

# Navier

## Rhéophysique et Milieux Poreux

### Mousses et Matériaux aérés

Olivier Pitois

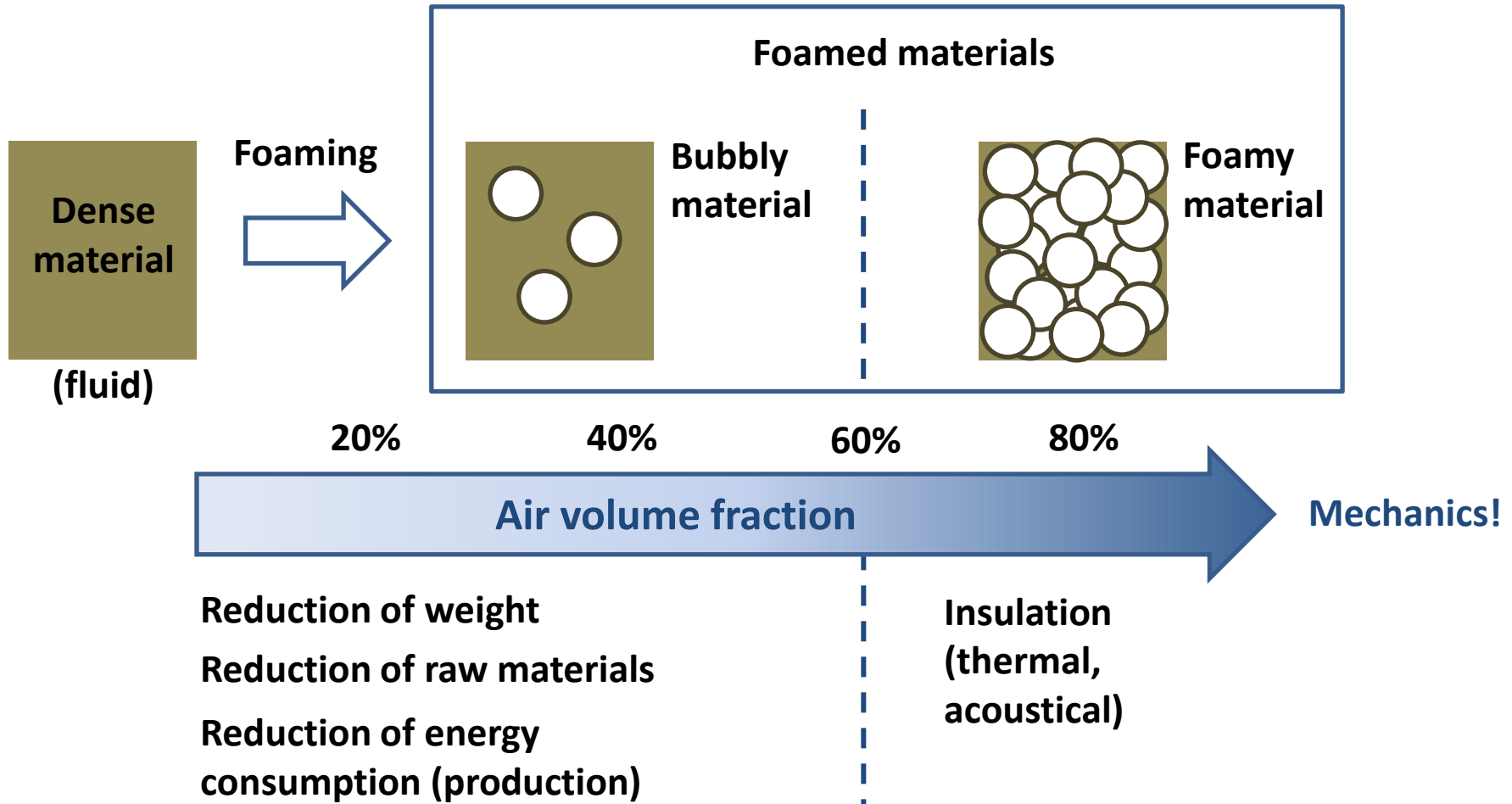
Xavier Chateau, Abdoulaye Fall, Julie Goyon, Yacine Khidas, Vincent Langlois,  
Guillaume Ovarlez, Florence Rouyer

PhDs: Benjamin Haffner, Lucie Ducloué, François Gorlier,  
Blandine Feneuil, Asmaa Kaddami

SIE 21 mai 2019



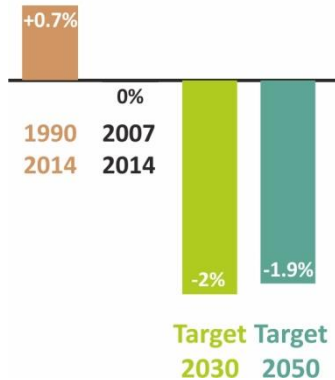
# Incorporation of air in dense materials



# Thermal insulation of buildings

## Isolants thermiques les plus utilisés

Energy consumption  
for the Building sector



Rénovations  
thermiques  
(400 000 / an)



Mousses plastiques



Laines minérales



Tour Grenfell (Londres, 2017)

Conductivité :  
 $0.024-0.03 \text{ W m}^{-1} \text{ K}^{-1}$

inflammable

Haute toxicité  
lors de la combustion

Chimie du pétrole

Recyclable pour certains  
plastiques

Energie grise : 500-1000  
 $\text{kWh/m}^3$

Conductivité :  
 $0.032-0.045 \text{ W m}^{-1} \text{ K}^{-1}$

Dégagement de fibres  
Cancérogènes jusqu'en  
2001 (IARC)  
Liant organique toxique  
(REACH)

Pas de recyclage

Energie grise : 250  $\text{kWh/m}^3$

### Mousses minérales

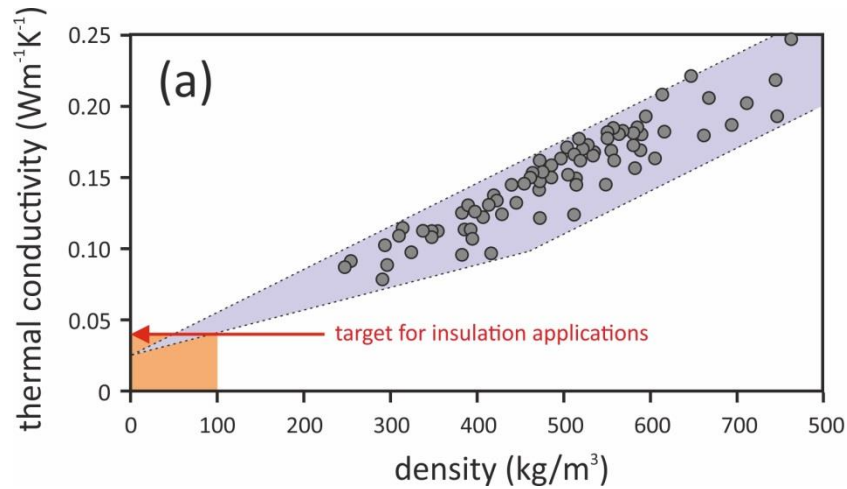
Les avantages des mousses plastiques  
sans leurs inconvénients ?

Problème actuel : **pas assez isolantes**

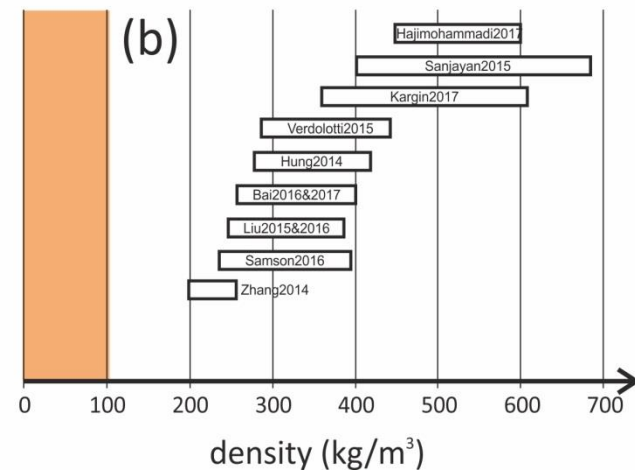
# Scientific challenges

## Enlightening examples:

Mousse de ciment



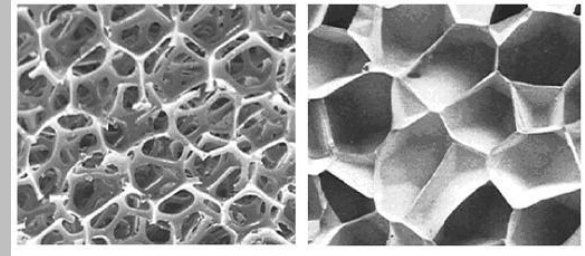
Mousse de géopolymère



# Scientific challenges

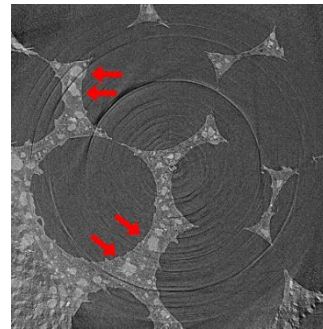
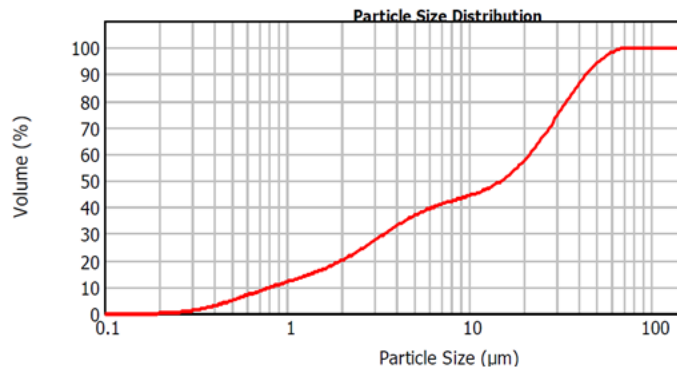
## Complex fluid foams (made from complex fluids)

Pour mémoire :

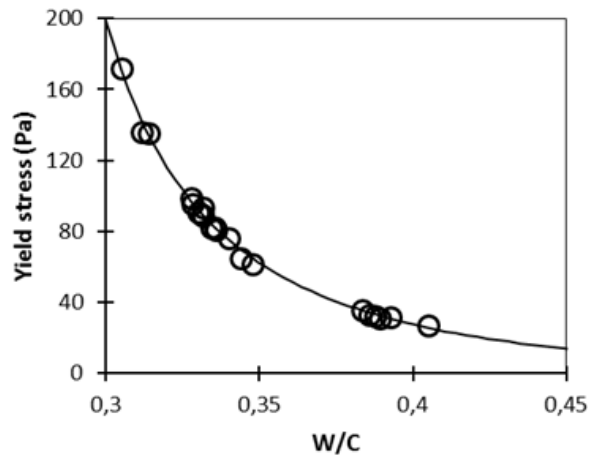


Mousses polymères

### Exemple: ciment



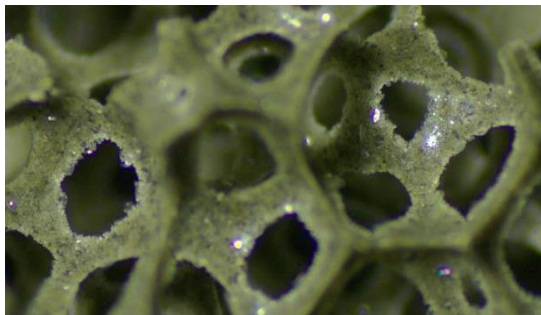
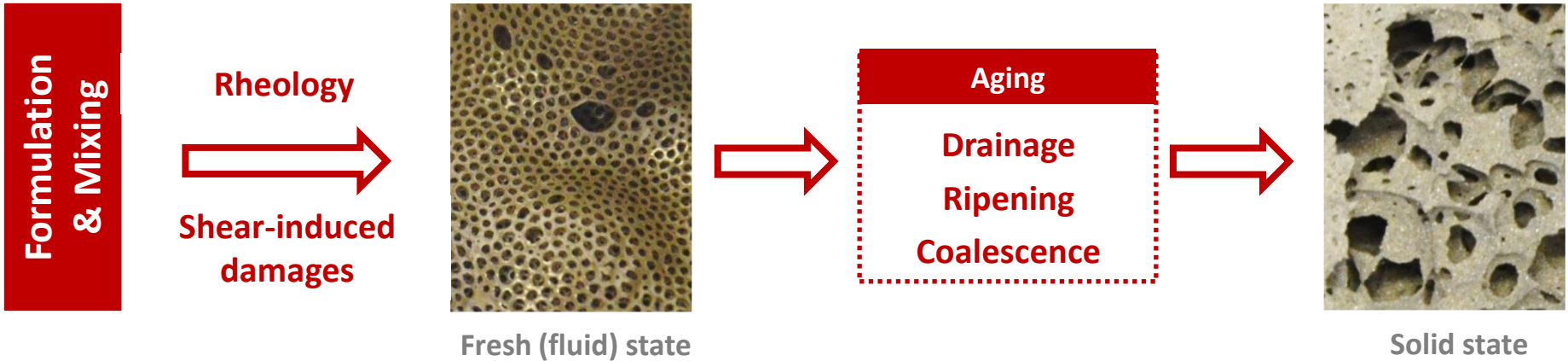
Les grains doivent se loger entre les bulles



Rhéologie complexe, très sensible à la formulation (eau/ciment, adjuvants, **tensioactifs !!!**)

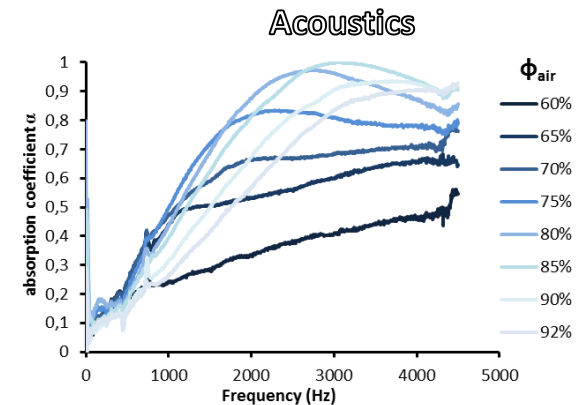
# Scientific challenges

## Control of the morphology



Cement foam, B. Feneuil (PhD, Navier)

Acoustics  
Mechanics  
Thermics  
Imbibition / Drying



# Research Objectives

## Complex fluid foams

**Understanding the effect of particle size  
on properties of foams**

**Understanding how complex rheology of the  
interstitial material changes the foam properties**

## Controlling the morphology of mineral foams

# **Plan of the presentation**

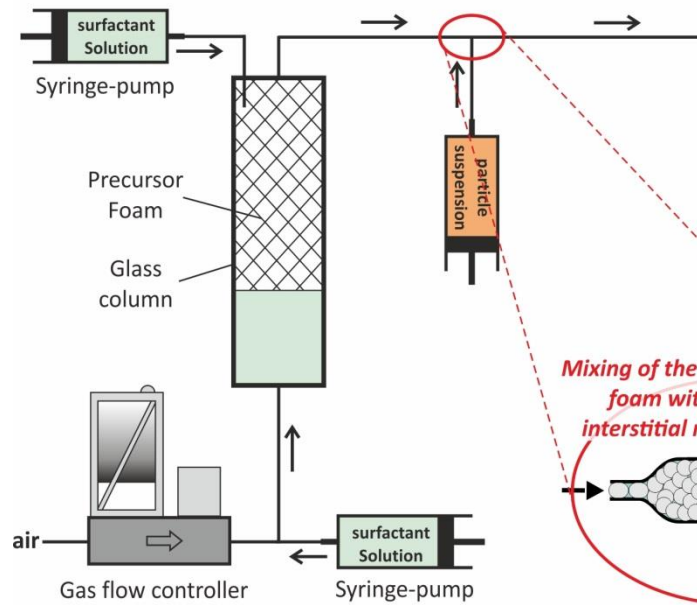
**I. Drainage of foams made from particle suspensions**

**II. Rhéologie of aerated systems**

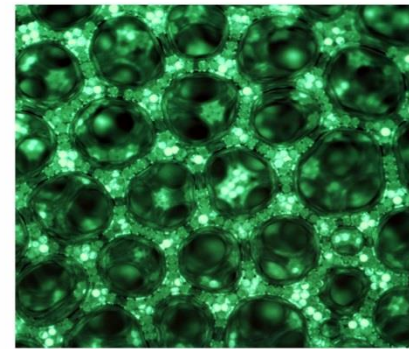
**III. Morphology control of mineral foams**



# High-precision foaming

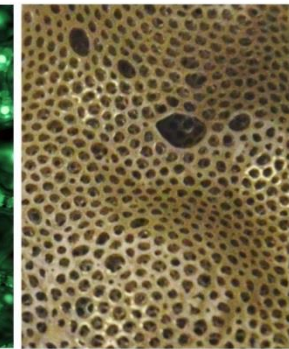


Model systems



1 mm

Materials



10 mm

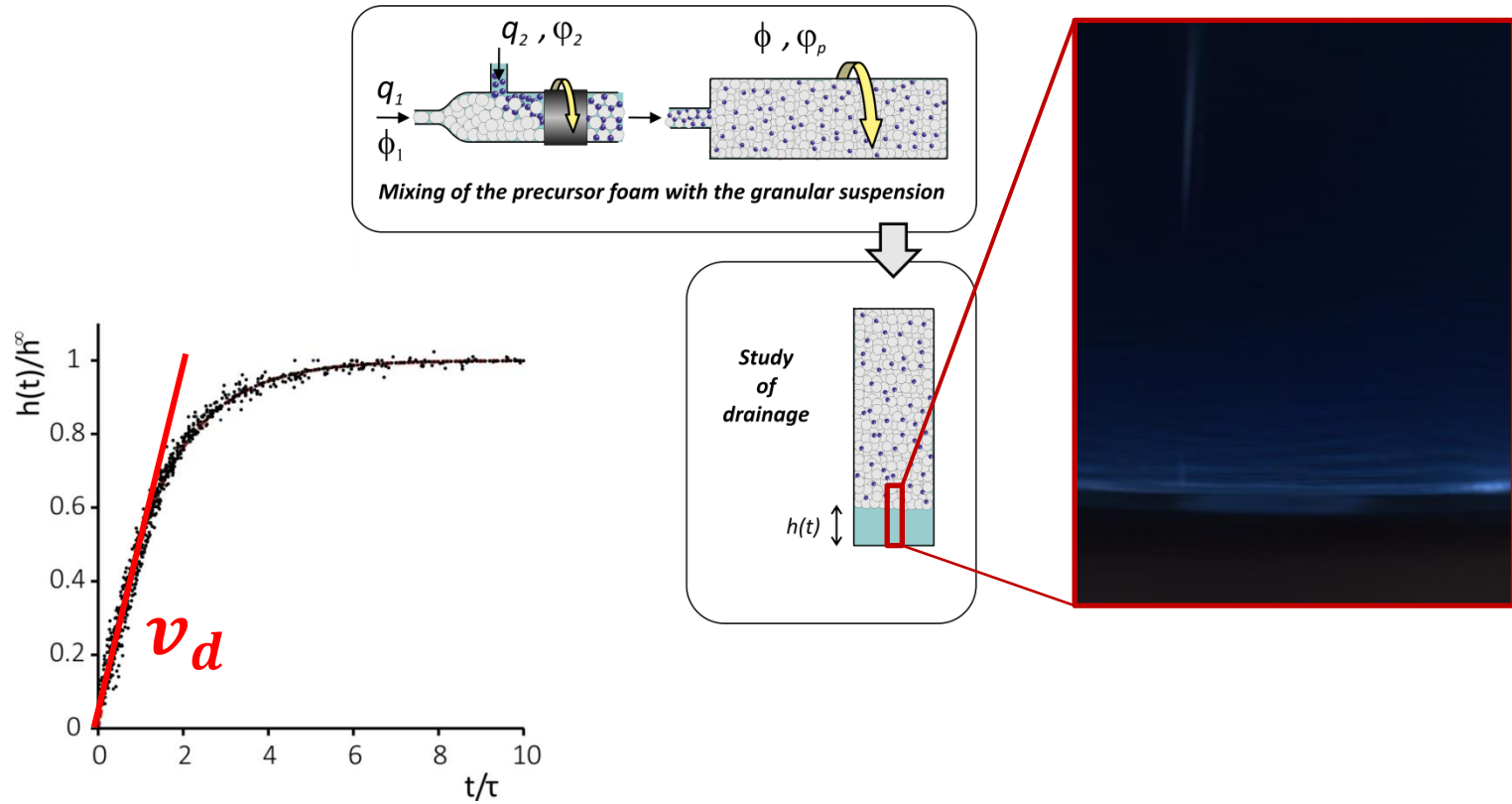
Control

Air volume fraction

Bubble size

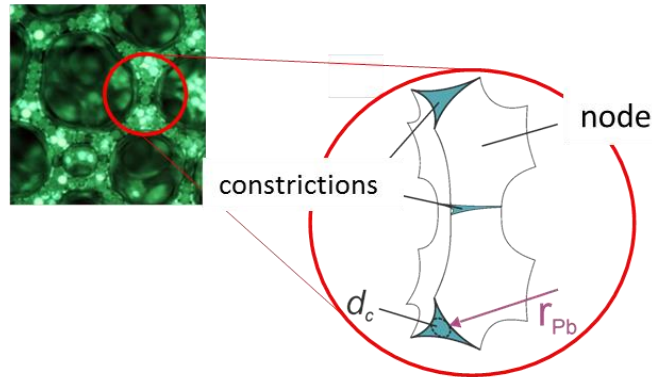
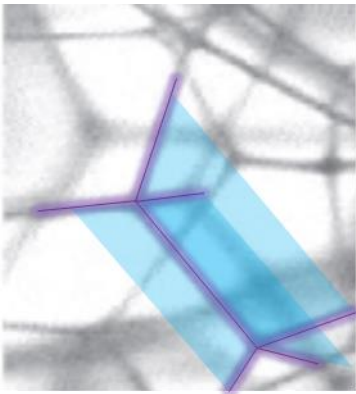
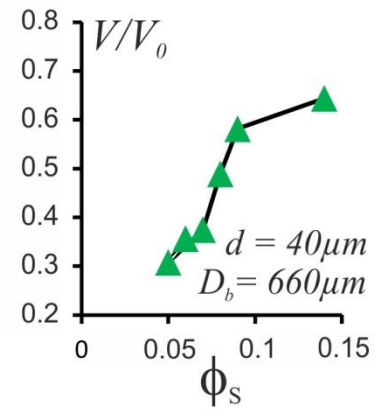
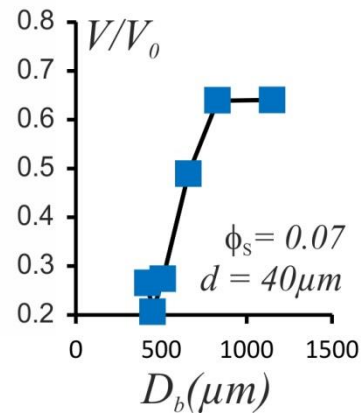
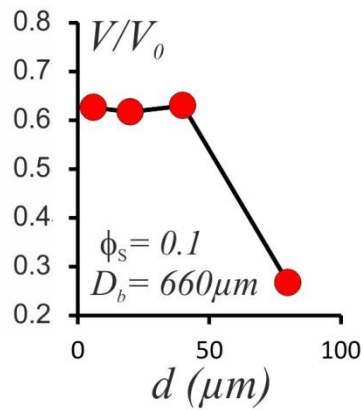
Composition of the interstitial phase

# Drainage of particle-loaded foams



# Drainage of particle-loaded foams

$$\varphi_p = 16\%$$

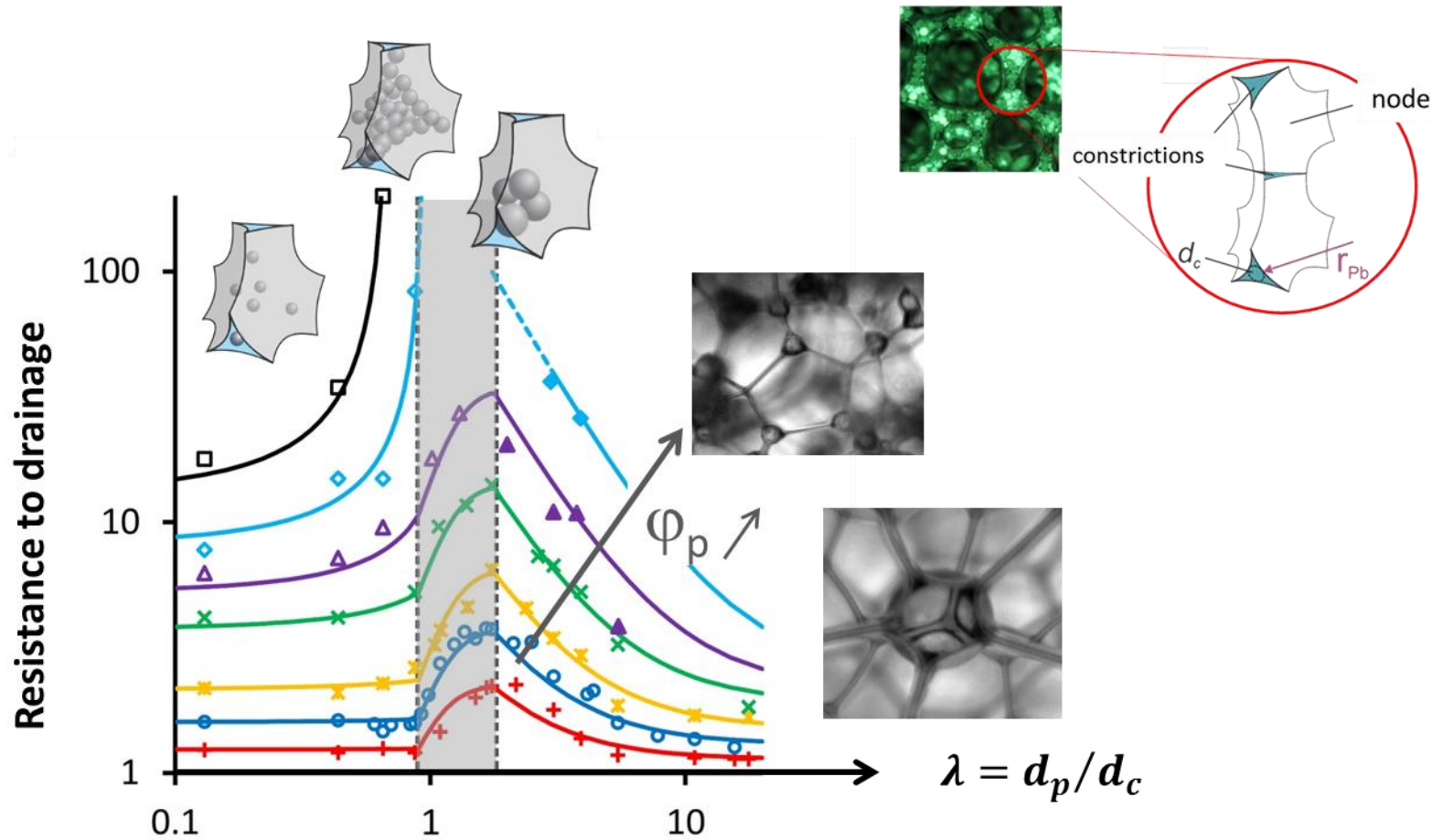


**Control parameter**

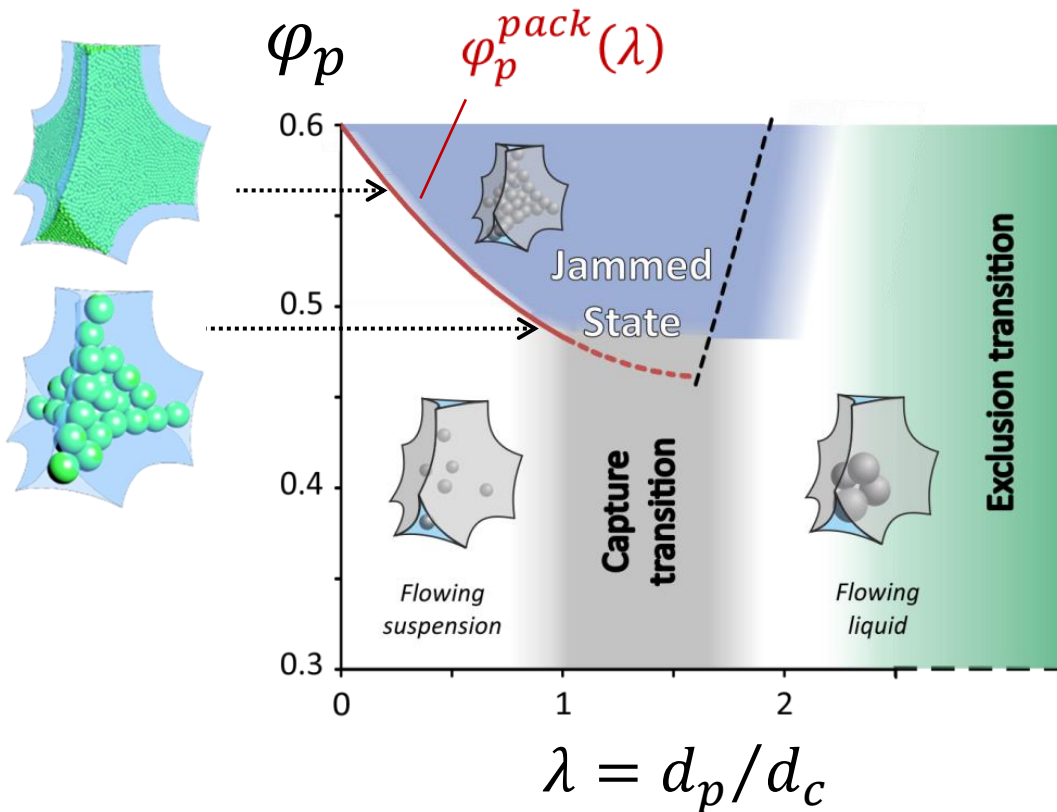
$$\lambda = \frac{d}{d_c(D_b, \phi)}$$

# Drainage of particle-loaded foams

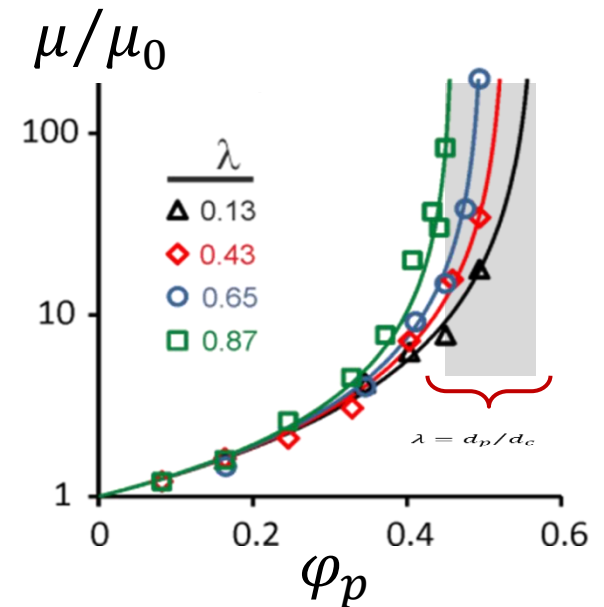
Thèse de Benjamin Haffner  
2012-2015



# Drainage of particle-loaded foams



Ecoulement et blocage de la suspension



B. Haffner, Y. Khidas, O. Pitois, *The drainage of foamy granular suspensions*, Journal of colloid and interface science (2015), 458, 200-208

F. Rouyer, B. Haffner, N. Louvet, Y. Khidas, O. Pitois, *Foam clogging*, Soft Matter (2014) 10, 6990-6998

Y. Khidas, B. Haffner, O. Pitois, *Capture-induced transition in foamy suspensions*, Soft Matter (2014) 10, 4137-4141

B. Haffner, Y. Khidas, O. Pitois, *Flow and jamming of granular suspensions in foams*, Soft Matter (2014) 10, 3277-3283

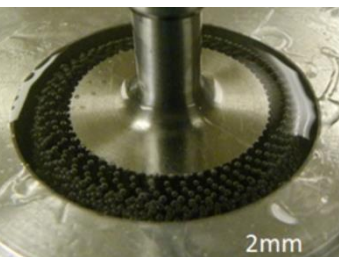
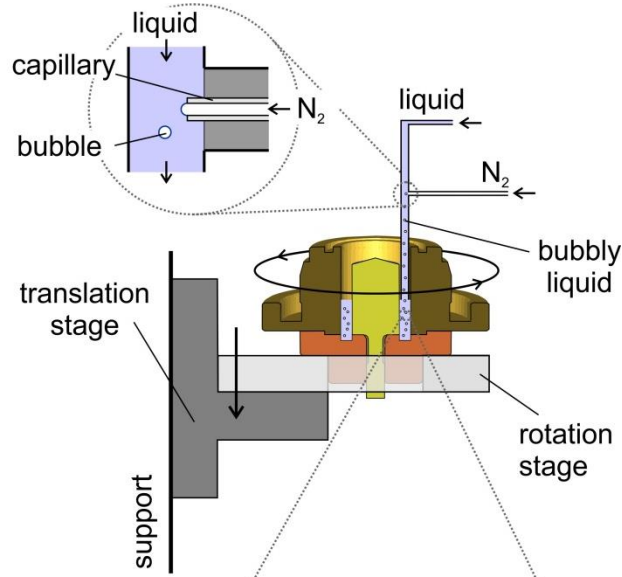
# Plan of the presentation

**I. Drainage of foams made from particle suspensions**

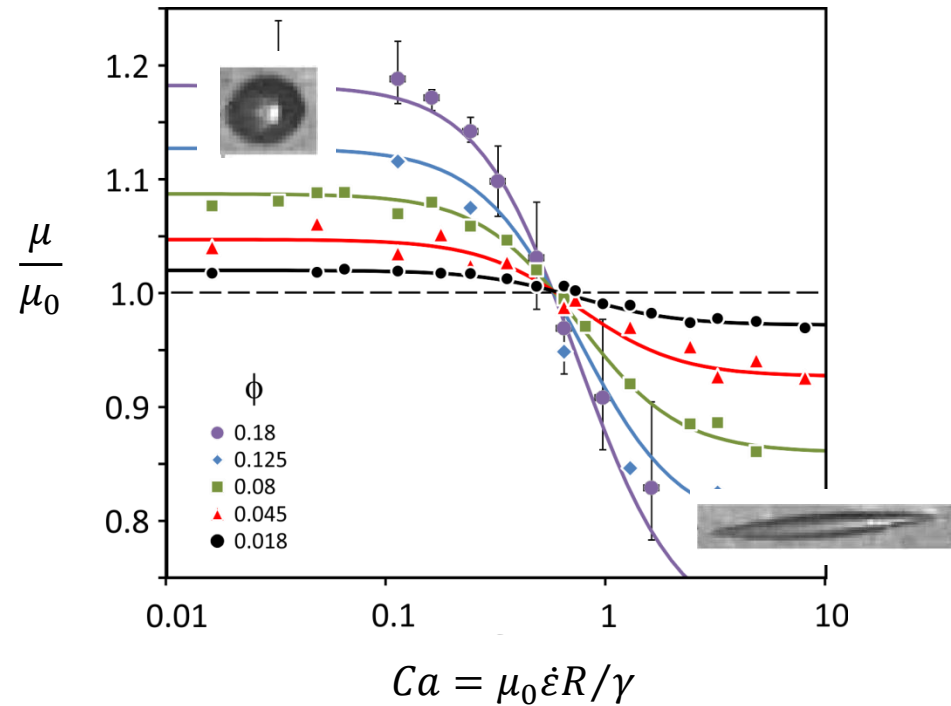
**II. Rhéologie of aerated systems**

**III. Morphology control of mineral foams**

# Shear viscosity of bubbly Newtonian liquids



Comparaison avec les modèles  
(Frankel & Acrivos - 1970)



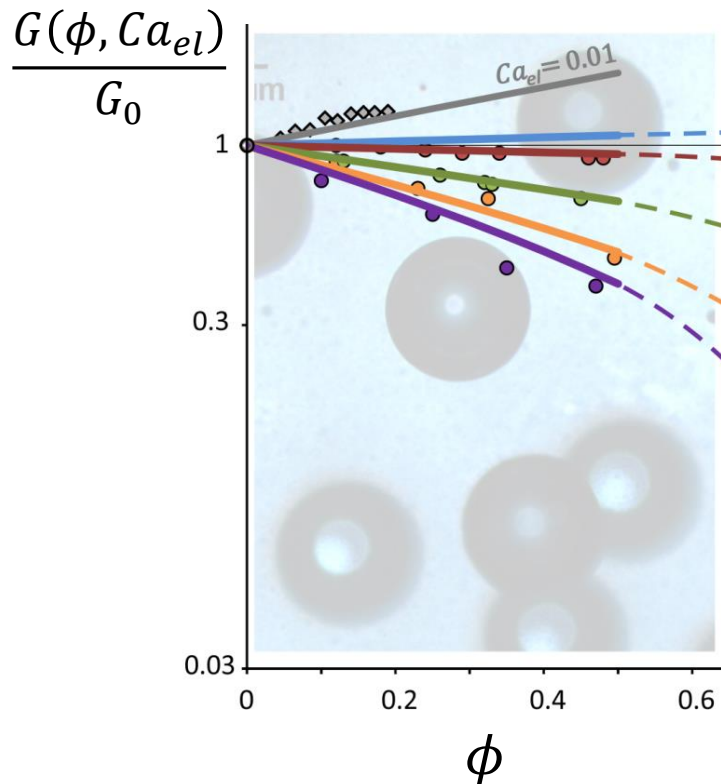
R. Morini, X. Chateau, G. Ovarlez, O. Pitois, L. Tocquer, Steady shear viscosity of semi-dilute bubbly suspensions, *Journal of Non-Newtonian Fluid Mechanics* 264, 19-24 (2019)

R. Morini, X. Chateau, G. Ovarlez, O. Pitois, L. Tocquer, Viscous friction of squeezed bubbly liquid layers, *Soft Matter* 14, 8372 (2018)

# Elasticity of soft bubbly materials

Thèse de Lucie Ducloué  
2011-2014

Nombre élasto-capillaire :  $Ca_{el} = RG_0/\gamma$



$$Ca_{el} \ll 1 \rightarrow G/G_0 \approx 1 + \phi$$

$$Ca_{el} = 0.5 \rightarrow G/G_0 \approx 1$$

$$Ca_{el} \gg 1 \rightarrow G/G_0 \approx 1 - \frac{5}{3}\phi$$

Régime dilué

**Modélisation pour le régime concentré**

$$\frac{G}{G_0} \approx 1 - \frac{\phi(2Ca_{el} - 1)}{1 + 6Ca_{el}/5 + 2\phi(2Ca_{el} - 1)/5}$$

L. Ducloue, O. Pitois, J. Goyon, X. Chateau, G. Ovarlez, Rheological behaviour of suspensions of bubbles in yield stress fluids, *Journal of Non-Newtonian Fluid Mechanics* (2015) 215, 31-39

L. Ducloue, O. Pitois, J. Goyon, X. Chateau, G. Ovarlez, Coupling of elasticity to capillarity in soft aerated materials, *Soft Matter* (2014) 10, 5093-5098

N.-T. Thy Linh, L. Ducloué, G. Ovarlez, X. Chateau, Overall Properties of a Soft Porous Material: Surface Tension Effects, *Proceedings of the Fifth Biot Conference on Poromechanics, ASCE* (2013) 1895-1902



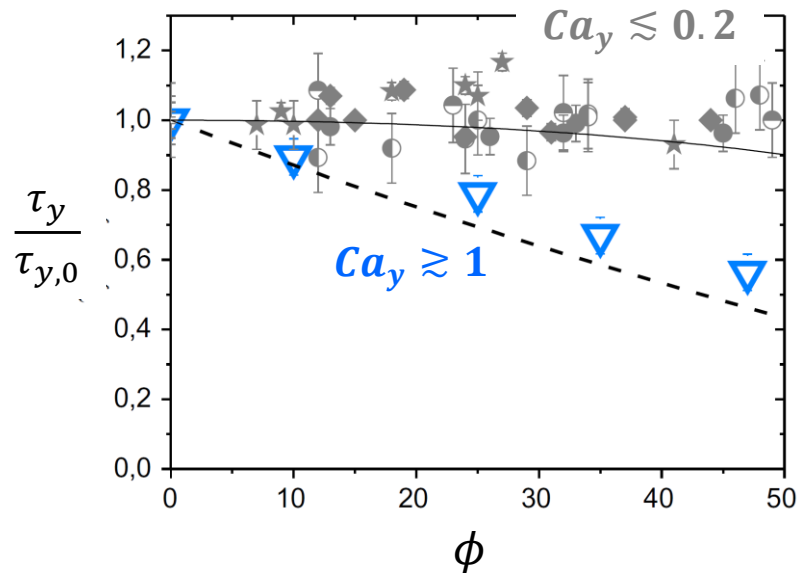
# Plasticity of bubbly yield stress fluids

Thèse de Lucie Ducloué  
2011-2014

Thèse de Blandine Feneuil  
2015-2018

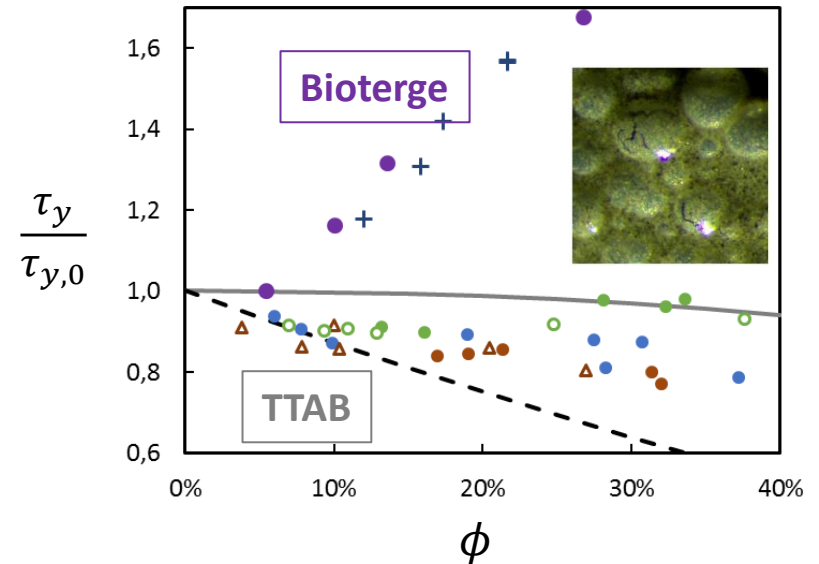
Nombre capillaire de Bingham  $Ca_y = R\tau_{y,0}/\gamma$

Emulsion concentrée



L. Ducloué, O. Pitois, J. Goyon, X. Chateau, G. Ovarlez.,  
Rheological behaviour of suspensions of bubbles in yield stress fluids,  
*Journal of Non-Newtonian Fluid Mechanics* (2015) 215, 31-39

Pâte de ciment



Thèse de B. Feneuil  
(2015-2018)

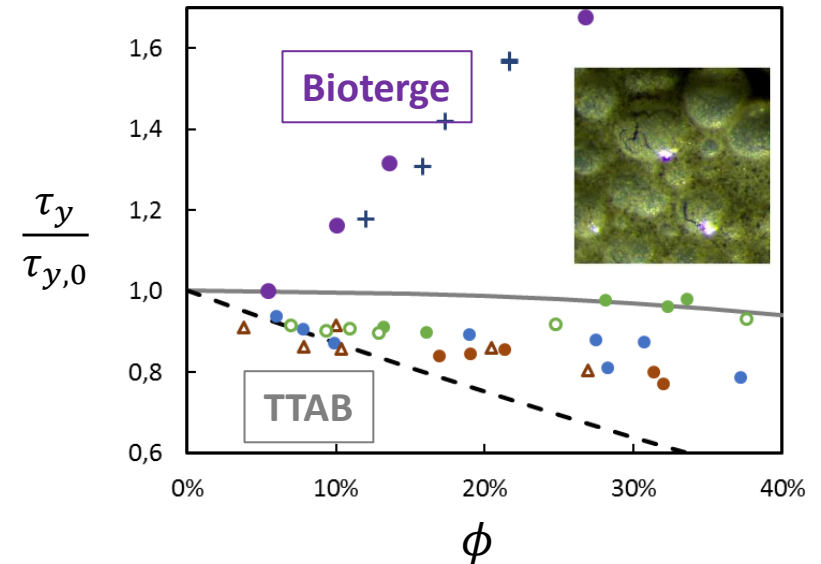
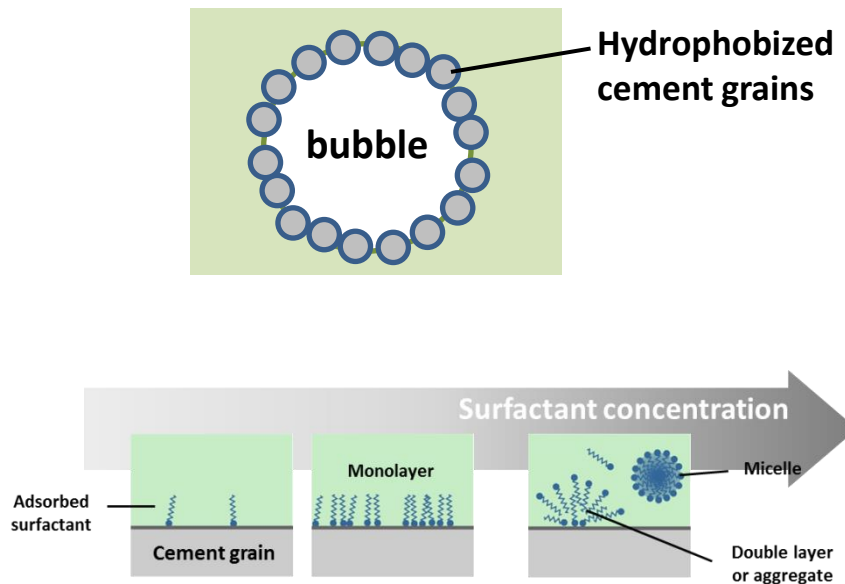
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Thèse de Lucie Ducloué  
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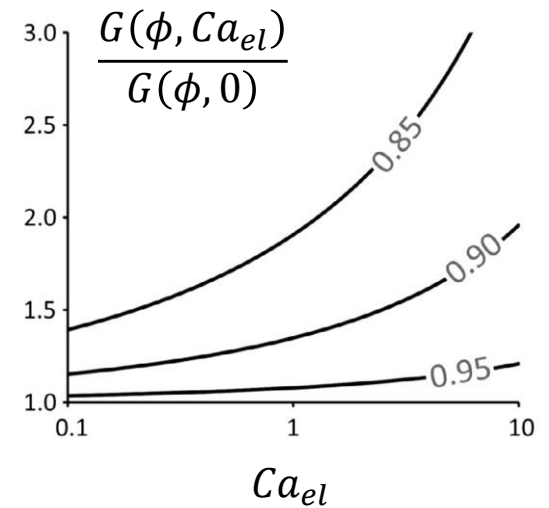
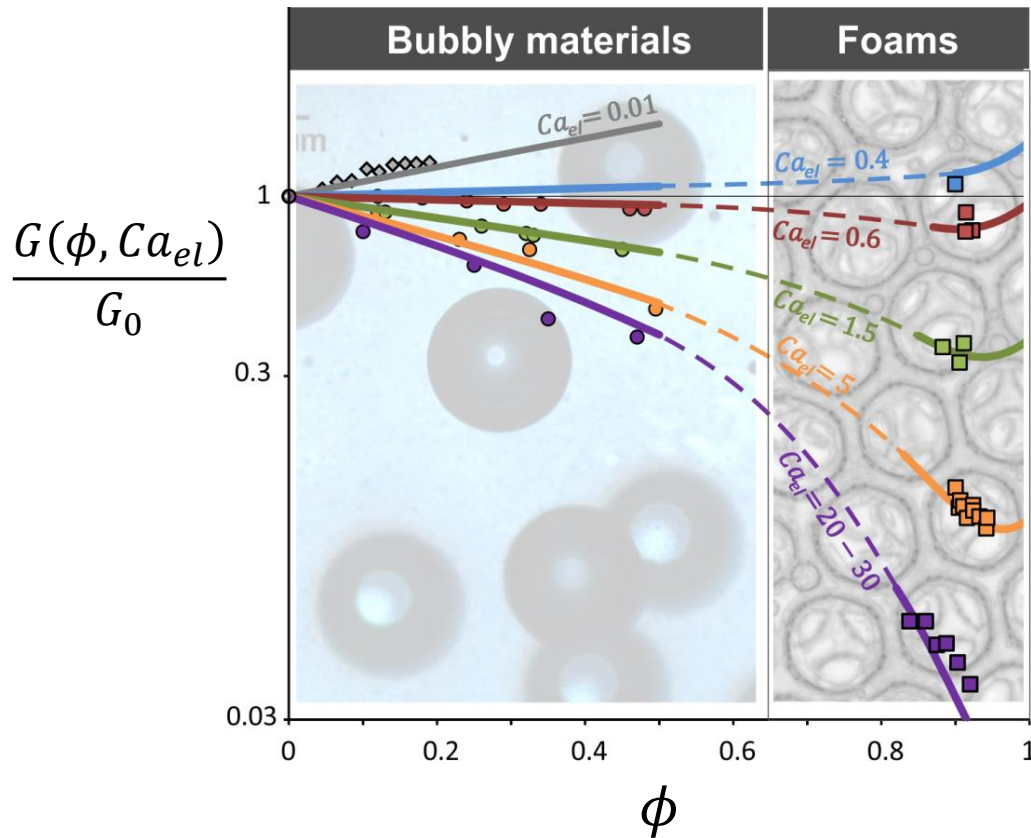
Thèse de Blandine Feneuil  
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Pâte de ciment

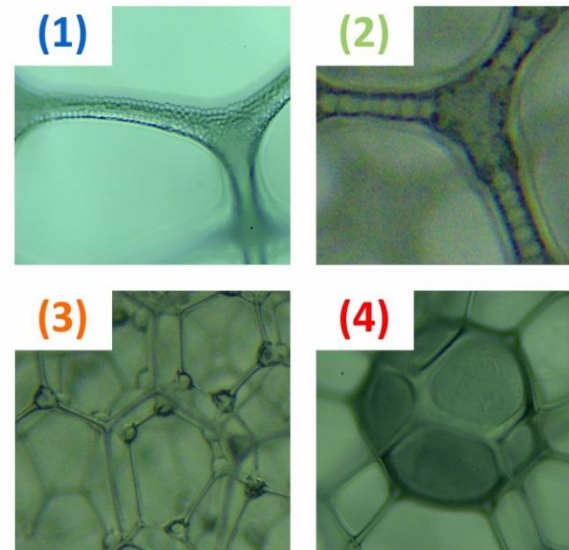
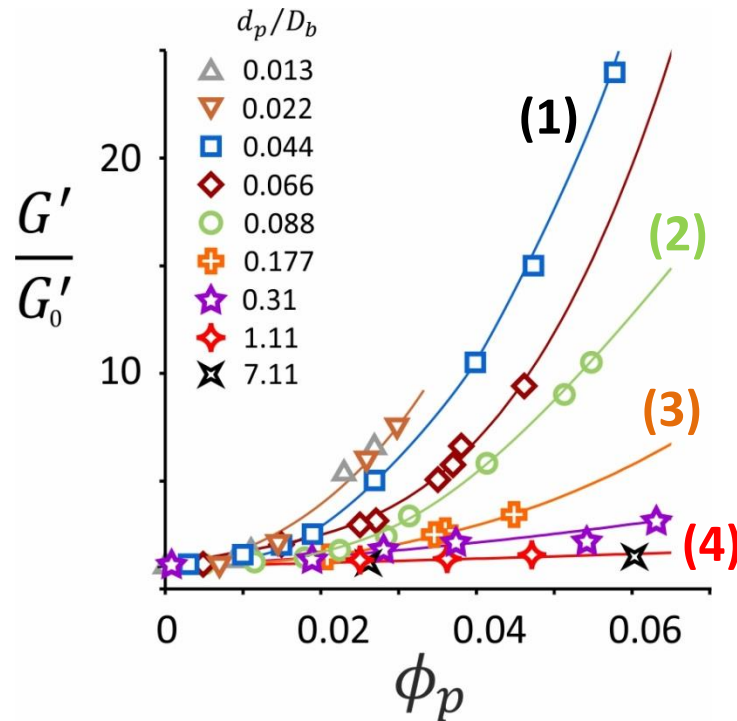


# Elasticity of soft solid foams

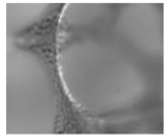
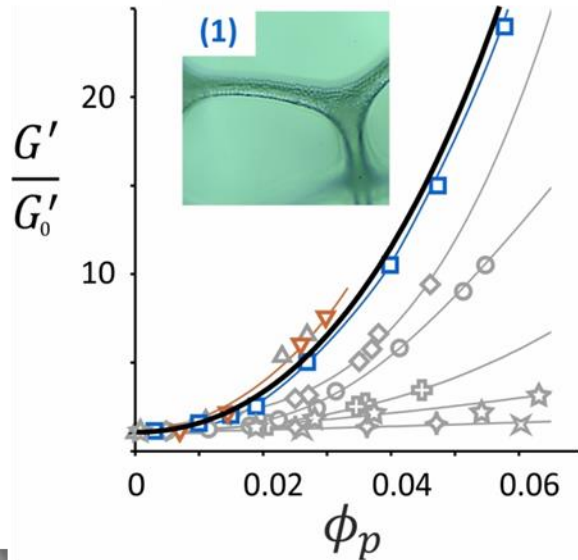


F. Gorlier, Y. Khidas, O. Pitois, Coupled elasticity in soft solid foams,  
*Journal of Colloid and Interface Science* 501 (2017) 103–111

# Elasticity of particle-loaded foams



# Elasticity of particle-loaded foams

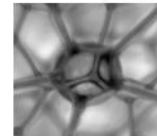
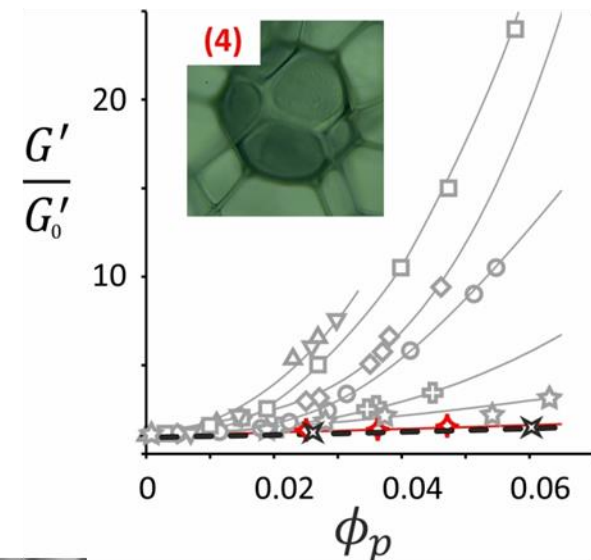


**Granular skeleton = elastic matrix**

$$G(\phi, \phi_p) \approx G_0(1 - \phi)^2 + G(\phi, 0)$$

$$G_0 \approx 150 \text{ kPa}$$

**Confinement pressure exerted by the bubbles  $P_c \approx 400 \text{ Pa}$**

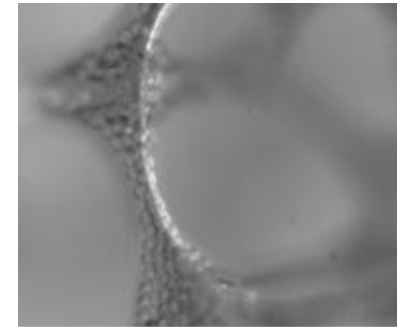
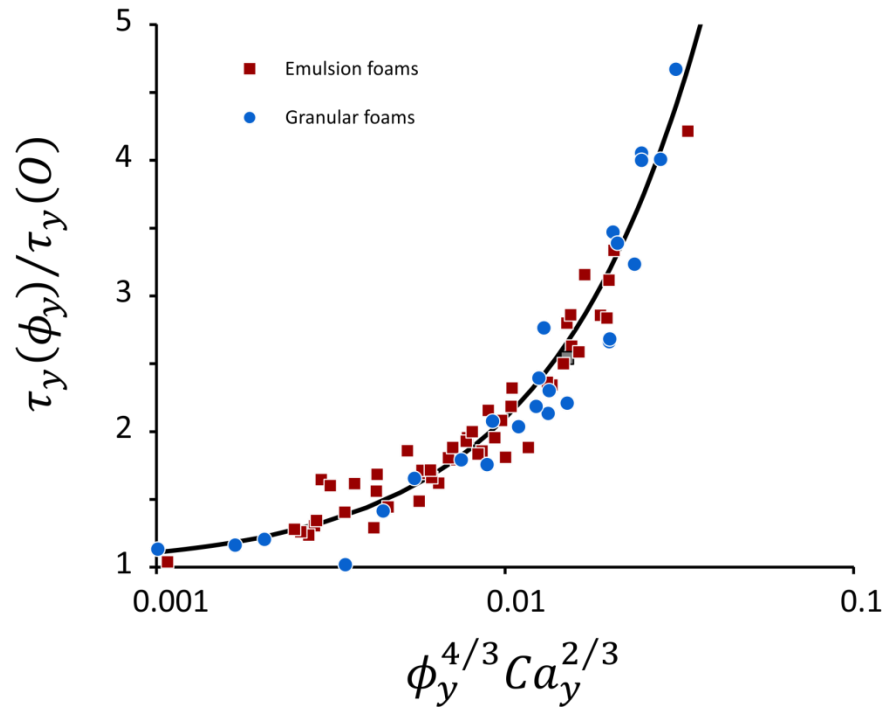


**Large solid inclusions in an elastic matrix (foam)**

$$G(\phi, \phi_p) \approx G(\phi, 0) \times \left(1 - \frac{\phi_p}{\phi_p^*}\right)^{-2.5\phi_p^*}$$

# Plasticity of complex foams

Thèse de François Gorlier  
2014-2017



Mohr-Coulomb

$$\tau_{y0} = 0.3 \times P_c$$

$$Ca_y = R\tau_{y0}/\gamma$$

# **Plan of the presentation**

**I. Drainage of foams made from particle suspensions**

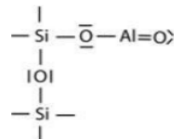
**II. Rhéologie of aerated systems**

**III. Morphology control of mineral foams**

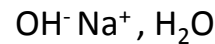
# Metakaolin foams (= geopolymers)

Thèse d'Asmaa Kaddami  
2016-2019

Métakaolin + Solution basique

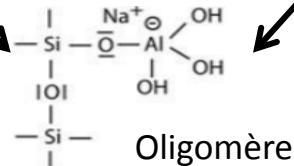


Silicate de sodium

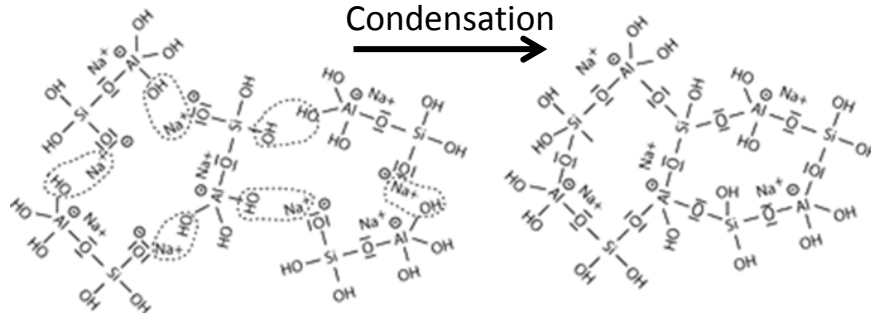


Temps de prise ~ heures

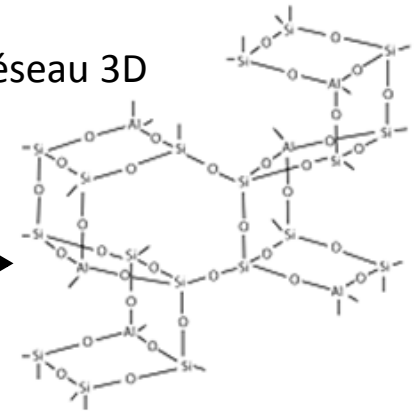
Matériau inorganique  
de structure semi-cristalline à  
amorphe



Condensation



Réseau 3D

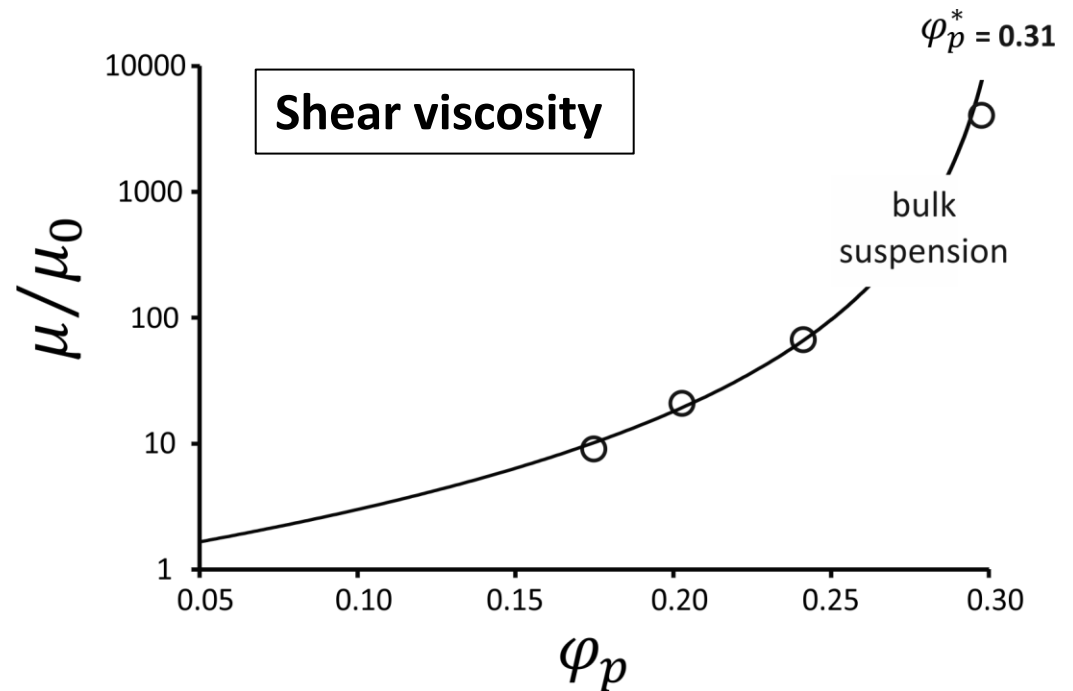
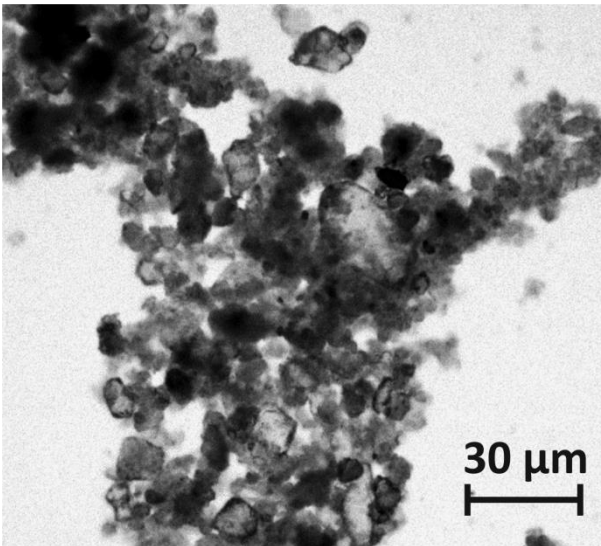




# Metakaolin foams (= geopolymers)

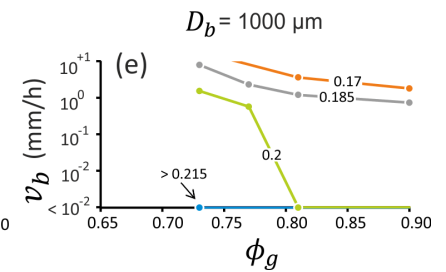
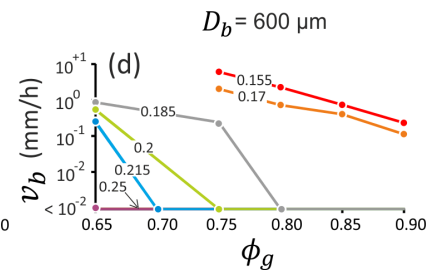
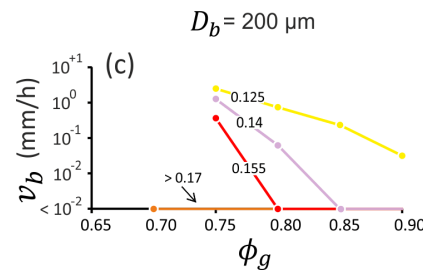
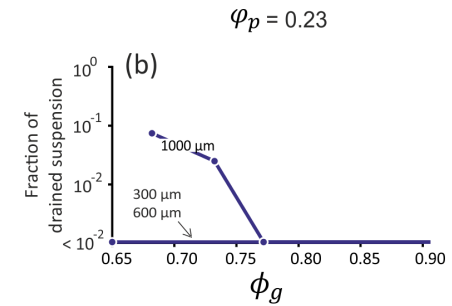
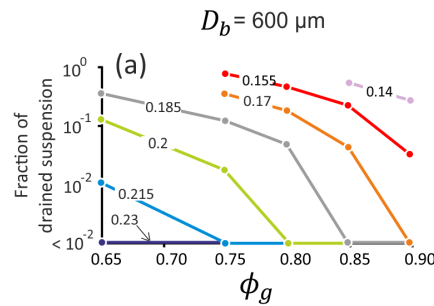
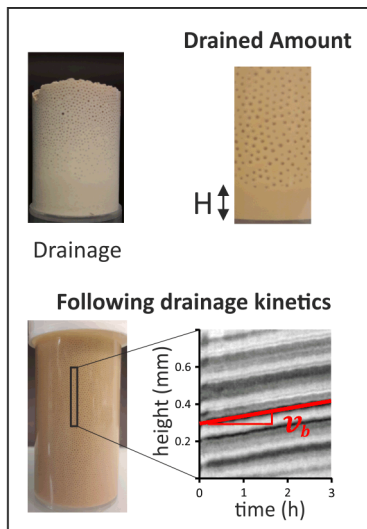
Thèse d'Asmaa Kaddami  
2016-2019

## Suspension of plate-like particles



# Metakaolin foams (= geopolymers)

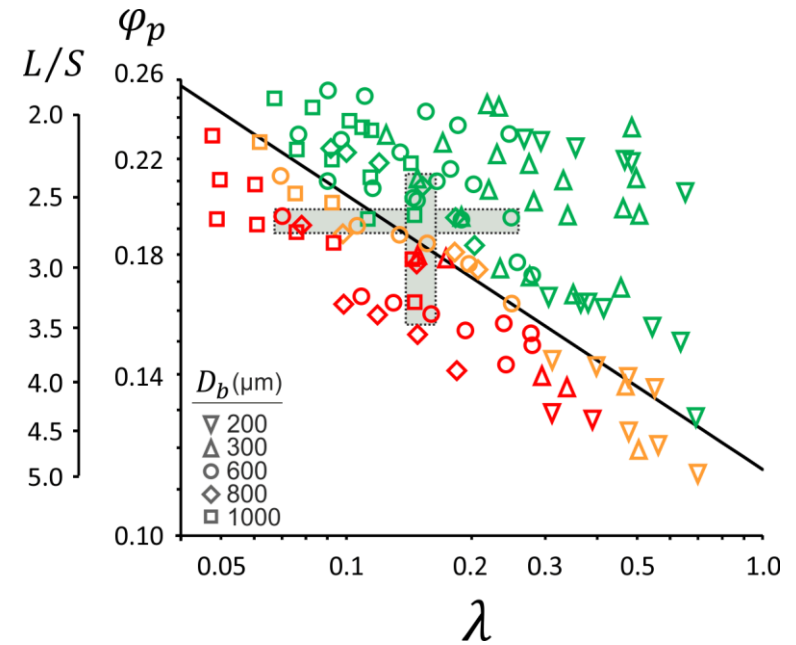
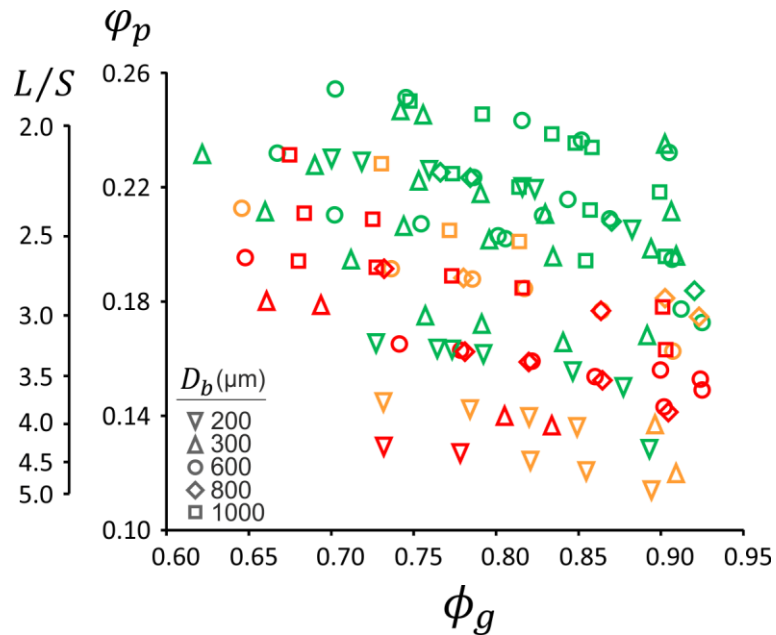
## Drainage



# Metakaolin foams (= geopolymers)

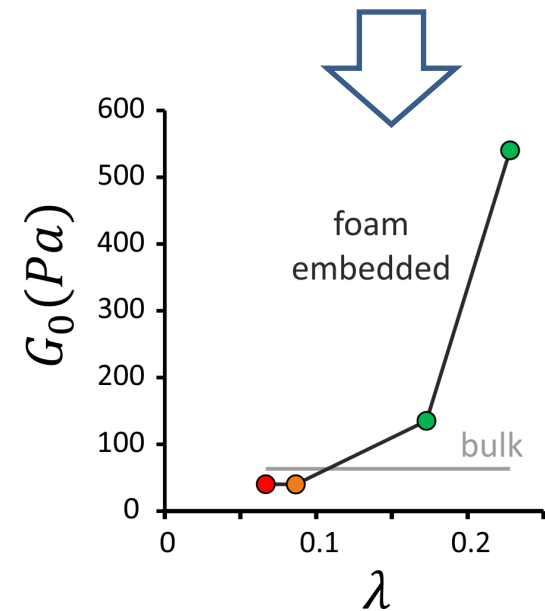
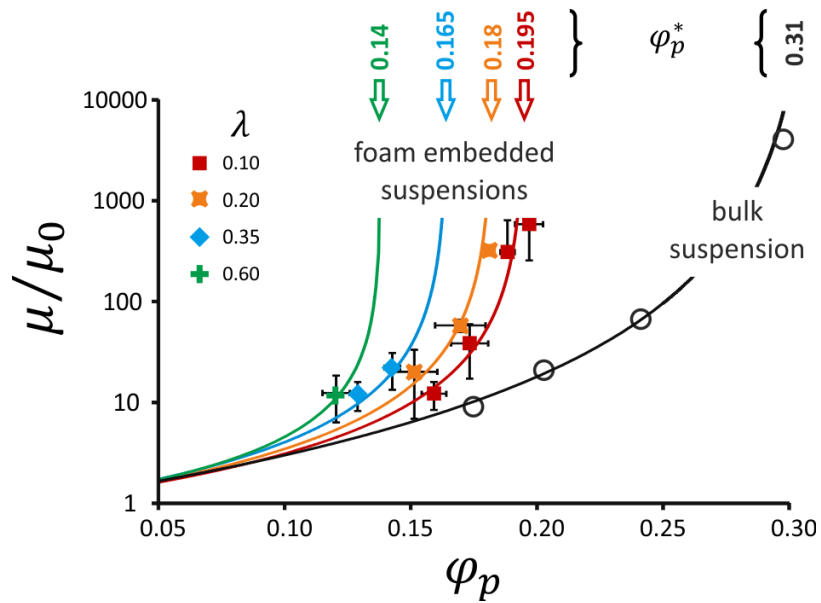
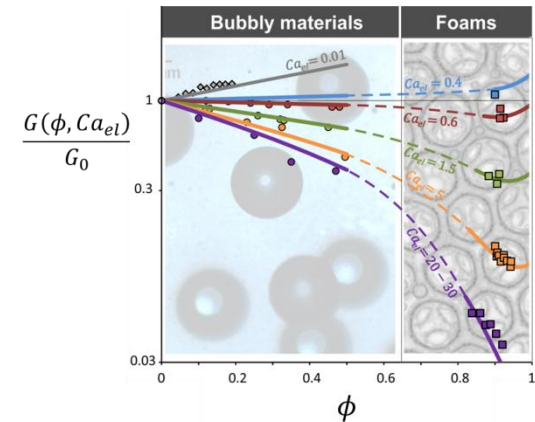
Thèse d'Asmaa Kaddami  
2016-2019

## Controlling the foam morphology



# Metakaolin foams (= geopolymers)

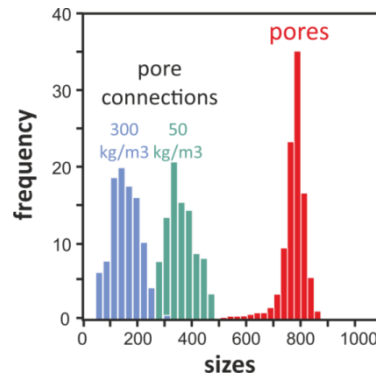
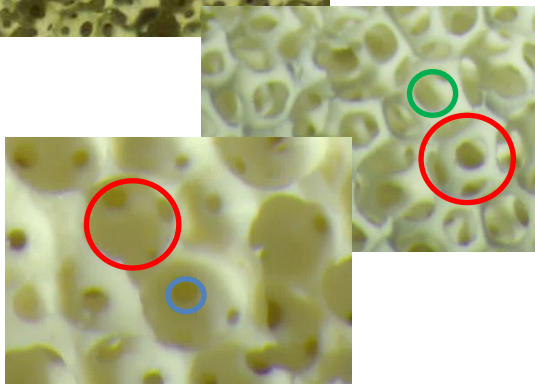
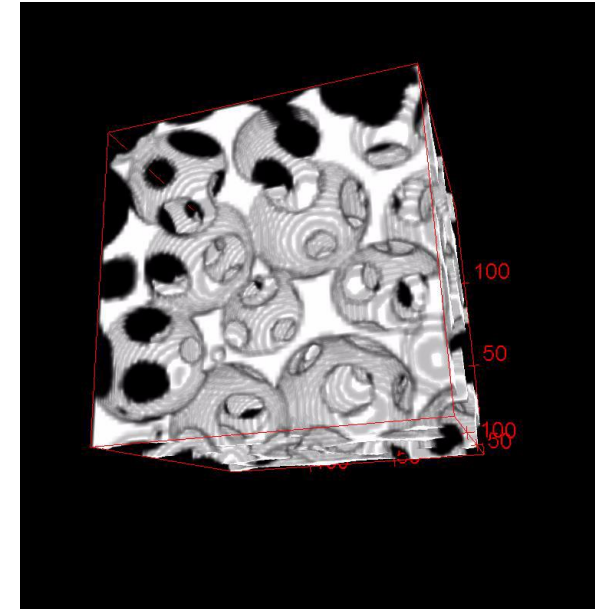
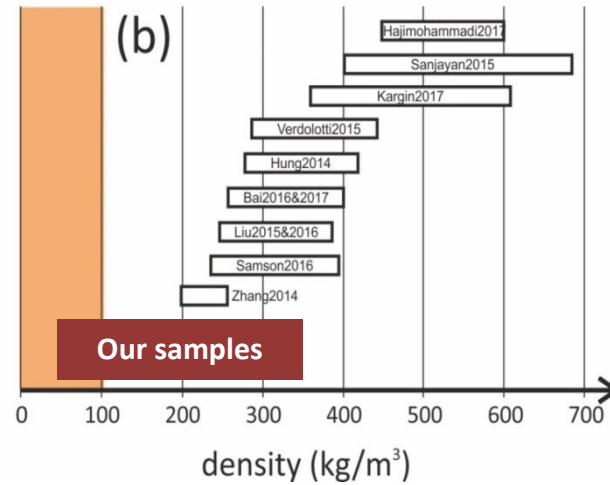
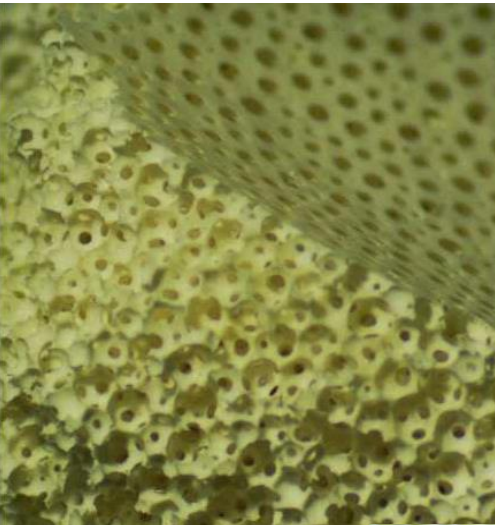
## Controlling the foam morphology



# Metakaolin foams (= geopolymers)

Thèse d'Asmaa Kaddami  
2016-2019

## Controlling the foam morphology

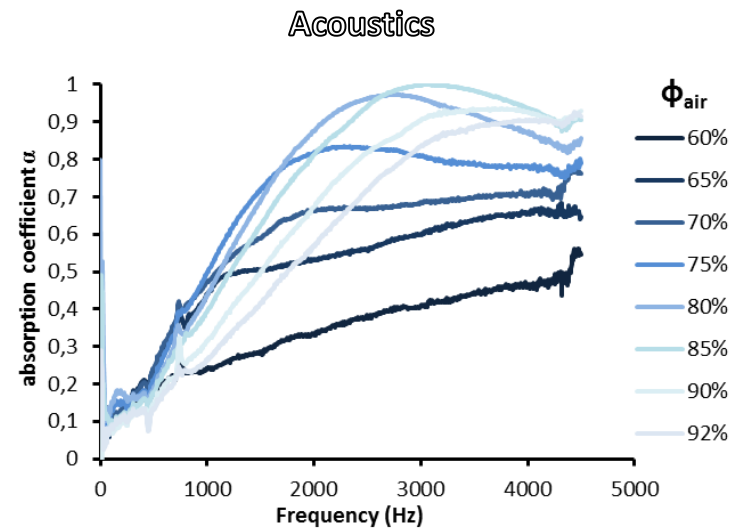
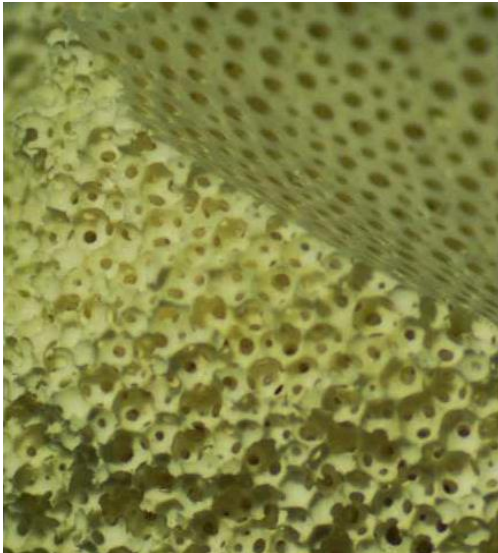


Dépôt de brevet (FR 17 62432)  
« Mousse de géopolymère et son  
procédé de fabrication »

# Metakaolin foams (= geopolymers)

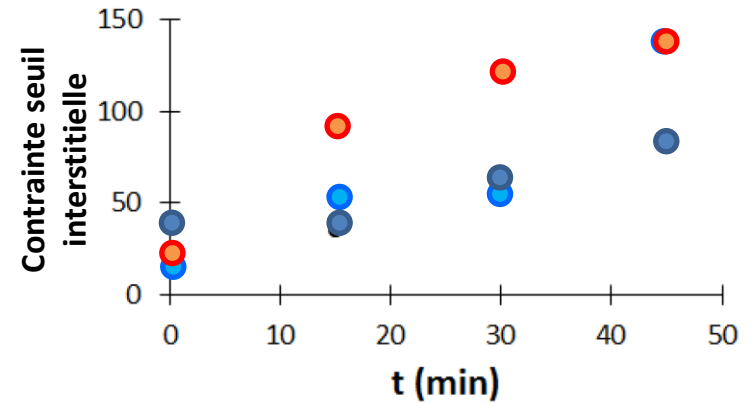
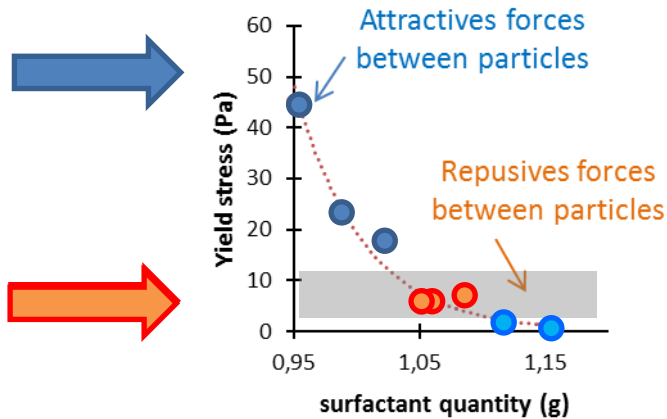
Thèse d'Asmaa Kaddami  
2016-2019

## Functional properties



# Cement foams

Effect of surfactant or superplasticizer on  
cement paste yield stress



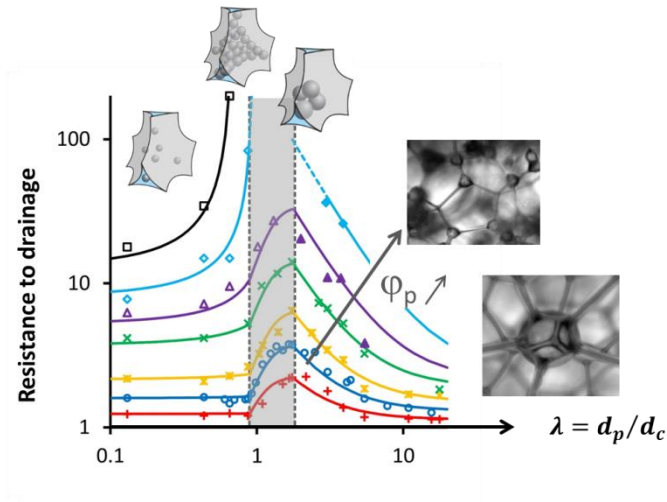
B. Feneuil, O. Pitois, N. Roussel, Effect of surfactants on the yield stress of cement paste, *Cement and Concrete Research* (2017) 100, 32–39

B. Feneuil, N. roussel, O. Pitois, Optimal cement paste yield stress for the production of stable cement foams, *Cement and Concrete Research* (2019)

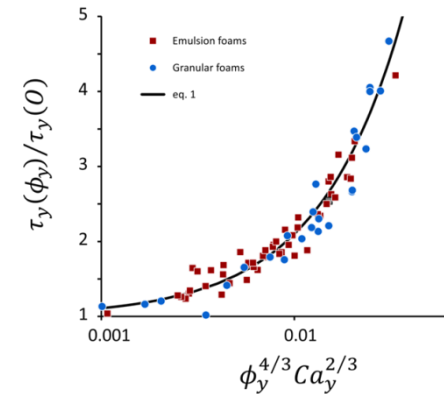
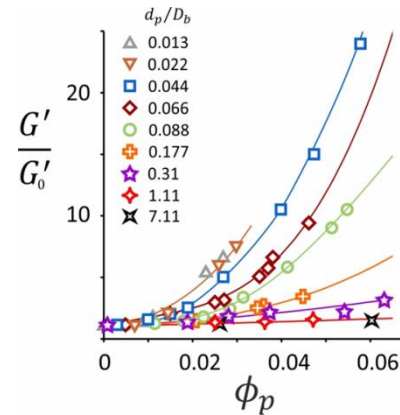
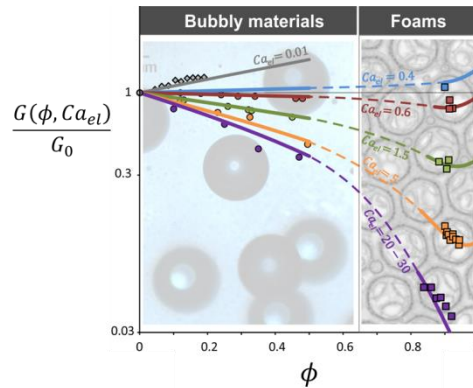
B. Feneuil, P. Aïmediou, M. Scheel, N. roussel, O. Pitois, Stability criterion for fresh cement foams, submitted to *Cement and Concrete Research* (2019)

# Summary

## I. Drainage of foams made from particle suspensions



## II. Rhéologie of aerated systems



## III. Morphology control of mineral foams

