Suspensions near the jamming transition

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Concentrated suspensions near jamming

Standard fresh concrete
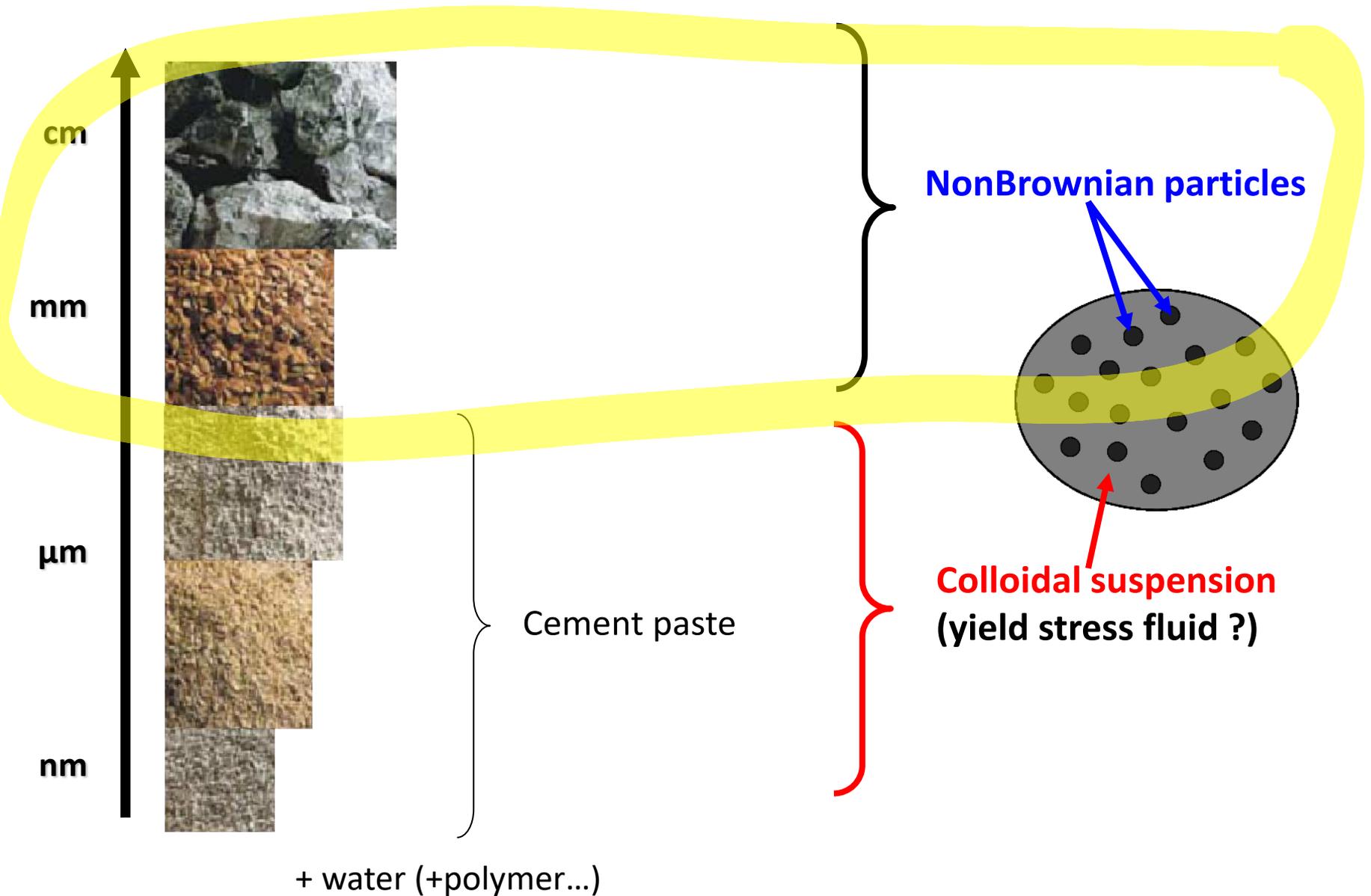

Self-compacting concrete

Solid (can be shaped) **at rest**

Liquid (flows under its own weight)

Concentrated suspensions vs. model materials

cm

mm

μm

nm

+ water (+polymer…)

Cement paste

NonBrownian particles

Colloidal suspension (yield stress fluid ?)

Static particle packings

Slow deposition   *Small vibrations*   *Periodic shearing*

Random loose packing   Random close packing   Hexagonal close packed configuration

$\phi = 0.52\text{-}0.55$ $\phi = 0.62\text{-}0.64$ $\phi = 0.74$
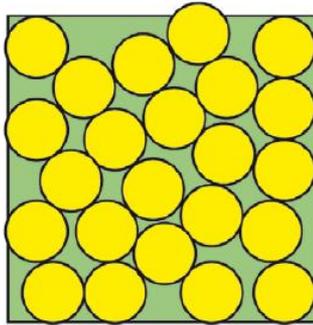
Source: nucleus.iaea.org

Particle fraction ϕ
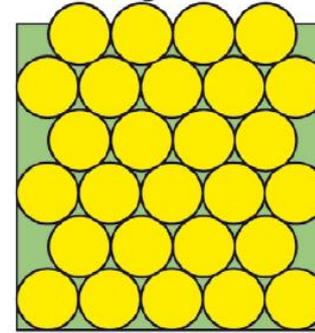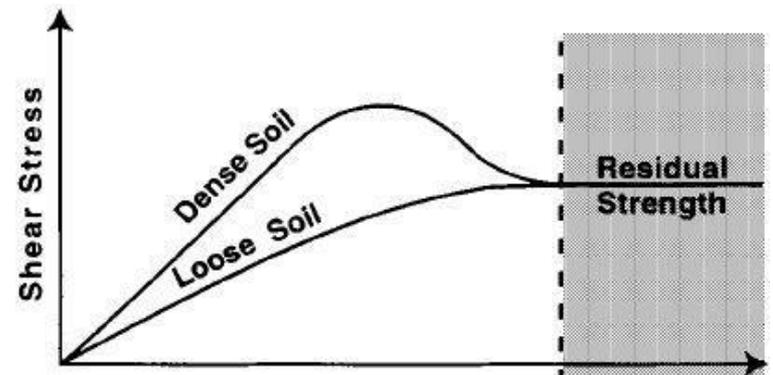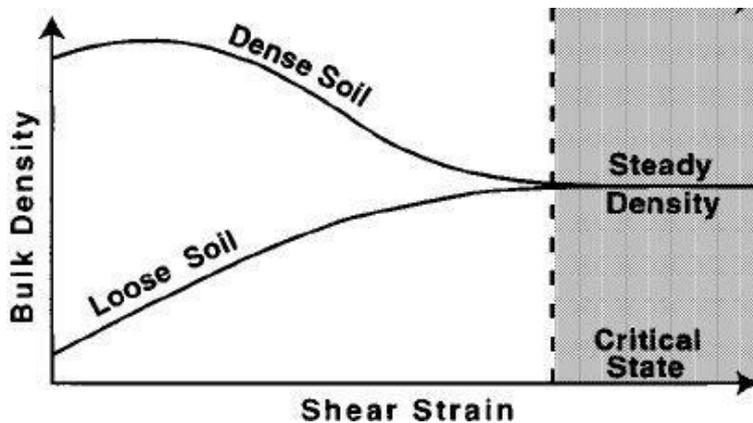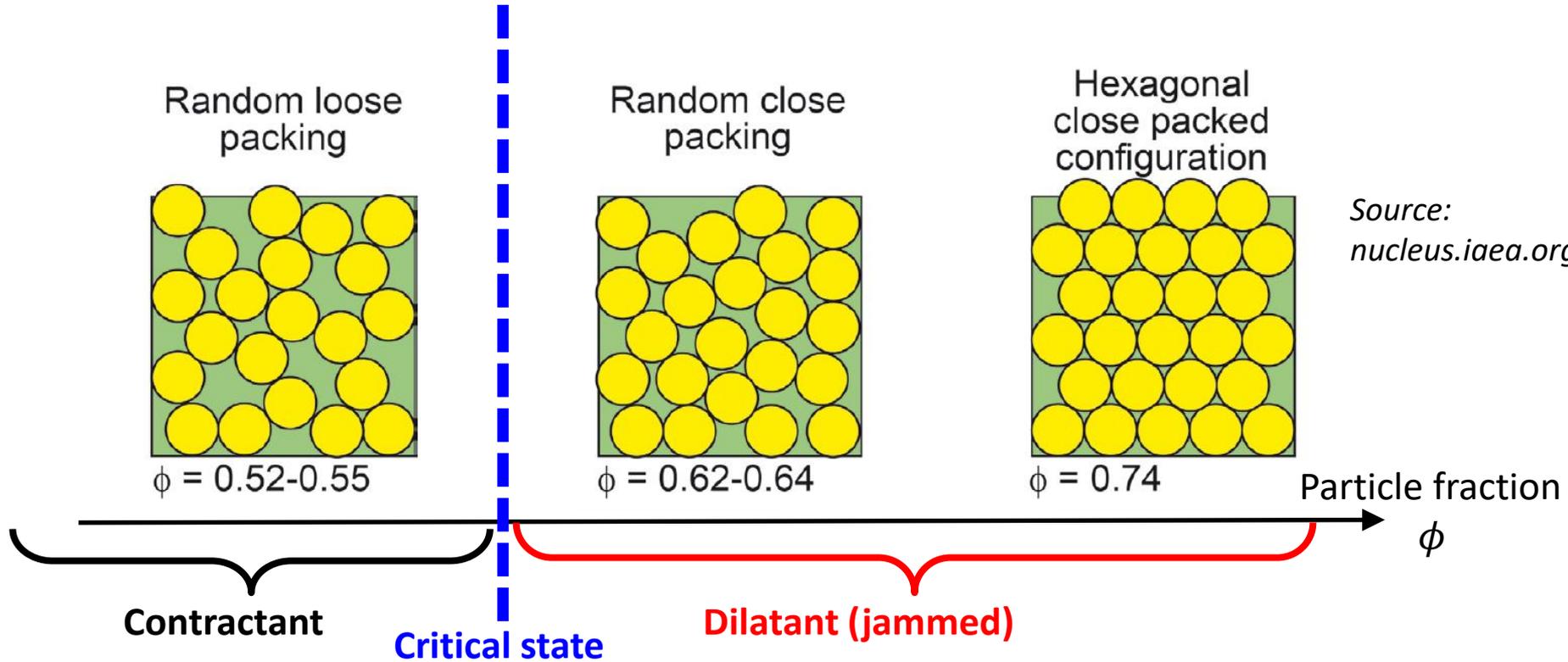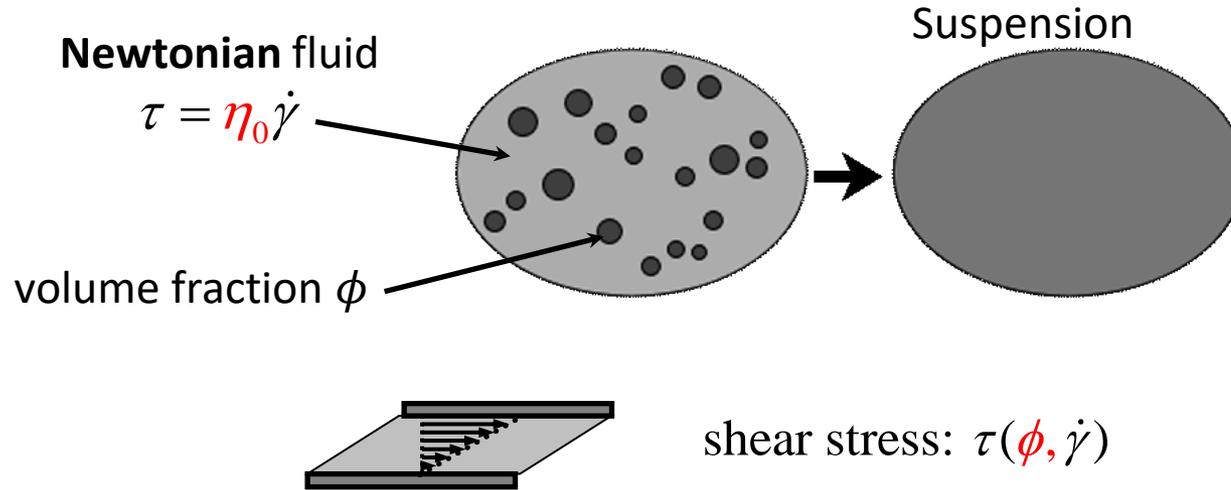
Sheared particle packings

Random loose packing
$\phi = 0.52-0.55$

Random close packing
$\phi = 0.62-0.64$

Hexagonal close packed configuration
$\phi = 0.74$

Particle fraction ϕ

Source: nucleus.iaea.org

Contractant

Critical state

Dilatant (jammed)

Dense Soil
Loose Soil
Bulk Density
Steady Density
Critical State
Shear Strain

Dense Soil
Loose Soil
Shear Stress
Residual Strength

Iverson et al. (1997)
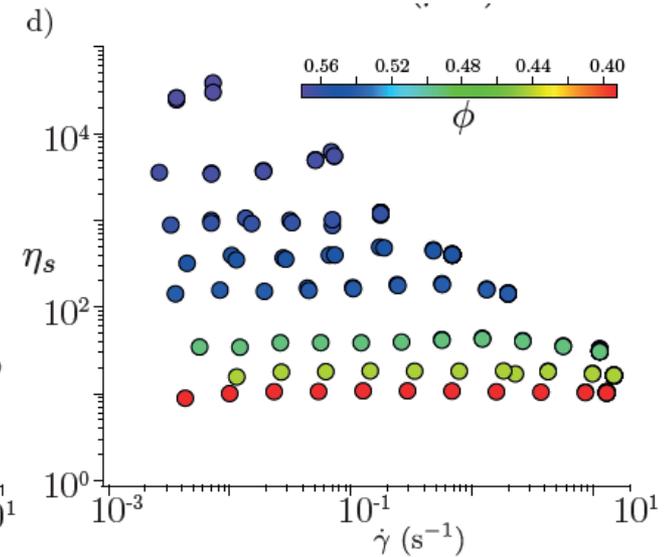
Macroscopic behavior of **viscous nonBrownian** suspensions

Newtonian fluid

$$\tau = \eta_0 \dot{\gamma}$$

Suspension

volume fraction ϕ

shear stress: $\tau(\phi, \dot{\gamma})$

Often shear thinning…

Sometimes « ideal » = **linear**

$\phi \uparrow$

Etcheverry (2022)

Macroscopic behavior of **viscous nonBrownian** suspensions

Newtonian fluid

$$\tau = \eta_0 \dot\gamma$$

Suspension : **linear** material

volume fraction ϕ

shear stress: $\tau = \eta_s(\phi)\eta_0\dot\gamma$

$\eta_s = A(\phi - \phi_J)^{-2}$

$$\eta_s(\phi) \propto \eta_0 \left(1 - \frac{\phi}{\phi_j}\right)^{-2}$$

Jamming

ϕ_j: *jamming fraction*
$\equiv$ *critical state*
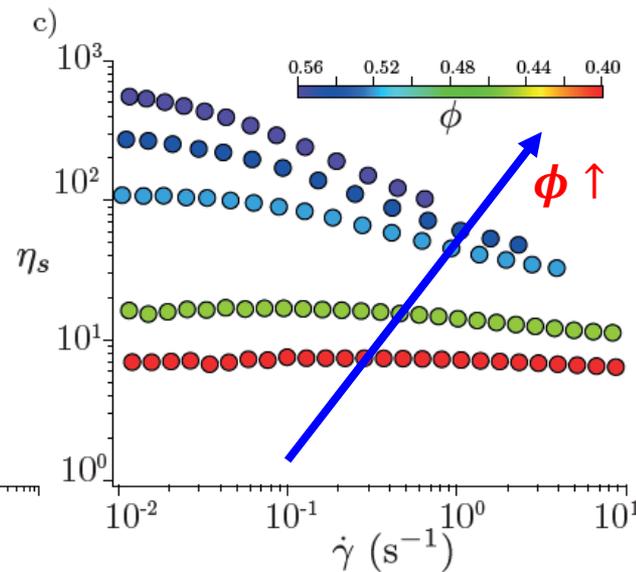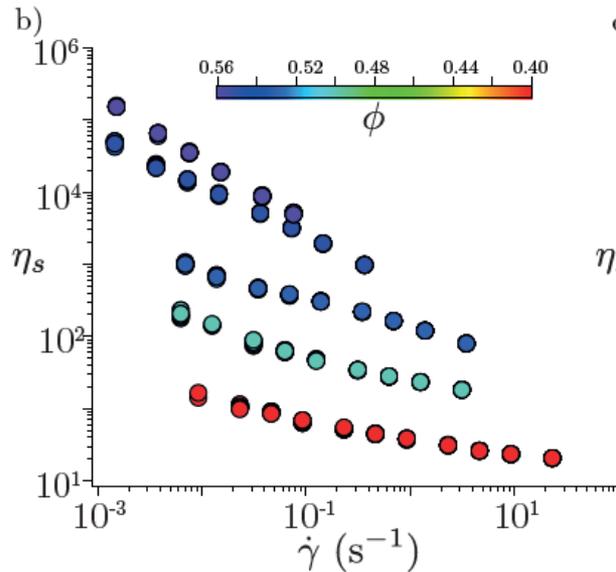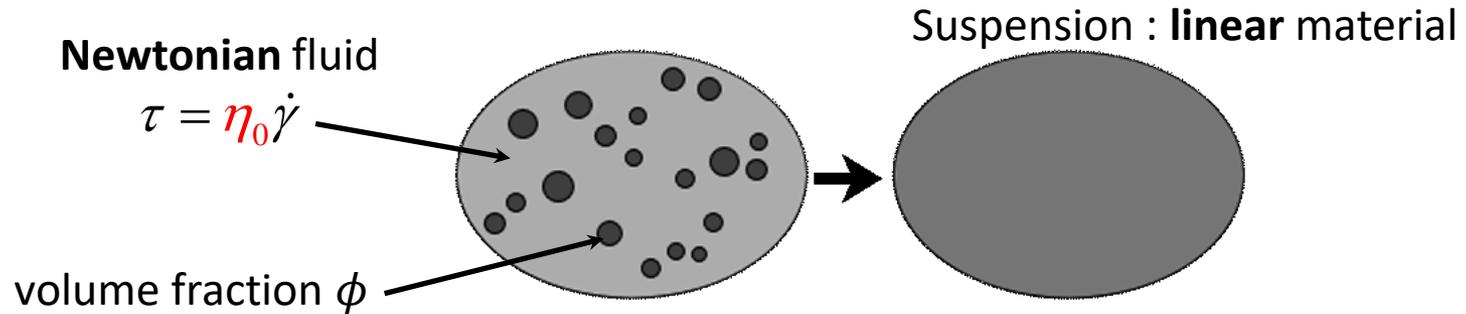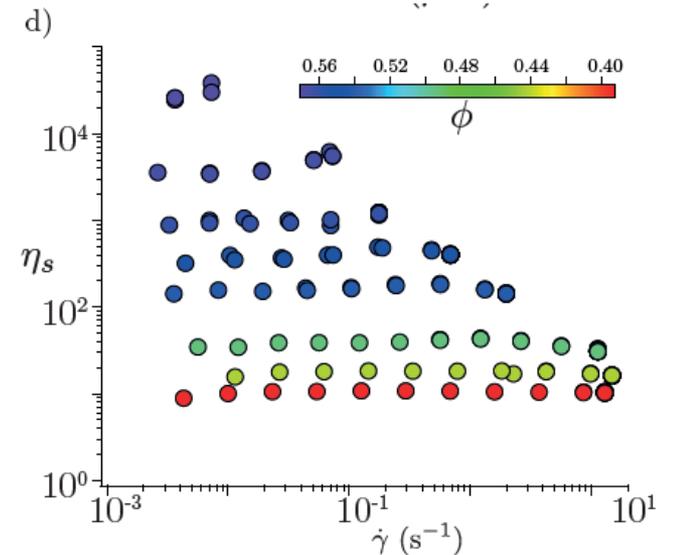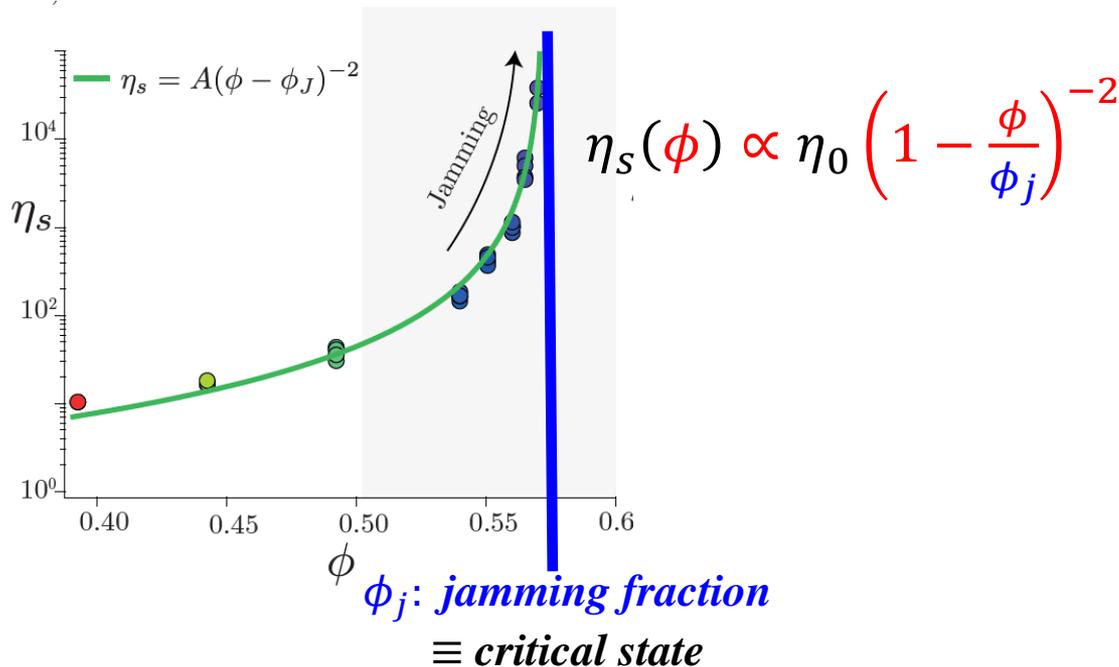
Etcheverry (2022)

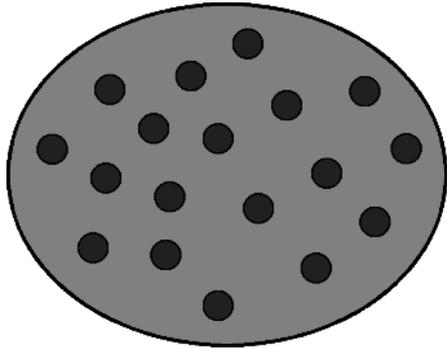# Suspensions viscosity: hydrodynamics + contacts

Simulations: Gallier et al. (2014)
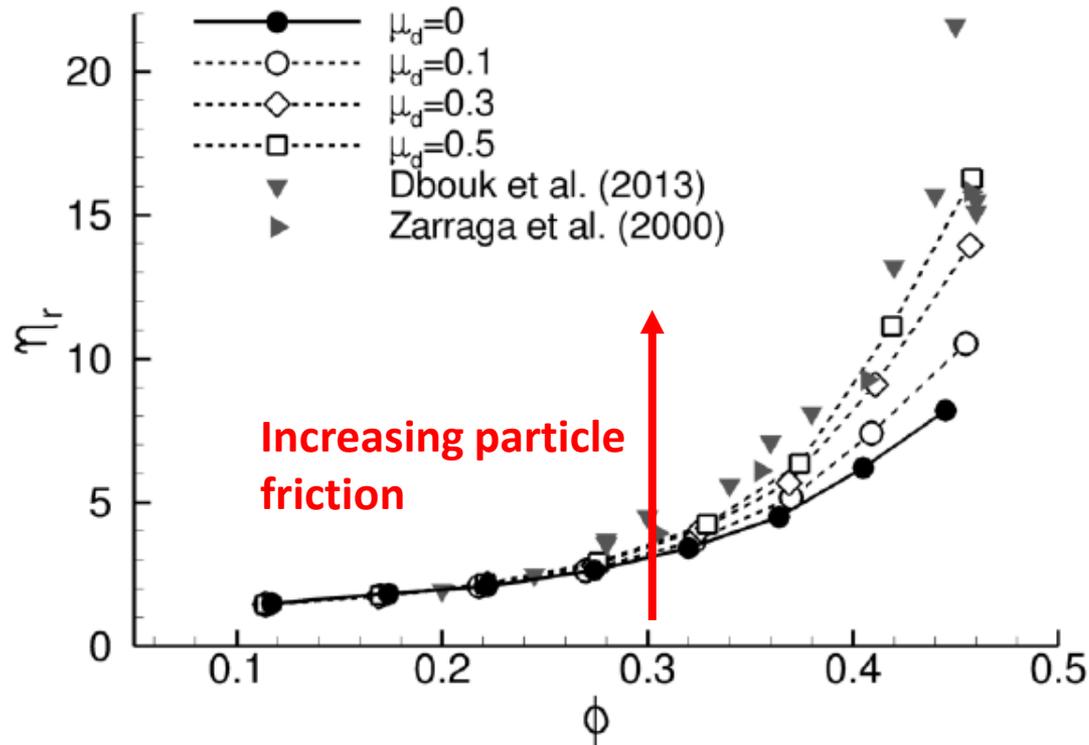
Interparticle friction $(\mu_p \simeq 0.5)$ **necessary for agreement with exp.**

For frictional grains, **contact contribution dominant for** $\phi \geq 40\%$
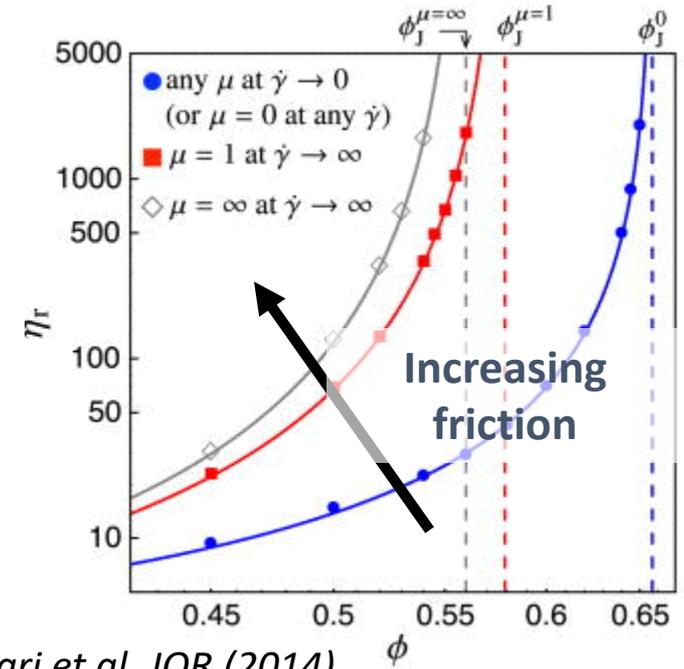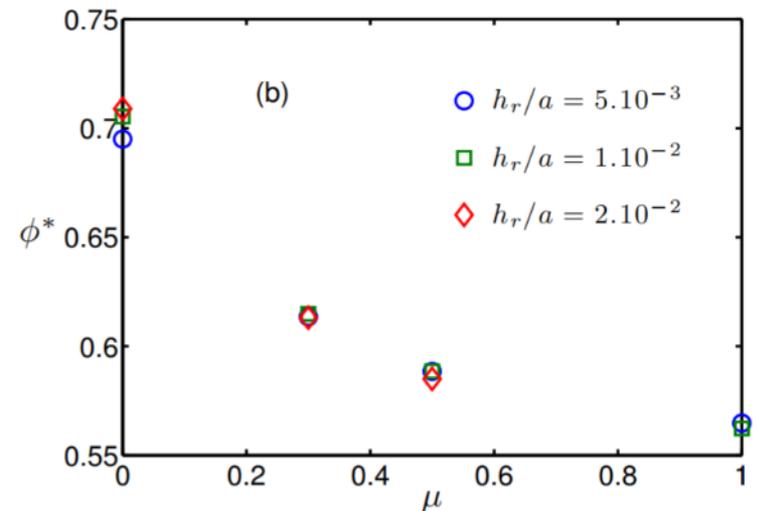
Role of interparticle friction

$$\eta_s(\phi) \propto \eta_s(0)\left(1 - \frac{\phi}{\phi_j}\right)^{-2}$$

ϕ_j decreases with interparticle friction

ϕ_j = critical state vol. fraction
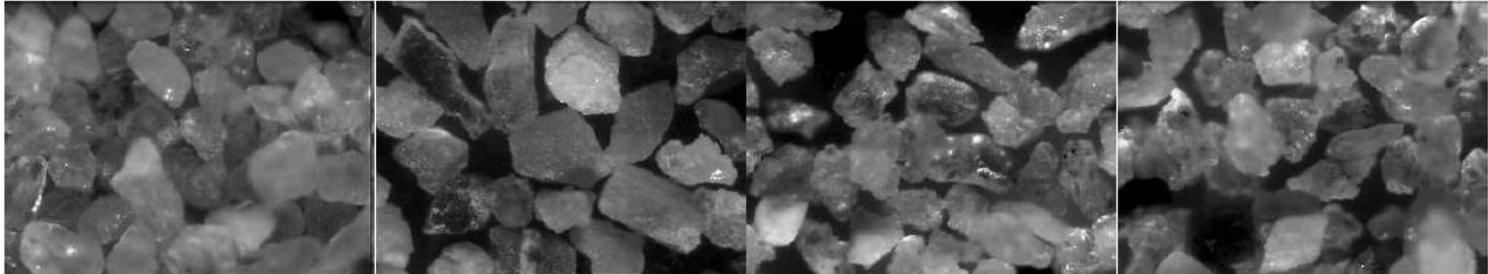of granular materials
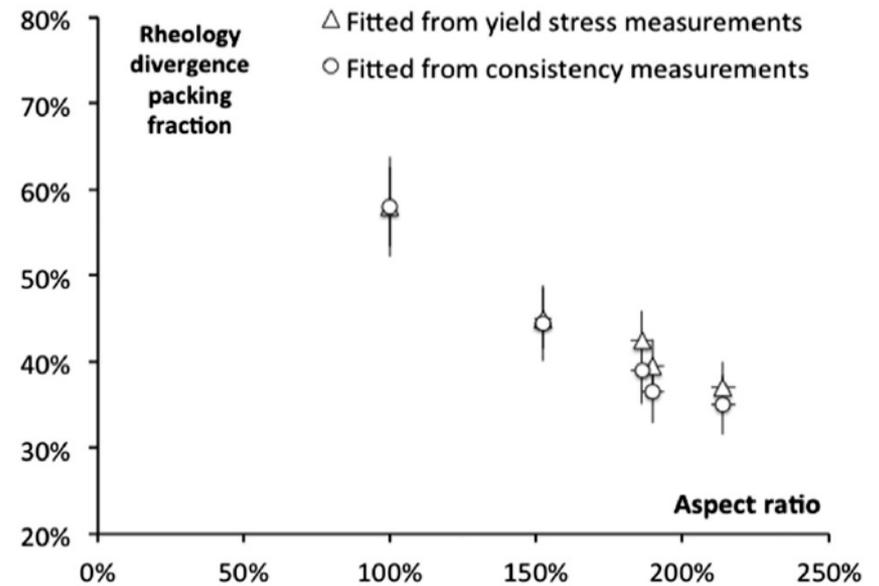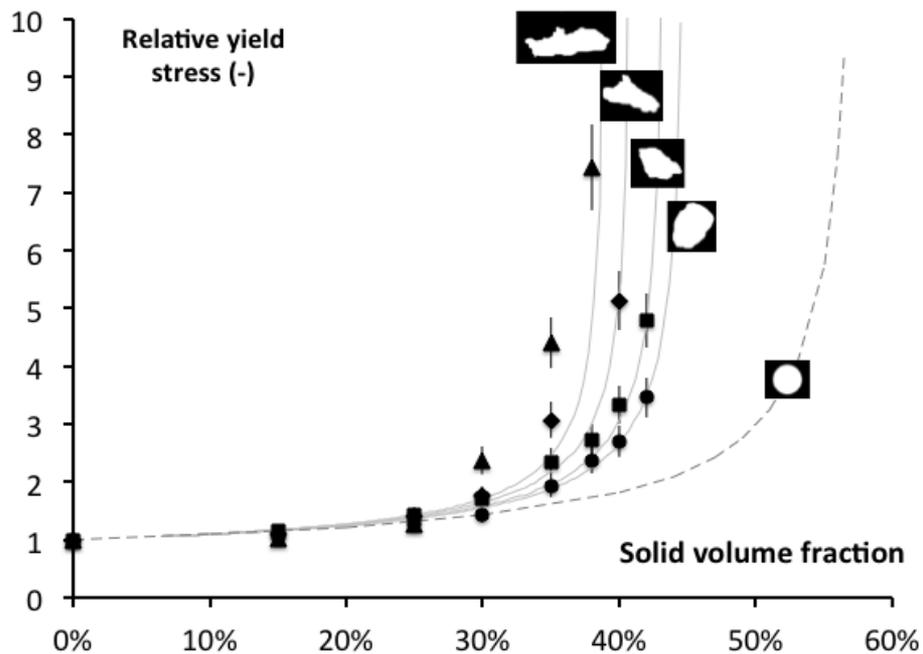
Mari et al, JOR (2014)

Peters et al., JFM (2016)

Impact of particle shape

Suspended in a concentrated emulsion

Hafid et al., Cem Conc Res (2016)

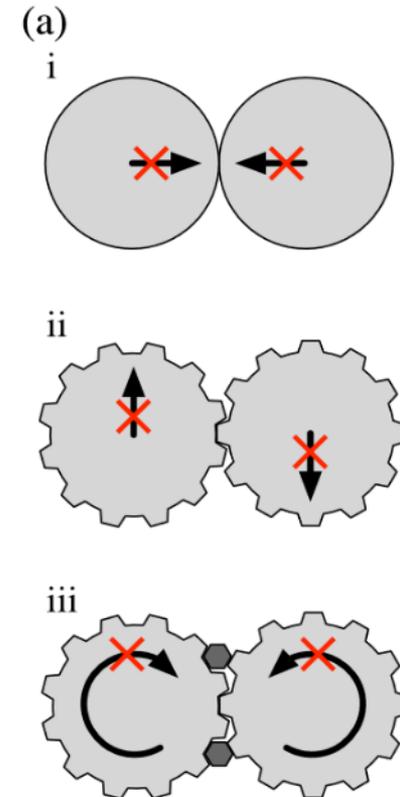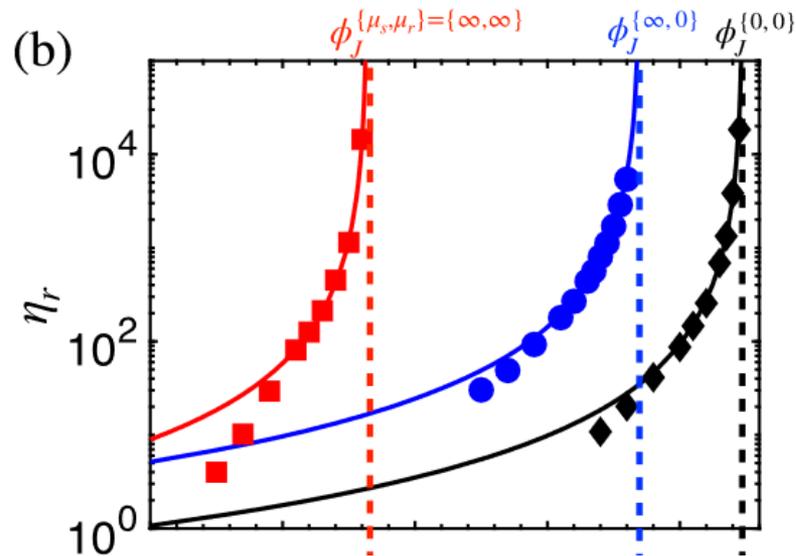## Identification of rolling resistance as a shape parameter in sheared granular media

Nicolas Estrada,[1,*] Emilien Azéma,[2,†] Farhang Radjai,[2] and Alfredo Taboada[3]
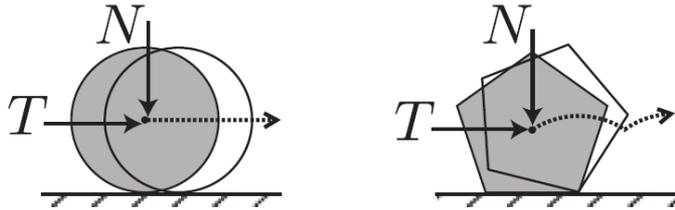
ϕ_j **decreases with rolling friction**
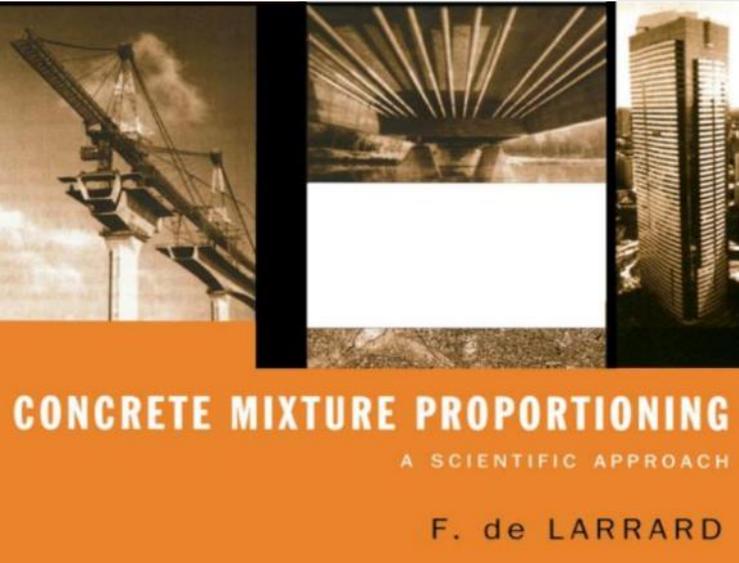
Singh et al. (2020)

Impact of polydispersity

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CONCRETE MIXTURE PROPORTIONING

A SCIENTIFIC APPROACH

F. de LARRARD

Review

Understanding the role of particle packing characteristics in rheo-physical properties of cementitious suspensions: A literature review
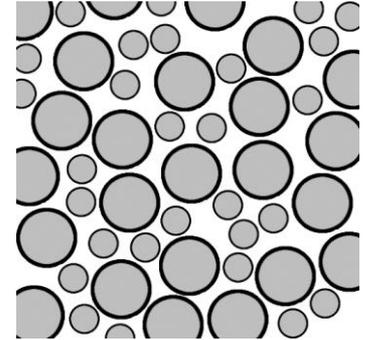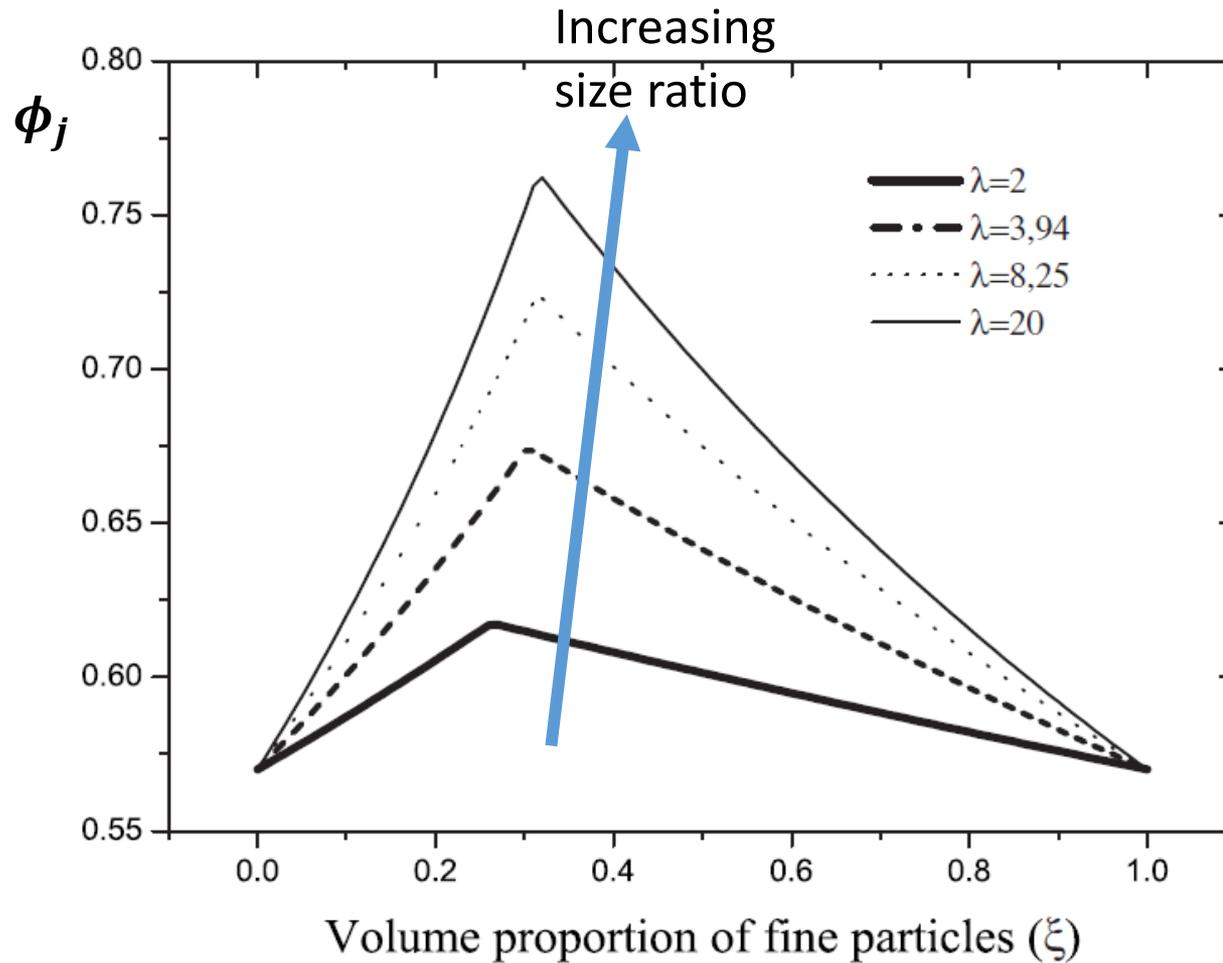
Iman Mehdipour, Kamal H. Khayat *

Loosening Effect   **Wall Effect**   **Wedging Effect**

(a)   (b)   (c)
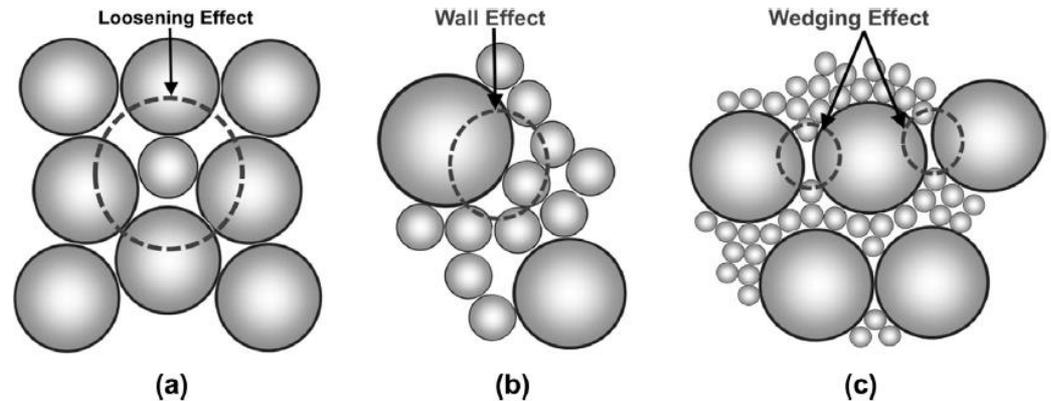
Computations for hardened concrete based on random close packing ϕ_{rcp}
→ what about ϕ_j ?

Bidisperse suspensions

Use packing model for rcp $\rightarrow$ **same equation for ϕ_j**

Increasing
size ratio

ϕ_j

Legend:
- $\lambda=2$
- $\lambda=3,94$
- $\lambda=8,25$
- $\lambda=20$

Volume proportion of fine particles (ξ)

Vu et al., JOR(2010)

Polydisperse suspensions

Pednekar, Chun, Morris, J. Rheol (2018):
Polydisperse suspension ≡ « statistically equivalent » suspension

(a)

(b)
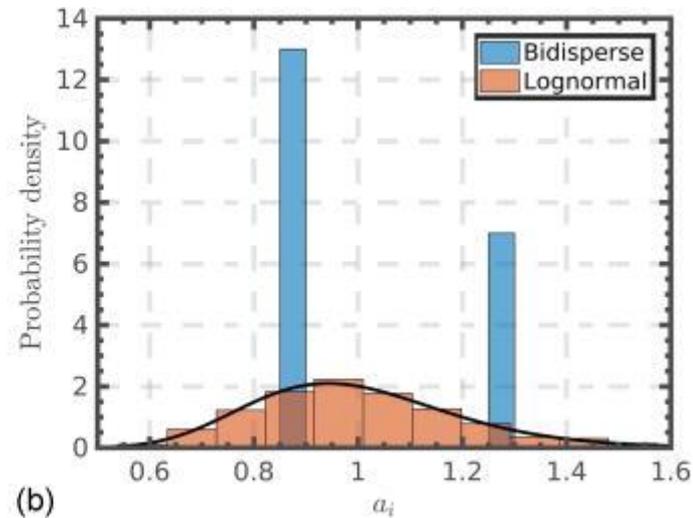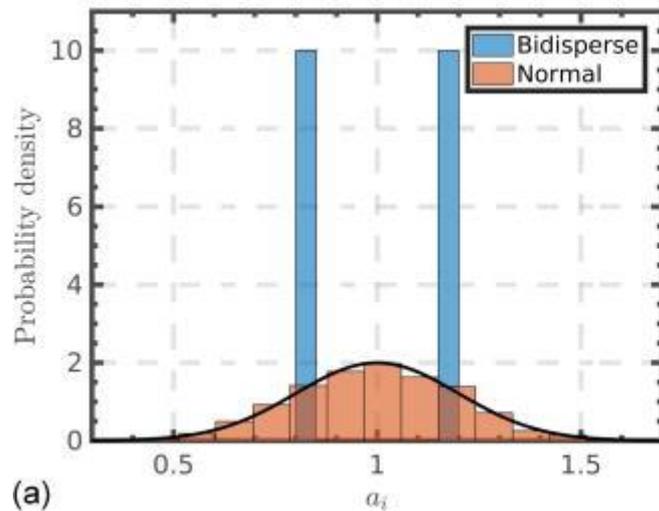
Use model of bidisperse suspension to compute jamming fraction ϕ_j

then $\eta_s(\phi) \propto \eta_s(0)\left(1 - \dfrac{\phi}{\phi_j}\right)^{-2}$
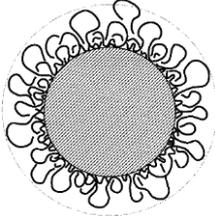
Increasing the jamming fraction

Reminder: $\textcolor{red}{\phi_j}(\textcolor{blue}{\mu_p})$ **decreases when interparticle friction** $\textcolor{blue}{\mu_p}$ **increases**

Need to kill friction
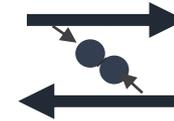
decrease $\textcolor{blue}{\mu_p}$
Add polymer
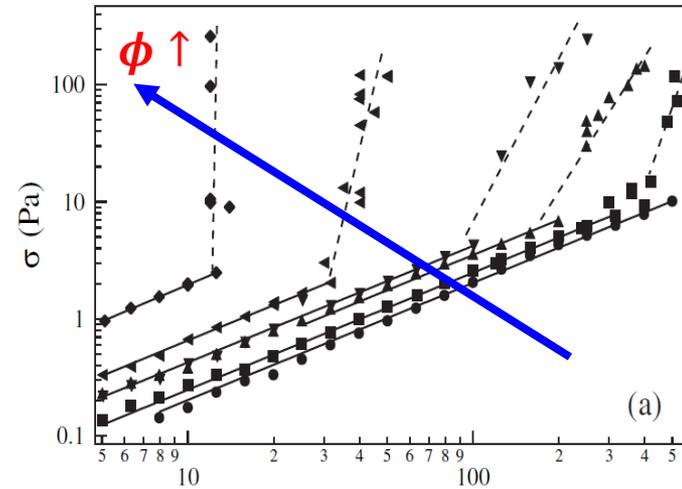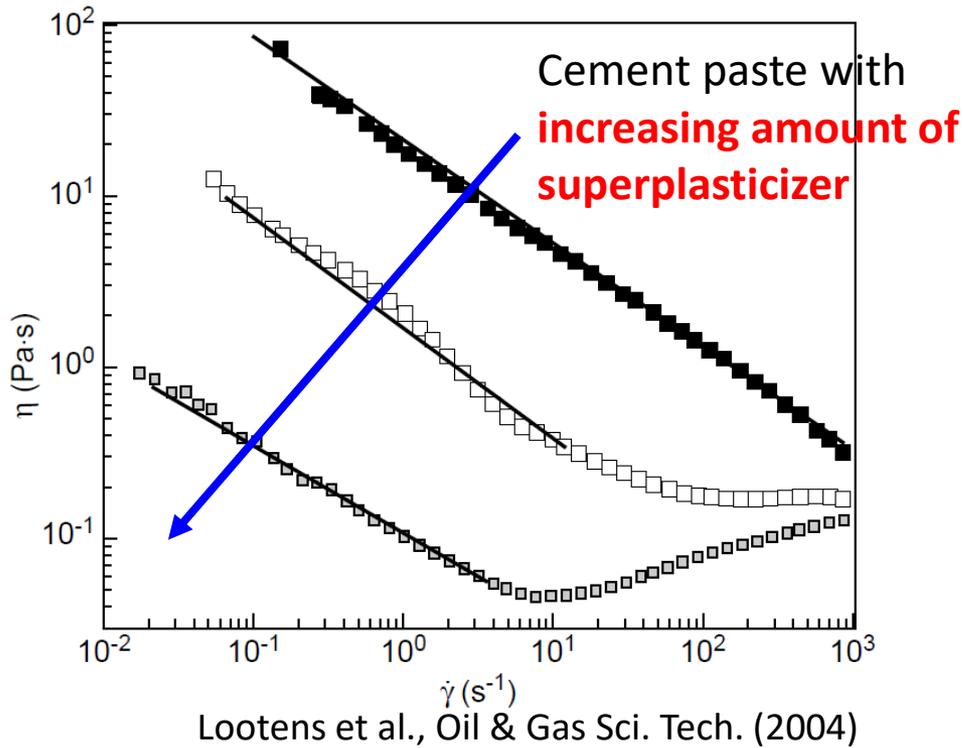Creates a repulsive barrier

e.g., cement
Toussaint et al., Rheol Acta 2009

prevent from contact formation
Play with flow configuration
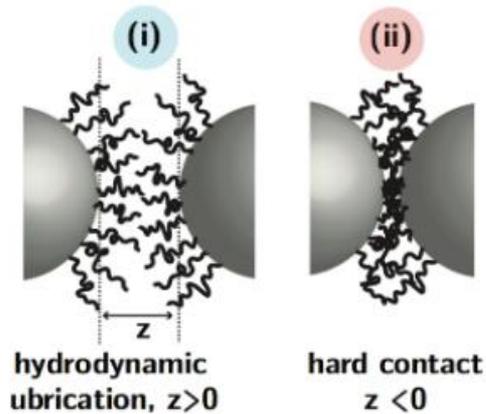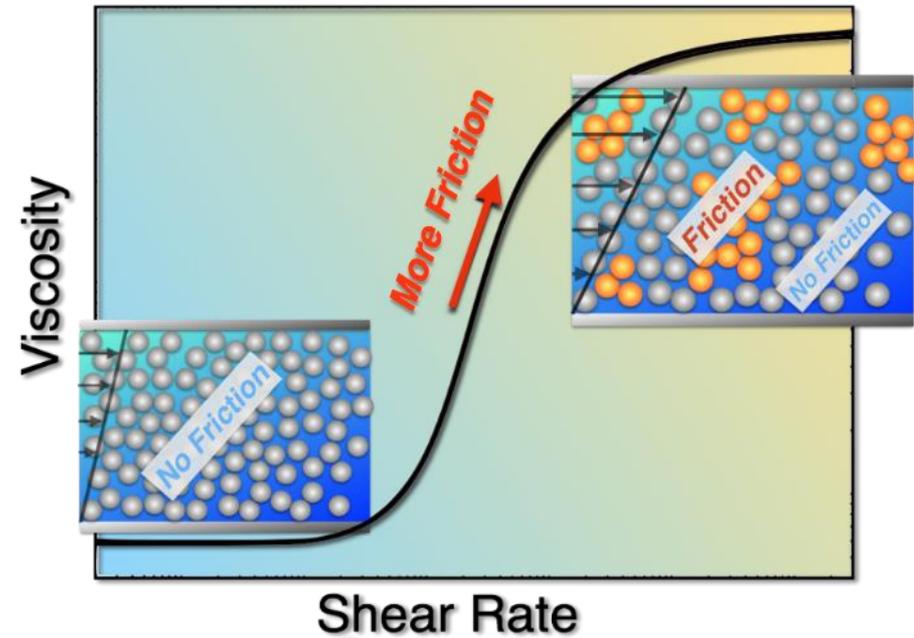
« Frictionless » suspensions

Cement paste with **increasing amount of superplasticizer**

Lootens et al., Oil & Gas Sci. Tech. (2004)

$\phi \uparrow$

Stabilized Silica particles
Lootens et al. (2005)

*Source:
Takemoto*
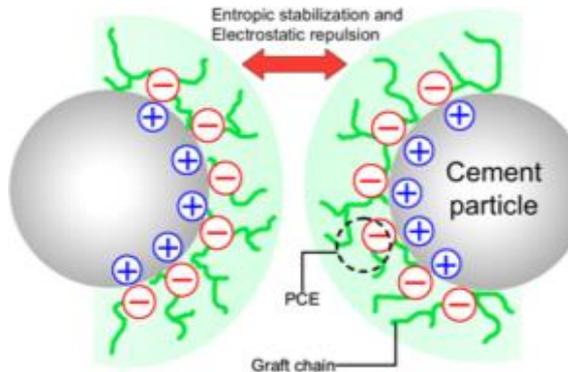
Side effect : **shear-thickening**
→ **something happens at the contact scale**

Shear-thickening: frictionless / frictional transition

*http://blairlab.georgetown.edu*

Short range repulsive colloidal force
introduces rate dependence
→ **no friction / friction transition**

Comtet et al., Nature communication 2017

Shear-thickening: frictionless / frictional transition

Mari et al, JOR 2014

http://blairlab.georgetown.edu

Short range repulsive colloidal force
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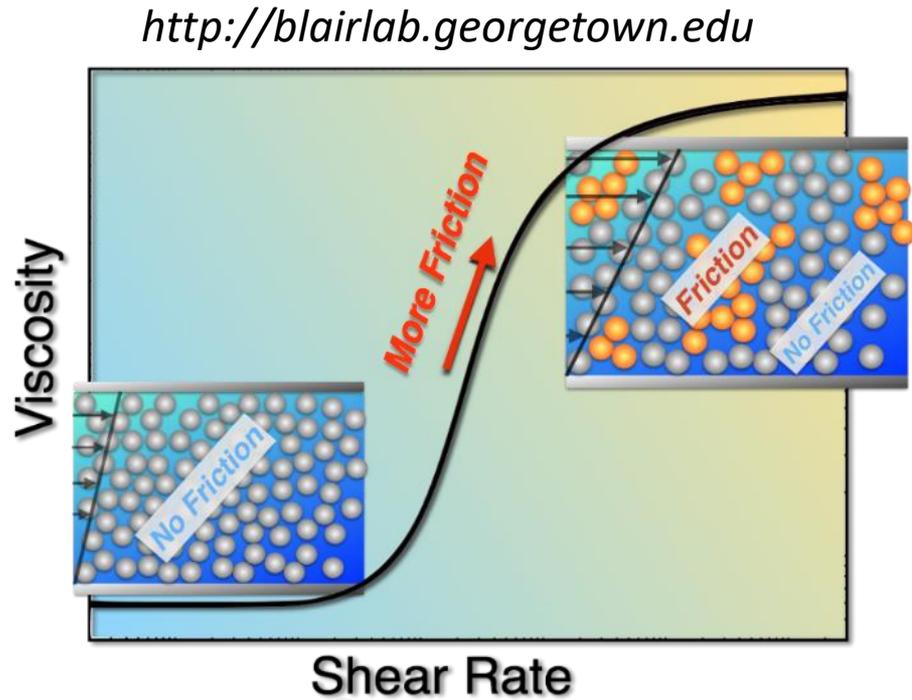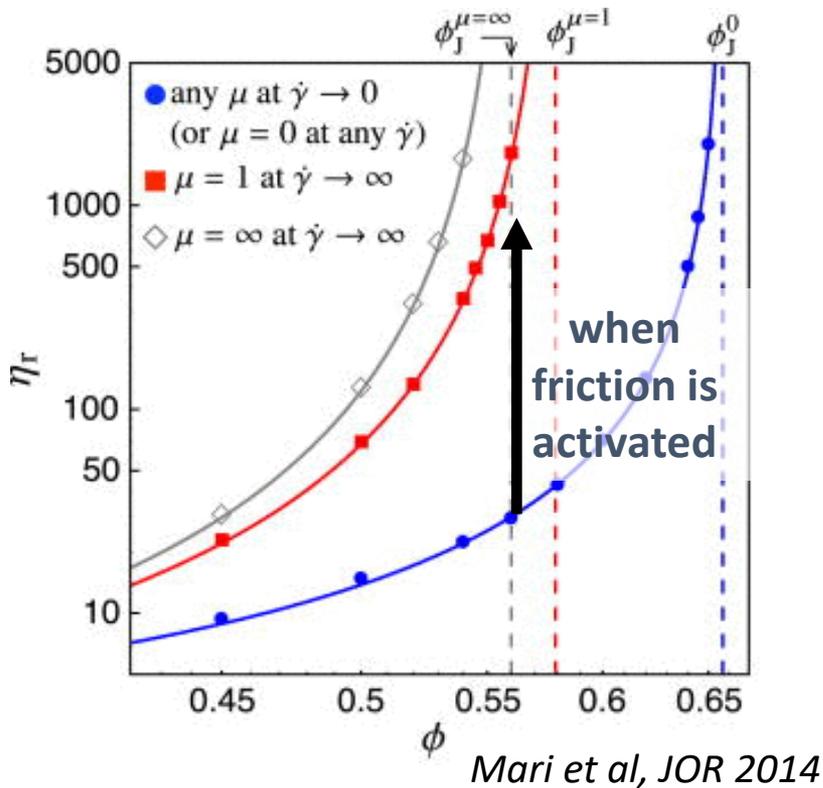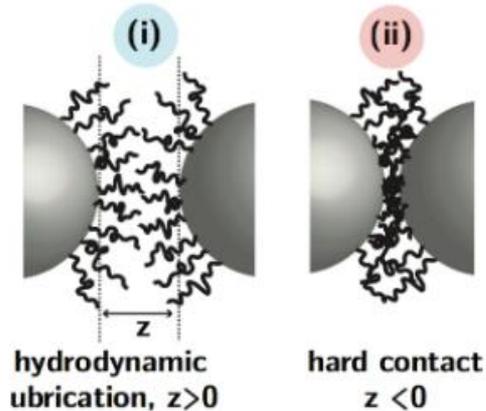
Shear-jamming: fluid / solid transition

Mari et al, JOR 2014

when friction is activated: jamming

Shear jamming
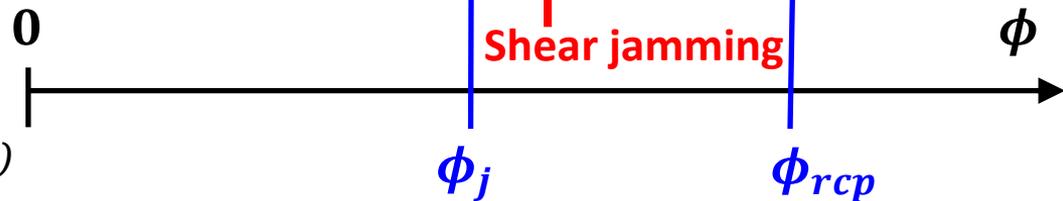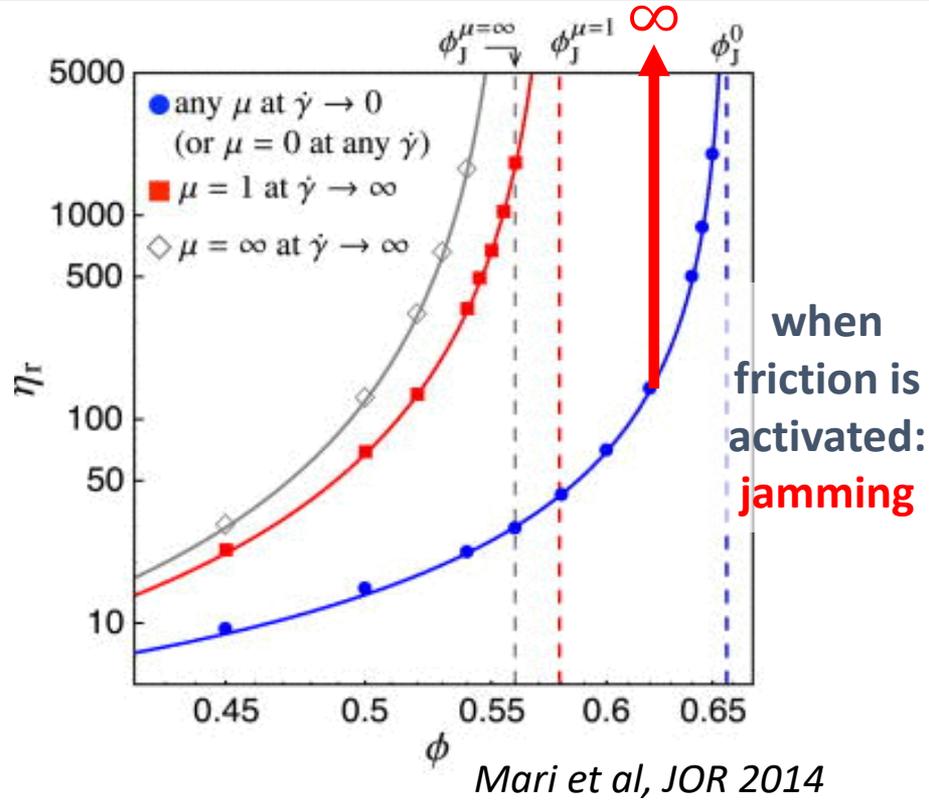
Hodgson et al., JOR (2022)

0 ϕ

ϕ_j ϕ_{rcp}
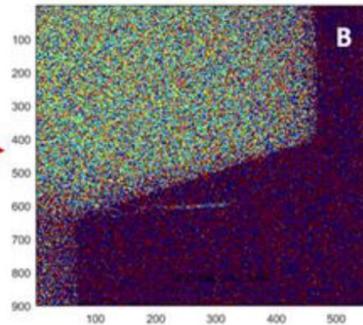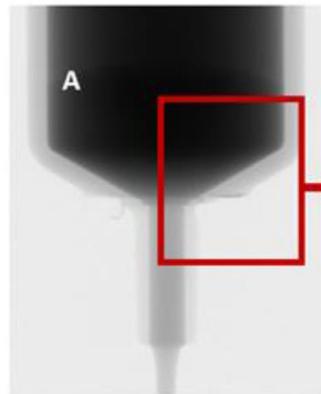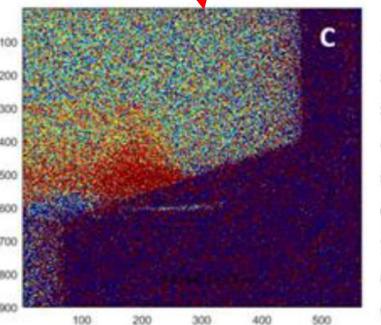
Shear-induced inhomogeneities at shear thickening
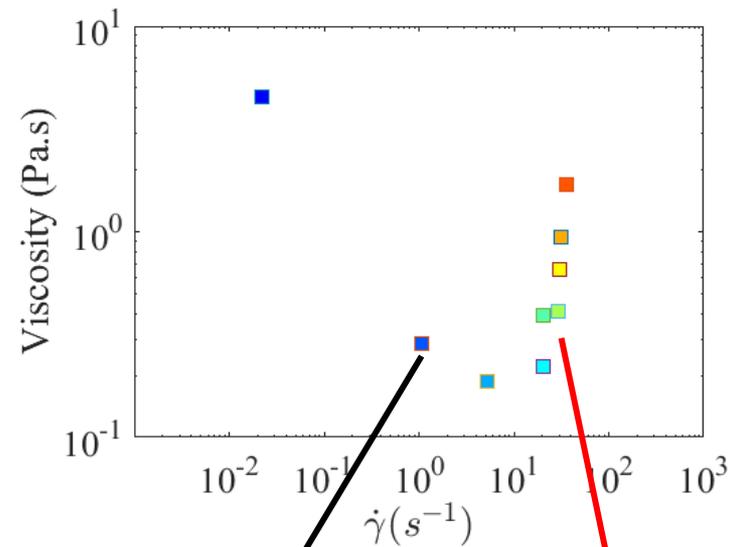
Vol. fraction maps
from X-ray imaging
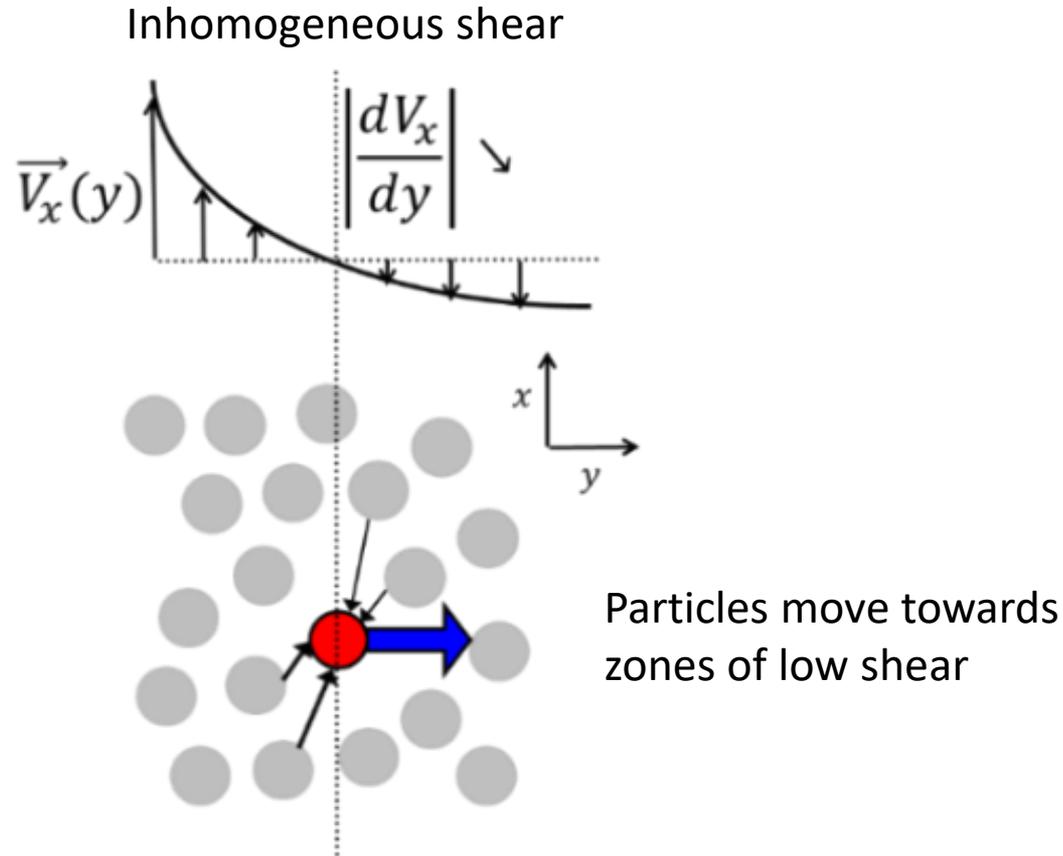
Gholami et al (2018)

homogeneous
extrusion

**inhomogeneous
extrusion**

O'Neill et al. (2019) ; (2024?)

Shear-induced migration in brief

Leighton & Acrivos 1987, Nott & Brady 1994...

Inhomogeneous shear

Particles move towards zones of low shear

$\Rightarrow$ **diphasic description; migration driven by $\nabla\sigma^p$**
   Crucial role of interparticle contacts

$\Rightarrow$ **enhanced @ shear thickening**

Reminder: $\color{red}{\phi_j}\color{black}(\color{blue}{\mu_p}\color{black})$ **decreases when interparticle friction** $\color{blue}{\mu_p}$ **increases**

Need to kill friction

decrease $\color{blue}{\mu_p}$
Add polymer
Creates a repulsive barrier

prevent from contact formation
Play with flow configuration

Macrocopic behavior, **contacts** and **microstructure**

Response to shear reversal

Contacts
(in compression)
are broken
(in traction)
before being reformed

$\simeq$contact stress

$\simeq$hydrodynamic stress

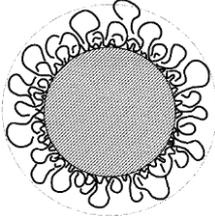*Blanc et al., J. Rheol. 2011 ; Peters et al., J. Rheol. 2016*

Increasing the jamming fraction

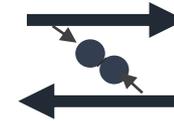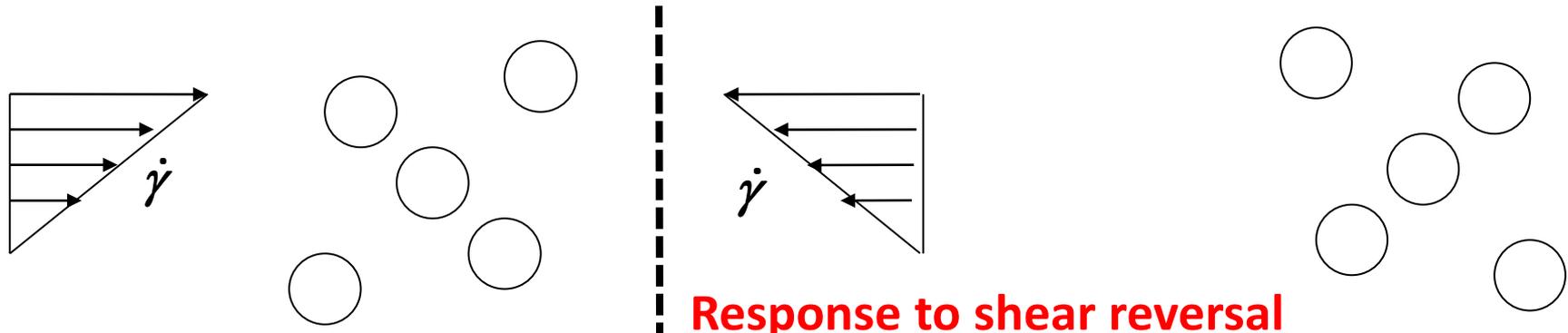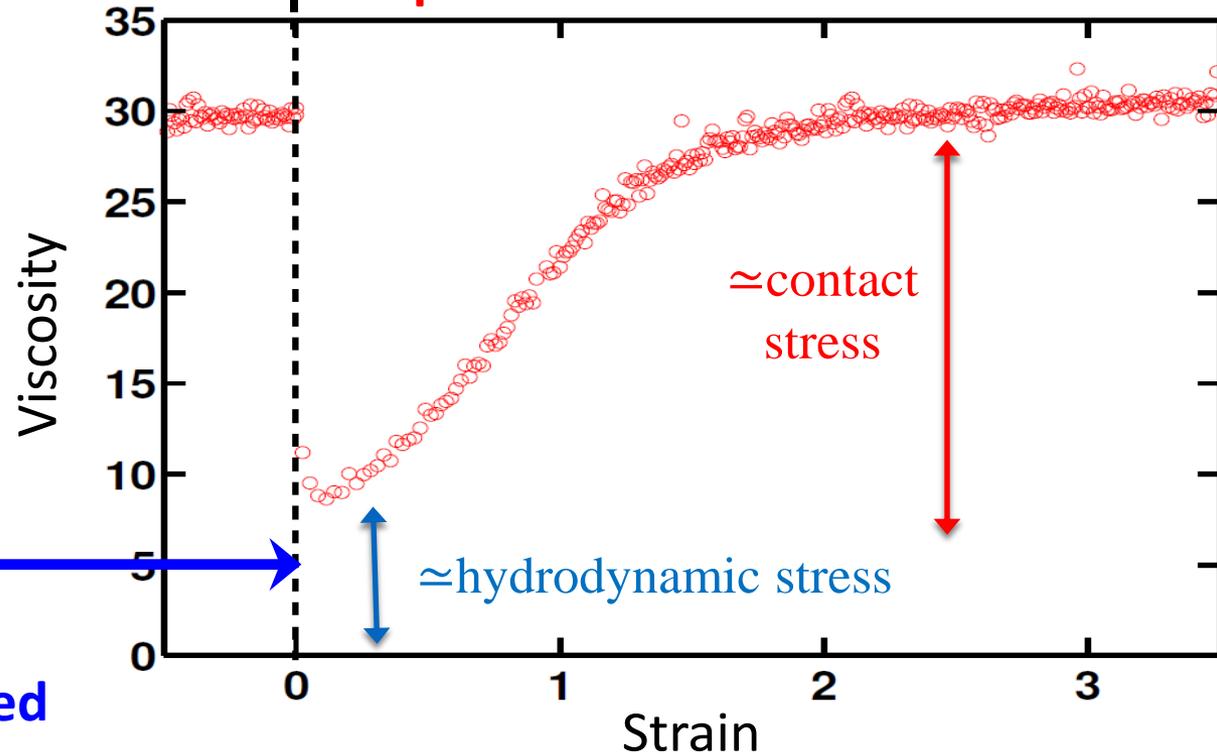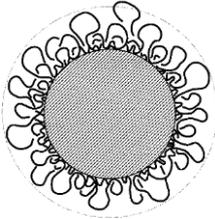**Reminder:** $\phi_j(\mu_p)$ **decreases when interparticle friction** μ_p **increases**
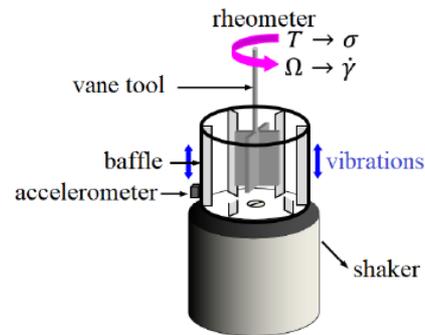
Need to kill friction

decrease μ_p
Add polymer
Creates a repulsive barrier

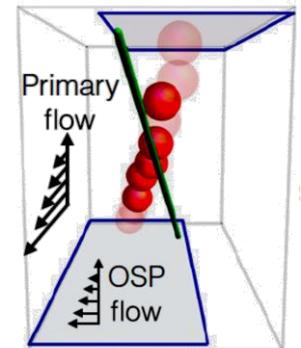**prevent from contact formation**
Play with flow configuration

Vibrations

orthogonal flow superimposed

Fluidization of a granular sediment

Hanotin et al. , PRL 2015

Shear-thickening suppression

Lin et al., PNAS 2016

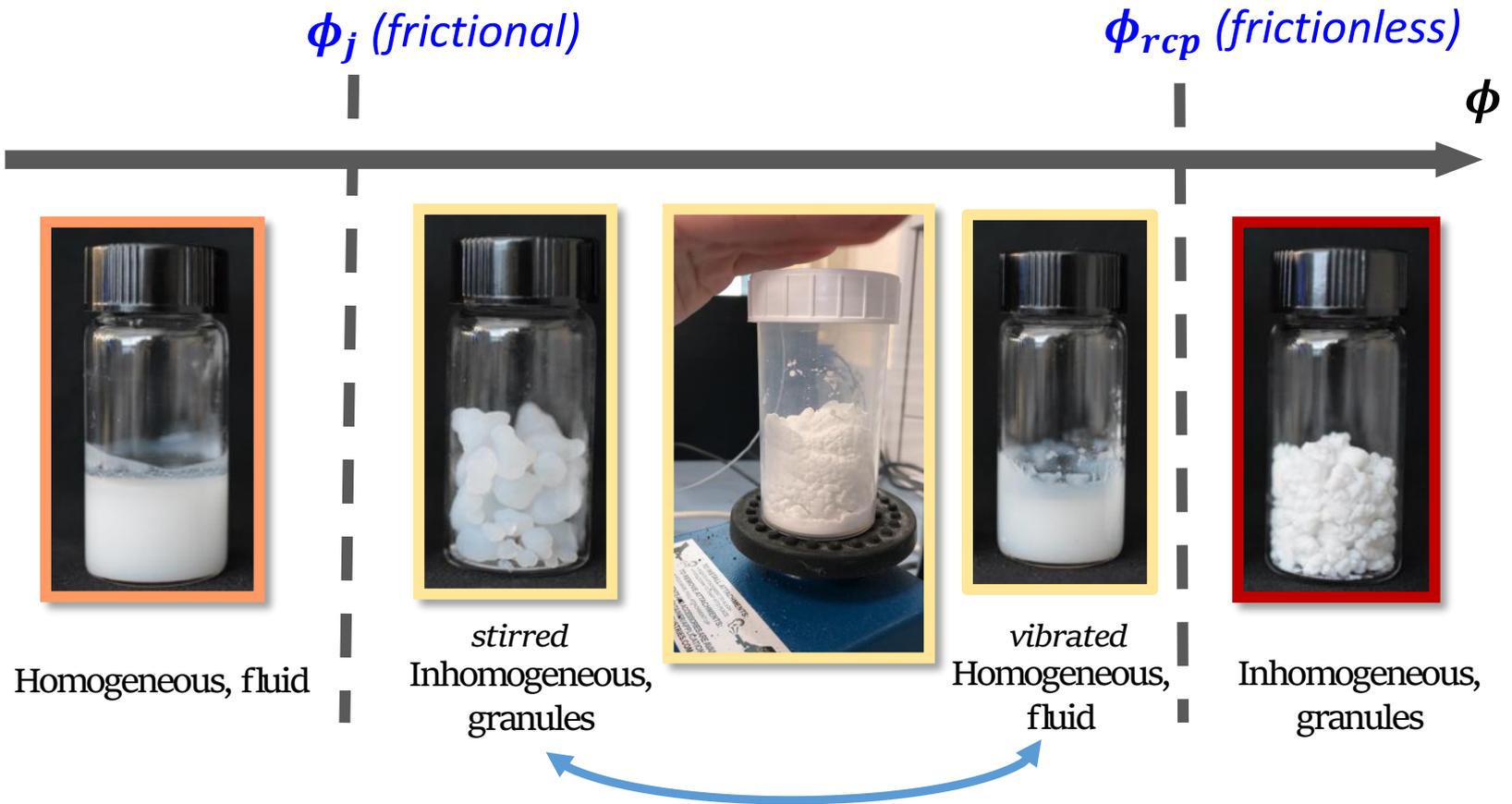# Rheology of vibrated suspensions : phenomenology
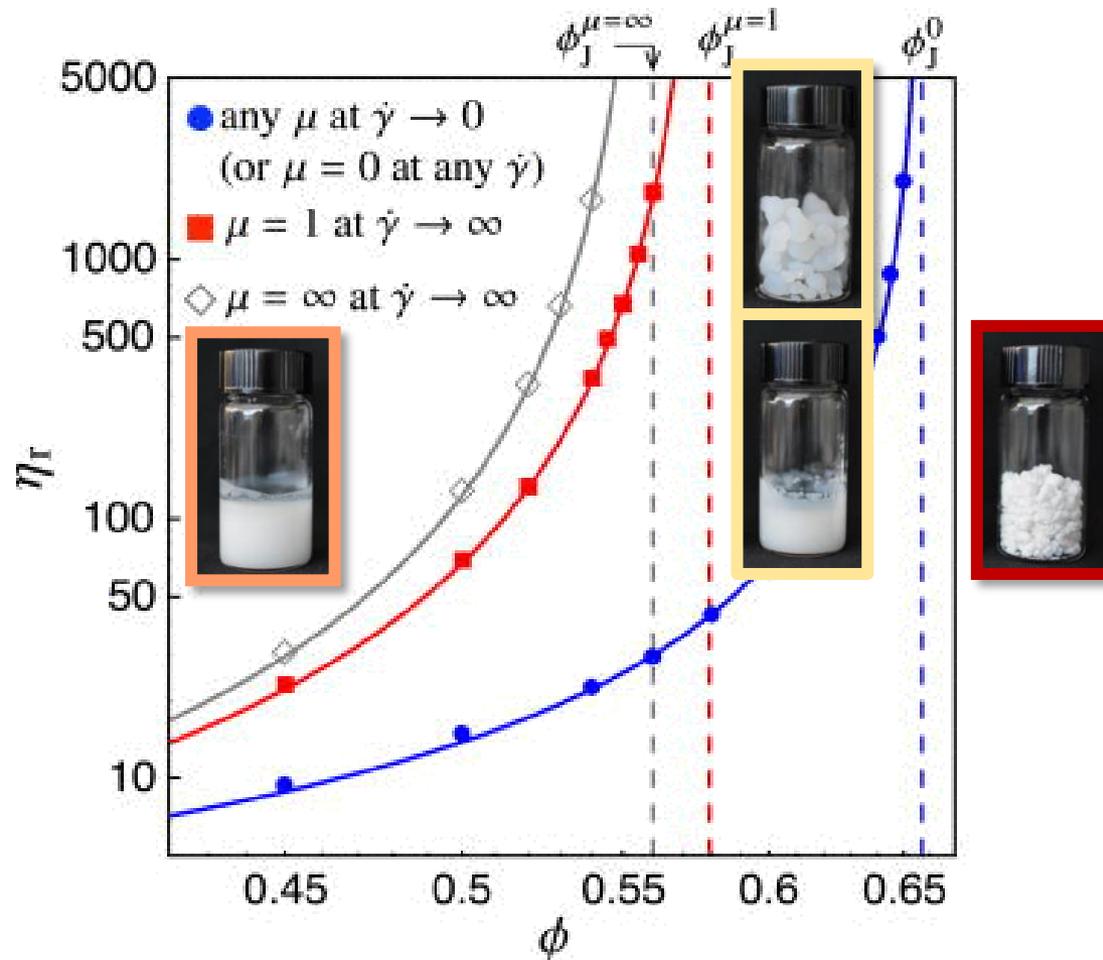
Silica suspension (Solvay), $\phi^{wt} = 0.29$

Vibrations and formulation

ϕ_j (frictional)

ϕ_{rcp} (frictionless)

ϕ

Homogeneous, fluid

stirred
Inhomogeneous, granules

vibrated
Homogeneous, fluid

Inhomogeneous, granules

Silica suspension (Solvay)

Conclusion

Rich nonlinear behavior
Crucial role of interparticle contacts
Beware inhomogeneities
Various levers: physico-chemistry and process