Interpore 2022
May 30th 2022

Liquid permeability through foam-filled porous media

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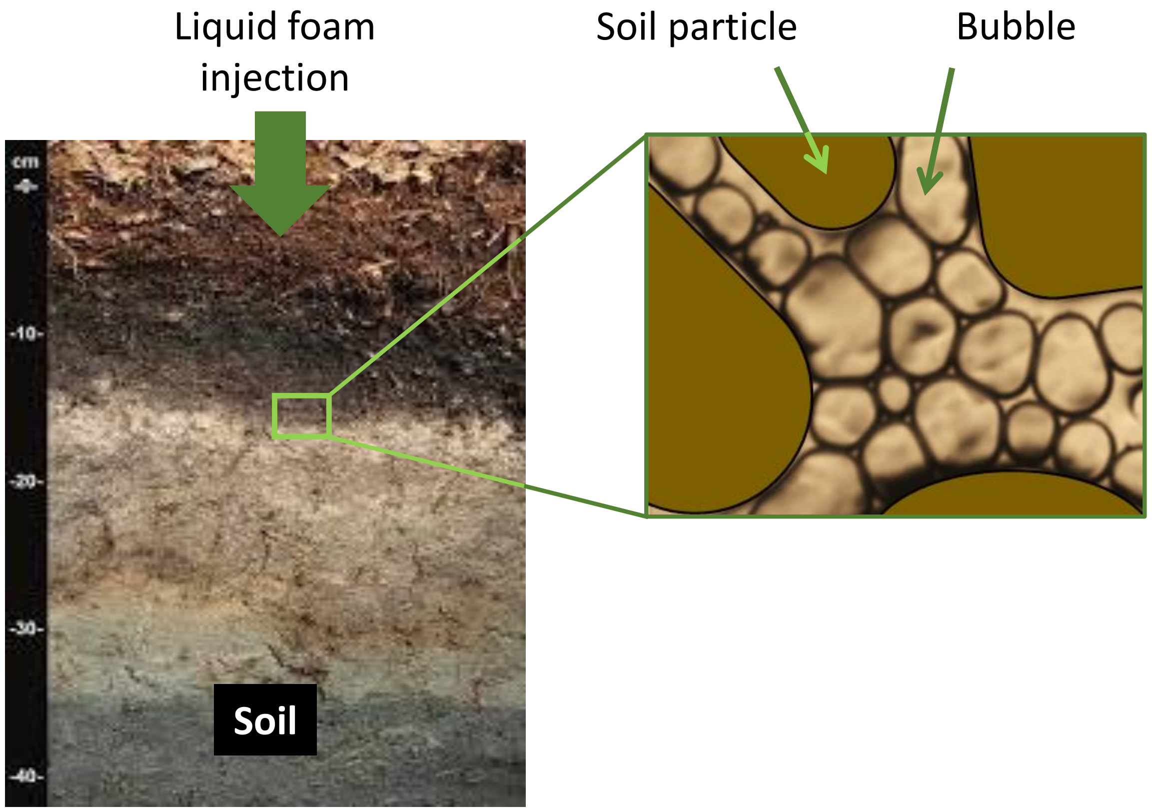
Founding :
Labex MMCD

Modélisation et Expérimentation Multi-Echelles des Matériaux pour la Construction Durable

Liquid foam in porous media

Context: oil extraction and soil depollution



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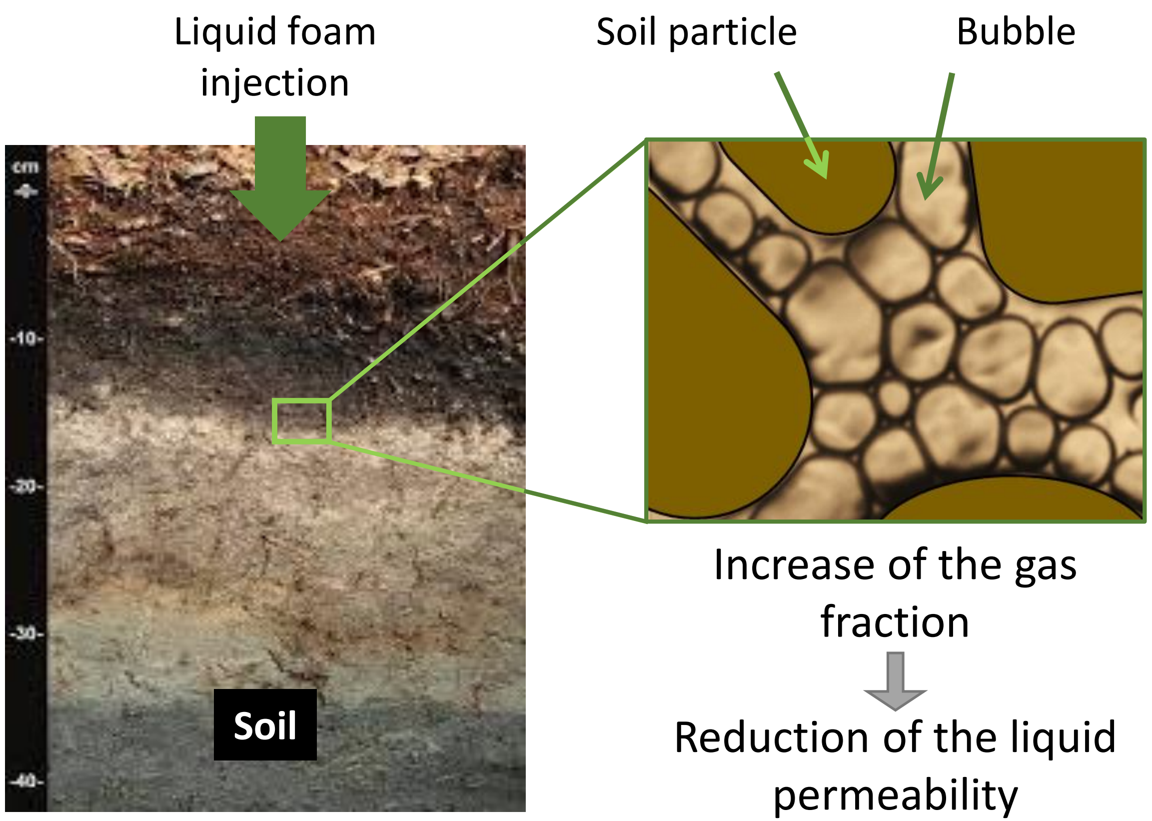


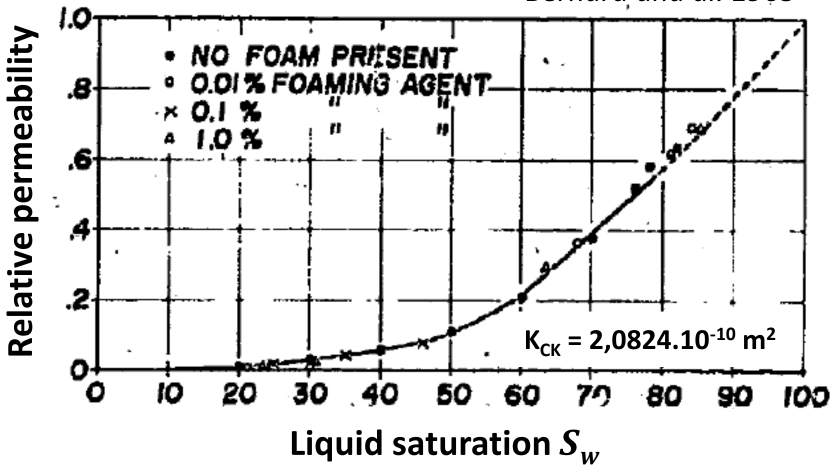
Increase of the gas fraction

↓

Reduction of the liquid permeability

It is usual to describe the flows of both gas and liquid phases in terms of relative permeability ($k_{rel} = k_{Sw}/k_{Sw=1}$) in function of liquid saturation S_w.

Bernard and al. 1965



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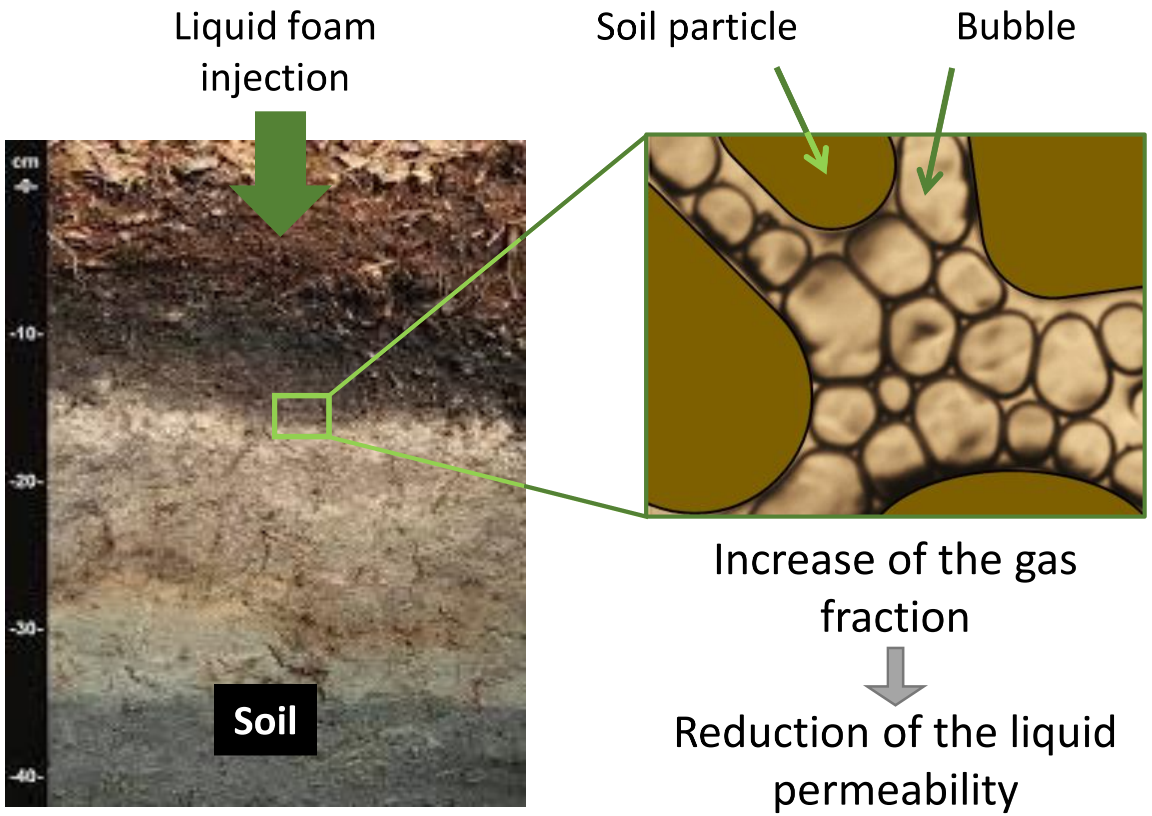

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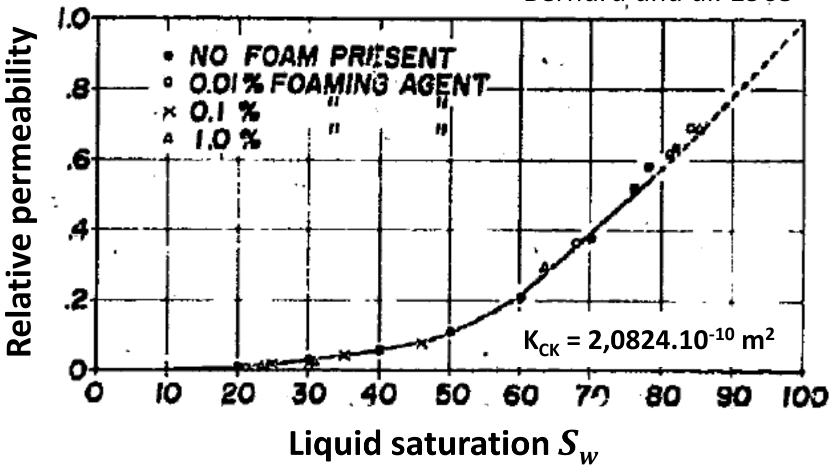


The liquid permeability is the same in the presence or in the absence of foam lamellae.

Eftekhari and al. 2017

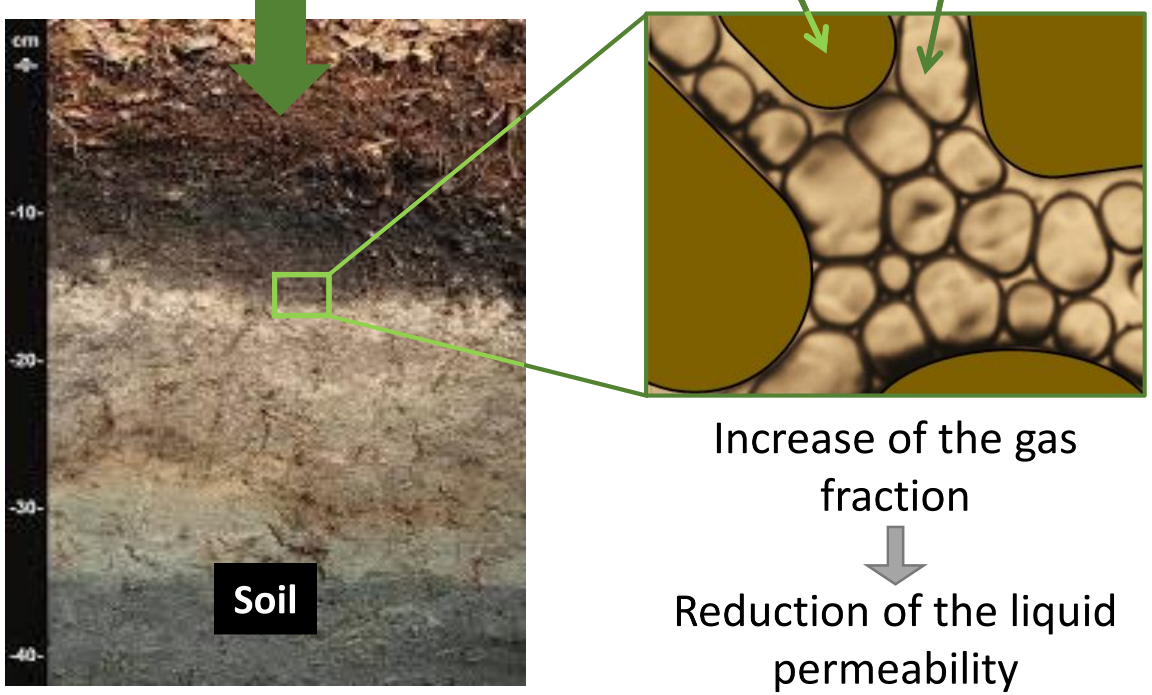
Liquid foam in porous media

Context: oil extraction and soil depollution

Liquid foam injection

Soil particle

Bubble



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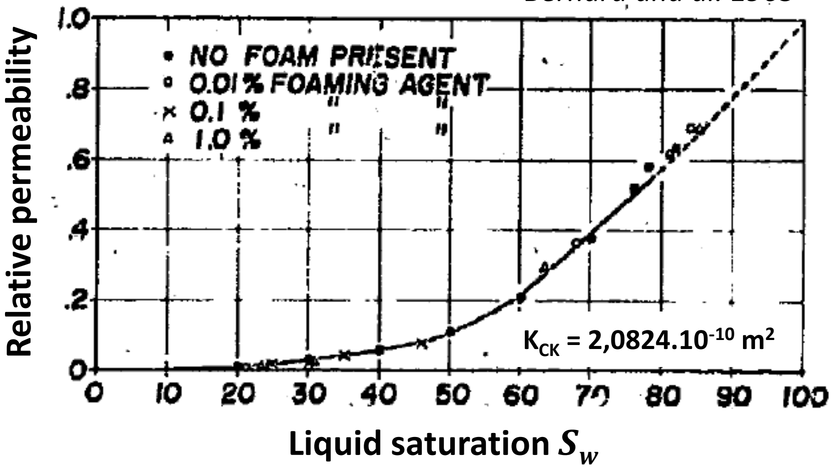


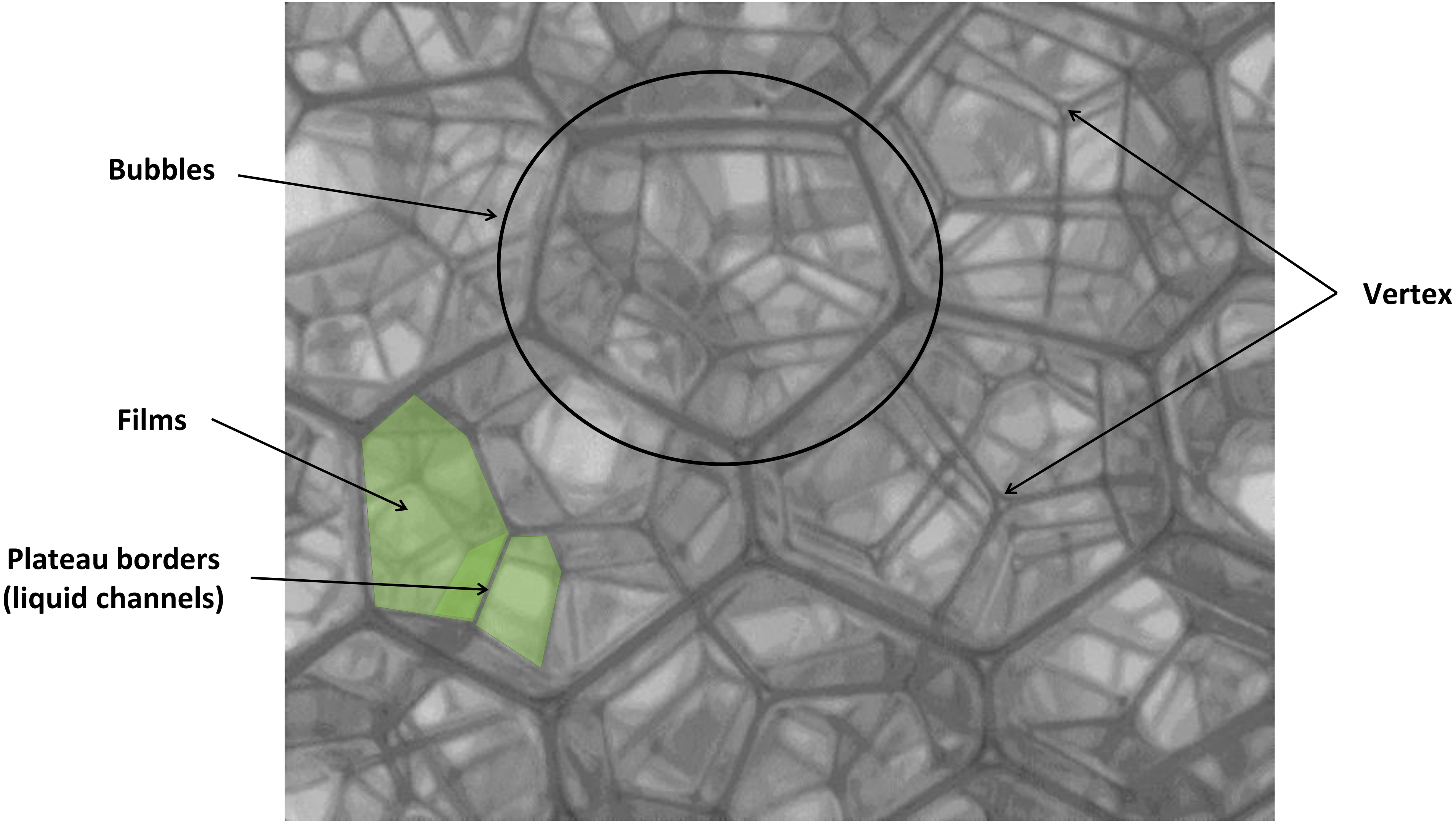
The liquid permeability is the same in the presence or in the absence of foam lamellae.

Eftekhari and al. 2017

Objective: to develop a model experiment to explore S_w **< 20%**, the effects of **surfactant** and **bubble size**.

Liquid foam and permeability of bulk foam

Structure of bulk foam



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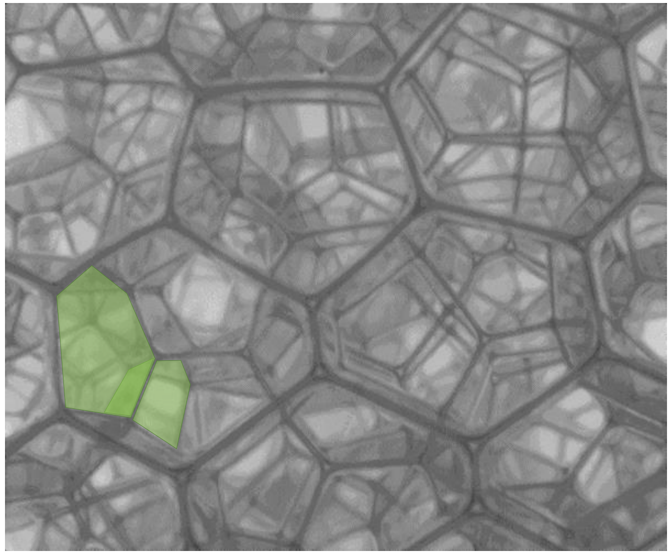
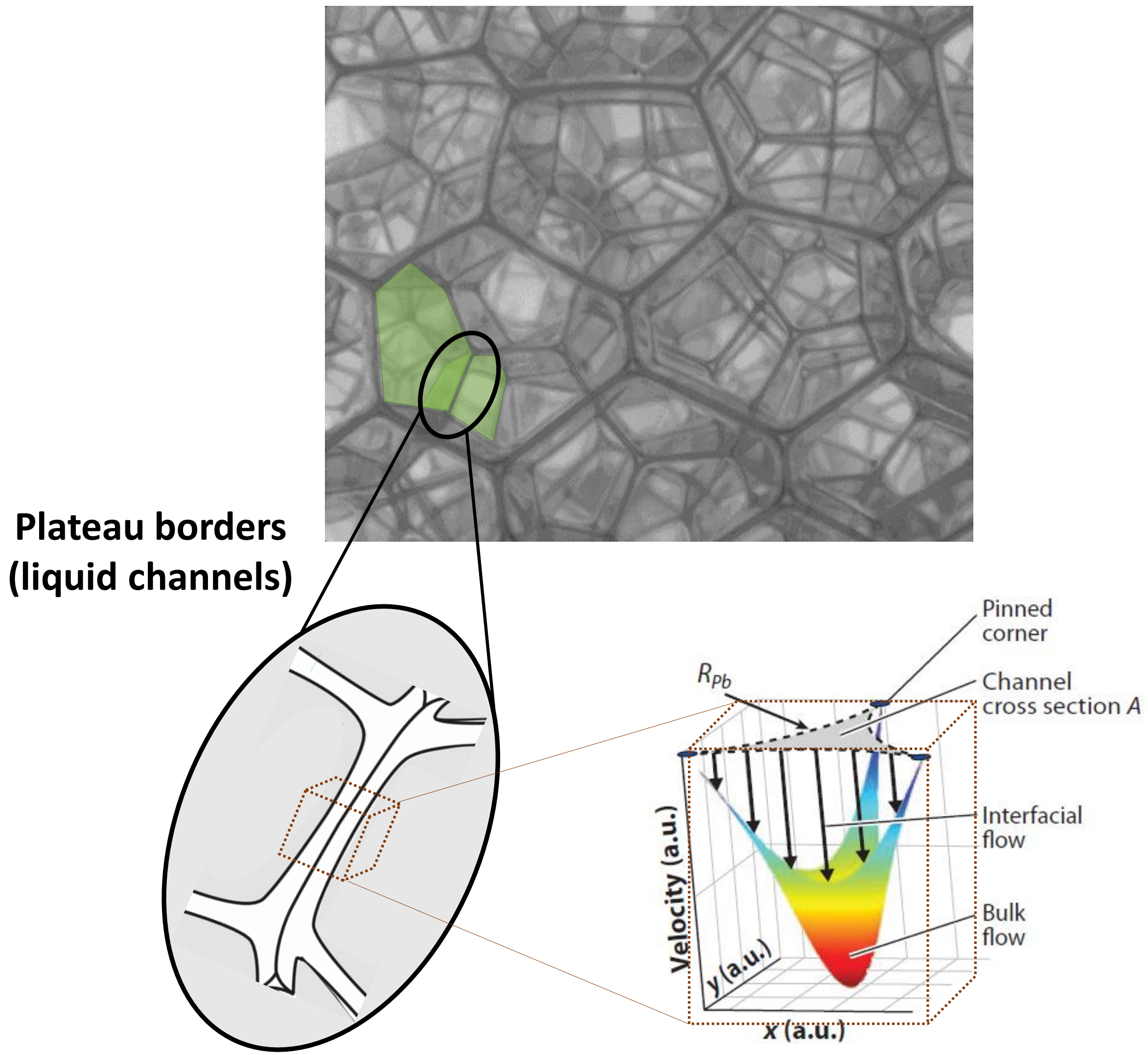


Plateau borders (liquid channels)

Liquid foam and permeability of bulk foam

Structure of bulk foam



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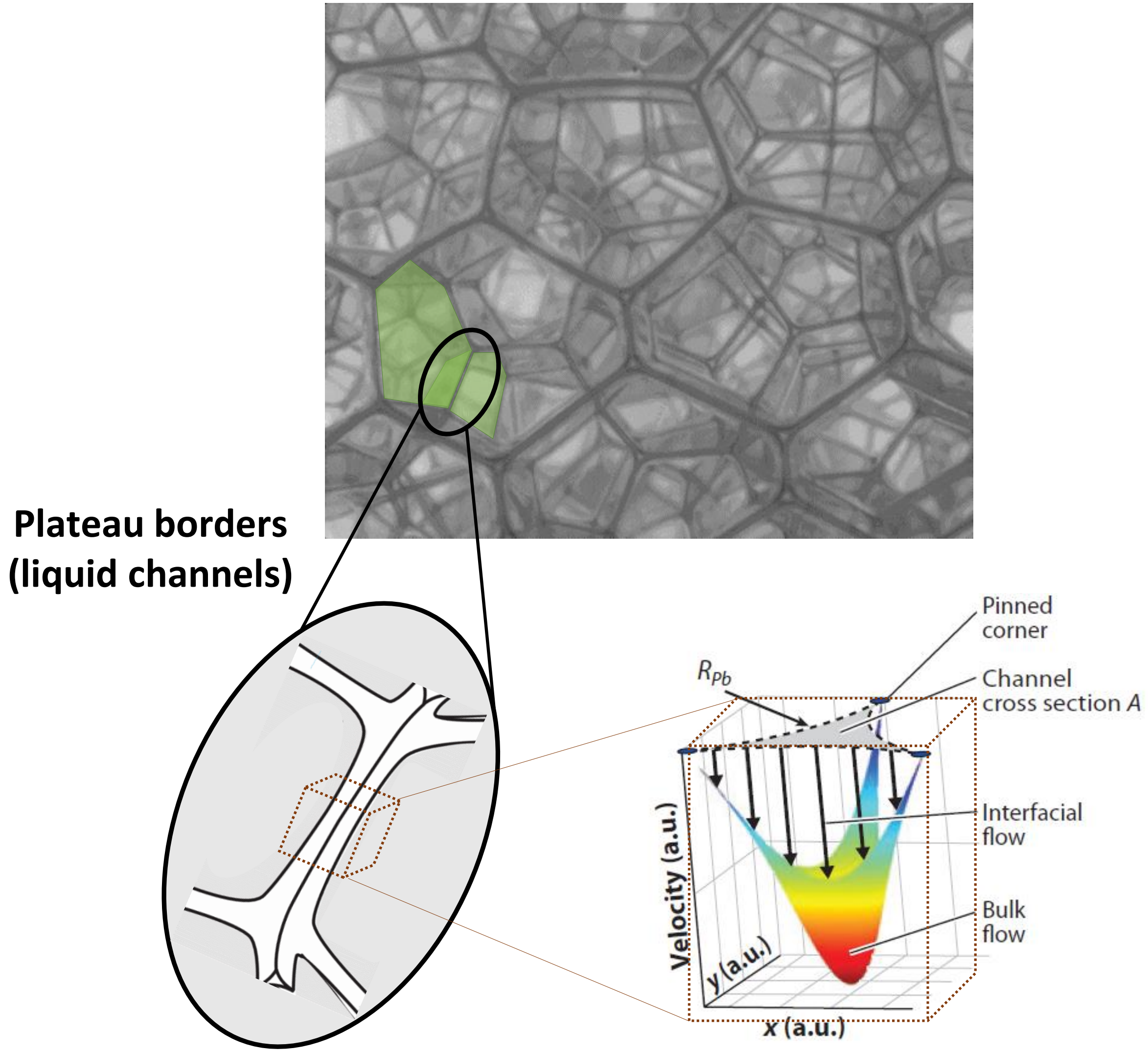
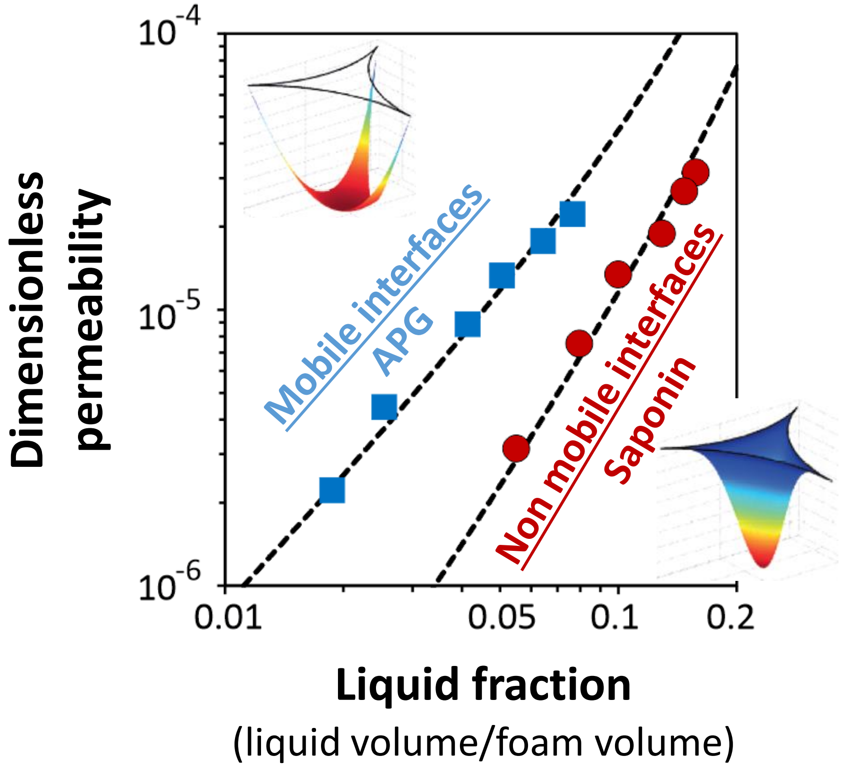
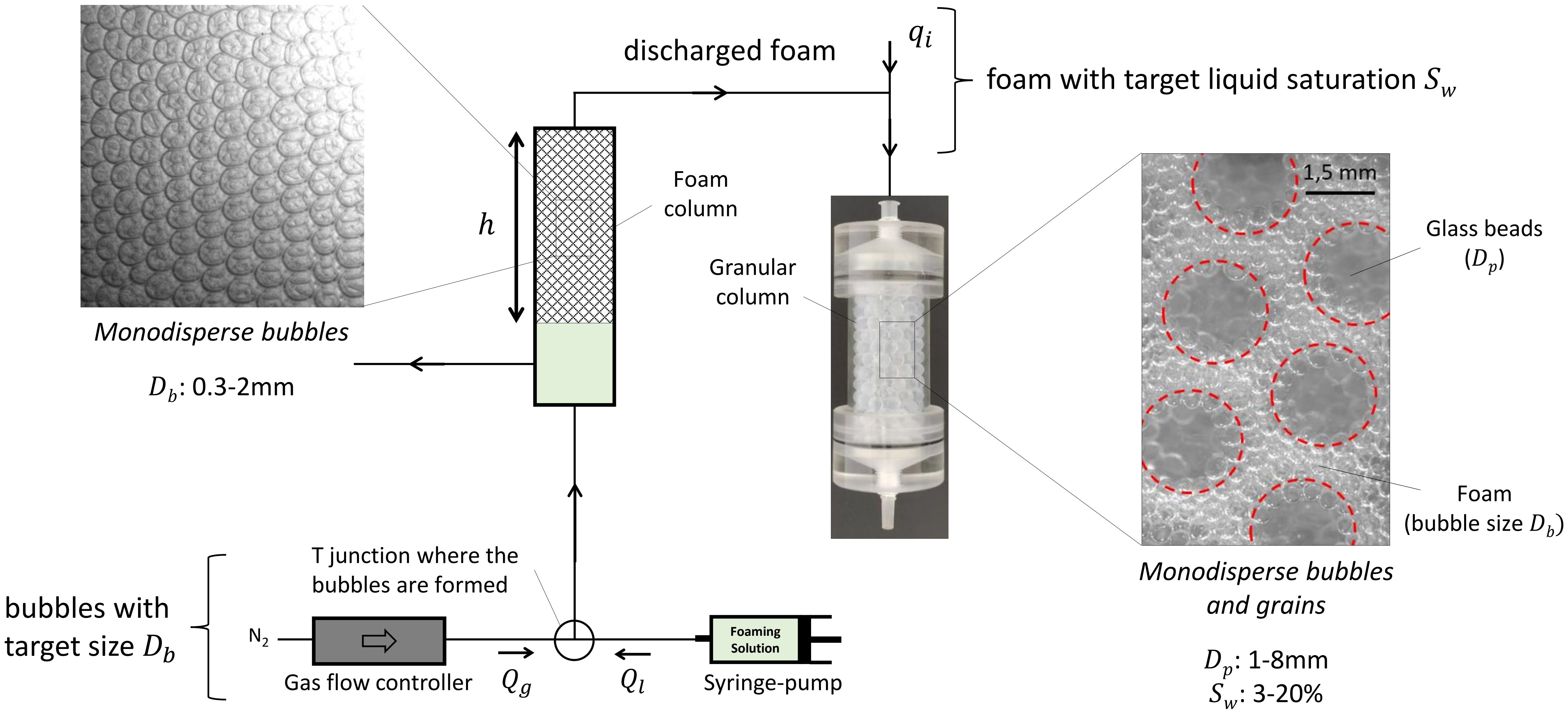


Two different surfactants:

Alkyl Polyglucosides (APG): derived from glucose
Saponin: present in different seeds or plants



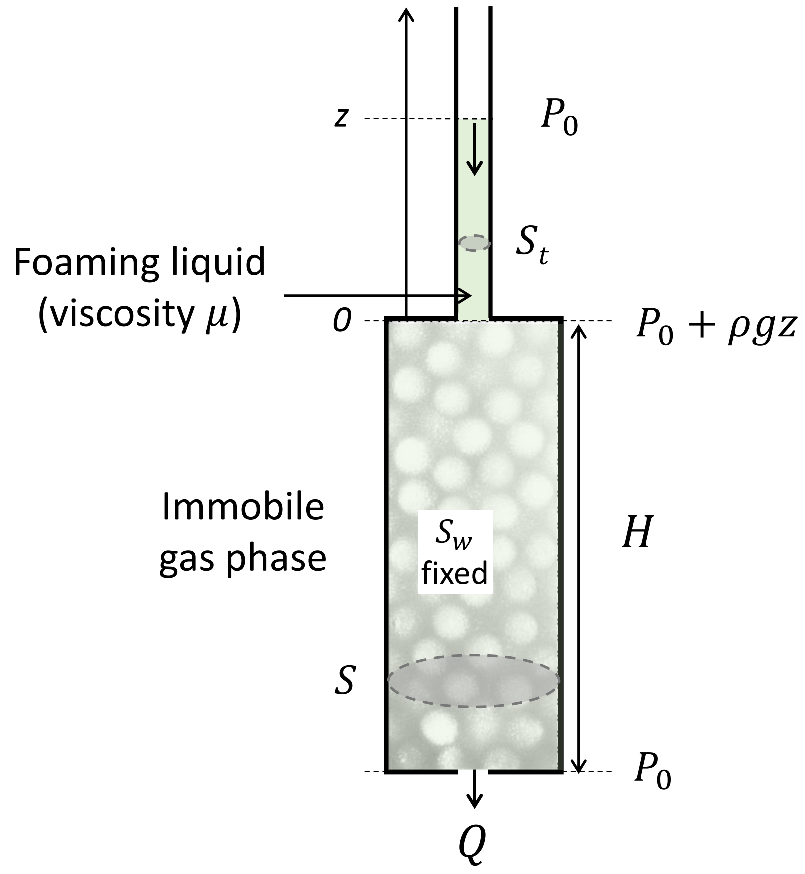
Foam production and filling of a granular packing

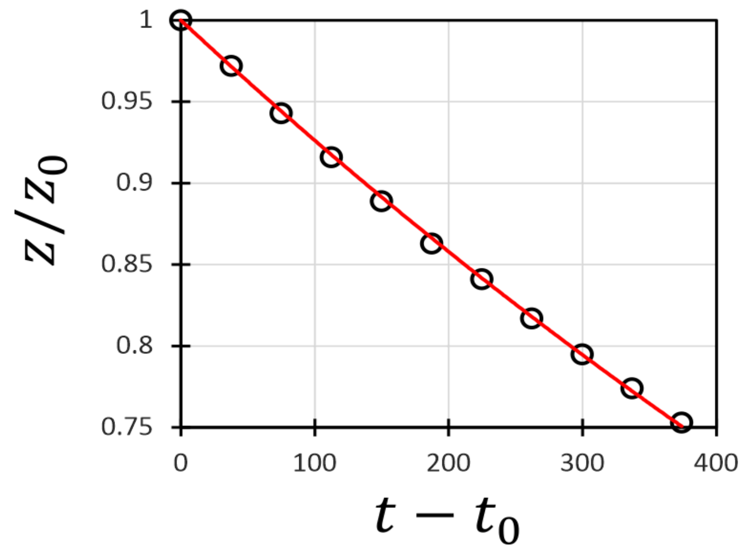


Hydraulic properties of foam-filled granular packing

Measurement of liquid permeability:

Darcy permeability k_D measured with the falling-head test





Continuous line:

$$\frac{z}{z_0} = exp(-\frac{S}{S_t}\frac{\mathbf{k_D}}{\mu}\frac{\rho g}{H}t)$$

fitted to the experimental points by tuning $\mathbf{k_D}$.

Hydraulic properties of foam-filled granular packing

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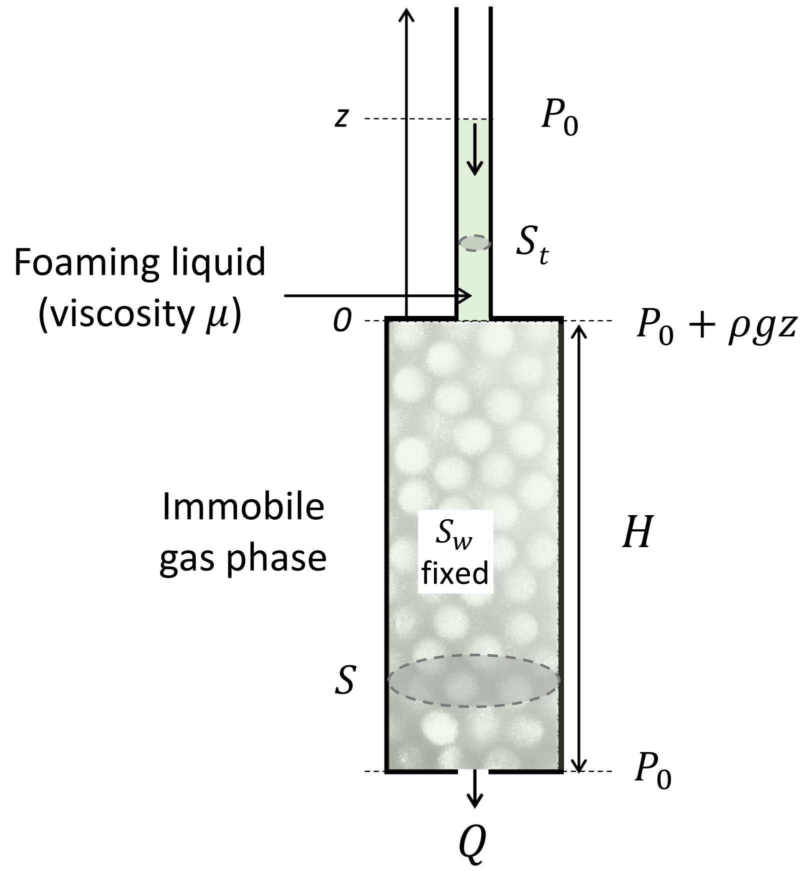

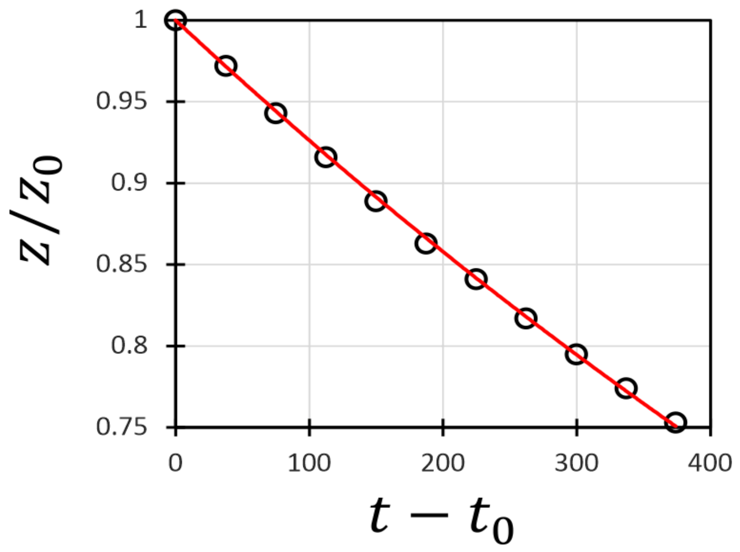

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Permeability of the confined foam: $k_f = k_D/p$

p : porosity of the granular media

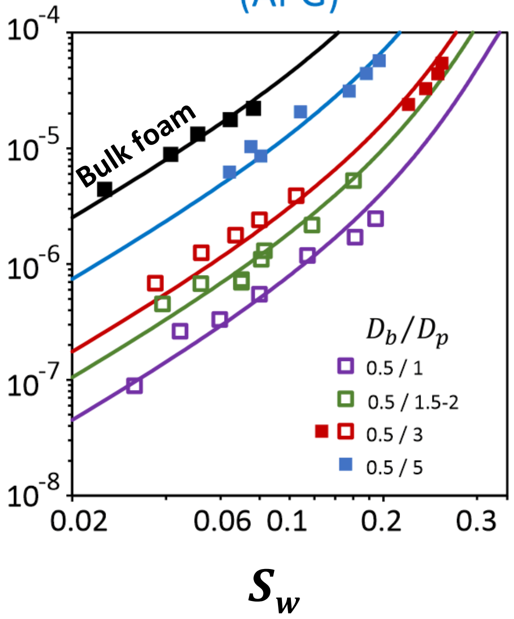
Hydraulic properties of foam-filled granular packing

Changing D_p for constant D_b value:

Mobile interfaces

(APG)

$$\tilde{k}_f = \frac{k_f}{D_b^2}$$



Non mobile interfaces

(saponin)

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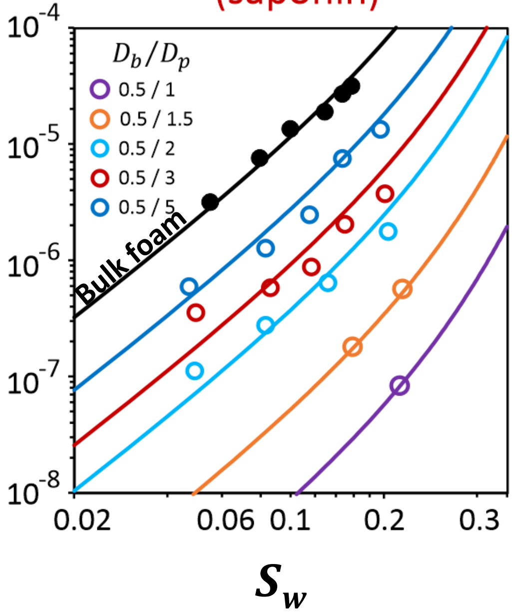

Hydraulic properties of foam-filled granular packing

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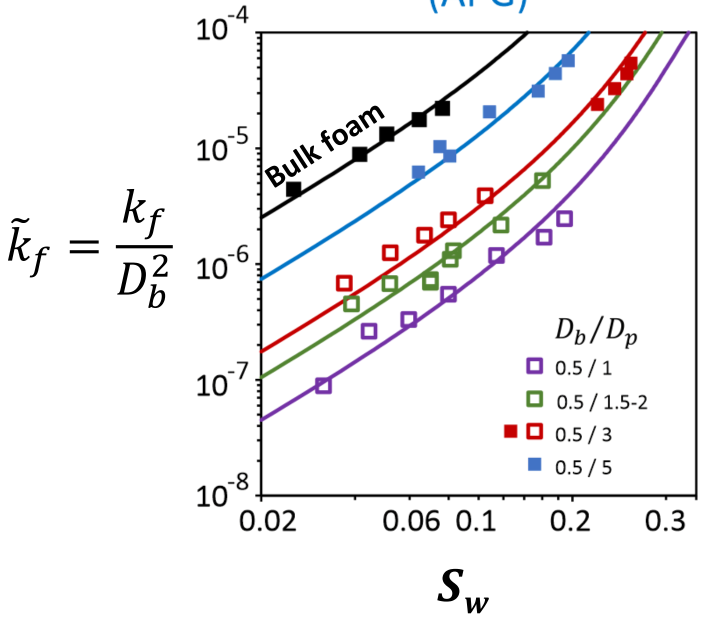

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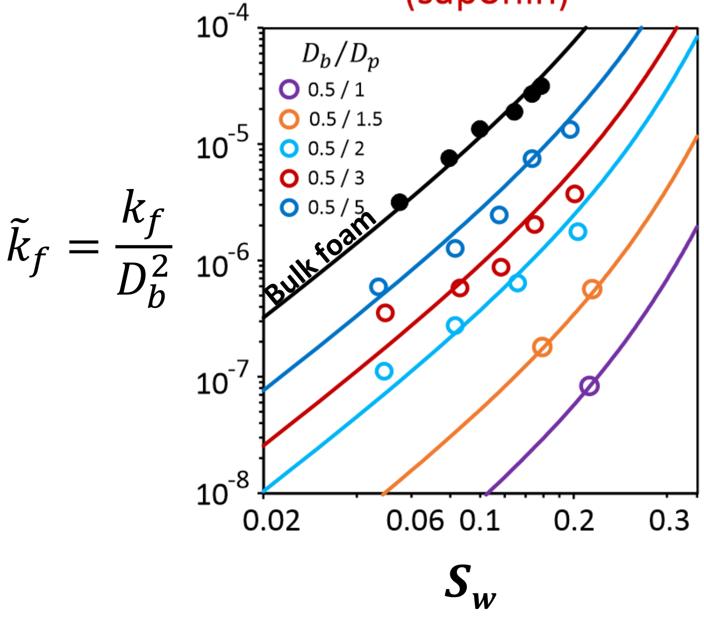
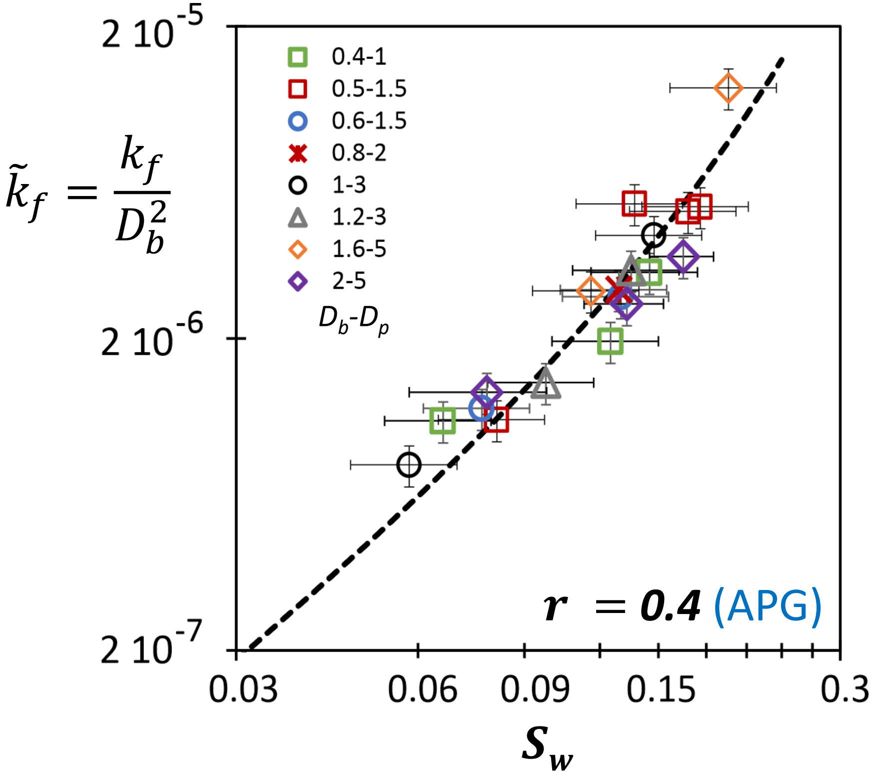


Changing both D_b and D_p for constant r value:

$$r = D_b / D_p$$



Hydraulic properties of foam-filled granular packing

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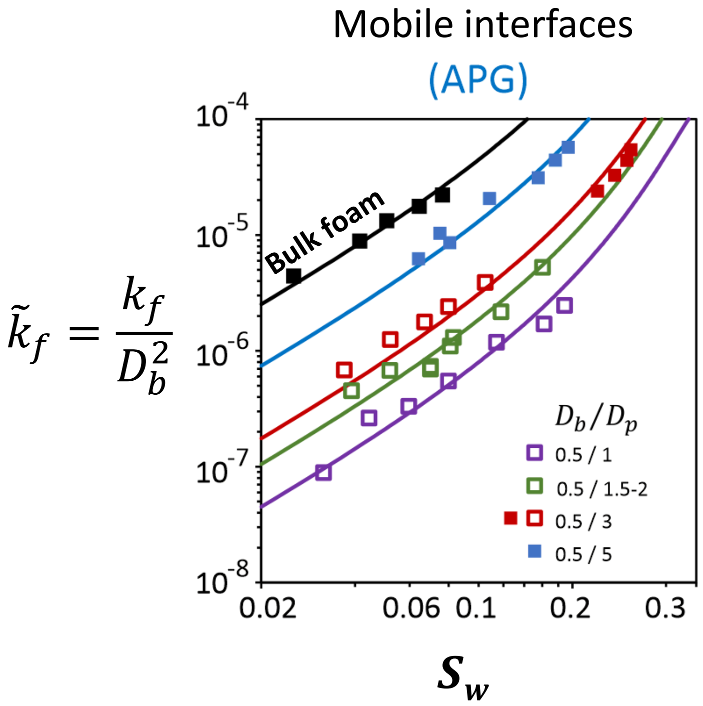

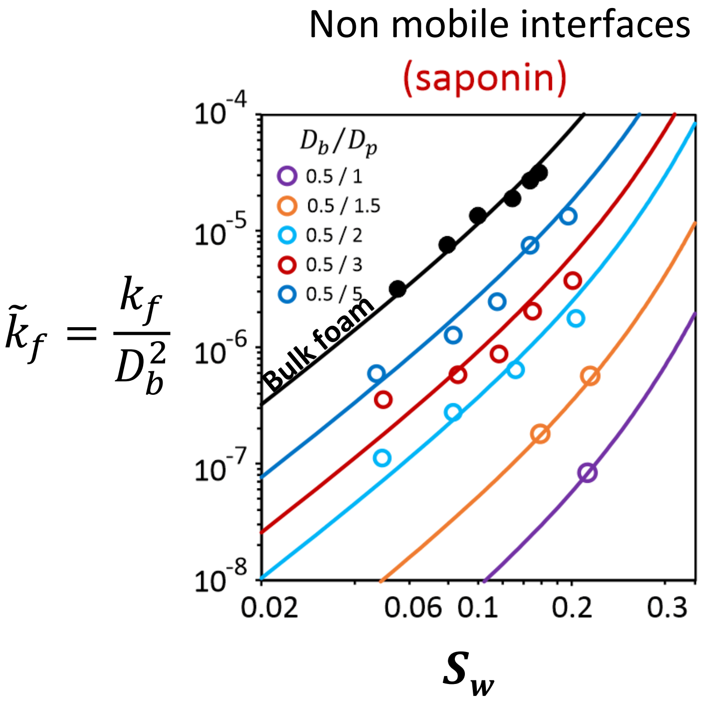

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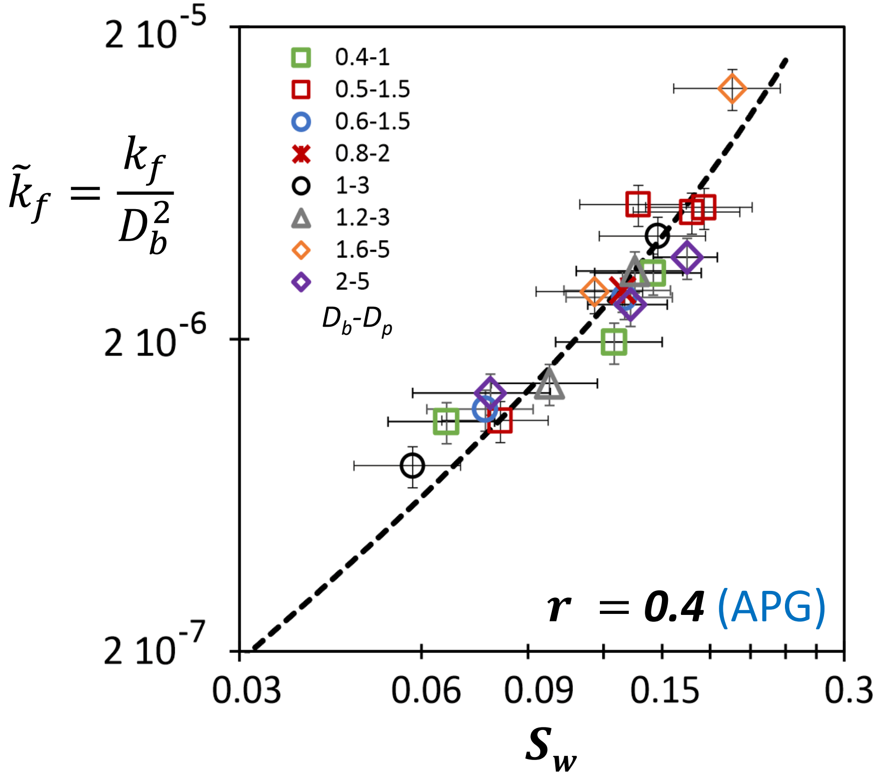
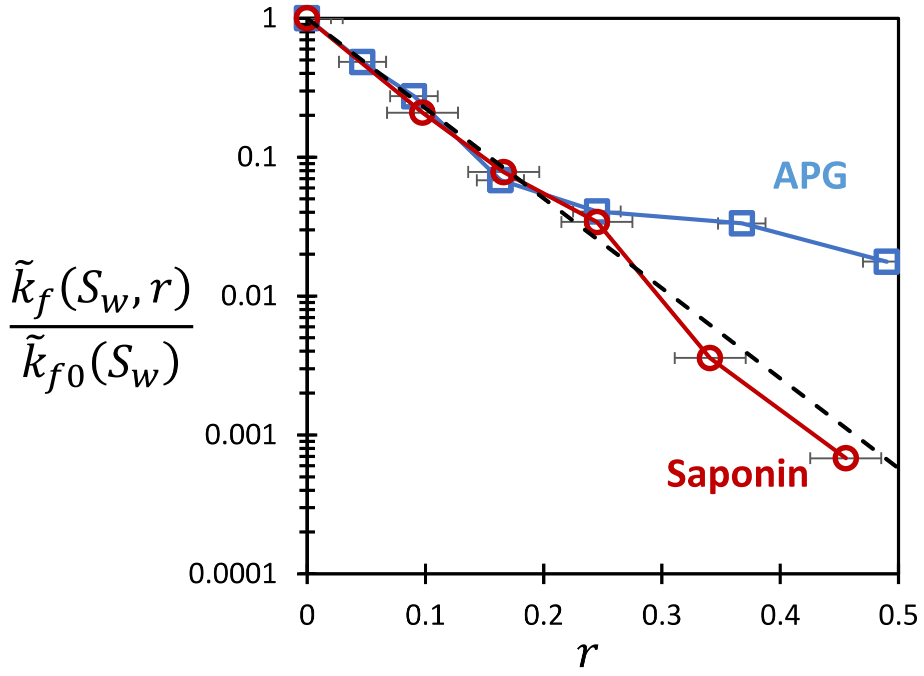


Control parameters for each surfactant: $r = D_b / D_p$ and S_w

Hydraulic properties of foam-filled granular packing

Evolution of the permeability according to the size ratio r:



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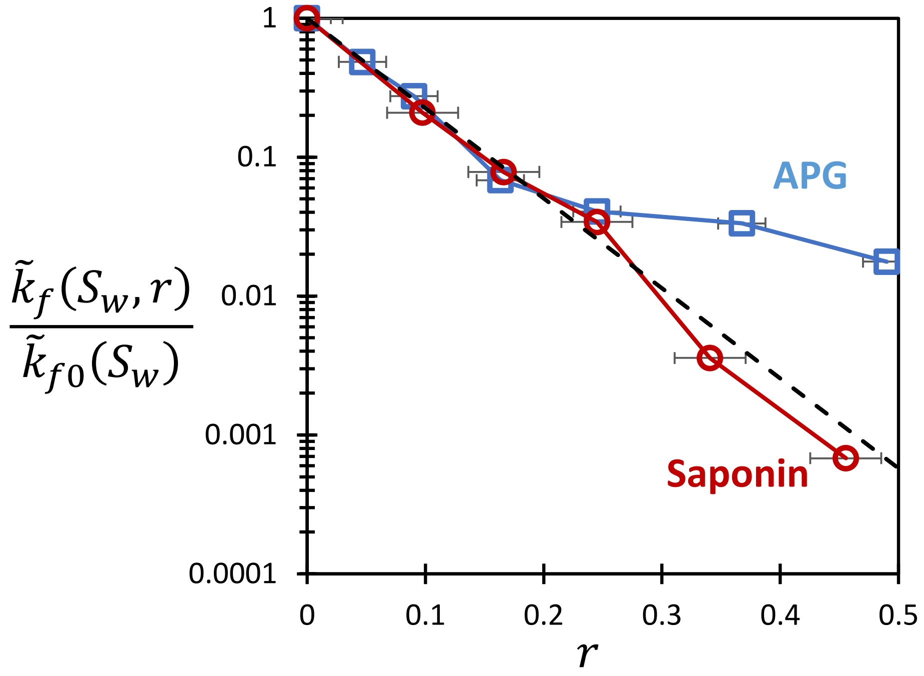

$r < 0.25$

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- No dependence of interfacial mobility

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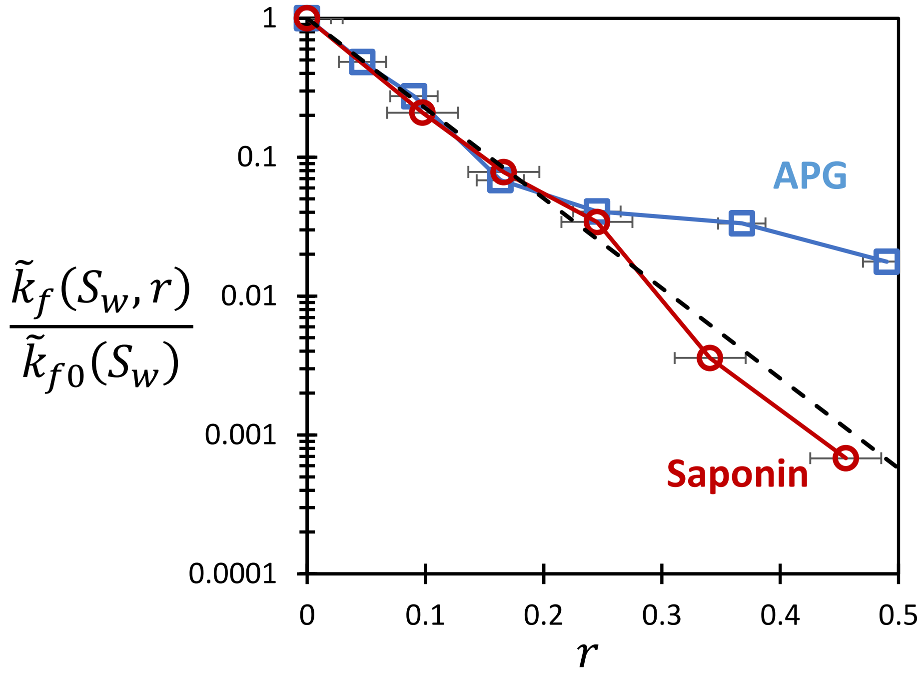

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- Coupling between the interfacial mobility and the geometry of the confined foam

Hydraulic properties of foam-filled granular packing

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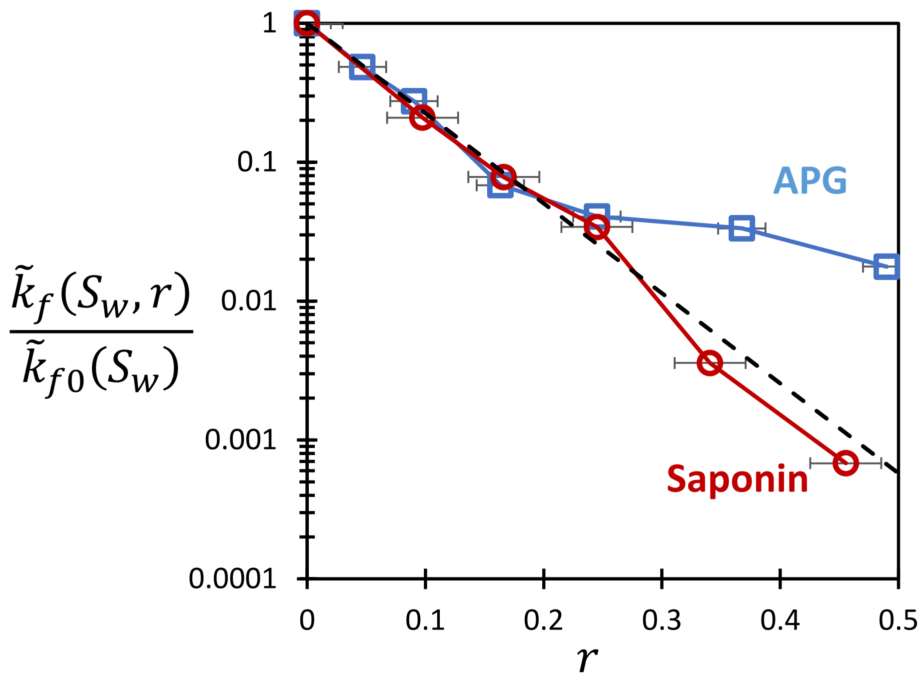

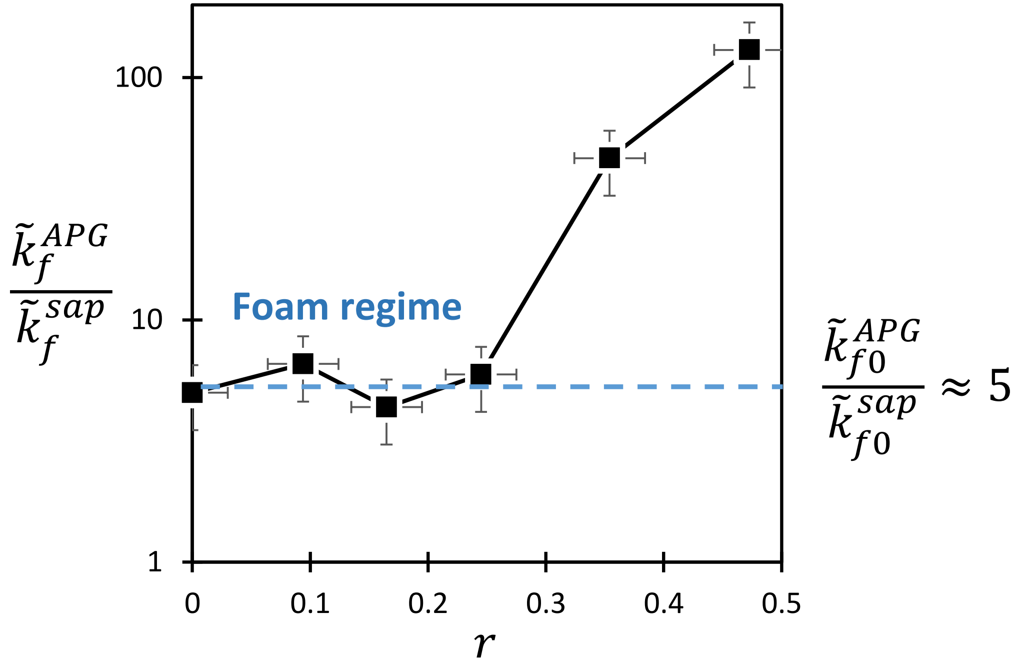

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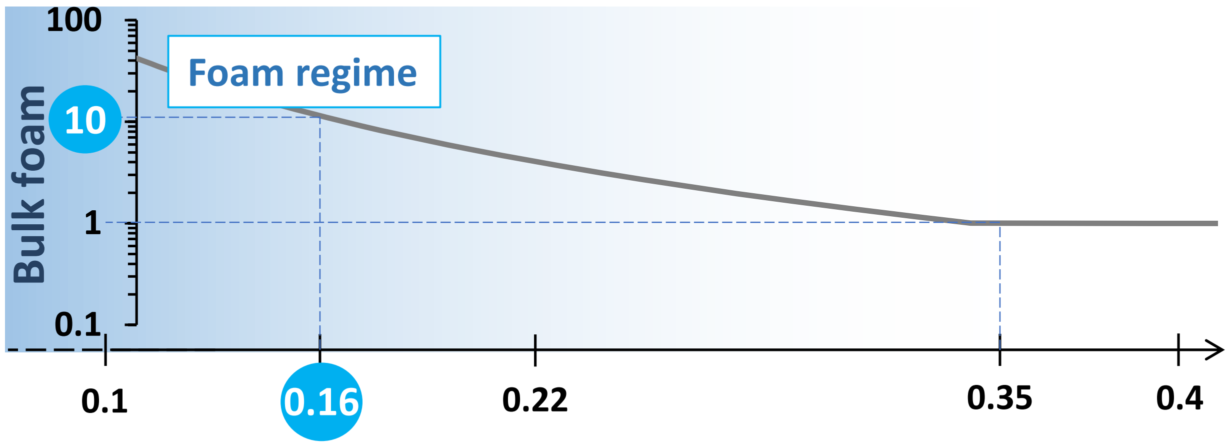
Hydraulic properties of foam-filled granular packing

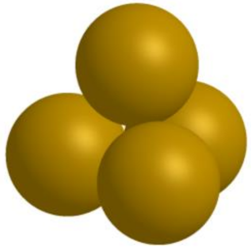
What about geometry of bubbles while r is changing?

Number of bubbles/tetrahedral pore



$r = D_b / D_p$

Tetrahedral arrangement of grains



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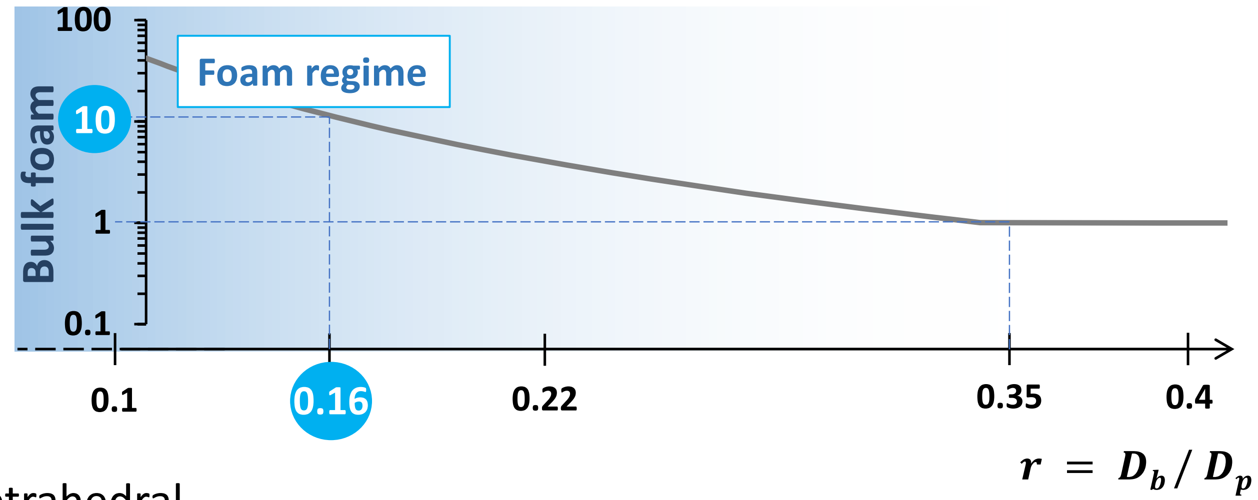

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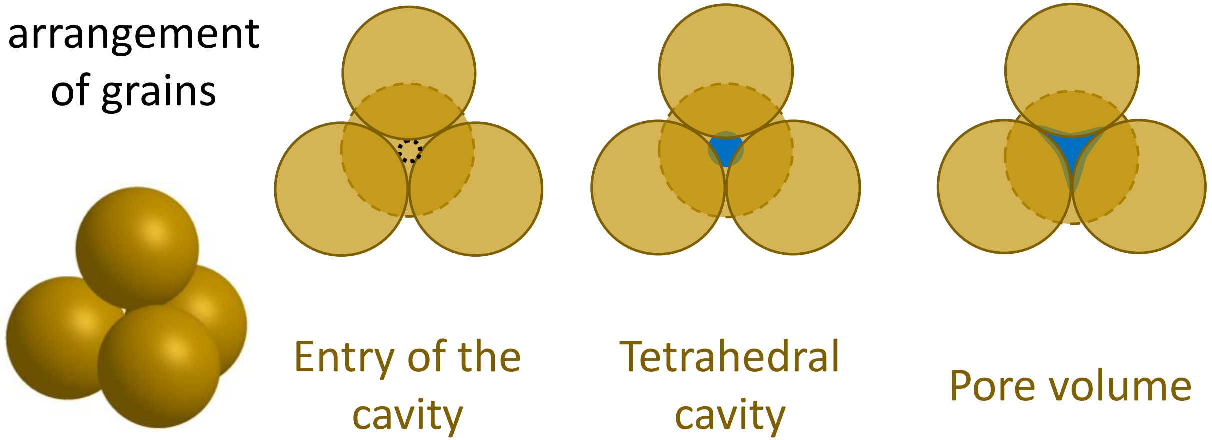

Hydraulic properties of foam-filled granular packing

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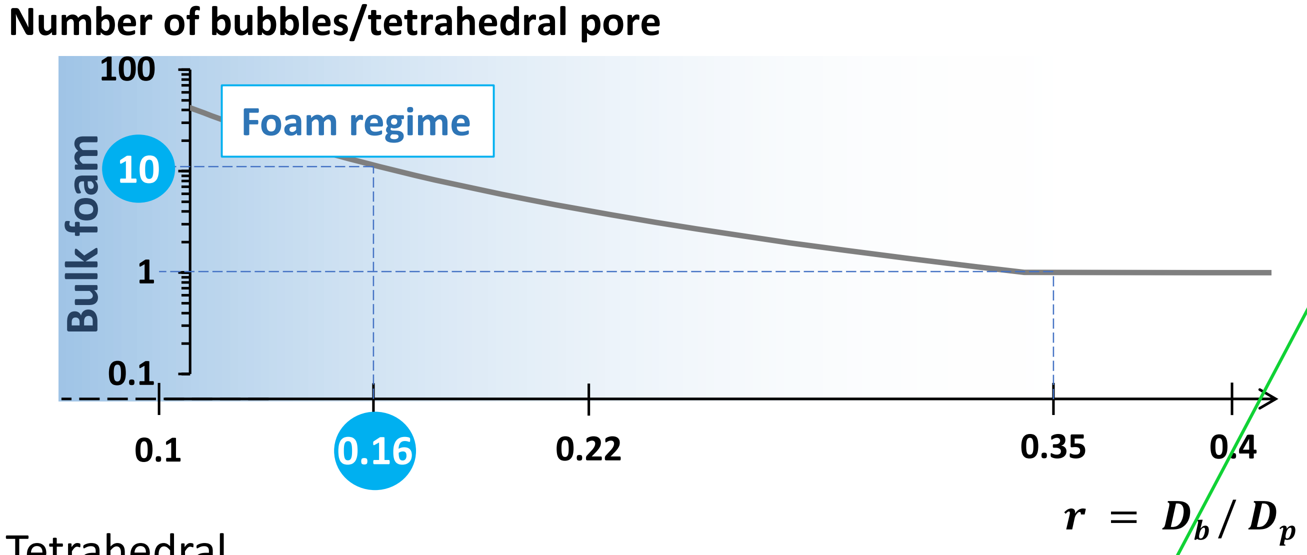
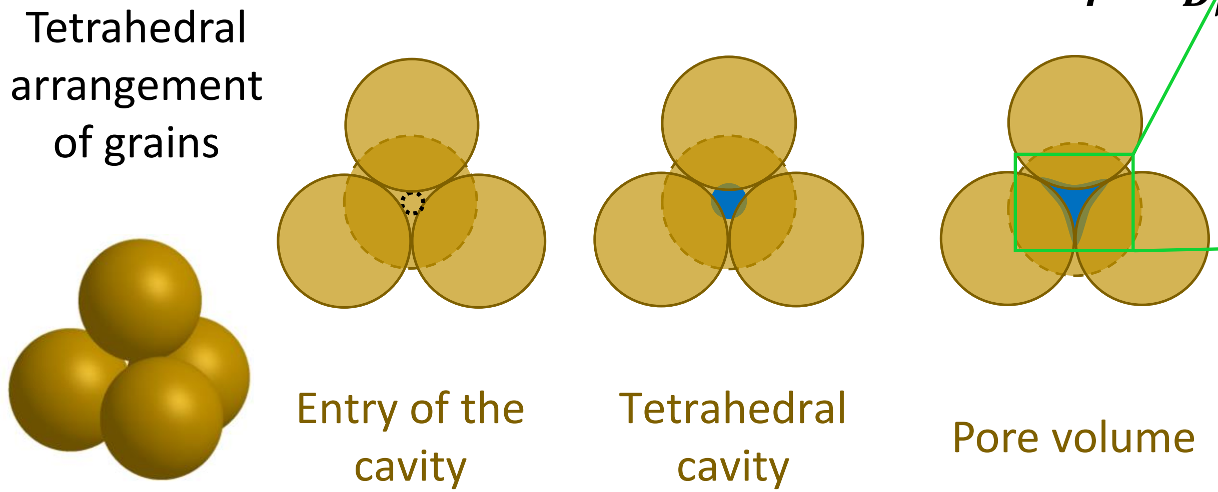
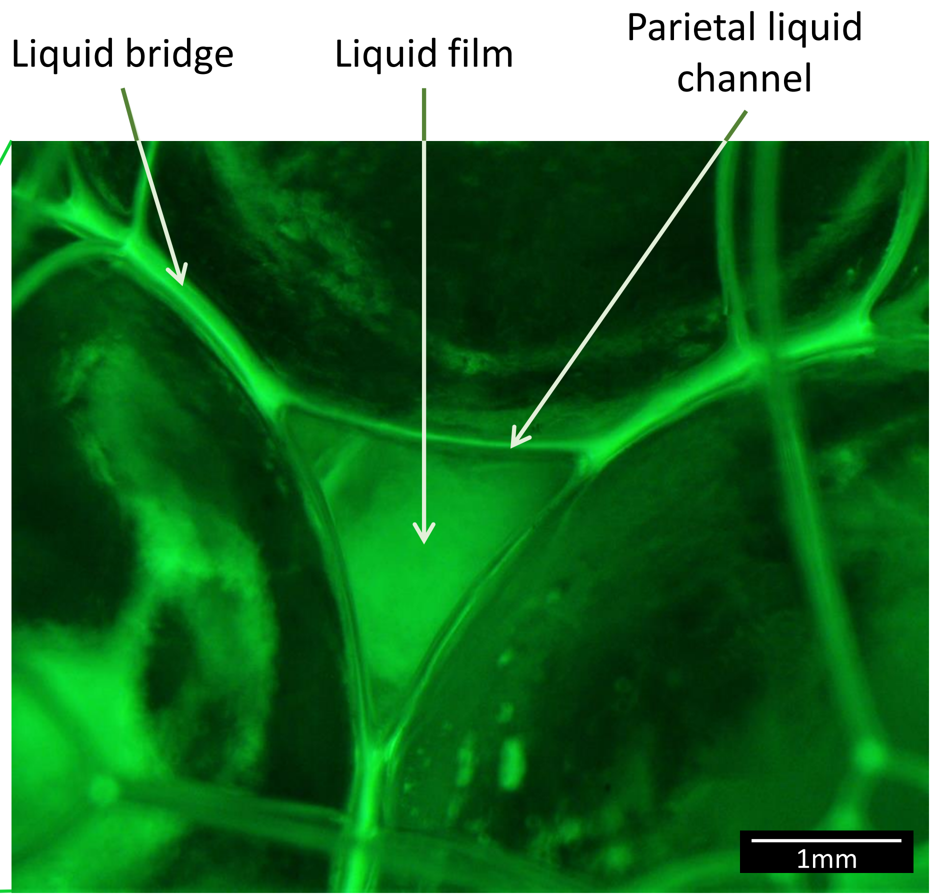




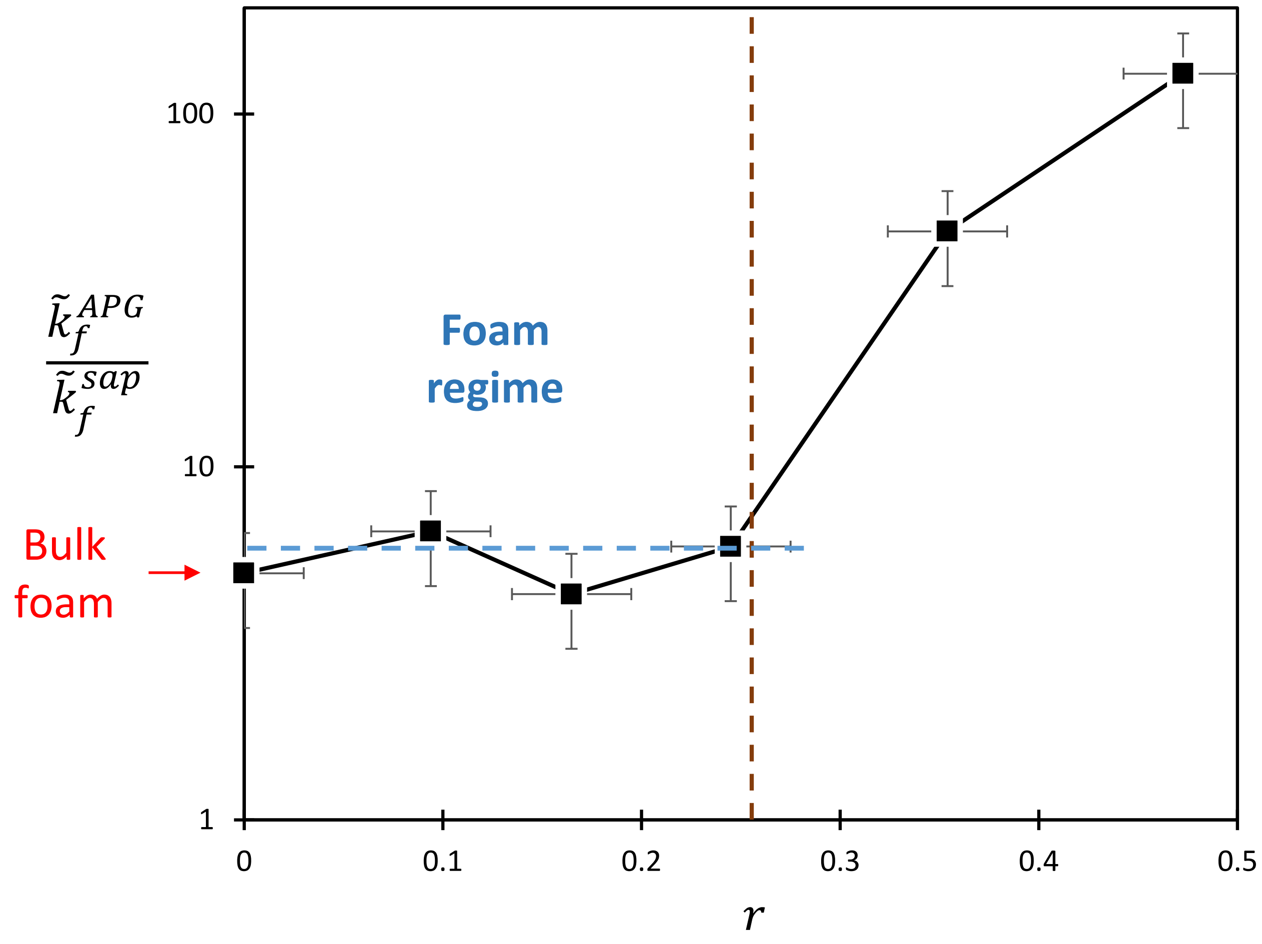


APG foam with fluorescein in granular packing

All the liquid bridges are connected together by parietal plateau borders which ensures liquid permeability at low liquid saturation.

Hydraulic properties of foam-filled granular packing

Permeability ratio of APG and saponin foam in function of r: two regimes



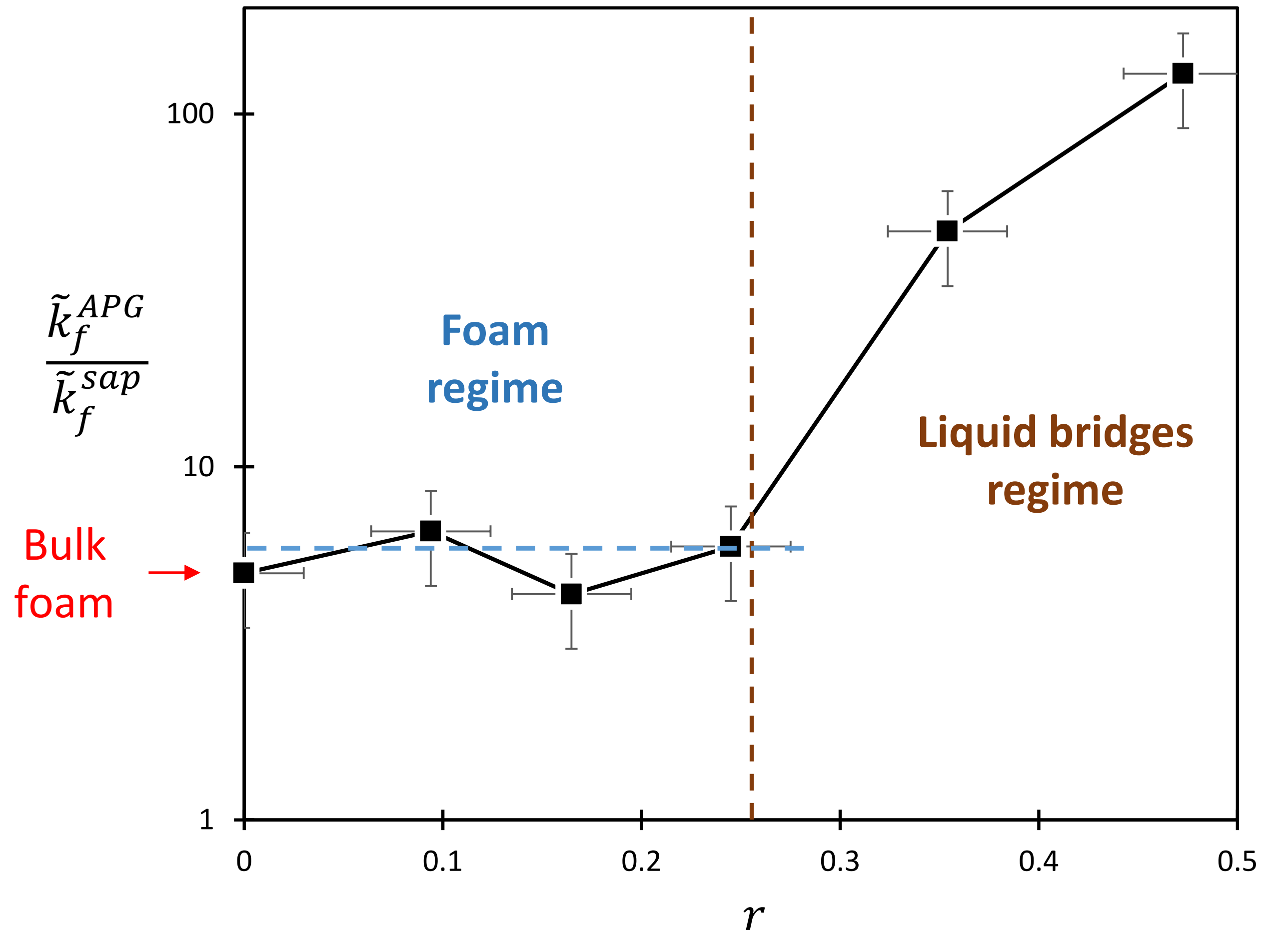
- $r \leq$ **0.25** : **Foam regime**

Several bubbles (foam)/pore

Permeability ratio comparable to unconfined foam

Hydraulic properties of foam-filled granular packing

Permeability ratio of APG and saponin foam in function of r: two regimes



- $r \leq$ **0.25** : **Foam regime**

Several bubbles (foam)/pore
Permeability ratio comparable to unconfined foam

- r **> 0.25** : **Liquid bridges regime**

Transition to ~ 1 bubble/pore (no more « bulk liquid channels » into pores)
Permeability is controlled by liquid bridges and their connectivity

The dominant effect of interfacial mobility in these liquid zones remains to be understood in details.

Conclusion - Liquid relative permeability through foam-filled porous media

- Setting up a model experiment of packed glass beads filled with monodisperse foam (highly controlled samples)

- The liquid permeability depends on three parameters:
  - ✓ **the interfacial mobility** (two surfactants: APG and saponin)
  - ✓ the bubble-to-grain size **ratio** $\boldsymbol{r}$ between 0.05 and 0.5
  - ✓ the liquid saturation $\boldsymbol{S_w}$ below 20%

- When plotting the ratio $\tilde{k}_f^{APG} / \tilde{k}_f^{sap}$, two regimes are revealed as a function of r:
  - ✓ for $r \lesssim 0.25$ the permeability ratio is equal to the ratio corresponding to the bulk foams
  - ✓ for $r > 0.25$ the permeability ratio is increased by one order of magnitude

- The latter regime involves *liquid foam bridges*, connected together by liquid channels formed by the foam on the surface of the grains, which ensures finite liquid permeability at low liquid saturation.

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Thanks for your attention

Any questions ?

Université Gustave Eiffel

Financement :
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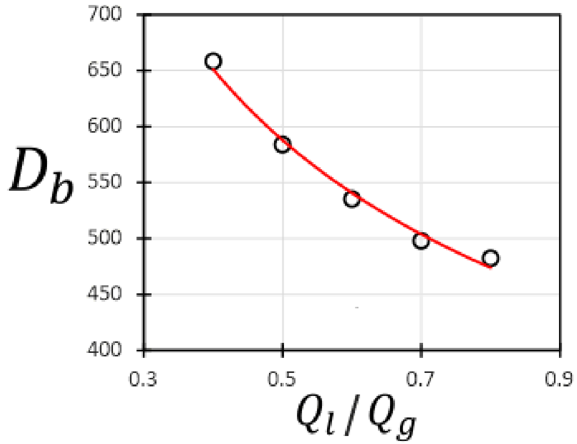
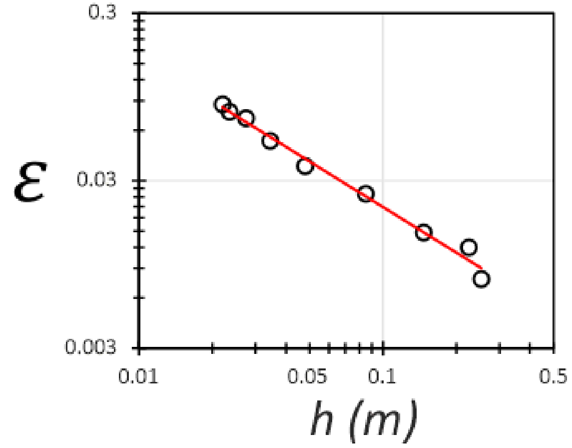
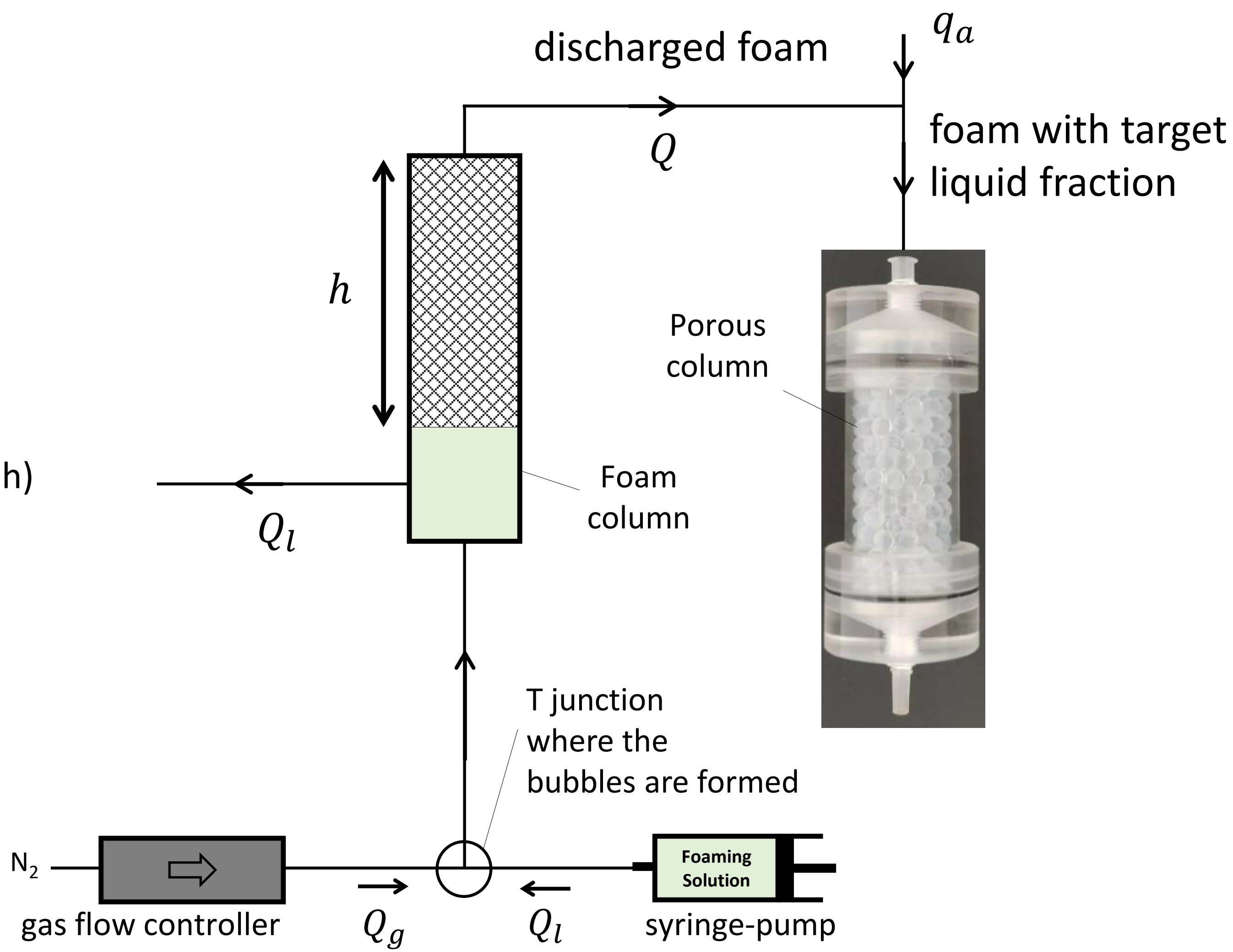
Foam production and filling of the granular packing

Control of bubble size : variation of the flow rate of the foaming solution and the gas (Q_l/Q_g)



Control of foam liquid fraction : variation of the foam height (h)





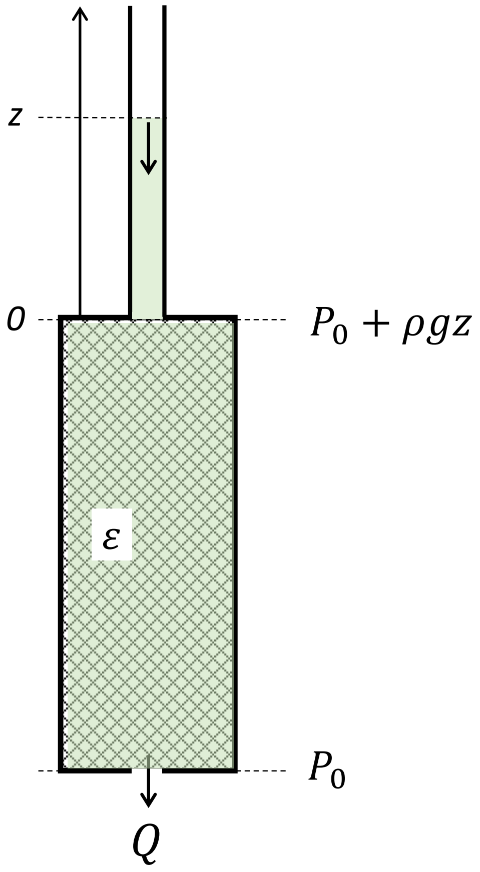
Hydraulic properties of foam-filled granular packing

Measurement of liquid permeability:

Darcy method:

Inspired by methods for measuring the permeability of porous materials

Imposed liquid fraction



Darcy law:

$$\frac{Q}{S} = \frac{k_D}{\mu}\frac{\Delta P}{L}$$

Flow rate:

$$Q = -S_t \frac{dz}{dt}$$

Permeability of the confined foam:

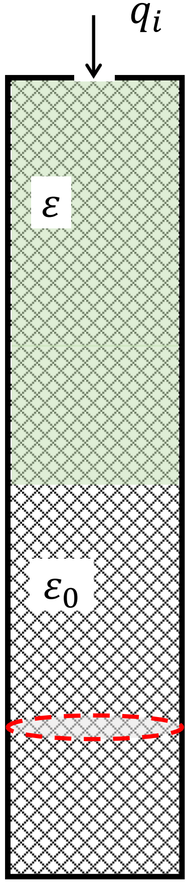
$$k_f = k_D / p$$

Bubbles are trapped

Forced drainage method:

Inspired by methods for measuring the liquid permeability of foam

Bubbles are untrapped



Front velocity v_f

Column section S

Darcy law:

$$\frac{q_i}{S} = \frac{k_f}{\mu}\rho g$$

Volume conservation:

$$\varepsilon = \varepsilon_0 + \frac{q_i}{S v_f}$$