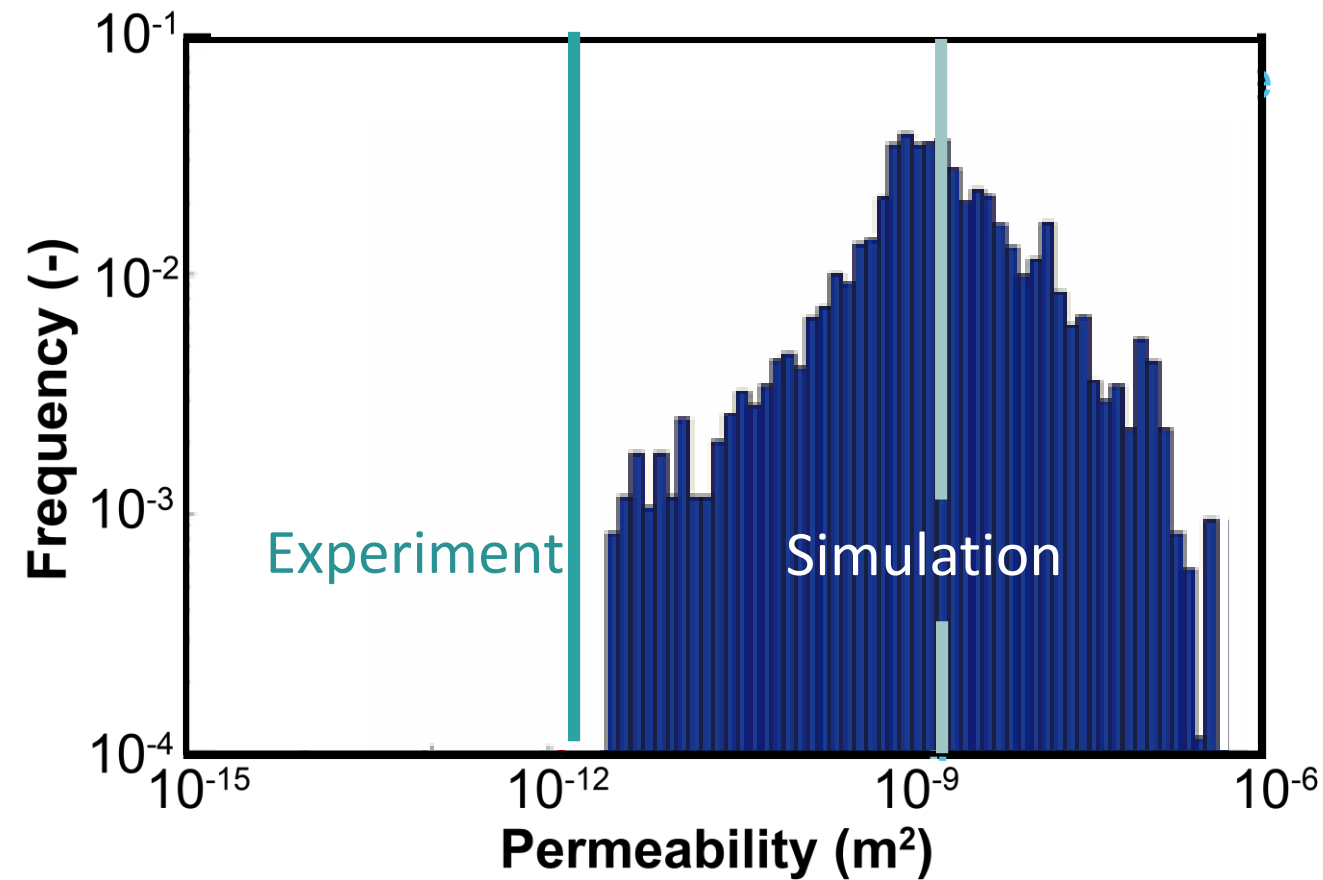
Tracer response



Frequency of local permeability



Frequency of local permeability



Difference may caused by

(i) Experiment

- removing wax
- accuracy of printing
- non-smooth surface

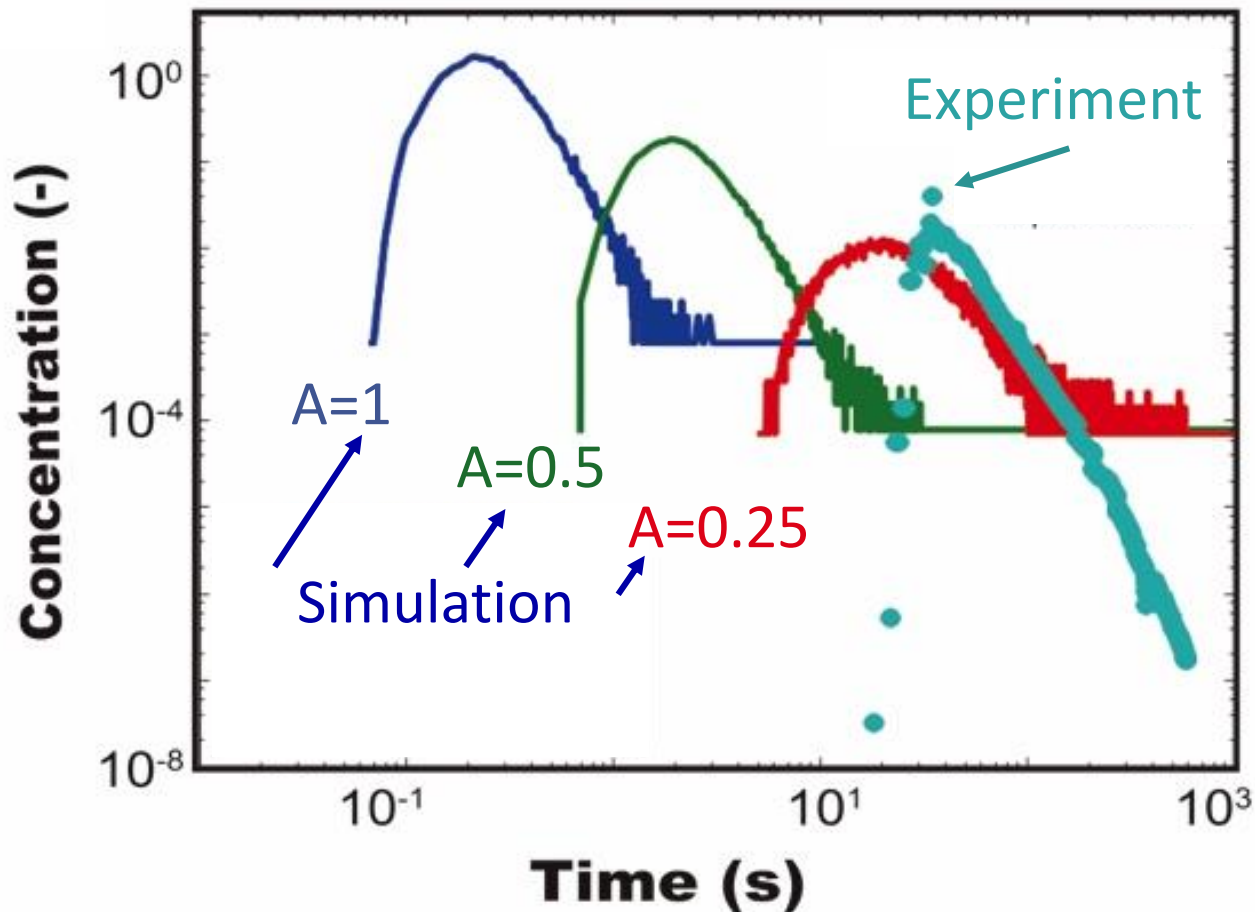
(ii) Simulation

- continuum model

Effective aperture

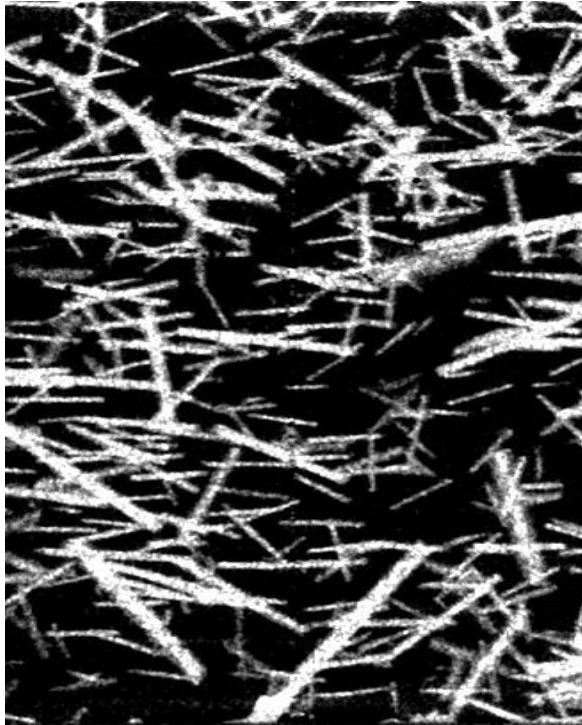
$$h' = Ah$$

A : reduced aperture factor
 η : designed aperture



Porosity by binary images

Experiment



Computational design



Simulation



Porosity 0.409

0.400

0.476

incomplete

< designed
fractures

overestimate

CT images suggest fracture network was created successfully.

Hexane is effective to remove wax.

Numerical simulation produced faster tracer responses than experiment.

Continuum model overestimated fracture permeability.

Acknowledgement: Prof. Noriaki Watanabe (Ct scanning)

JSPS Postdoctoral Fellowships for JSPS Research Fellow