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Mechanism of the viscoelastic behavior of slurry

スラリーの粘弾性挙動のメカニズム

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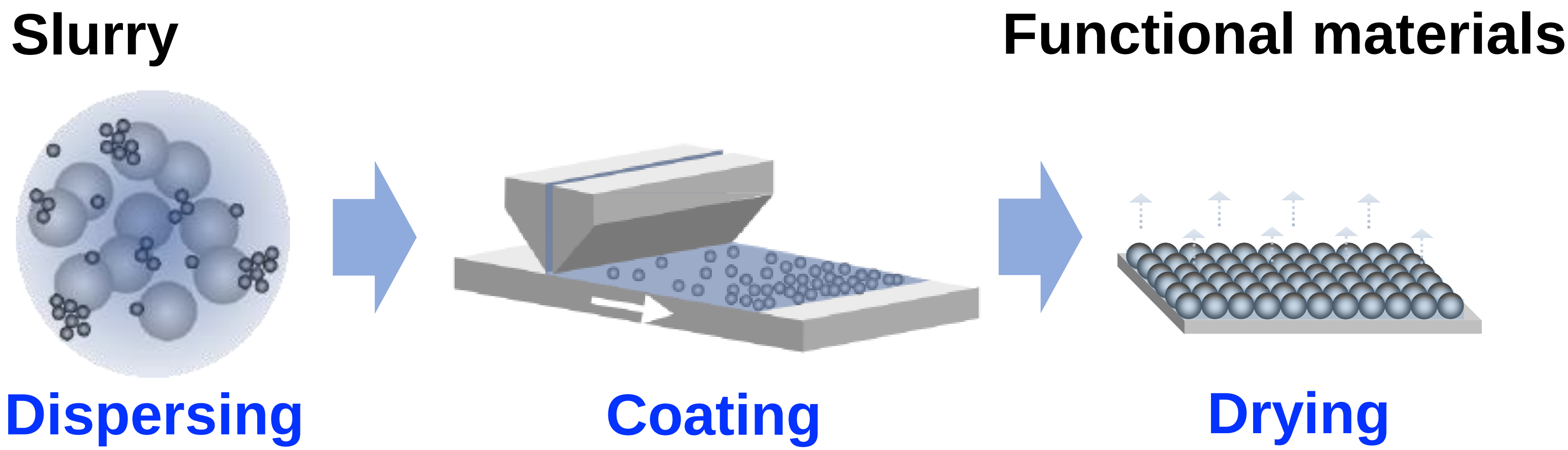
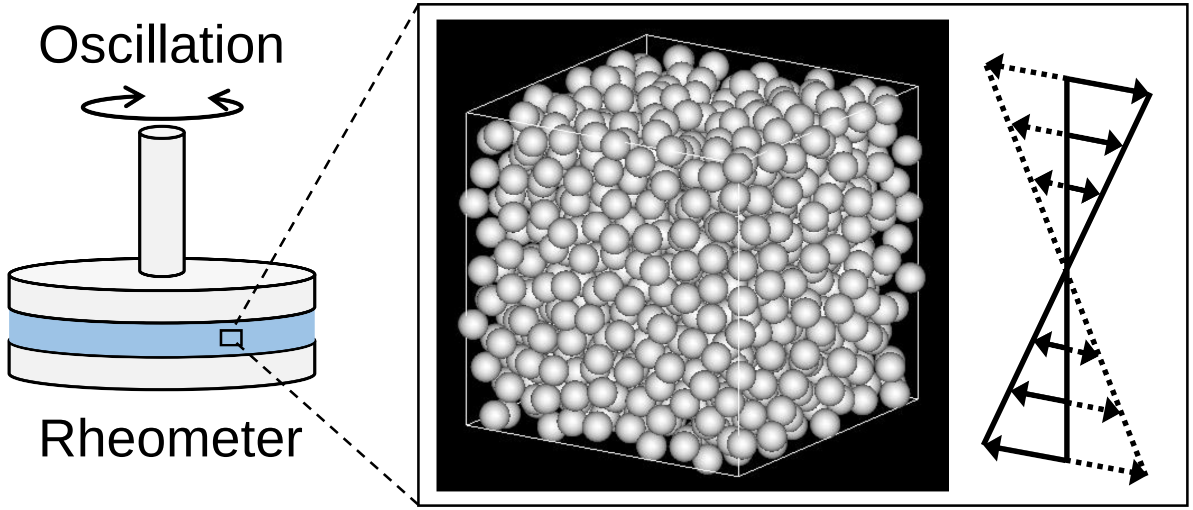
Material Fabrication from Slurry



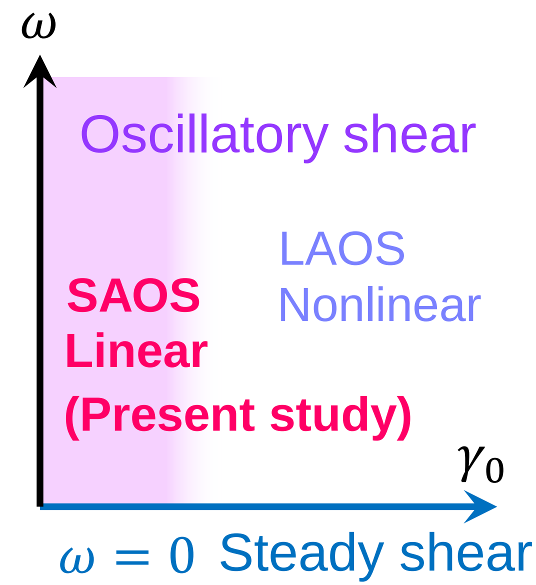
Viscoelasticity can be an index of process

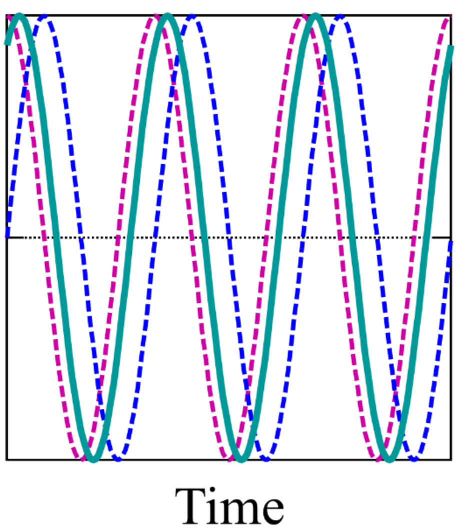
- Structure of particles (aggregation/dispersion)
- Coating properties
- Influence of dispersing/coating on post-process

Viscoelasticity



Oscillatory shear





Strain: $\gamma_0 \sin \omega t$

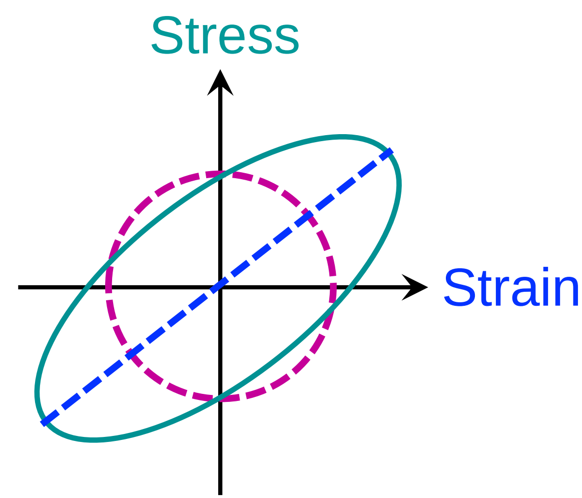
Shear rate: $\gamma_0 \omega \cos \omega t$

Stress: $\sigma_0 \sin(\omega t + \delta)$

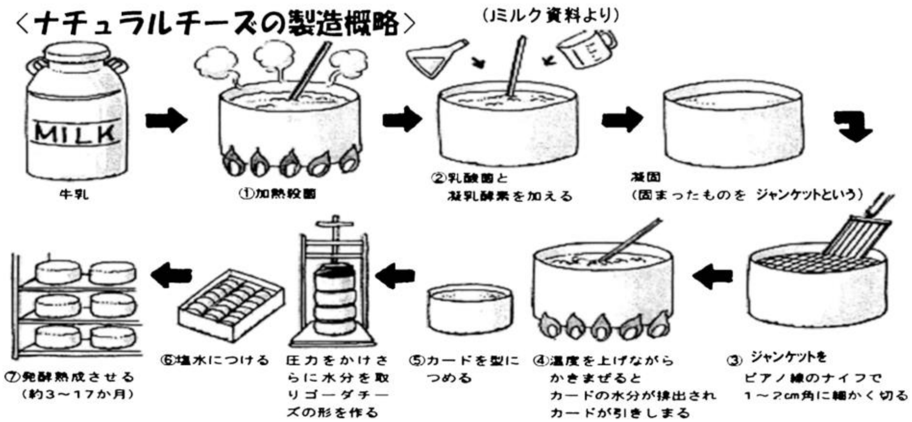
$= \gamma_0 (G' \sin \omega t + G'' \cos \omega t)$

Storage modulus: G'

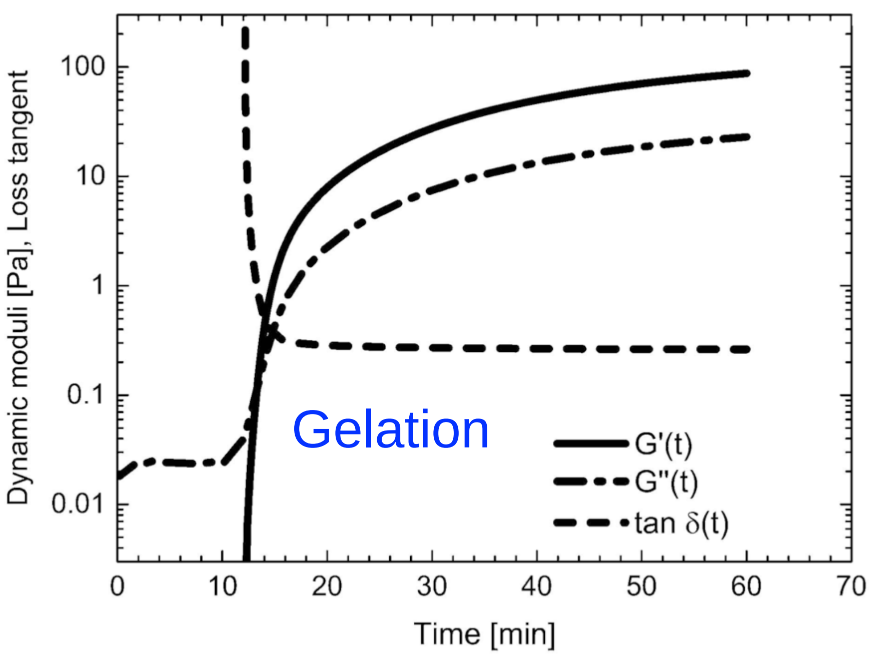
Loss modulus: G''



Example 1: foods (cheese)



(a) LT-milk with *H. erinaceum*



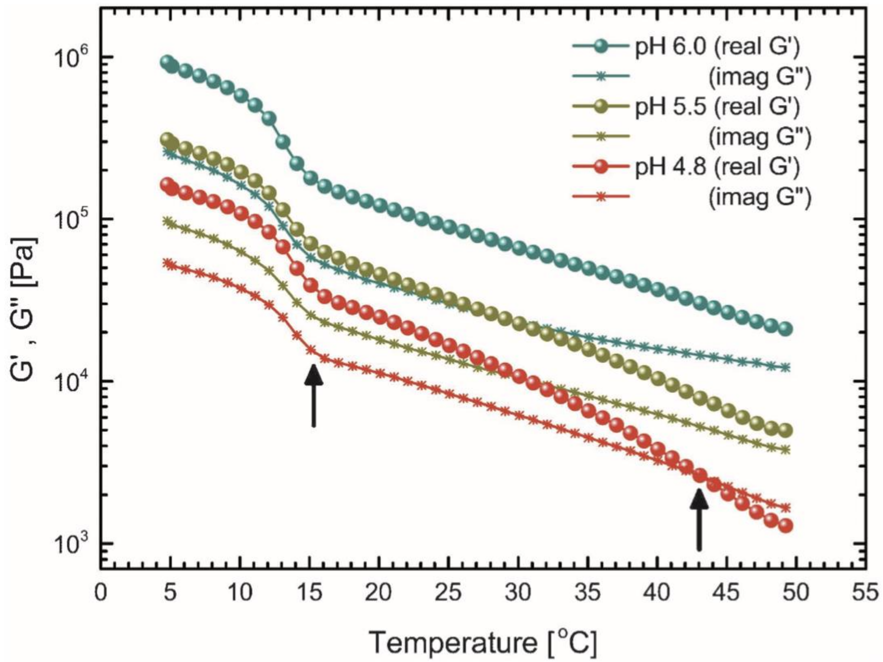


Fig. 8 Temperature dependences of the visco-elasticities of curds under different pH conditions. Each upward arrow indicates the sol-gel transition point (right) and the shoulder caused by lipid-globule melting (left).

谷本守正, ミルクサイエンス **69**, 83 (2020).

Example 2: screen printing

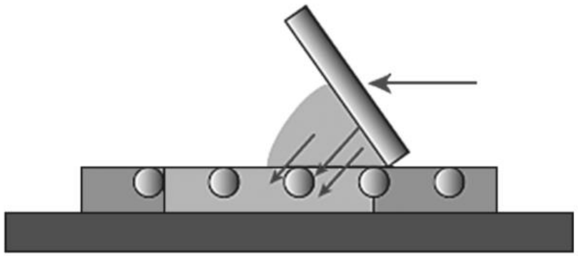


Fig. 2　スクリーン印刷でのインク供給のメカニズム

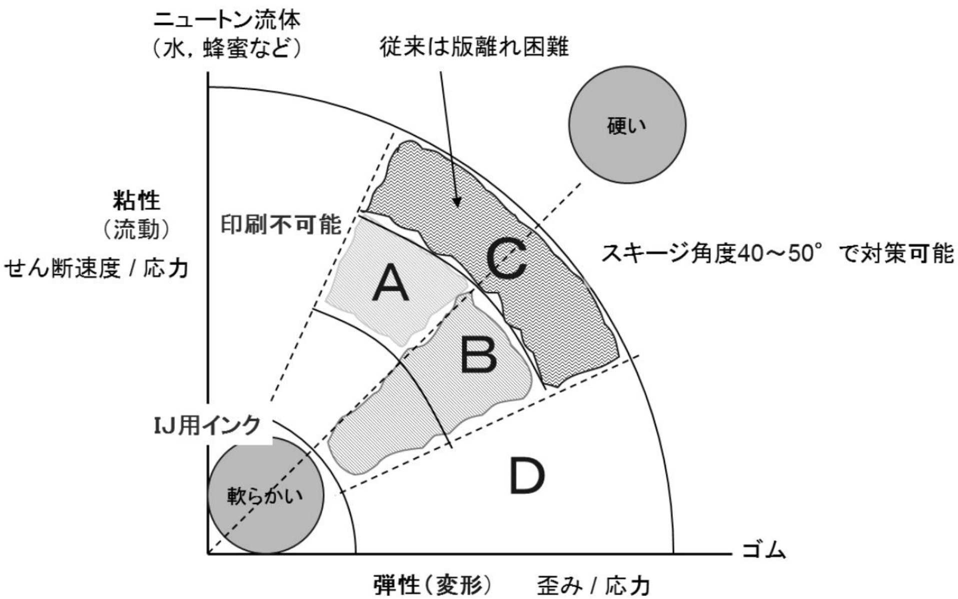


Fig. 6　「粘弾性マップ」でのスクリーン印刷用ペーストの印刷性

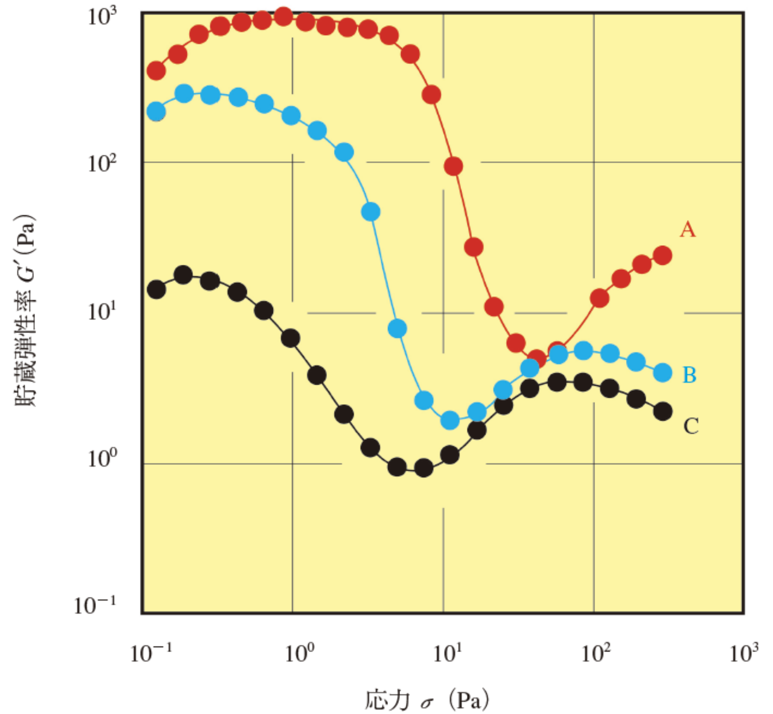


図 5　異なるバインダー樹脂で調製した蛍光体インキにおける貯蔵弾性率の応力依存性

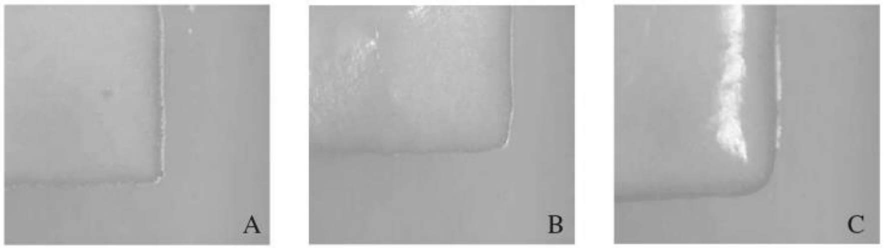


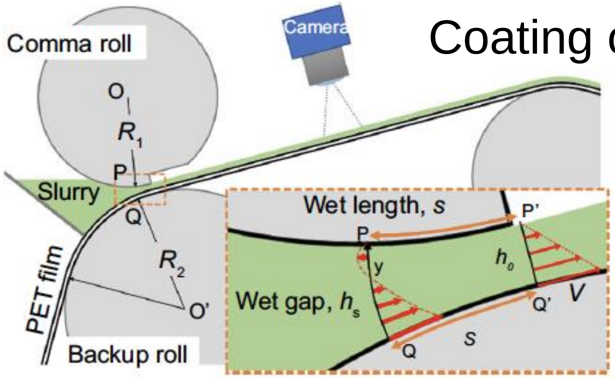
図 6　印刷パターンの顕微鏡写真

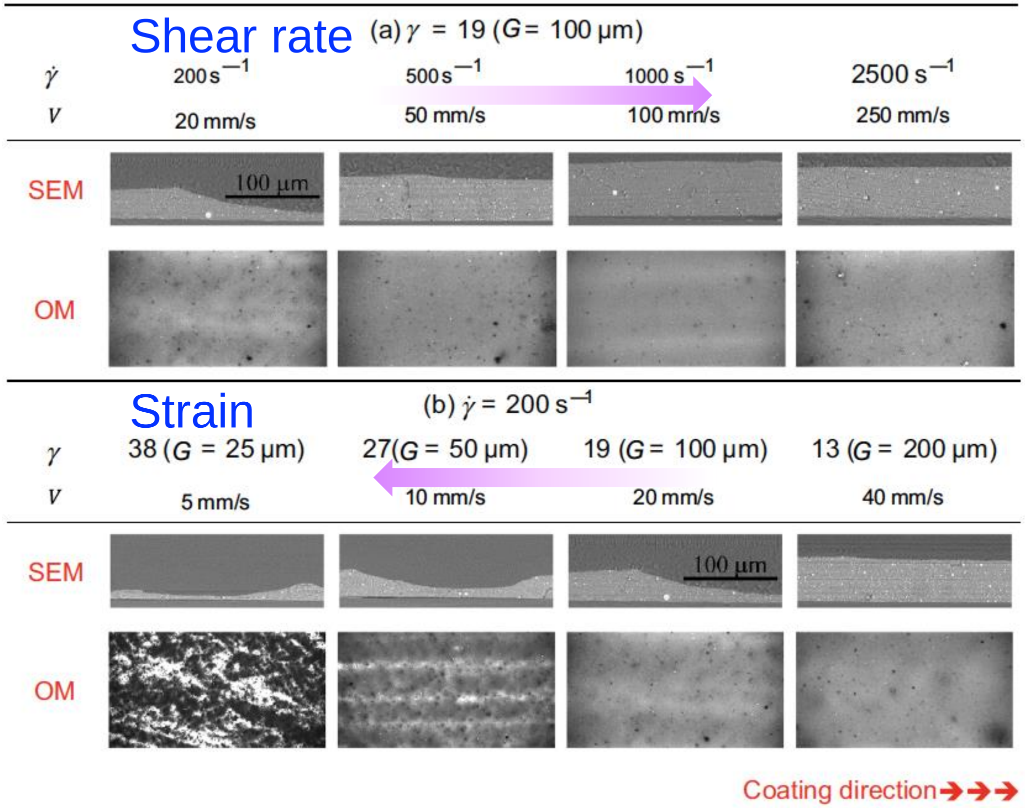
佐野康, 日本写真学会誌 **77**, 65 (2014).

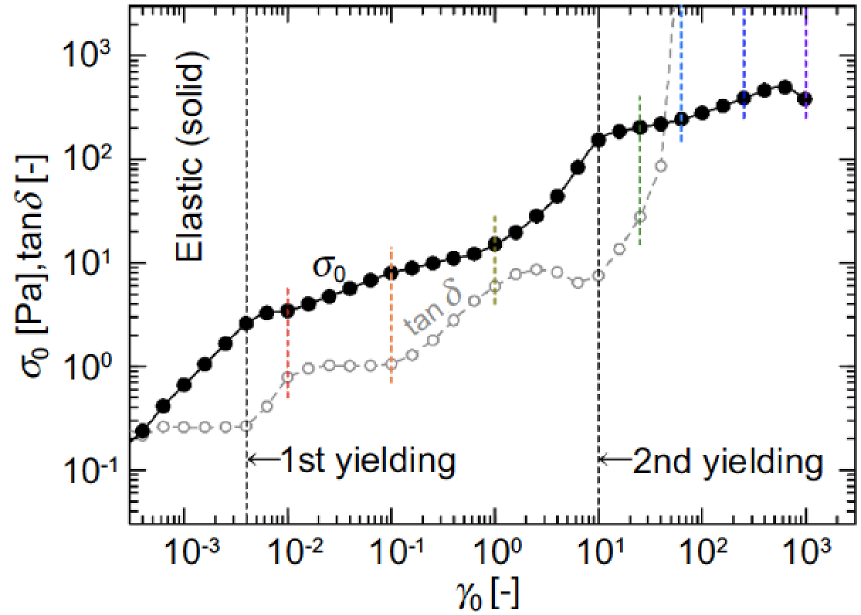
大坪泰文, 成形加工 **22**, 392 (2010).

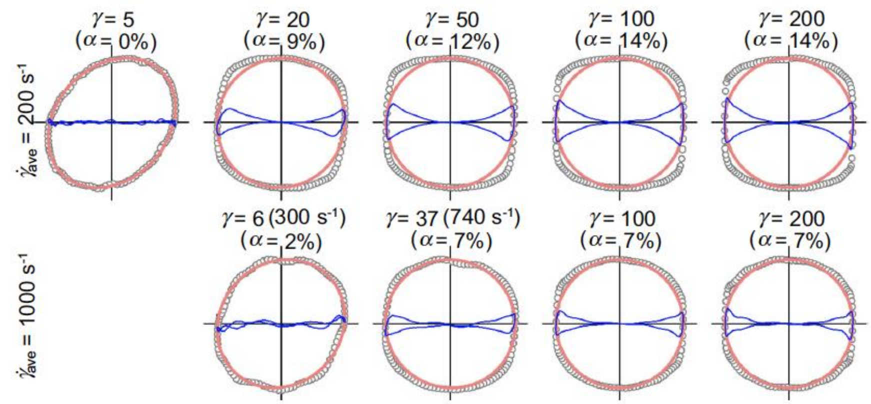
Example 3: uniformity of coated layer

Coating of silica slurry









Komoda *et al*., J. Coat. Technol. Res. **19**, 61 (2022).

Objective

- Constructing a simple particle-scale model that describes the viscoelastic behavior of slurry
- Visualizing the motion of particles that is related to the viscoelastic behavior
- Investigating the effects of interparticle interactions on the viscoelastic behavior

Equation of motion of particles

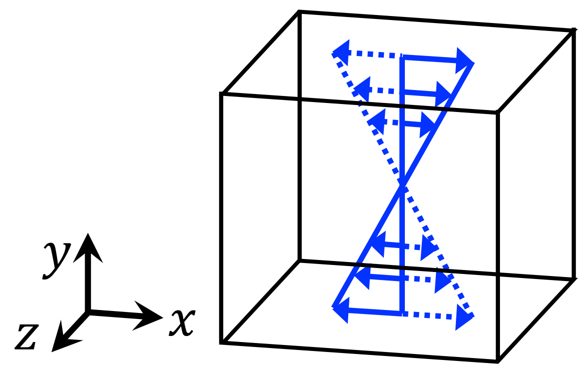
$$M\dot{\boldsymbol{V}} = -\zeta(\boldsymbol{V} - \boldsymbol{V}_{\rm ex}) + \boldsymbol{F}^{\rm cnt} + \boldsymbol{F}^{\rm DLVO}$$

Fluid — Interparticle

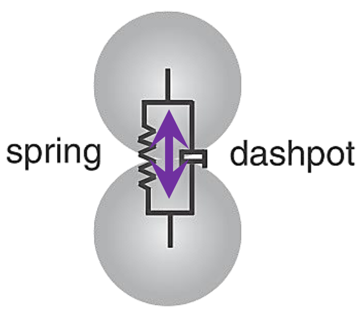
- **Hydrodynamic drag**: $-\zeta(\boldsymbol{V} - \boldsymbol{V}_{\rm ex})$

  Oscillatory shear flow

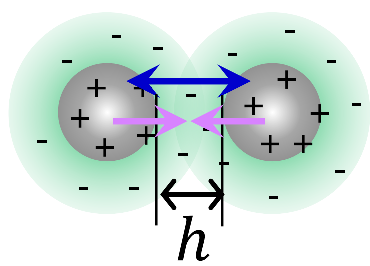
  $\boldsymbol{V}_{\rm ex} = \dot{\gamma}(t) y\, \boldsymbol{e}_x \qquad \dot{\gamma}(t) = \gamma_0 \omega \cos \omega t$

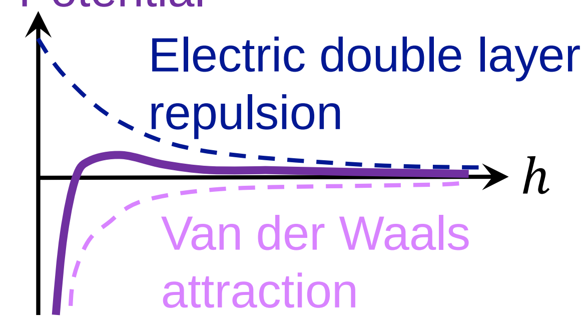


- **Contact force**: $\boldsymbol{F}^{\rm cnt}$



- **DLVO force**: $\boldsymbol{F}^{\rm DLVO}$





→ **Dispersion / Aggregation**

- **Boundary conditions**

  x, z: Periodic, y: Lees-Edwards

Dynamic modulus

Input

Shear strain $\gamma(t) = \gamma_0 \sin \omega t$

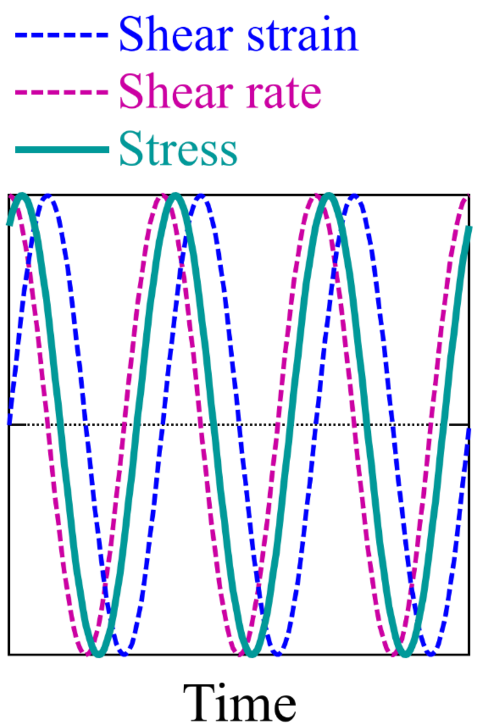
Shear rate $\dot{\gamma}(t) = \gamma_0 \omega \cos \omega t$

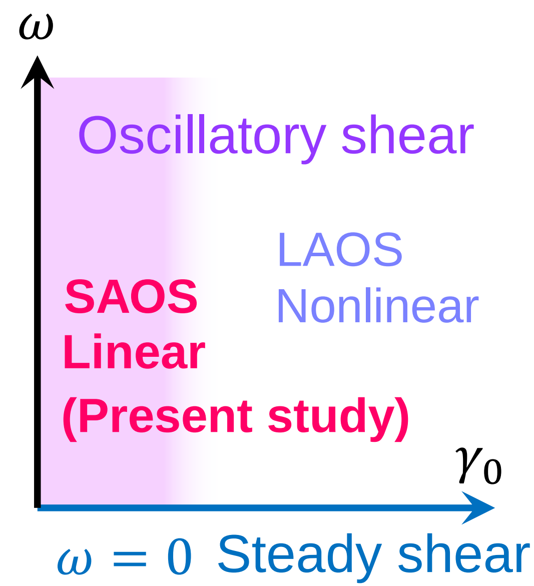
Output

Stress $\sigma(t) = \sigma_0 \sin(\omega t + \delta)$

$= \gamma_0 (G' \sin \omega t + G'' \cos \omega t)$

$G' = \dfrac{\sigma_0}{\gamma_0} \cos \delta \quad G'' = \dfrac{\sigma_0}{\gamma_0} \sin \delta$





Dynamic modulus

- Storage modulus (Elastic)

$$G'(\omega) = \frac{\omega}{\pi \gamma_0} \int_0^{2\pi/\omega} \sigma(t) \sin \omega t \, \mathrm{d}t$$

- Loss modulus (Viscous)

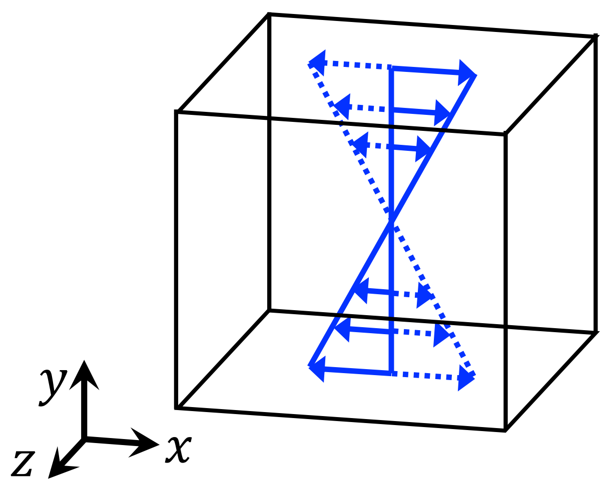
$$G''(\omega) = \frac{\omega}{\pi \gamma_0} \int_0^{2\pi/\omega} \sigma(t) \cos \omega t \, \mathrm{d}t$$

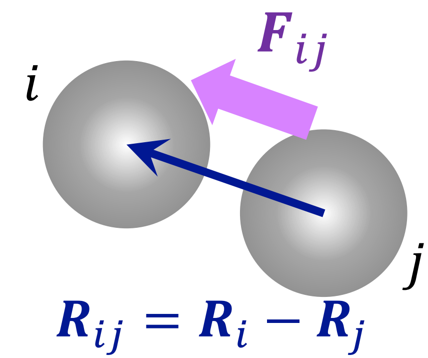
Stress

$$\sigma = \sigma_{\mathrm{f}} + \sigma_{\mathrm{p}} = \eta\left(1 + \frac{5}{2}\phi\right)\dot{\gamma} - \frac{1}{V}\sum_{i<j} F_{ij}^{x} R_{ij}^{y}$$

Fluid
(Einstein's viscosity equation)

Interparticle





- Storage modulus

$$G' = G'_{\mathrm{p}}$$

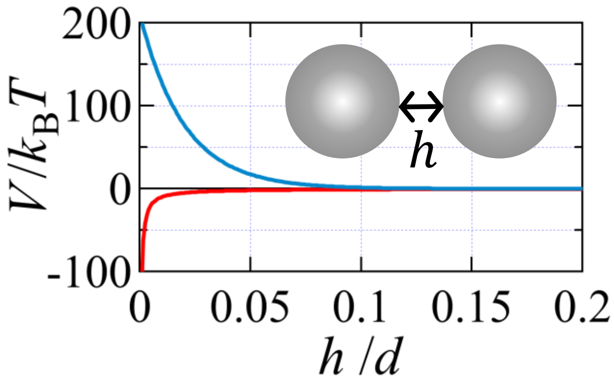
- Loss modulus

$$G'' = G''_{\mathrm{f}} + G''_{\mathrm{p}} = \eta\omega\left(1 + \frac{5}{2}\phi\right) + G''_{\mathrm{p}}$$

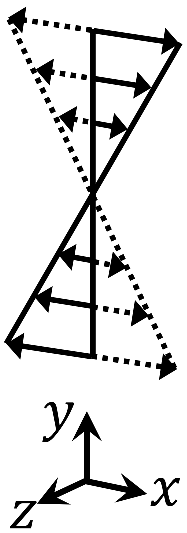
Simulation Conditions

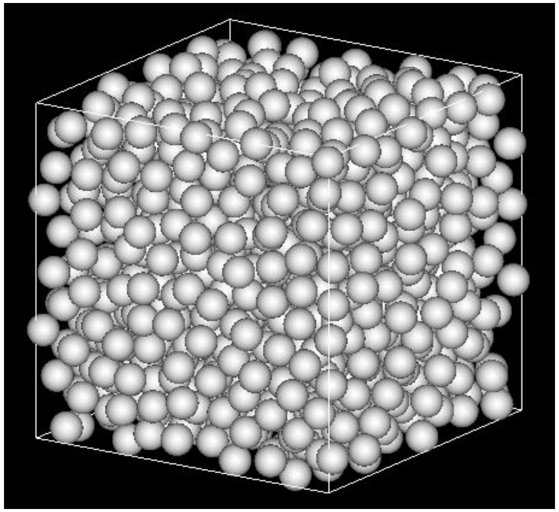
Particles

- Diameter: $d = 1\ \mu\text{m}$
- Concentration: $45\ \text{vol\%}$
- Zeta potential: $0\ \text{mV}$, $20\ \text{mV}$



$U_x(t) = \dot{\gamma}(t)y$





Side length: $22.7d$

Fluid: Water

- Ionic strength: $0.23\ \text{mM}$

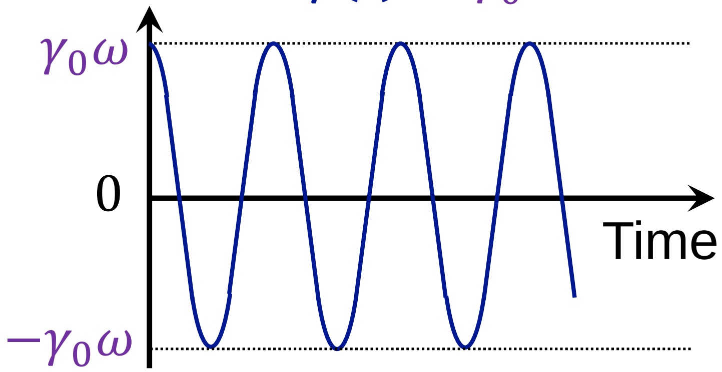
Shear flow

- Strain: $\gamma_0 = 1 \times 10^{-3} - 3$
- Frequency: $\omega\tau = 3.6 \times (10^{-3} - 10^{2})$

$\tau = 3\pi\eta d^2/F$

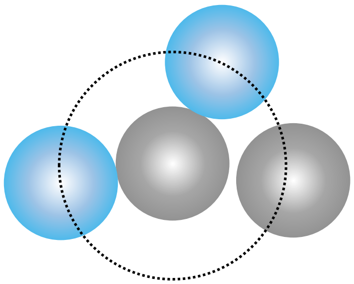
F : Force between contacting particles

Shear rate $\dot{\gamma}(t) = \gamma_0\omega\cos\omega t$

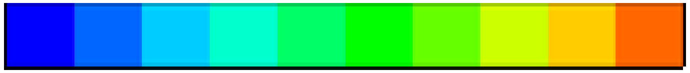


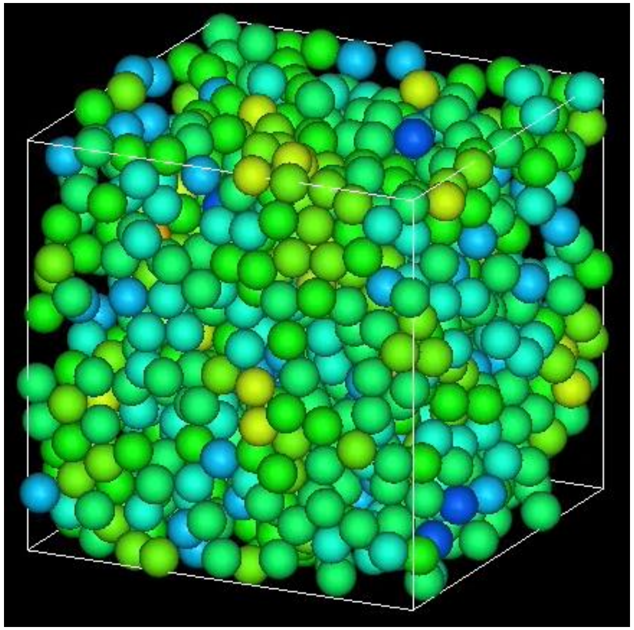
Structure of particles

Aggregation

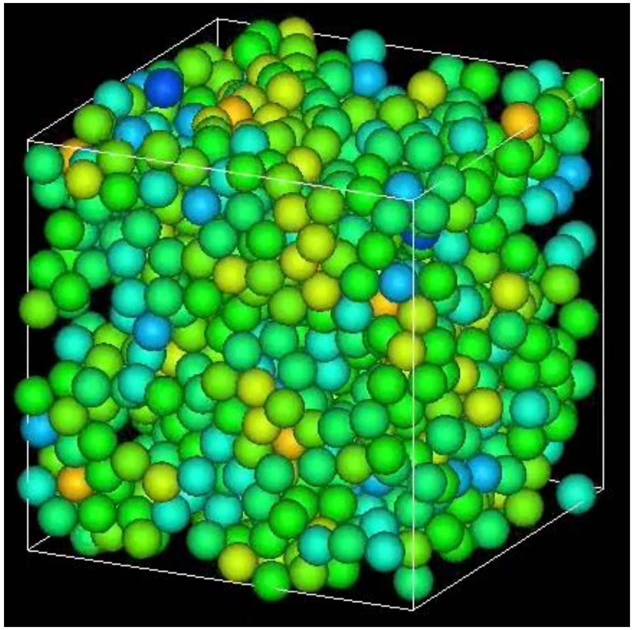


Contact number

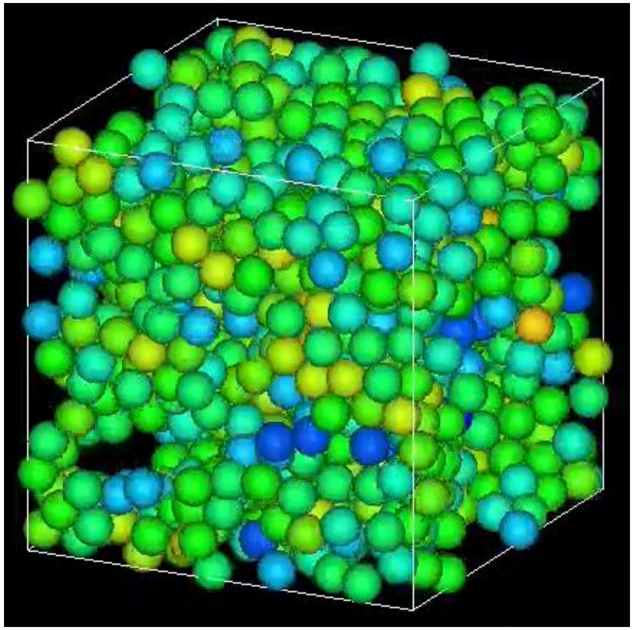




$\gamma_0 = 0.01$



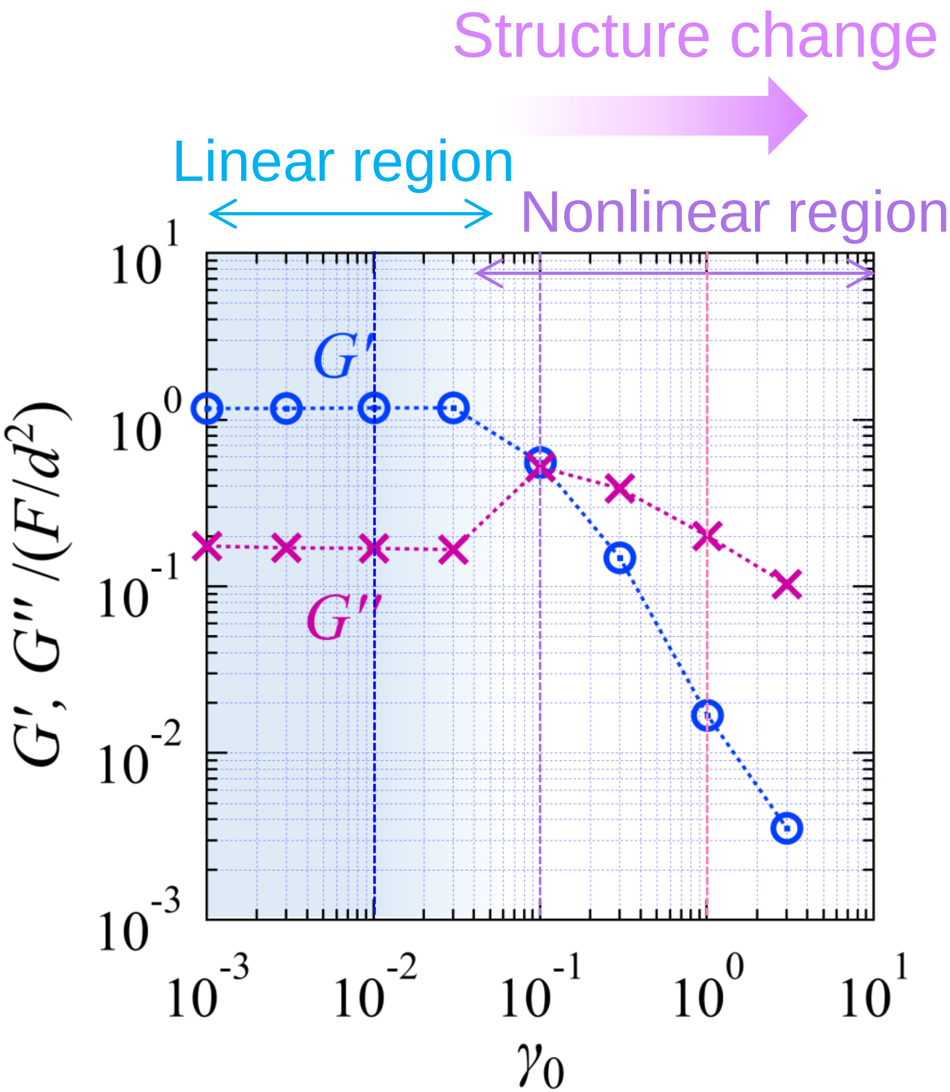
$\gamma_0 = 0.1$

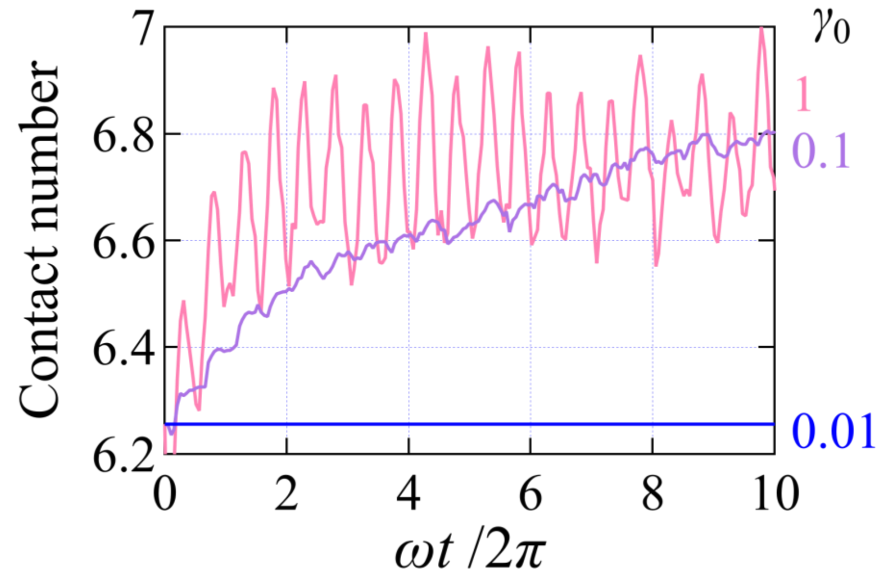


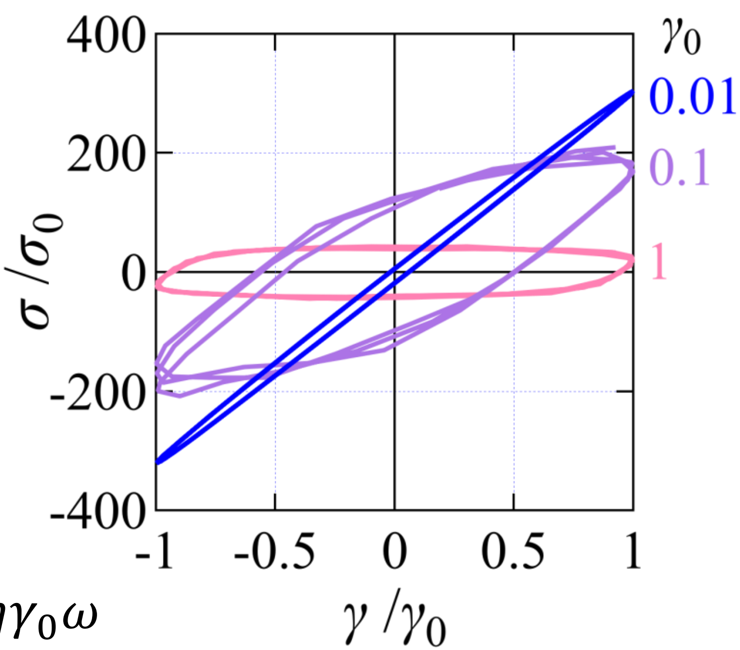
$\gamma_0 = 1$

Strain dependence

Aggregation





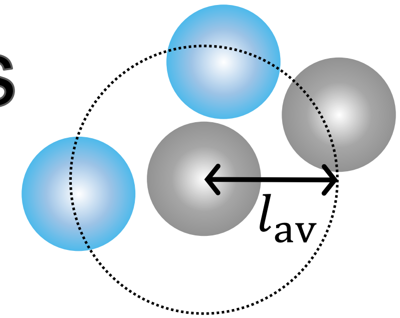


$\omega\tau = 3.6 \times 10^{-2}$

$\sigma_0 = \eta\gamma_0\omega$

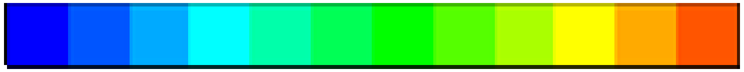
Structure of particles

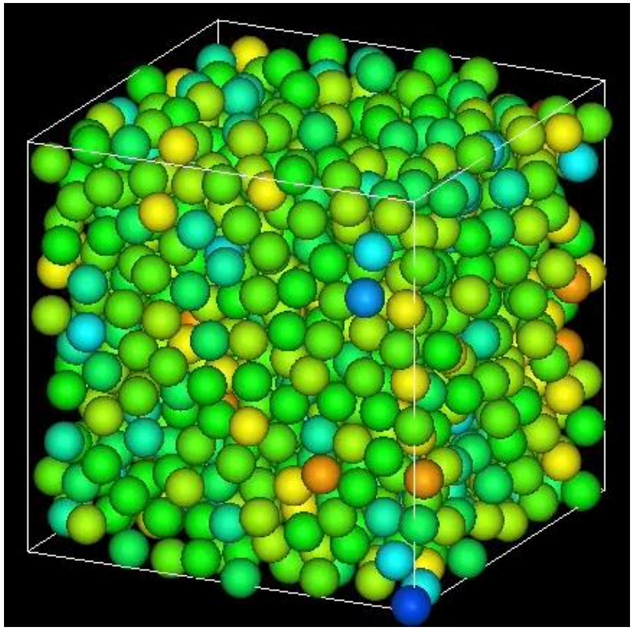
Dispersion



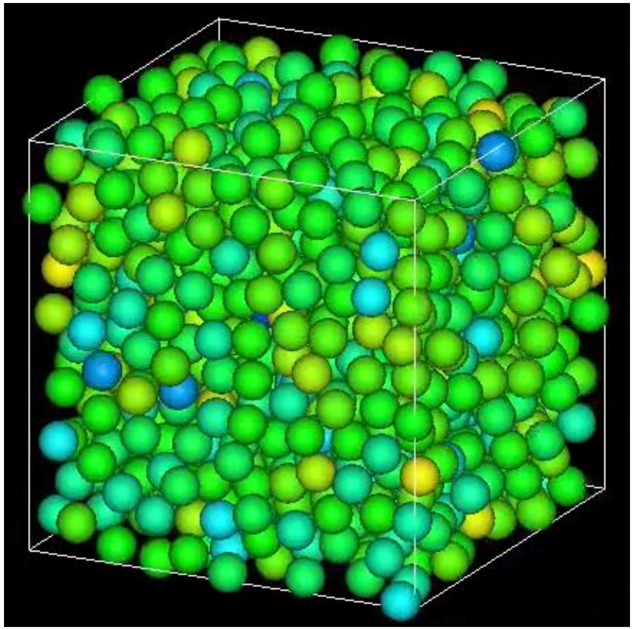
$l_{\mathrm{av}}/d = (\text{Volume fraction})^{-1/3}$

Coordination number

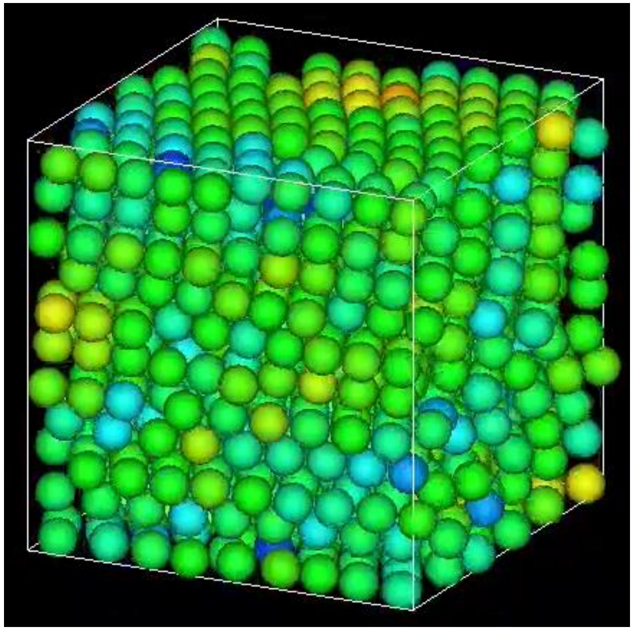




$\gamma_0 = 0.01$

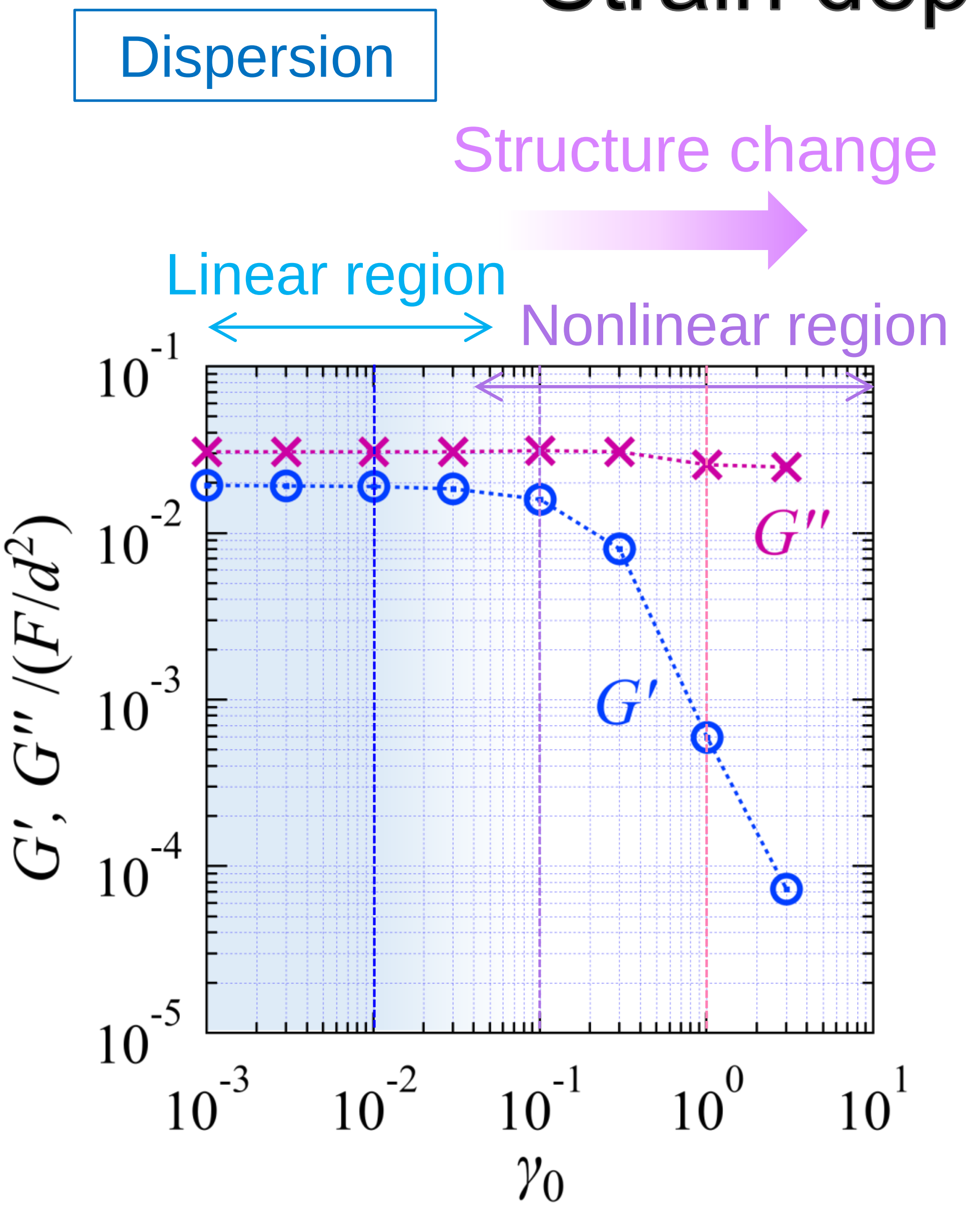


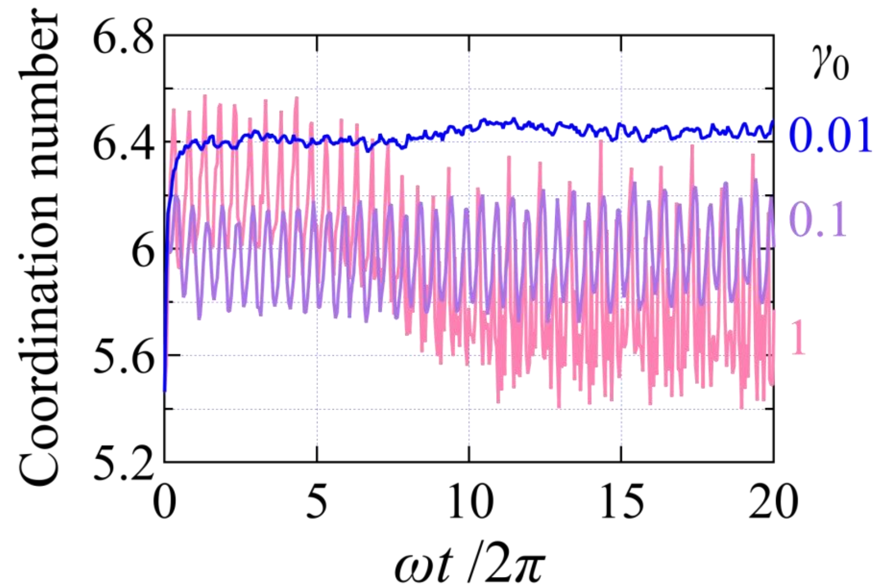
$\gamma_0 = 0.1$

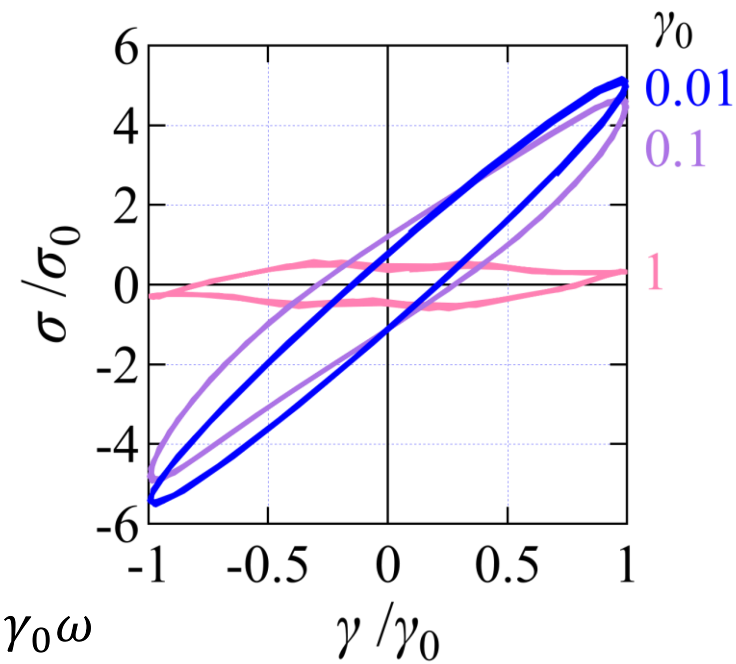


$\gamma_0 = 1$

Strain dependence



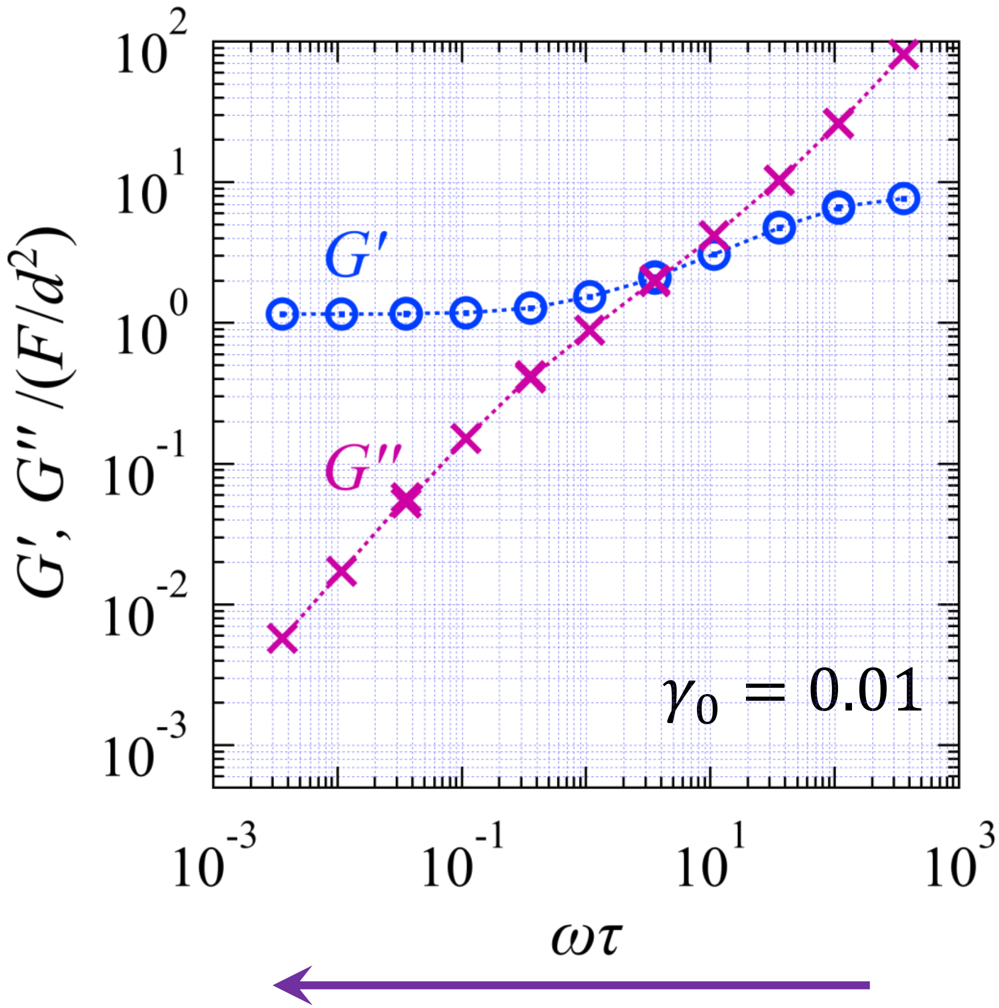




$\sigma_0 = \eta \gamma_0 \omega$

Frequency dependence

Aggregation



Larger interparticle force
Lower frequency

Interparticle force = Drag force

$$F = 3\pi\eta d U$$

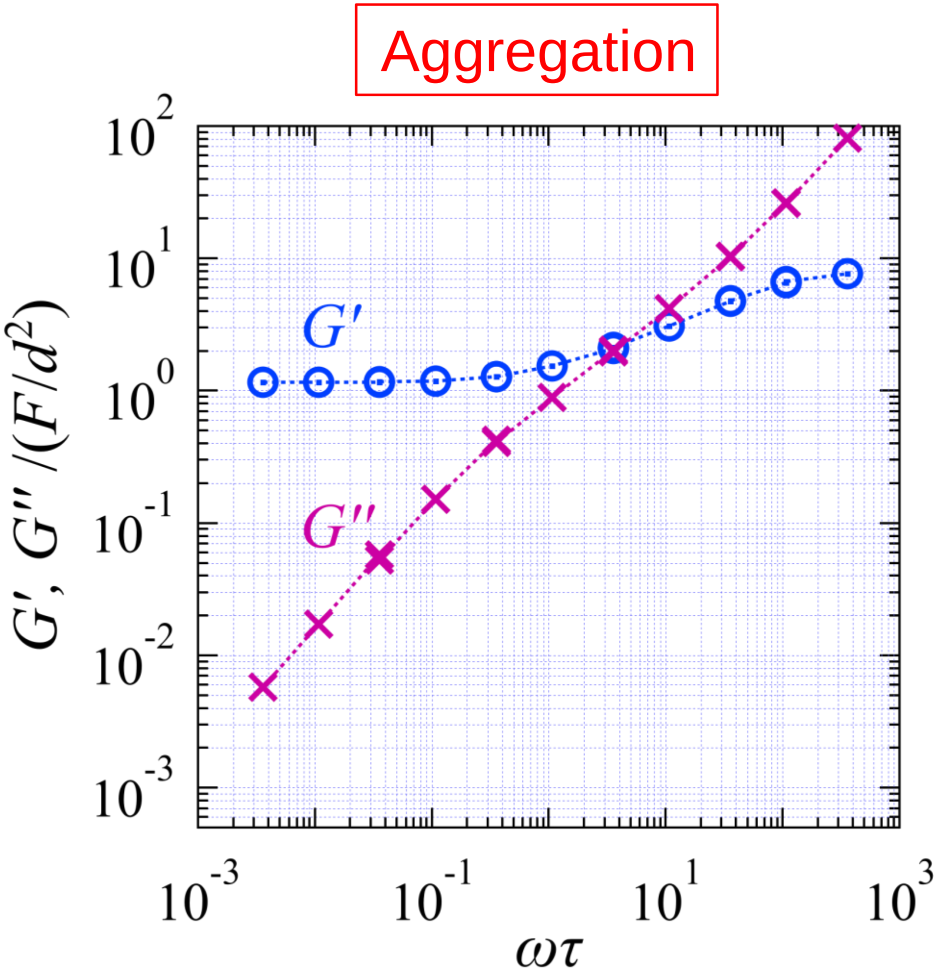
Velocity of adhesion

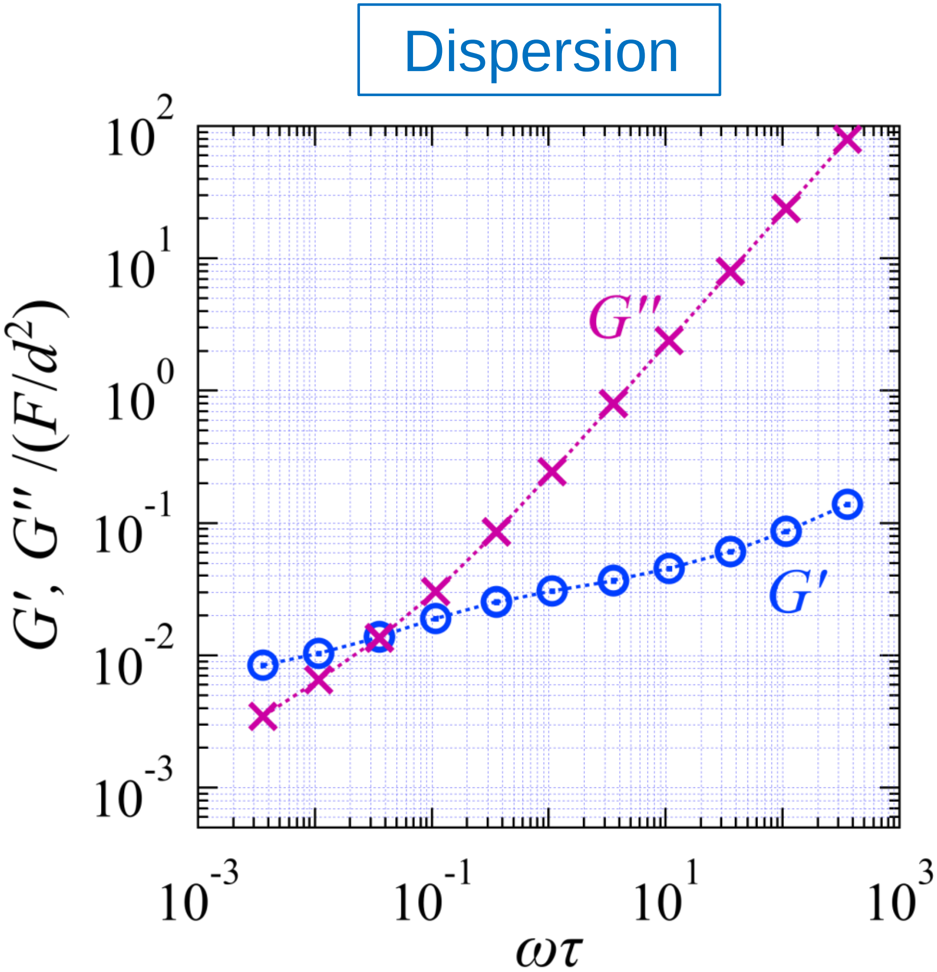
$$U = \frac{F}{3\pi\eta d}$$

Relaxation time

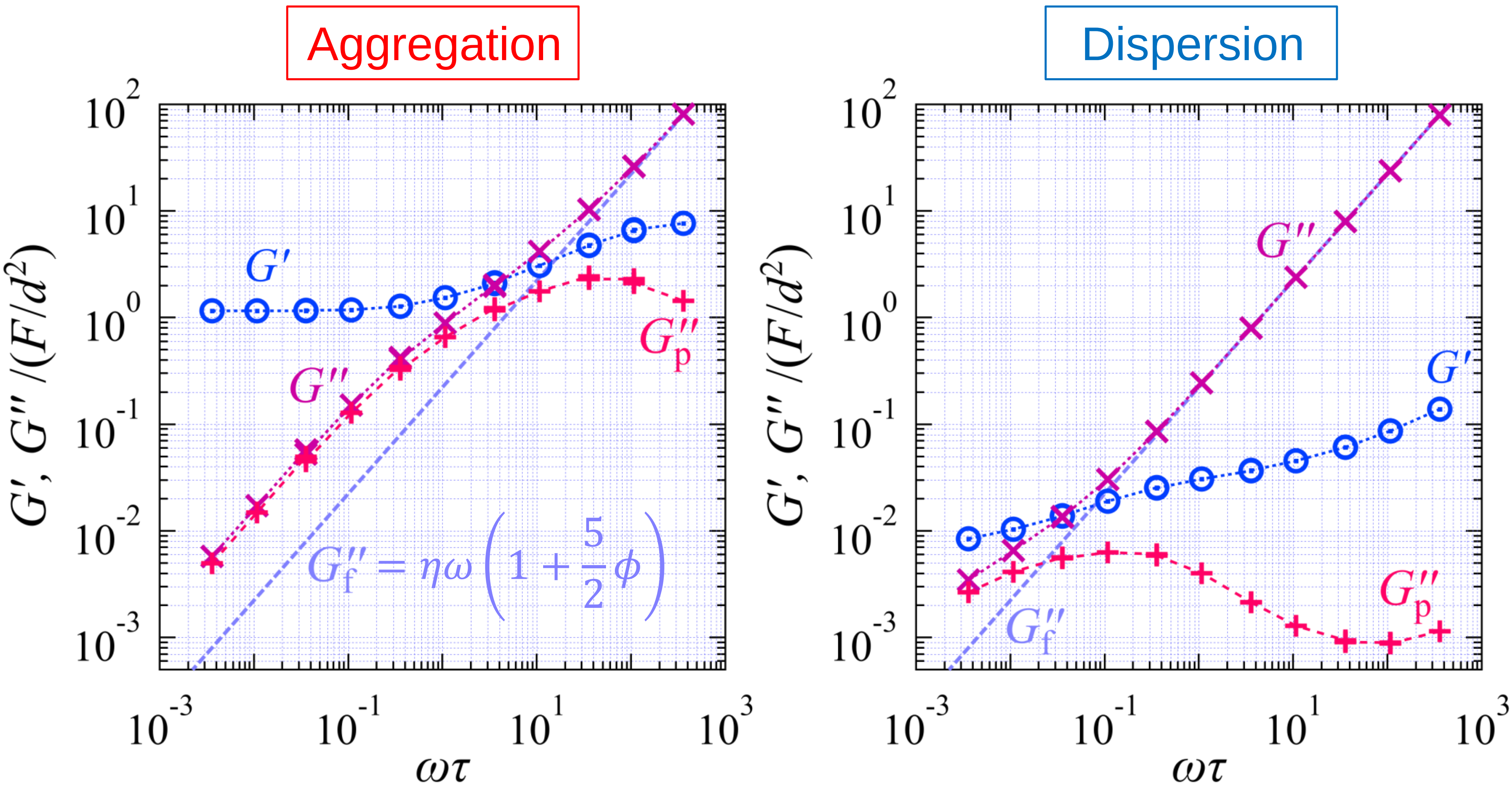
$$\tau = \frac{d}{U} = \frac{3\pi\eta d^2}{F}$$

Frequency dependence



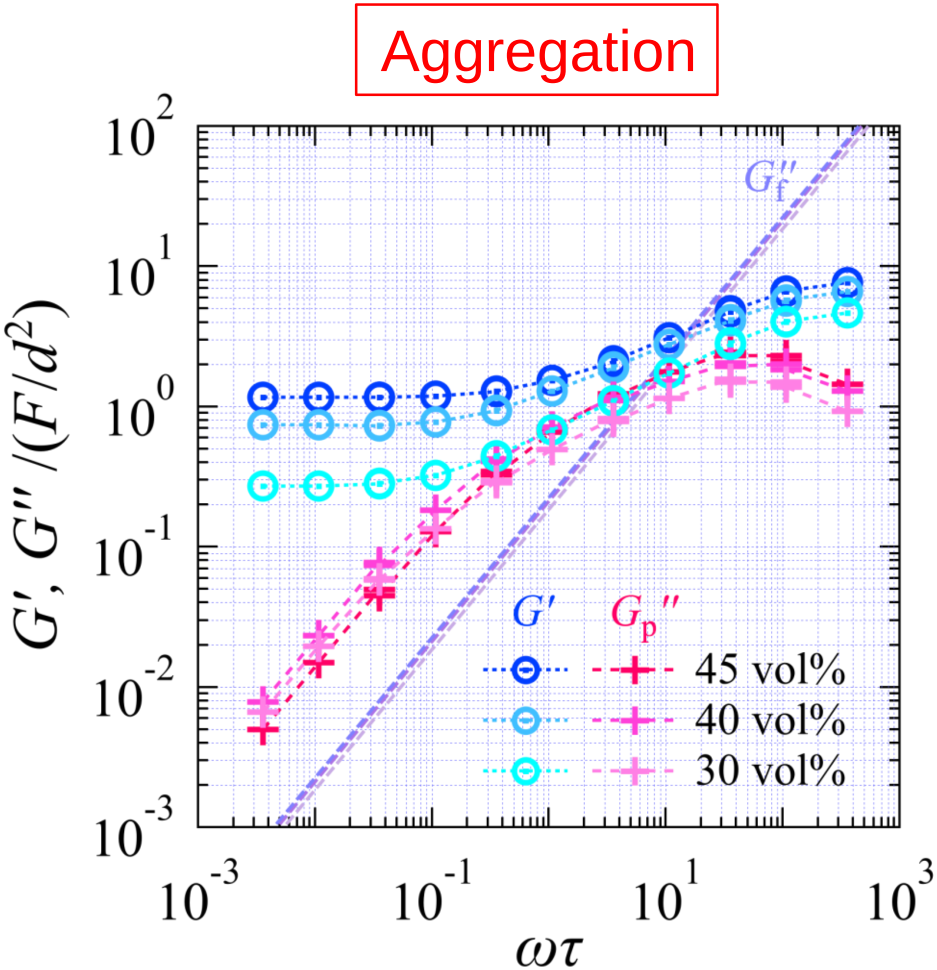


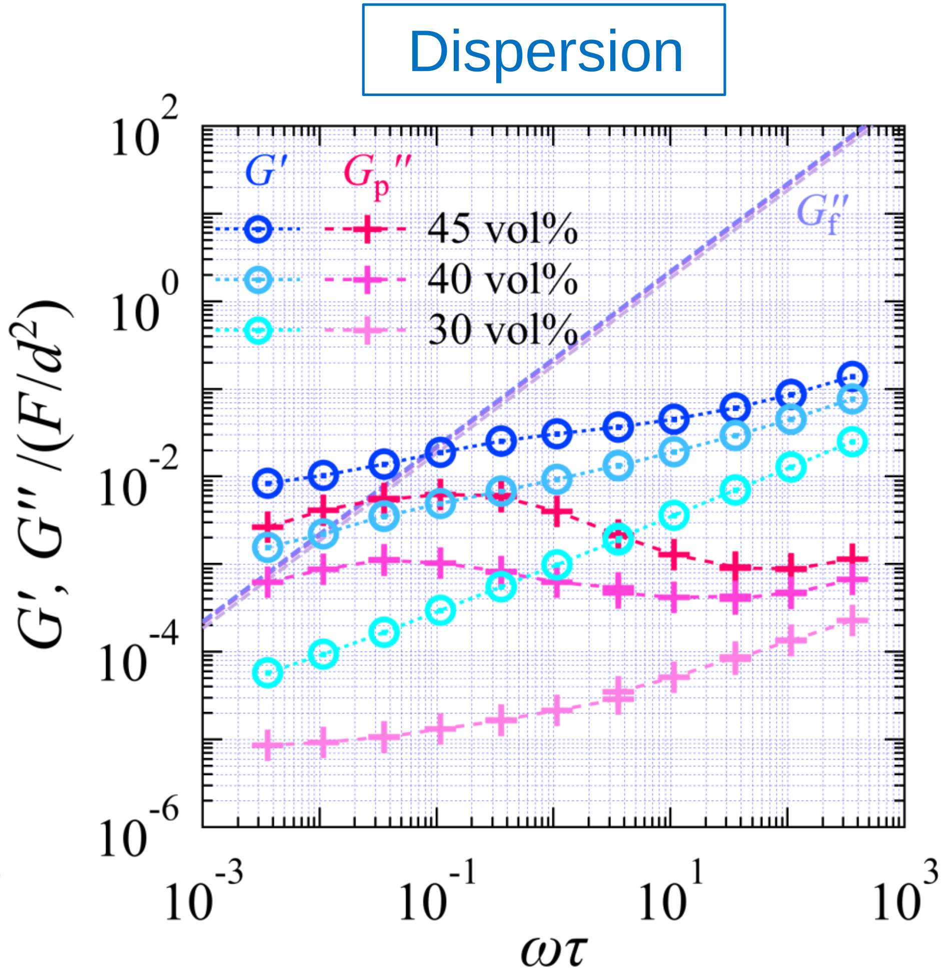
Frequency dependence



Decomposition of loss modulus: $G'' = G''_f + G''_p$

Effects of particle concentration





Summary

- Viscoelasticity can be described by a simple model that only considers drag force and interparticle force
- Both attractive and repulsive interaction can provide elasticity
- Strain dependence reflects the structure change of particles
- Frequency dependence:
  - Aggregated particles provide a finite value of G' in low frequency limit
  - G'' is dominated by fluid part G''_{f} at high frequency
  - Non-monotonic behavior of G'' would appear for concentrated slurry