

Friction modifies poroelasticity of a yeast clog



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^c Poromechanics Lab, Oxford University

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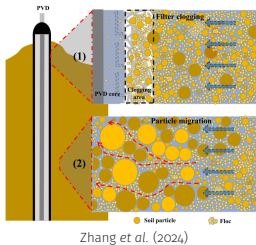


InterPore – May 19-22nd, 2026

Definition of **clogging**

Accumulation of particles at the solid surface of a porous media flowed by a suspension.

- > Environment
 - **Soil remediation**
- > Industry
 - **Filtration**, buried resources



Zhang et al. (2024)



From cerahelix.com

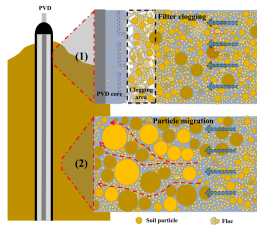
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What is (bio)clogging ?

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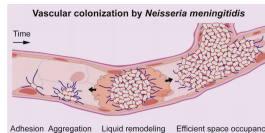
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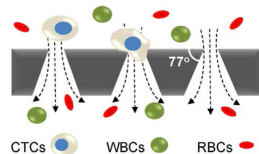
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Bioclogging: clogging with biological objects

- > Bio-medicine
 - **Brain diseases**
 - **Diagnostic**
- > Food industry
 - **Yeast filtration** (beer, ...)



Bonazzi et al. (2018)

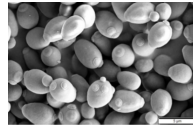


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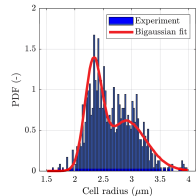
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> Well-known **mechanical properties**

- Ovoid, polydisperse in size



From Wikipedia

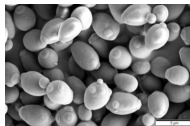


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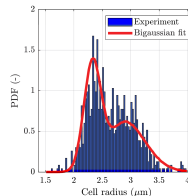
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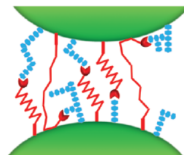
- Ovoid, polydisperse in size
- Specific adhesion/friction mechanism
- Pressurized elastic shell



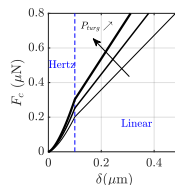
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From El-Kirat Chatel et al. (2014)

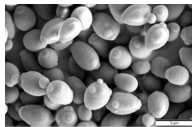


From Vella et al. (2021) & T. Desclaux thesis

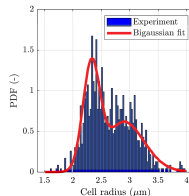
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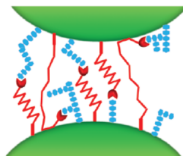
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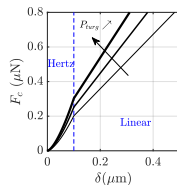
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> Well-controlled **biological behaviour**

- Cells collected in exponential growing phase
- Add of antibiotic to **stop proliferation**



From El-Kirat Chatel et al. (2014)



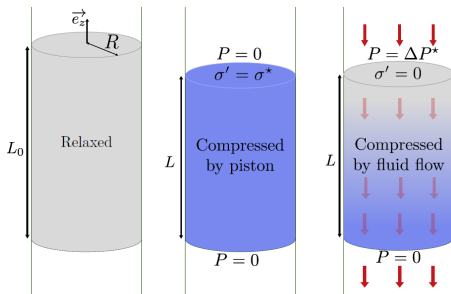
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(Poro)mechanics of a yeast clog

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- a soft porous media
- in a confined environment

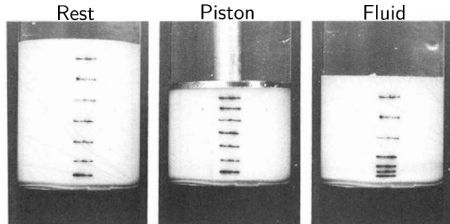


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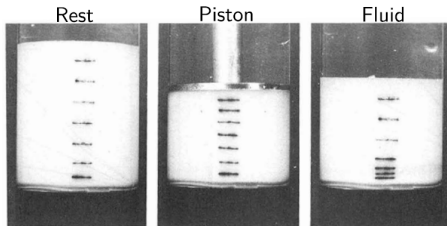


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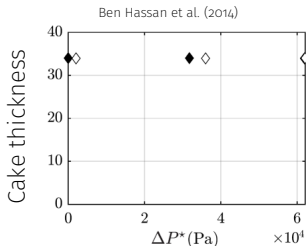
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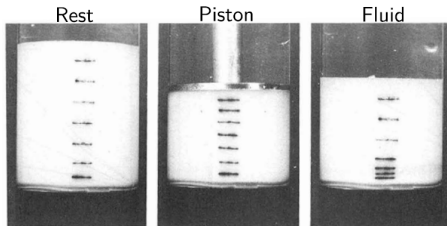
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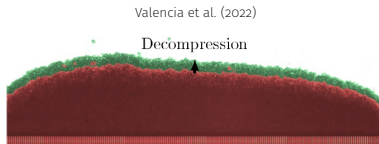
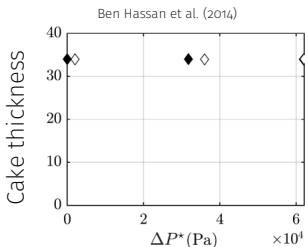
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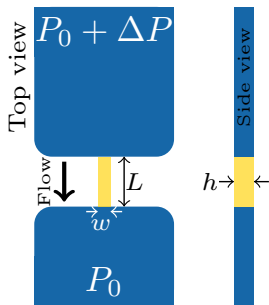
Could confinement explain these differences ?

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Bioclogging in a microfluidic chip

5

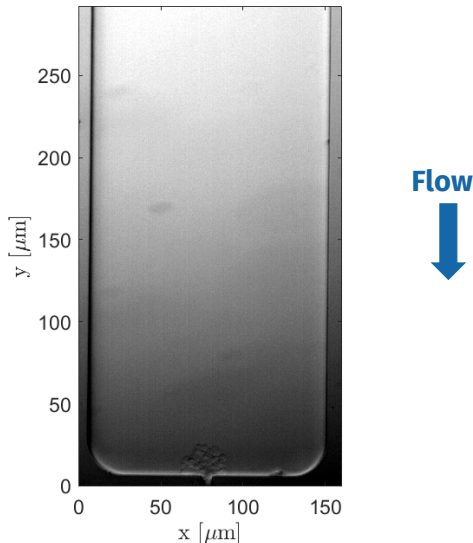
- > Microfluidic silicon-glass channels



Dimensions

- > Depth: $h = 6.5 \mu\text{m}$
- > Width: $w = 6 \mu\text{m}$
- > Length: $L = 50 \mu\text{m}$
- > Yeast: $\varnothing \approx 4.5 \mu\text{m}$

- > Clog generation by accumulation, speed up 25x



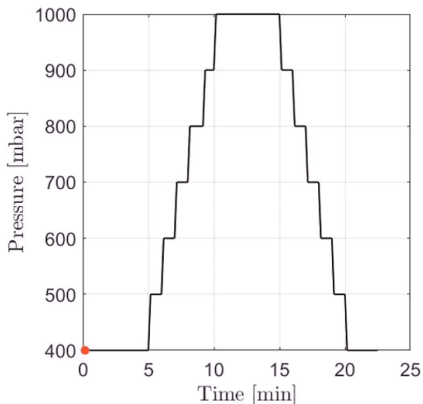
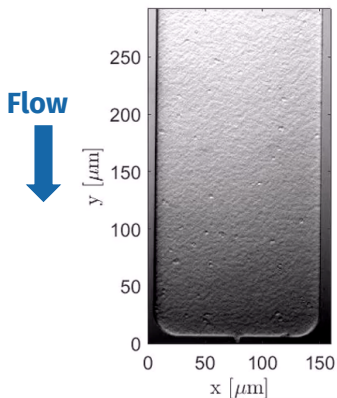
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How to measure the mechanical properties of a yeast clog ?

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- > Use of **microfluidics**: controlled environment, confinement, direct visualization
- > Quasi-2D yeast assembly

Fluid-driven sollicitation

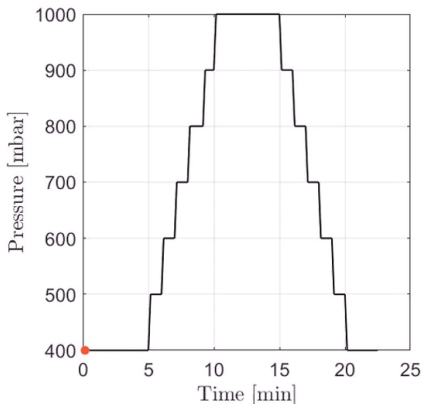
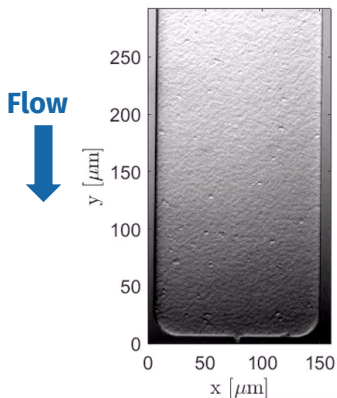


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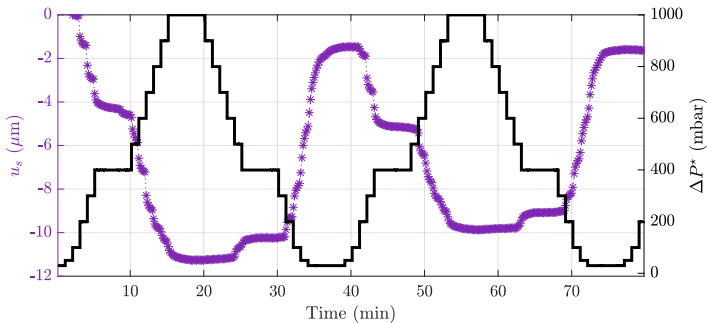
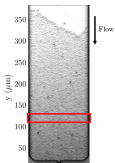


Relation stress/deformation

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Displacements time-evolution

Time-evolution at $y = 120 \mu\text{m}$ from the pore

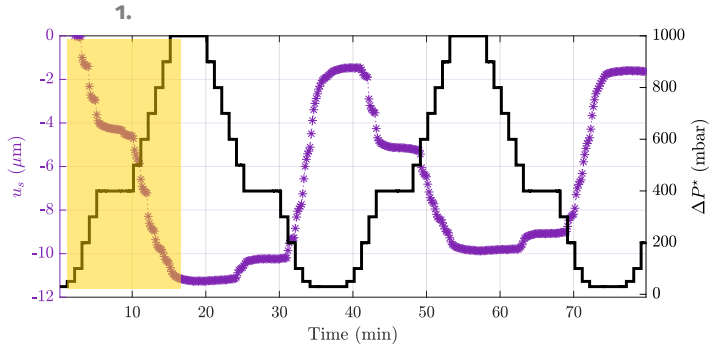
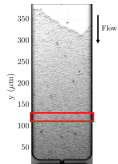


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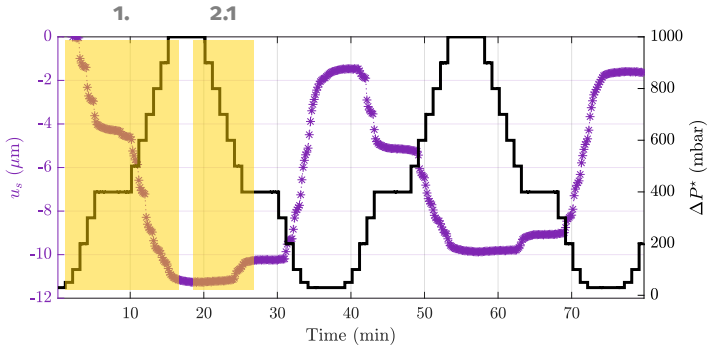
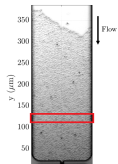


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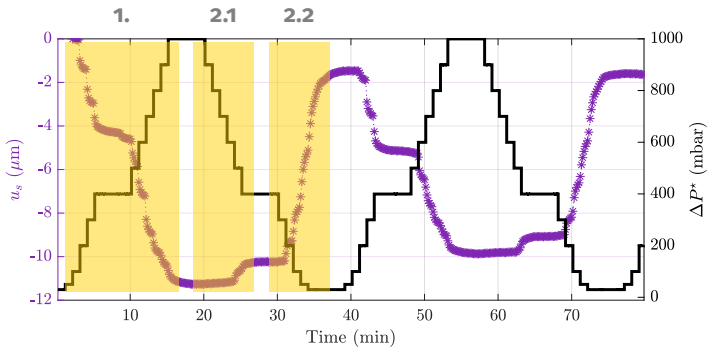
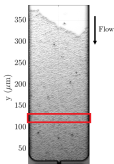


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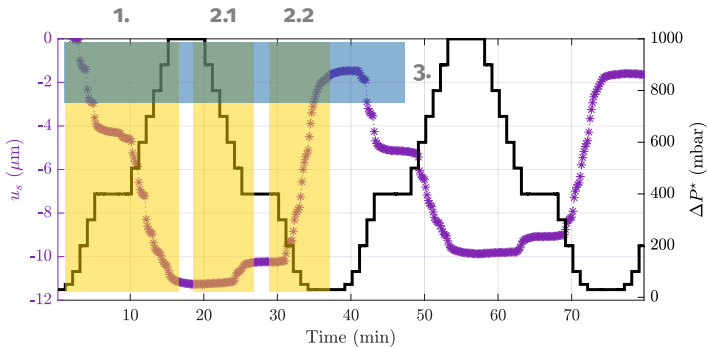
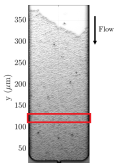


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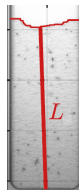
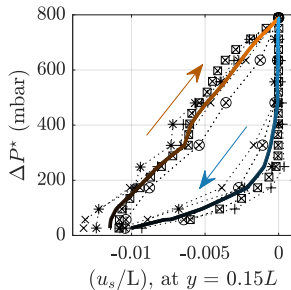
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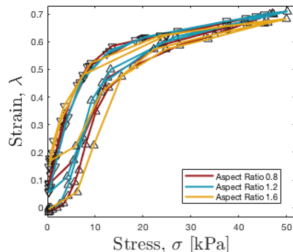
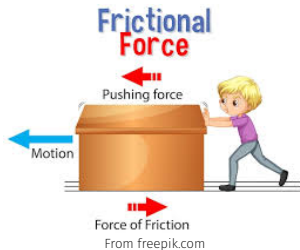
1. Compression: large displacements
2. Decompression:
 - 2.1 High ΔP^* : small displacements
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3. Few plasticity (internal rearrangements)

- > Good reproducibility
- > Hysteretic behaviour
- > Signature of energy dissipation during the process



> Could the friction to the walls be an ideal suspect ?

- Started to be investigated for non-granular soft porous media



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- **Yet**, biological cells are slippery on glass/silicon

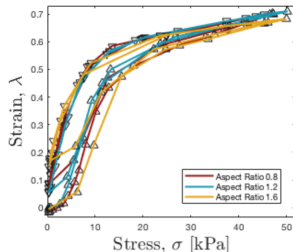
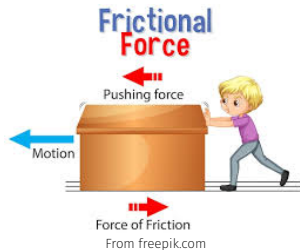
Coulomb's friction coef. $\sim 0.03 - 0.06$

For human endothelial cells on glass

Dunn et al. (2007)



From physioextra.ca



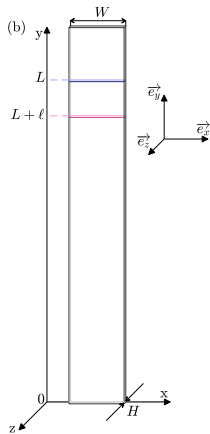
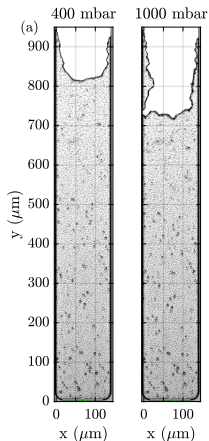
Lutz's thesis (2021)

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Let's take a closer look at friction

> 2D problem

- All quantities uniform over \vec{e}_x



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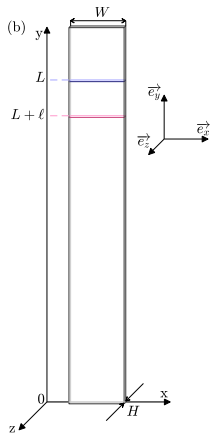
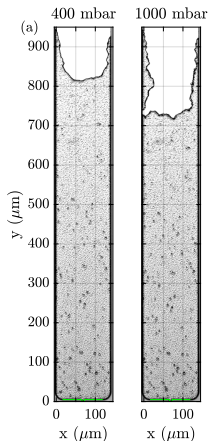
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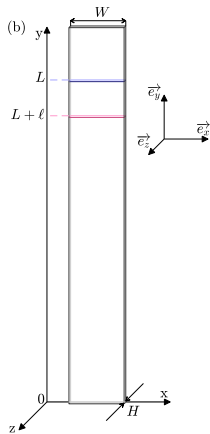
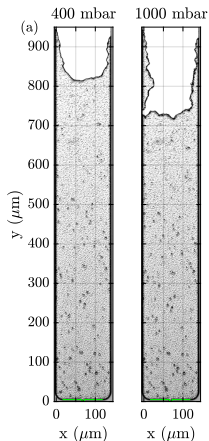
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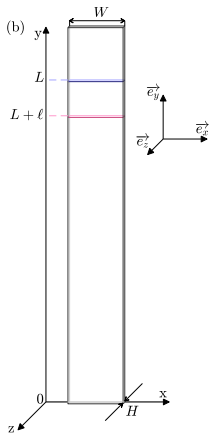
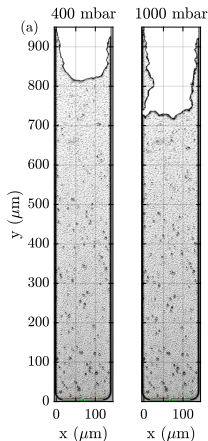
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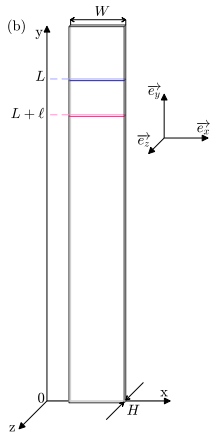
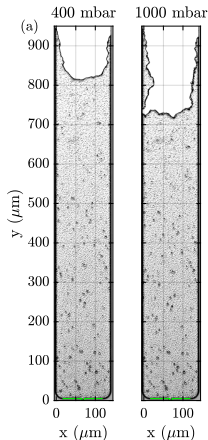
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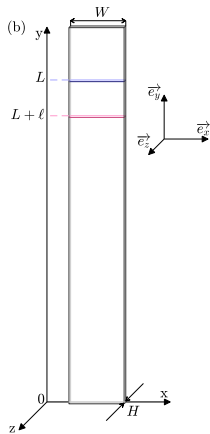
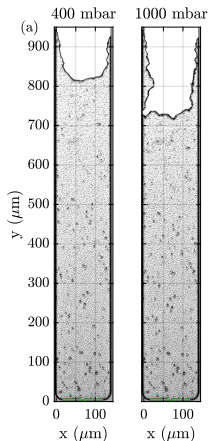
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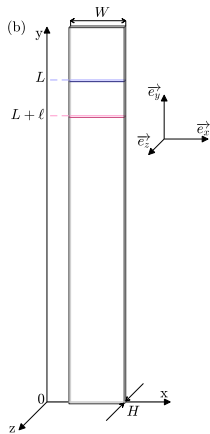
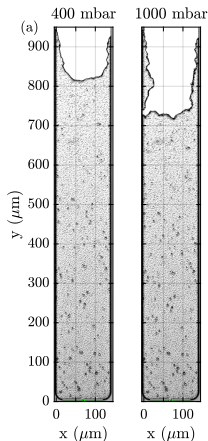
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Wall stress

Depth of the device



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$$\int_0^H (\nabla \cdot \sigma) dz = \vec{0} \Rightarrow \partial_y \sigma'_{yy} + \frac{2\sigma'_F}{H} = \partial_y P$$

↓ Wall stress
↑ Depth of the device

Friction coefficient

> Couloumb's law: $|\sigma'_F| \leq \mu |\sigma'_{zz}|$

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Let's take a closer look at friction

- > 2D problem
 - All quantities uniform over \vec{e}_x
- > Porous medium with Darcy flow
- > Solid: linear elastic, incompressible
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↑ Friction forces
↑ Applied forces

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Friction coefficient μ
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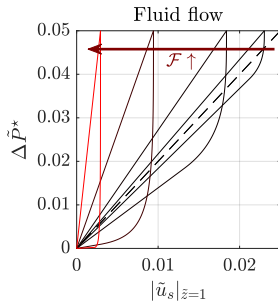
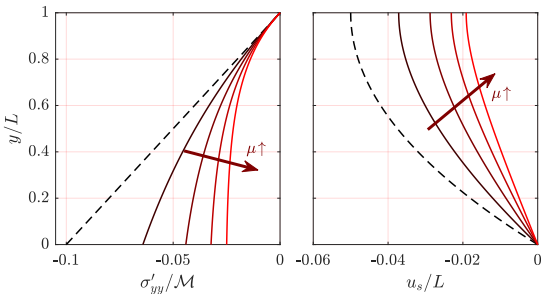
Device aspect ratio is a key parameter

Fluid-driven compression:

- > Stress profile \neq linear
- > Displacements no longer quadratic
- > Hysteresis on stress/deformation relation

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

- > Dashed lines: frictionless case



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

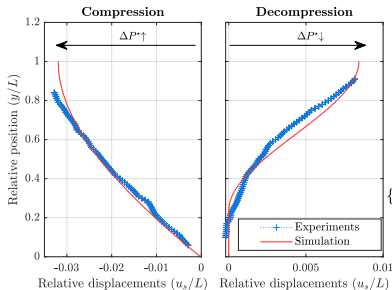
Reproduction of fluid-driven experiments

Calibration:

- > Two free parameters (μ , \mathcal{M})
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$$\Delta P_{\text{ref}}^* = 325 \text{ mbar}$$

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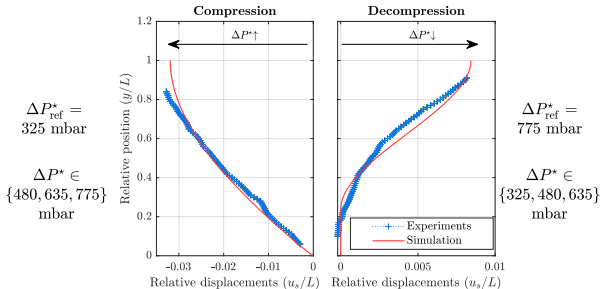
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- > $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa
 - Consistent with yeast mechanics and on-glass friction



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Reproduction of fluid-driven experiments

12

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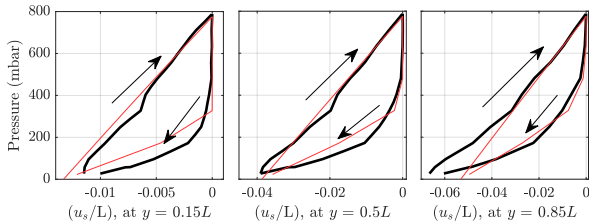
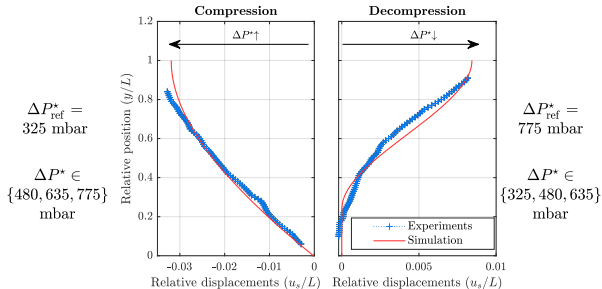
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Full hysteresis cycle reproduced

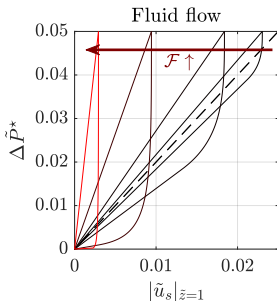
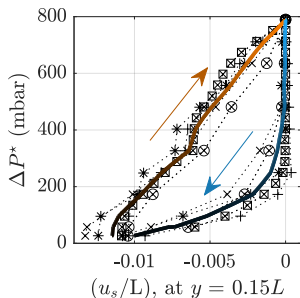


- > **Wall friction modifies poroelasticity of a yeast clog**

- > **Friction number** involves aspect ratio

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

- > **Good agreement** with experimental results



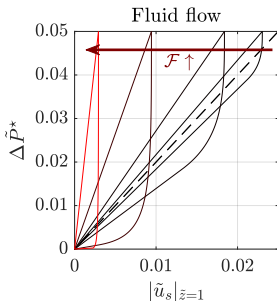
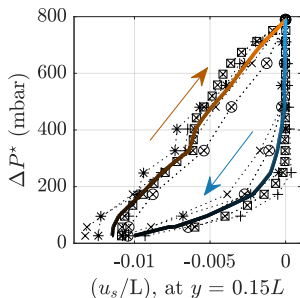
$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Take-home messages

- > Highly non-linear mechanics
 - Hysteretic stress-deformation characteristics
- > **Friction** with the wall is the key
 - Even for slippery materials
 - Aspect ratio drives the intensity of friction

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

- > A faithful reproduction of experimental results
 - Fair estimation of friction coeff. and elastic modulus
 - Captures the hysteresis for fluid-driven forcing

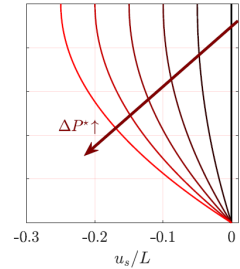
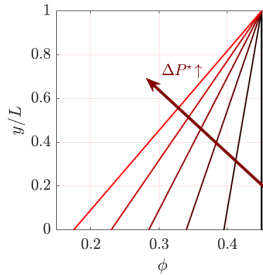


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What does poromechanics theory foresee ?

Fluid-driven compression

- > Stress gradient in the medium
- > Porosity (ϕ) gradient
- > Quadratic displacements (u_s)



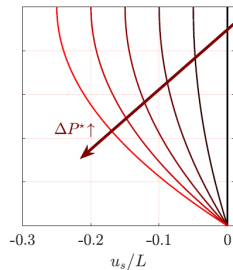
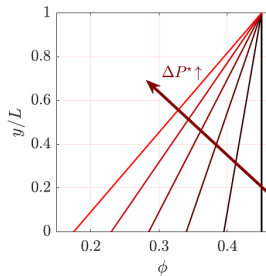
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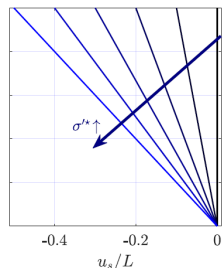
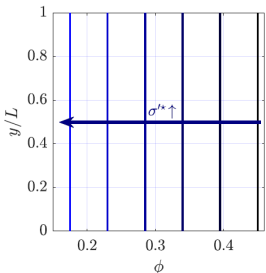
Fluid-driven compression

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Piston-driven compression

- > Stress uniformly transmitted
- > Uniform porosity (ϕ)
- > Linear displacements (u_s)

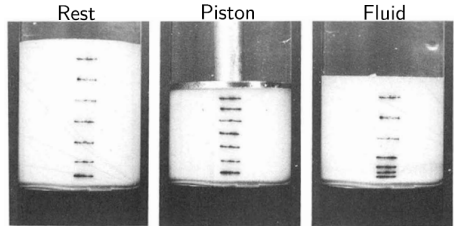


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Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

> Fluid flow \rightarrow Darcy's law



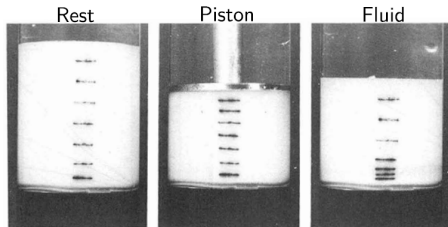
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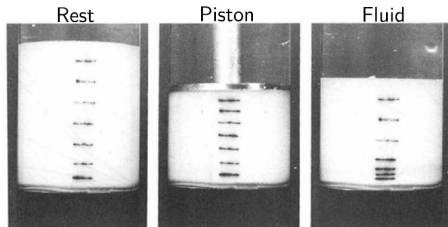
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Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

- > Fluid flow \rightarrow Darcy's law
- > Solid mechanical properties \rightarrow linear elastic
- > Permeability \rightarrow uniform



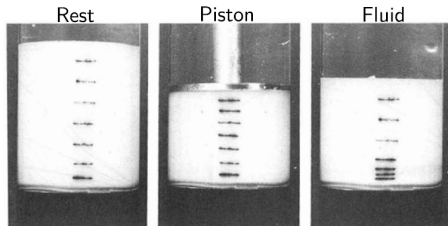
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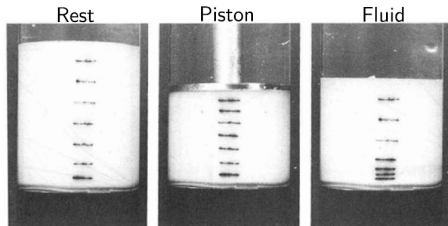
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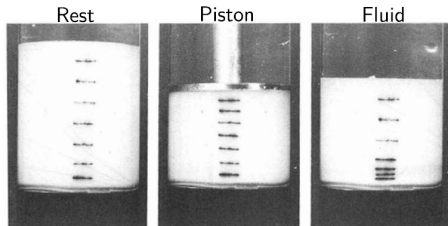
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- > Mechanical equilibrium

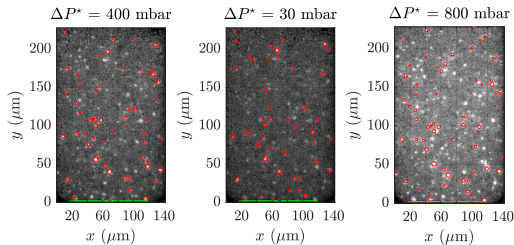


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Fluorescent hydrogel probes:

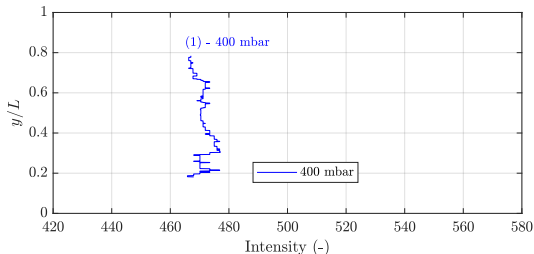
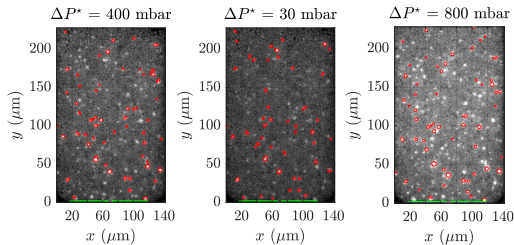
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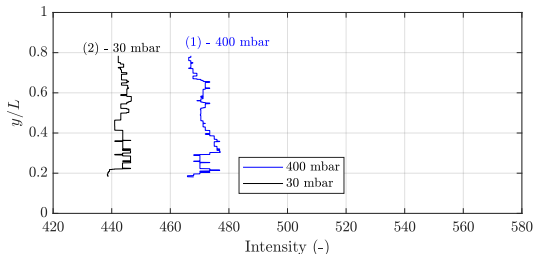
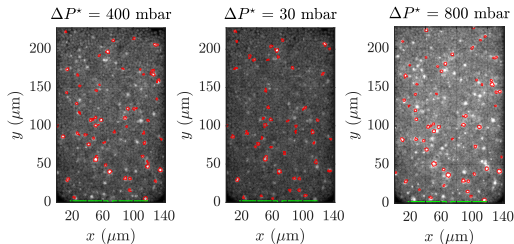
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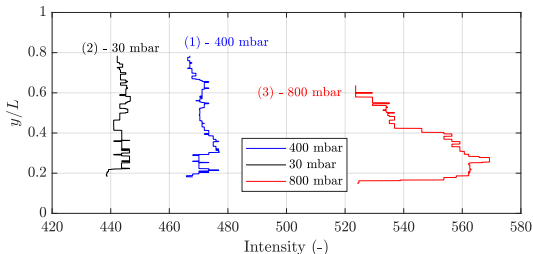
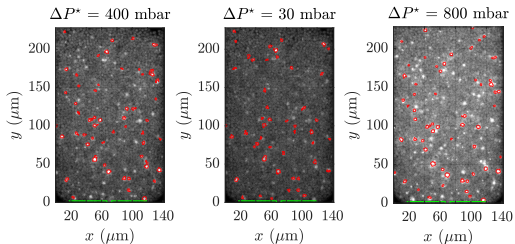
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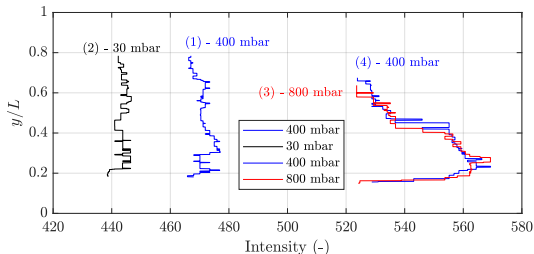
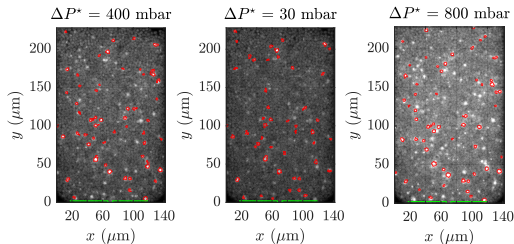
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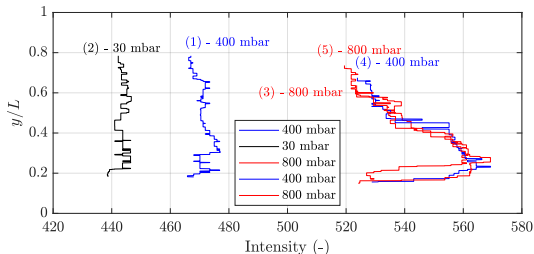
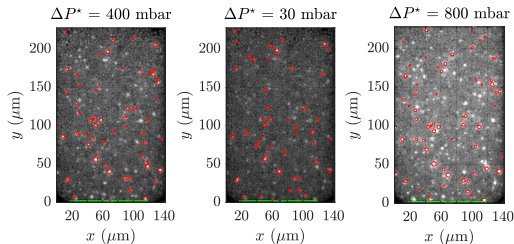
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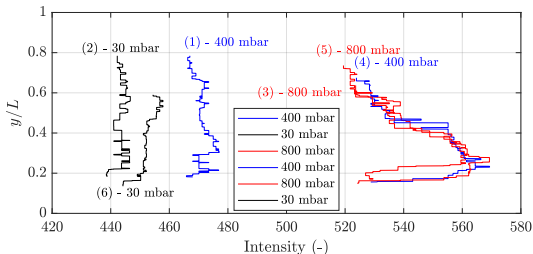
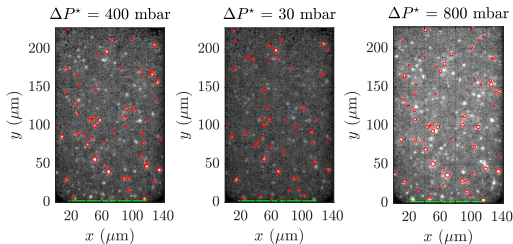
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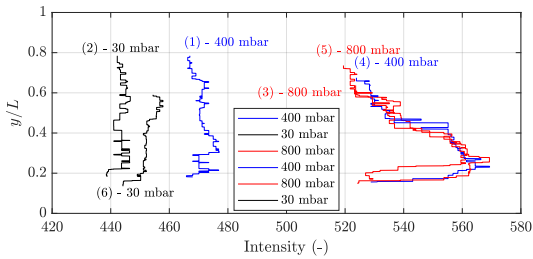
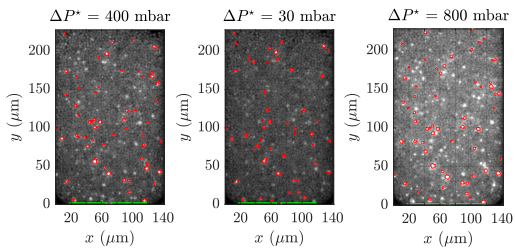
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- > Stress gradient through the clog
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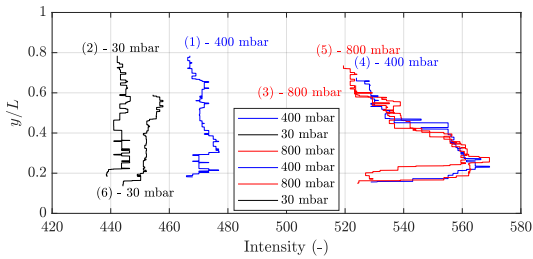
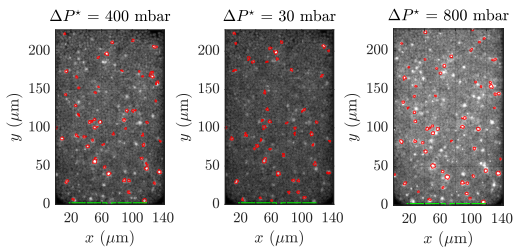
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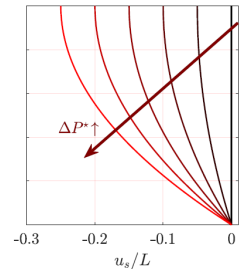
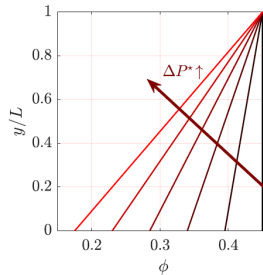
Which origin for this energy dissipation and elastic energy storage ?

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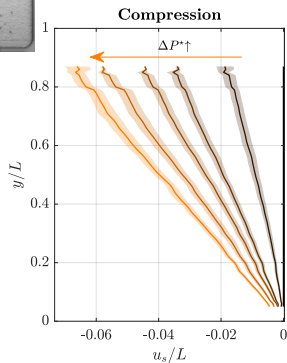
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Compression

- > Staggered displacement steps
- > Non quadratic profile



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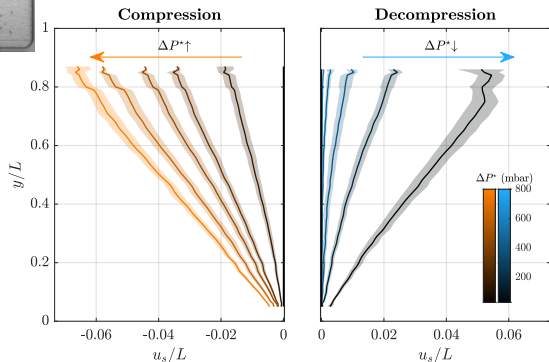
Relative displacement profiles

Compression

- > Staggered displacement steps
- > Non quadratic profile

Decompression

- > Non quadratic profile
- > No displacement at decompression start
- > Large displacements at the end



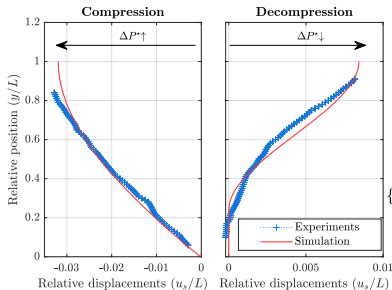
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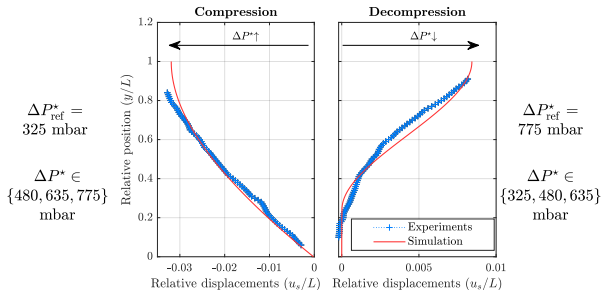
20

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Reproduction of fluid-driven experiments

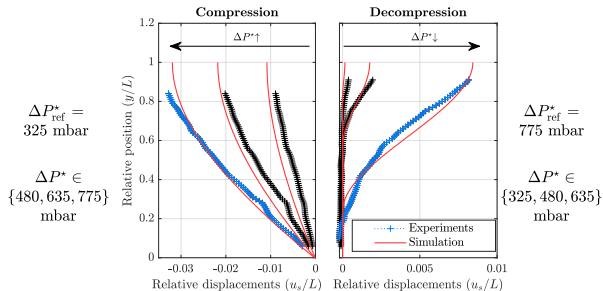
20

Calibration:

- > Two free parameters (μ , \mathcal{M})
- > Two u_s profiles used (blue)

Results:

- > $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa
 - Consistent with yeast mechanics and on-glass friction
- > Other u_s profiles reproduced



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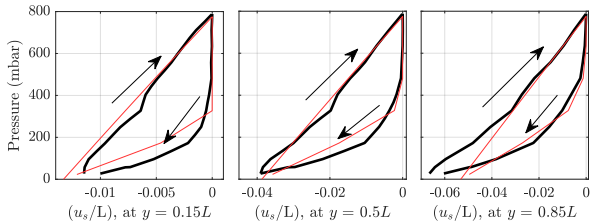
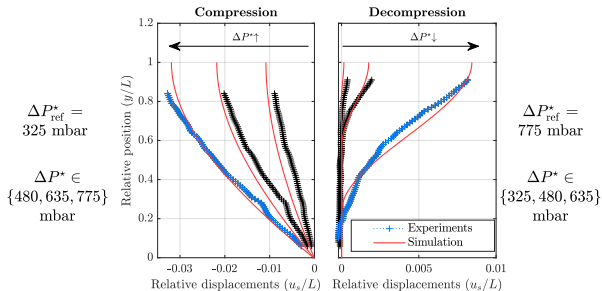
Reproduction of fluid-driven experiments

Calibration:

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- > Two u_s profiles used (blue)

Results:

- > $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa
 - Consistent with yeast mechanics and on-glass friction
- > Other u_s profiles reproduced
- > Full hysteresis cycle reproduced



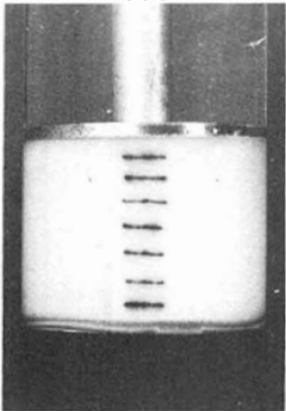
$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

What does poromechanics theory foresee ?

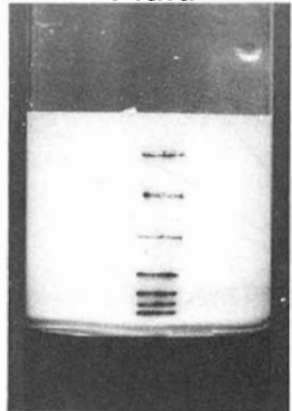
Rest



Piston



Fluid



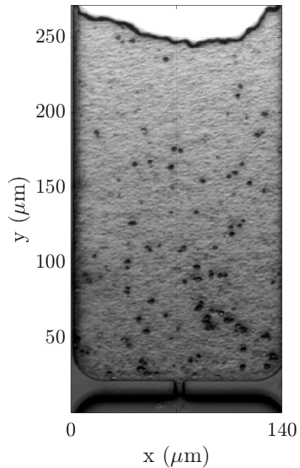
From Parker et al. (1987)

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

How to measure the mechanical properties of a yeast clog ?

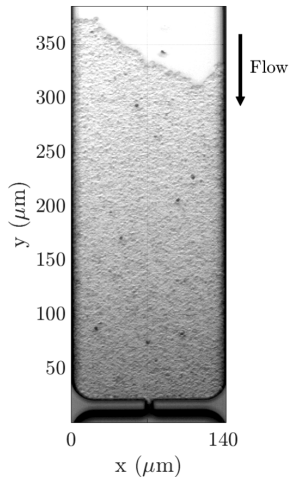
Piston-driven solicitation
(using an air bubble)

$\Delta P^* = 400$ mbar



Fluid-driven solicitation

$\Delta P^* = 327$ mbar

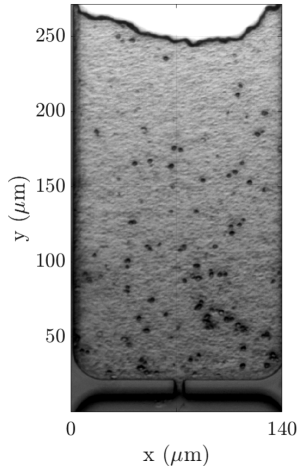


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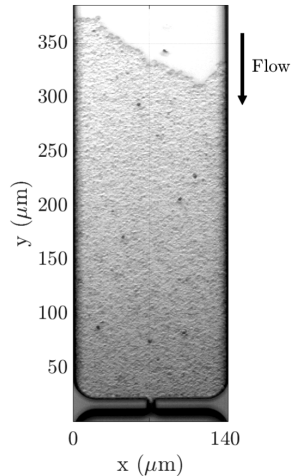
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Fluid-driven solicitation

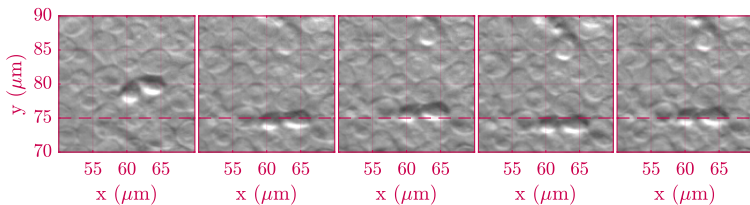
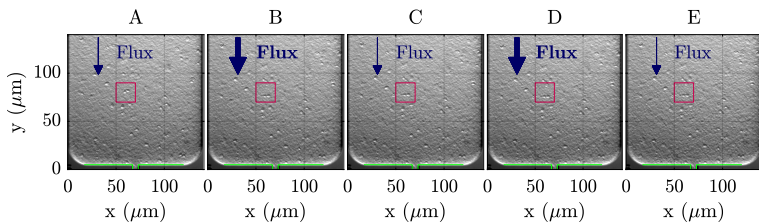
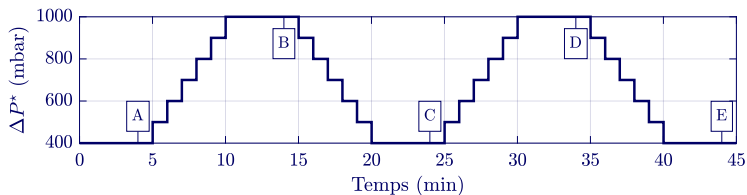
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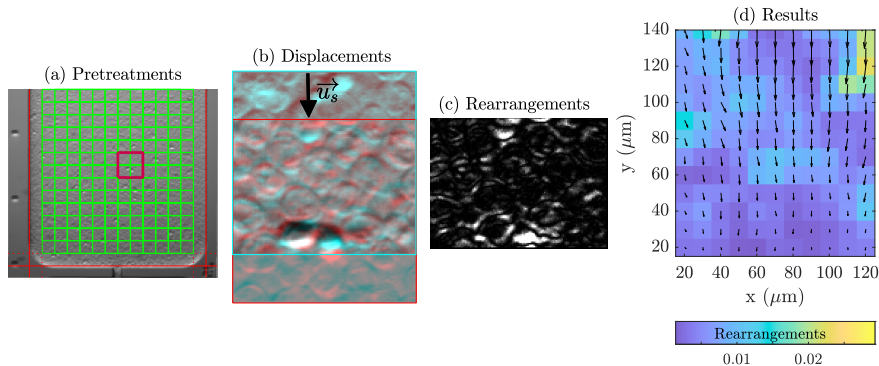
Relation stress/deformation \rightarrow Focus on fluid-driven case

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Mechanical sollicitation vs. displacement



$$\mathcal{F} = \frac{2\mu\kappa L}{H} \sim \frac{F_f}{F_a}$$

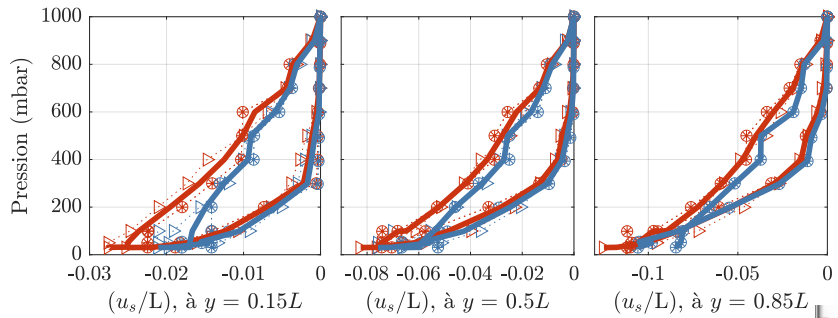


- > Method adapted from Cerbino *et al.* (2021)
- > First step similar to Particle Image Velocimetry

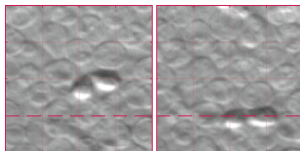
$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Influence of local rearrangements of yeasts ?

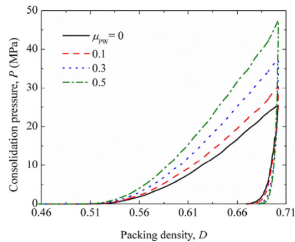
> Weak irreversibility due to rearrangements



- > Could the hysteresis be due to local rearrangement ?

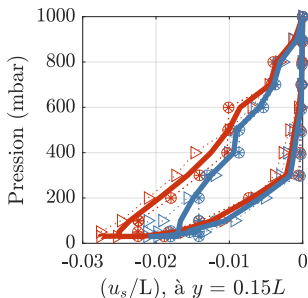


- > Could the hysteresis be due to local rearrangement ?
- Classical observation in dry granular media mechanics

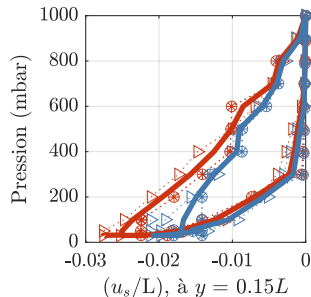


He et al. (2018)

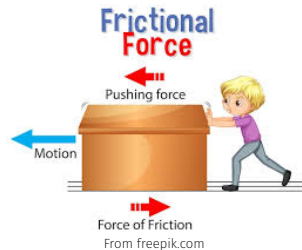
- > Could the hysteresis be due to local rearrangement?
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 - **But**, still hysteretic for the second cycle



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- > Could the friction to the walls be an ideal suspect ?

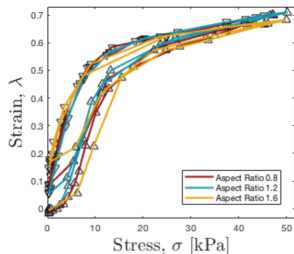
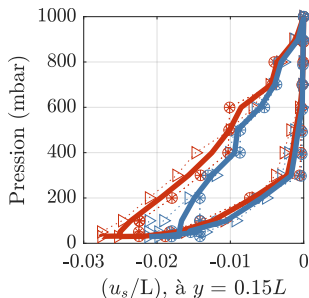


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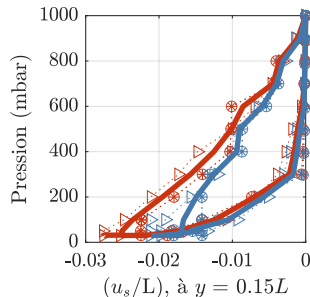
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- Started to be investigated for non-granular soft porous media



- > Could the hysteresis be due to local rearrangement ?
 - Classical observation in dry granular media mechanics
 - **But**, still hysteretic for the second cycle



Coulomb's friction coef. $\sim 0.03 - 0.06$

For human endothelial cells on glass

Dunn et al. (2007)

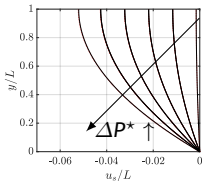
- > Could the friction to the walls be an ideal suspect ?
 - Started to be investigated for non-granular soft porous media
 - **Yet**, biological cells are slippery on glass/silicon



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

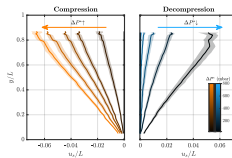
Theory (poromechanics)

> Quadratic profile of displacements



Experiments (yeast clog)

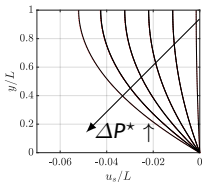
> **Linear profile** of displacements



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

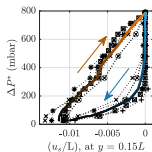
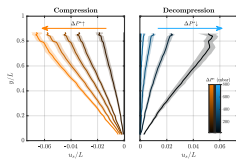
Theory (poromechanics)

- > Quadratic profile of displacements
- > Elastic behaviour expected



Experiments (yeast clog)

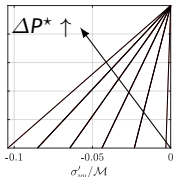
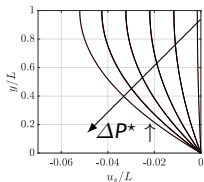
- > **Linear profile** of displacements
- > **Hysteresis** with energy dissipation



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

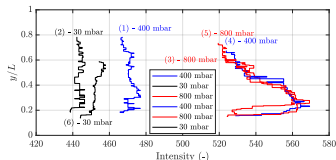
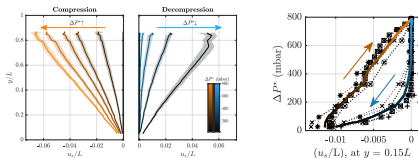
Theory (poromechanics)

- > Quadratic profile of displacements
- > Elastic behaviour expected
- > Stress gradient under compression



Experiments (yeast clog)

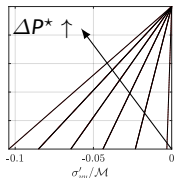
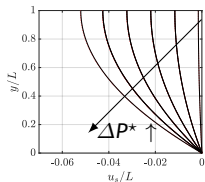
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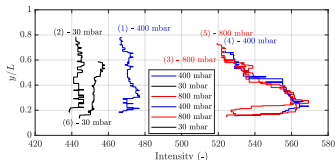
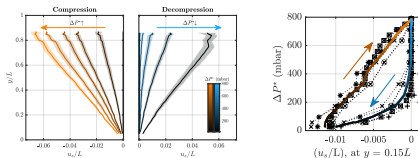
Theory (poromechanics)

- > Quadratic profile of displacements
- > Elastic behaviour expected
- > Stress gradient under compression
- > No potential energy storage



Experiments (yeast clog)

- > **Linear profile** of displacements
- > **Hysteresis** with energy dissipation
- > Stress gradient under compression
- > Potential **energy storage**



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Summary of the model for resolution

Name	Equation
Mass conserv. (fluid)	$\partial_t \phi + \partial_y(\phi v_f) = 0$
Definition of q	$q = \phi v_f + (1 - \phi)v_s$
Mass conserv. (solid)	$\partial_y q = 0$
Darcy	$\phi \times (v_f - v_s) = -\frac{k}{\eta} \partial_y P$
Solid constit. law	$\sigma'_{yy} = \mathcal{M} \frac{\phi - \phi_0}{1 - \phi_0}$
Mechanical equil.	$\partial_y \sigma'_{yy} + \frac{2\sigma'_F}{H} = \partial_y P$
Coulomb's law	$\begin{cases} \sigma'_F = \text{sgn}(v_s) \mu K \sigma'_{yy} & \iff v_s > 0 \\ \sigma'_F = -\frac{H\eta}{2k} q - \frac{H}{2} \partial_y \sigma'_{yy} & \iff \left \frac{H\eta}{2k} q + \frac{H}{2} \partial_y \sigma'_{yy} \right \leq \mu K \sigma'_{yy} \end{cases}$

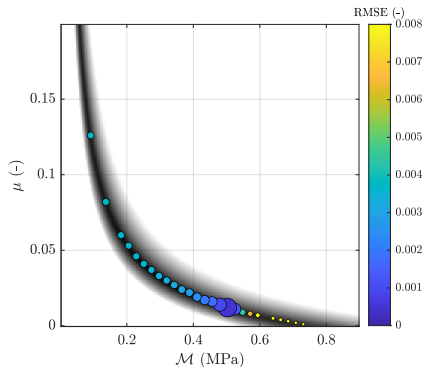
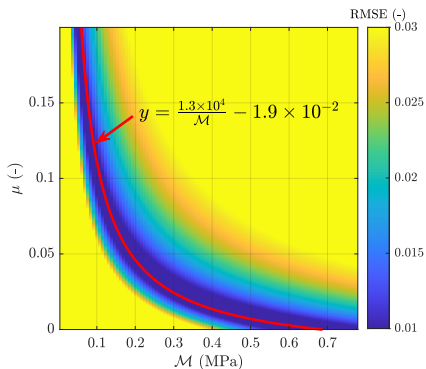
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- > Can be solved analytically in some specific cases
- > In general case, a numerical resolution is necessary

> RMSE: Root Mean-Square Error



> One sweep on a compression profile

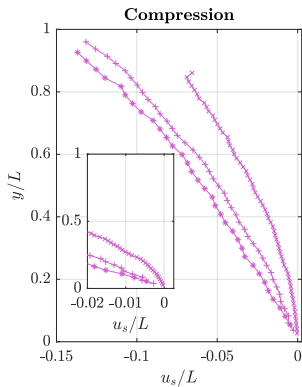
> One sweep on a decompression profile based on compression results

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

What do we get for piston-driven solicitation ?

30

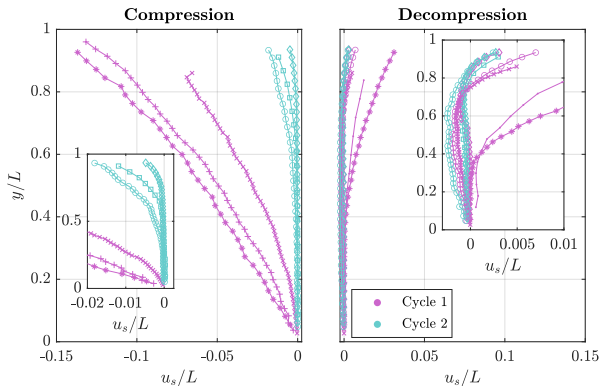
- > Linear displacement profiles
- > Less reproducibility



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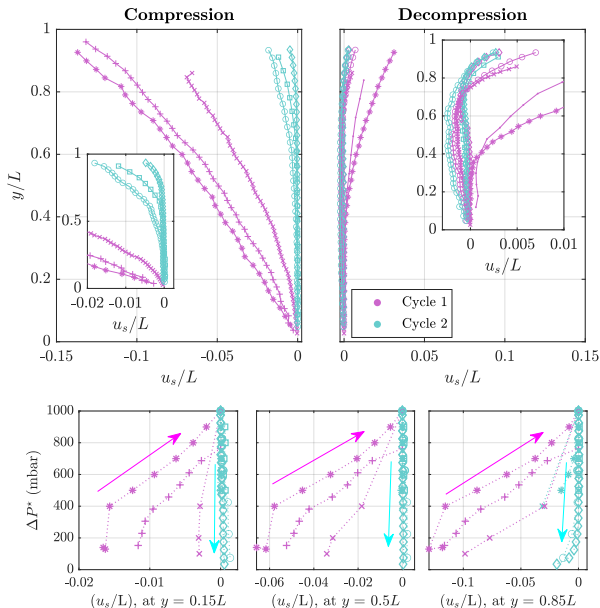
- > Linear displacement profiles
- > Less reproducibility
- > Decompression: very weak displacements
- > Exotic behaviour at decompression



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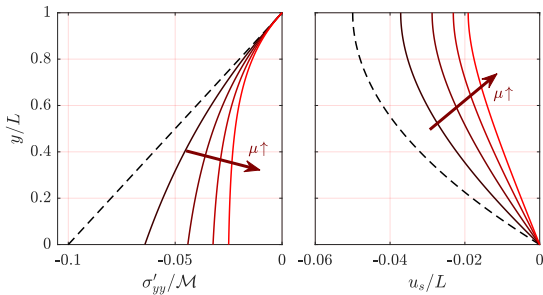
What do we get for piston-driven solicitation ?

- > Linear displacement profiles
- > Less reproducibility
- > Decompression: very weak displacements
- > Exotic behaviour at decompression
- > Energy dissipation by hysteresis
- > Strong differences between the cycles



Fluid-driven compression:

- > Stress profile \neq linear
- > Displacements no longer quadratic

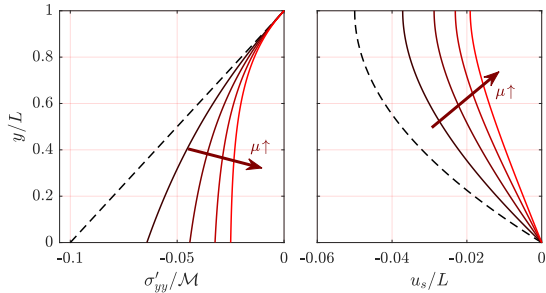


$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

Model behaviour

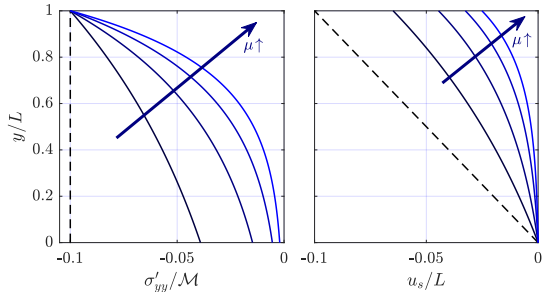
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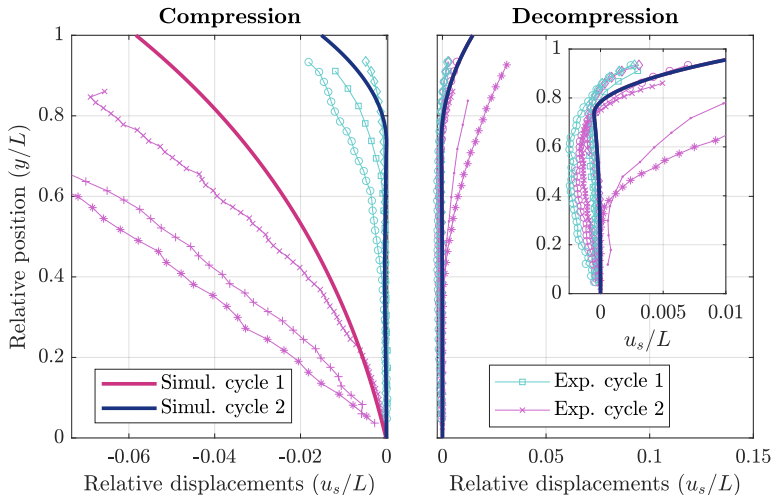


Piston-driven compression:

- > Stress exponentially damped
- > Displacements exponentially damped



$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$



- > Acceptable agreement with experimental data
- > Exotic behaviour at decompression is validated by the model