Drying wet powders with shear to prevent agglomerate formation

IFPRI AGM 2025: Carry Le Rouet

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Objective & Approach

Characterizing the formation of agglomerates during drying with different model powders and shear conditions

Industrial drying of materials:

Large range of shear conditions
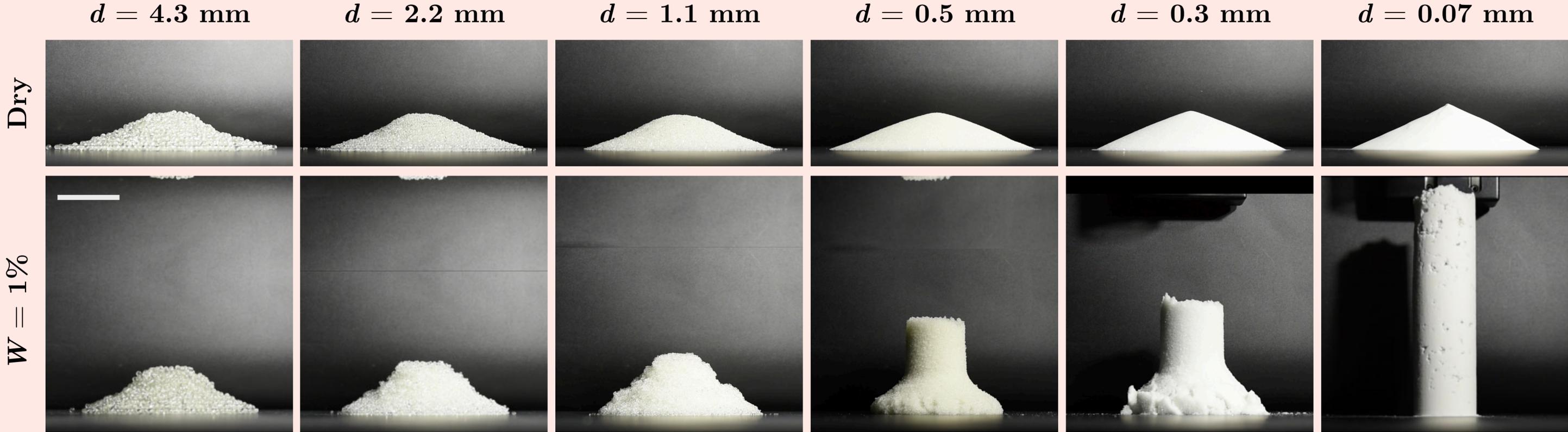Large range of powder properties

Our approach:

Shear conditions using model geometries
Model cohesive granular materials

An approach to understand agglomerate evolution through model experimental geometries and stress conditions
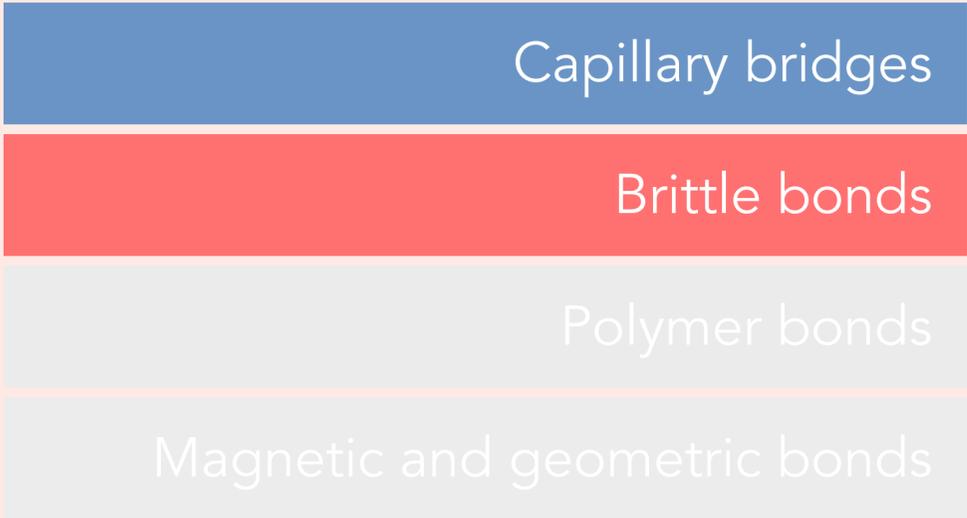
Cohesion + shear = agglomerates

How does the applied shear control agglomerate distributions? evolution?
How does the kind of cohesion modify agglomeration? (brittle, or reforming)

Natural agglomeration vs. the behavior of controlled agglomerates in shear

Experimental models for cohesive granular materials
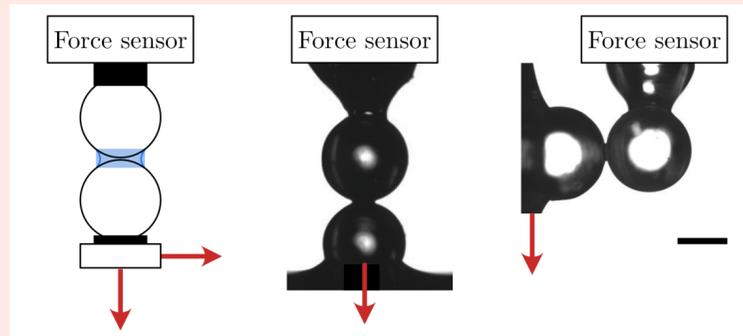
Measuring inter-particle adhesion forces
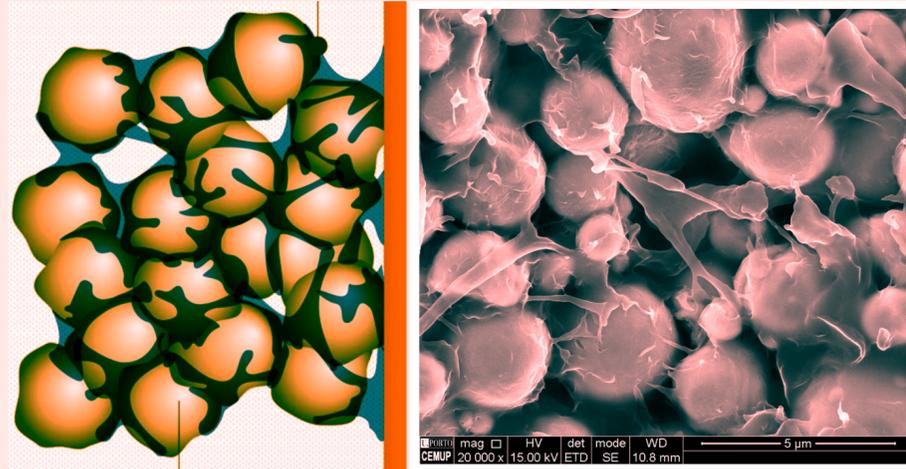

$$\mathrm{Bo} = \frac{F_c}{F_w}$$
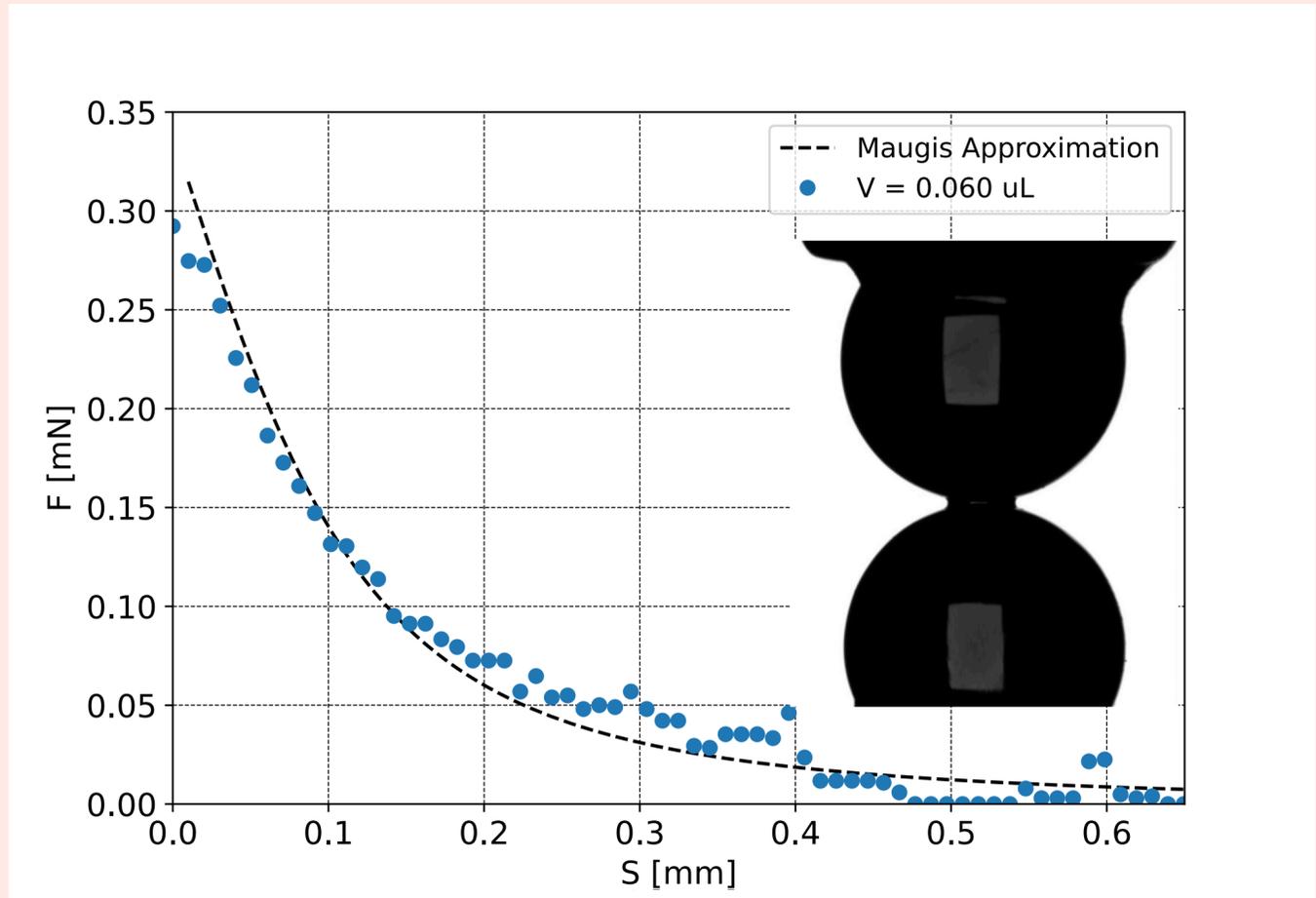
Pitois *et al.* (2000) JCIS
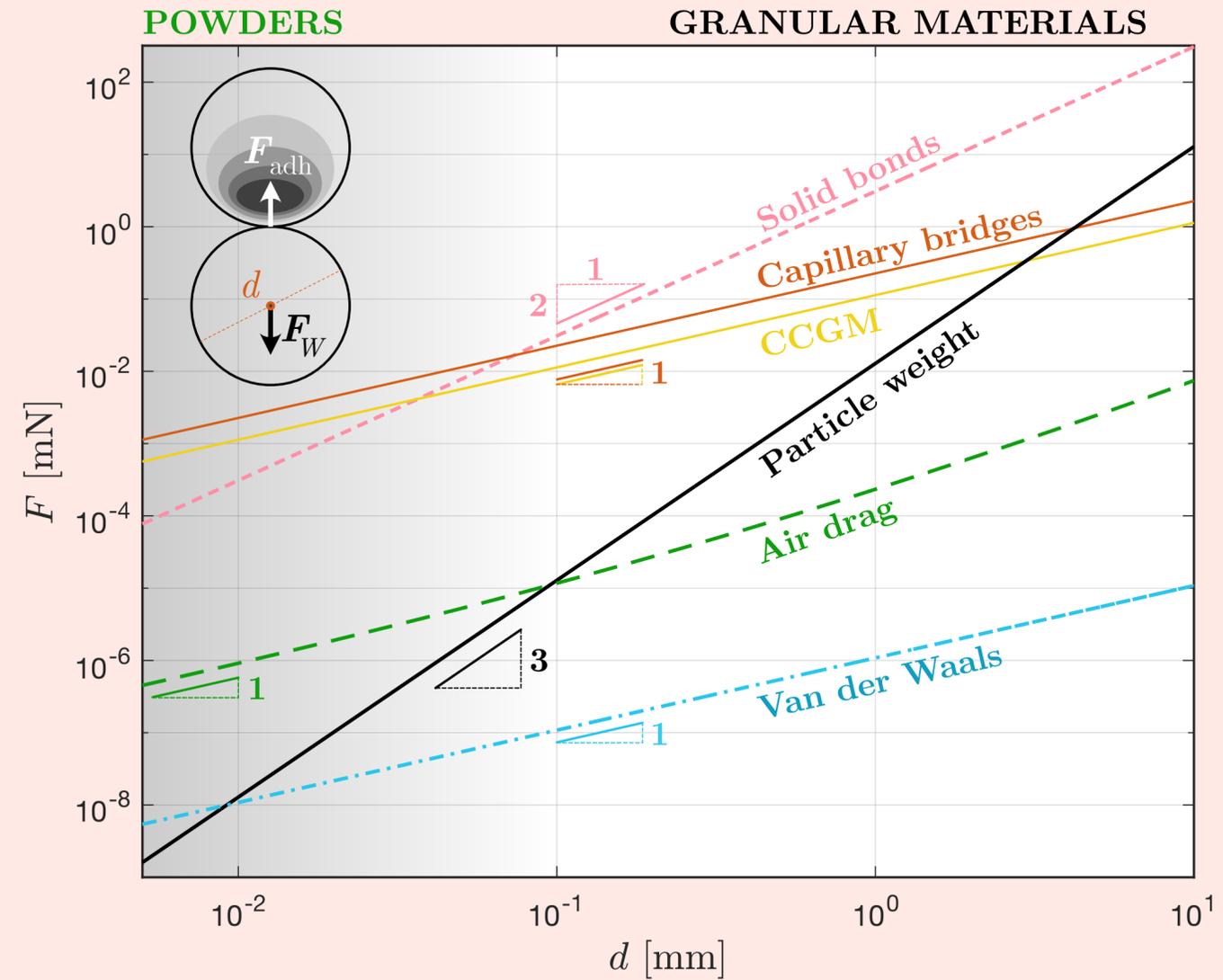
$$F = 2\gamma\pi R\cos\theta\left[1 - 1/\sqrt{1 + 2\zeta/\pi RS^2}\right]$$

Measuring inter-particle adhesion forces

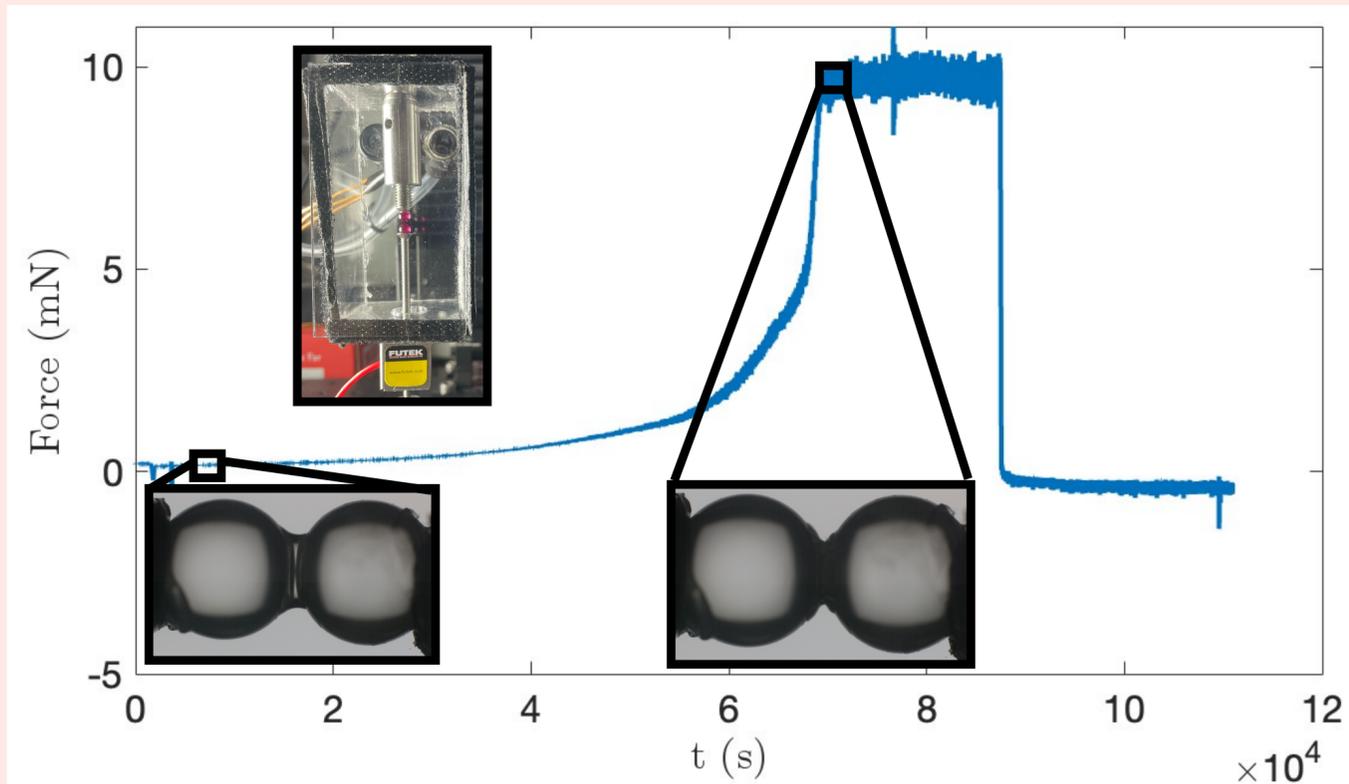Polymers modify capillary forces. However, most existing models only account for simple Newtonian fluids.

High-Speed Camera

Humidity Chamber

Force sensor

LED Backlight

z

r

$S(z)$

R_{min}

θ

F

$v(z)$

0.000 s

F_{peak}

Force

Gap
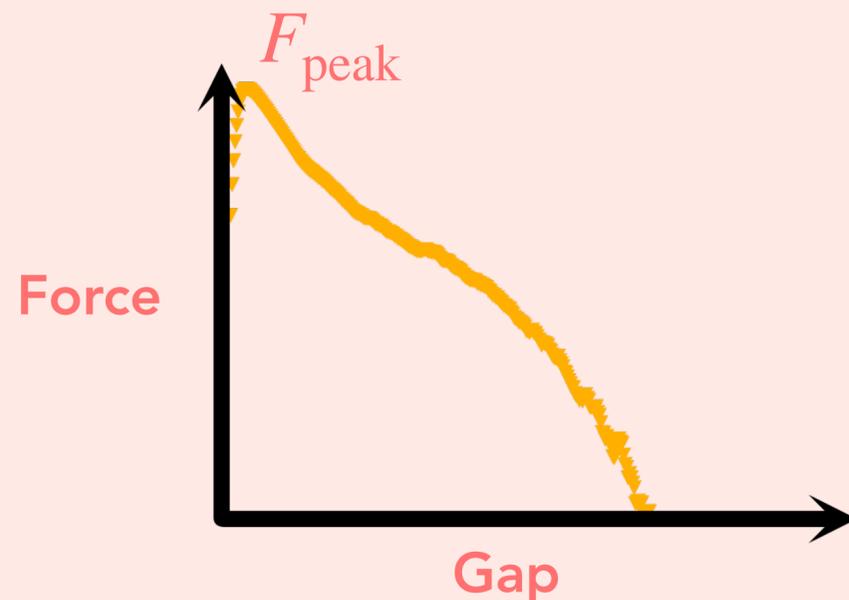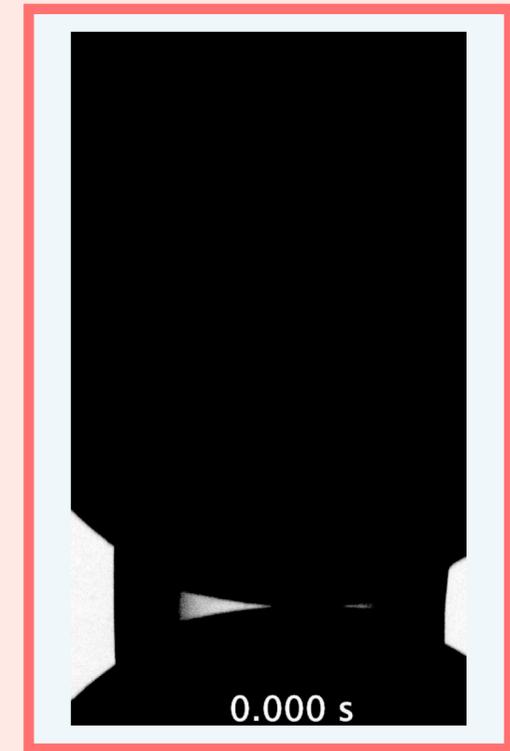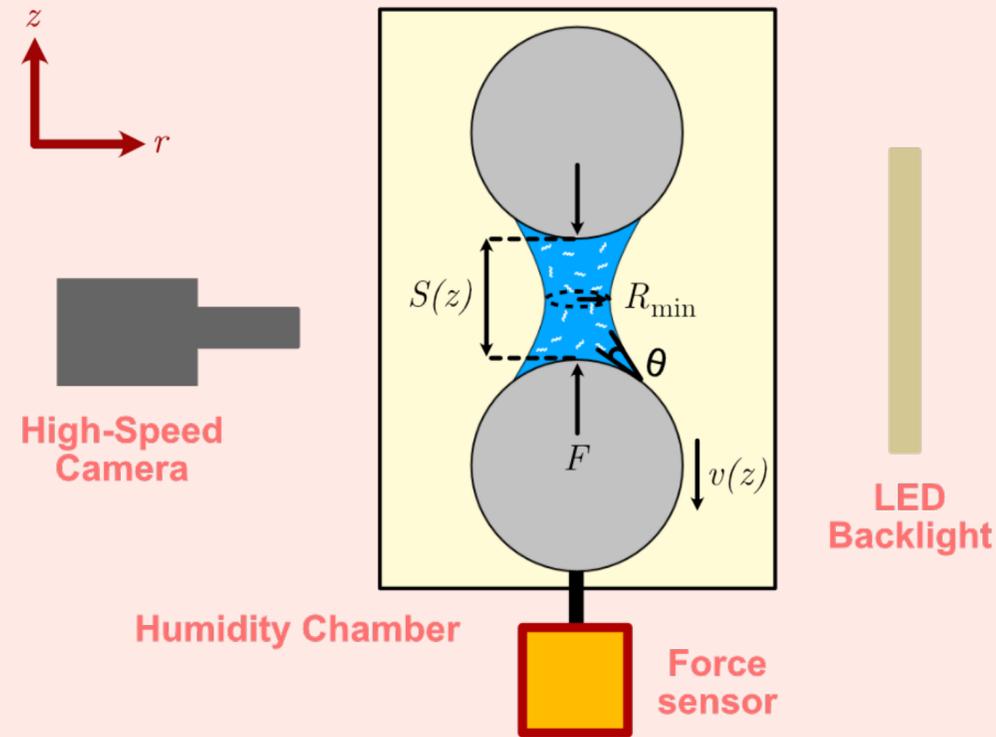
$$F_{peak} \propto R v^n$$

▼ R = 1.0 mm
▼ R = 1.5 mm
▼ R = 2.0 mm
▼ R = 2.5 mm
▼ R = 3.0 mm

Peak Force [mN]

1.0

0.5

0.2

Rate of Separation [mm/s]

0.01   0.10   1.00   10.00

# Measuring inter-particle adhesion forces

Saturated NaCl
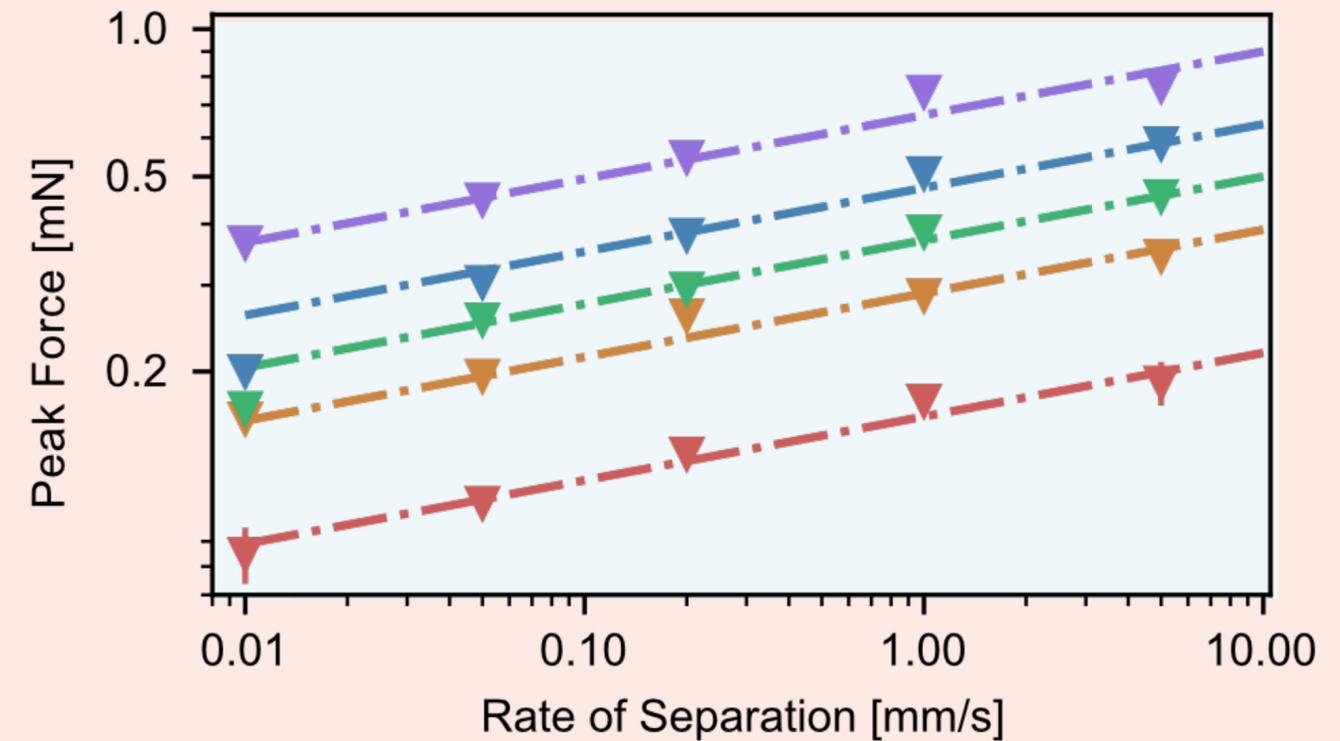
- Evaporation of salt solutions, particle laden liquid systems results in solid deposits between particles.

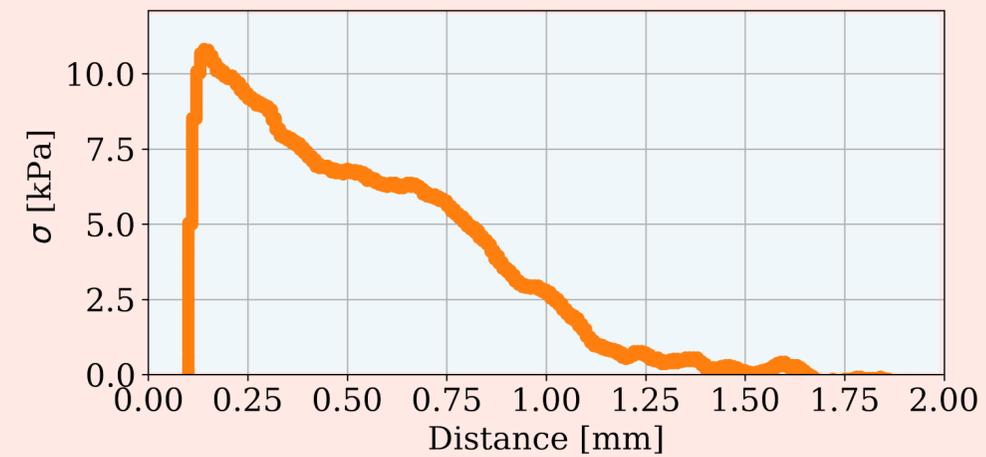- Solid deposits results in increase in the capillary forces between particles
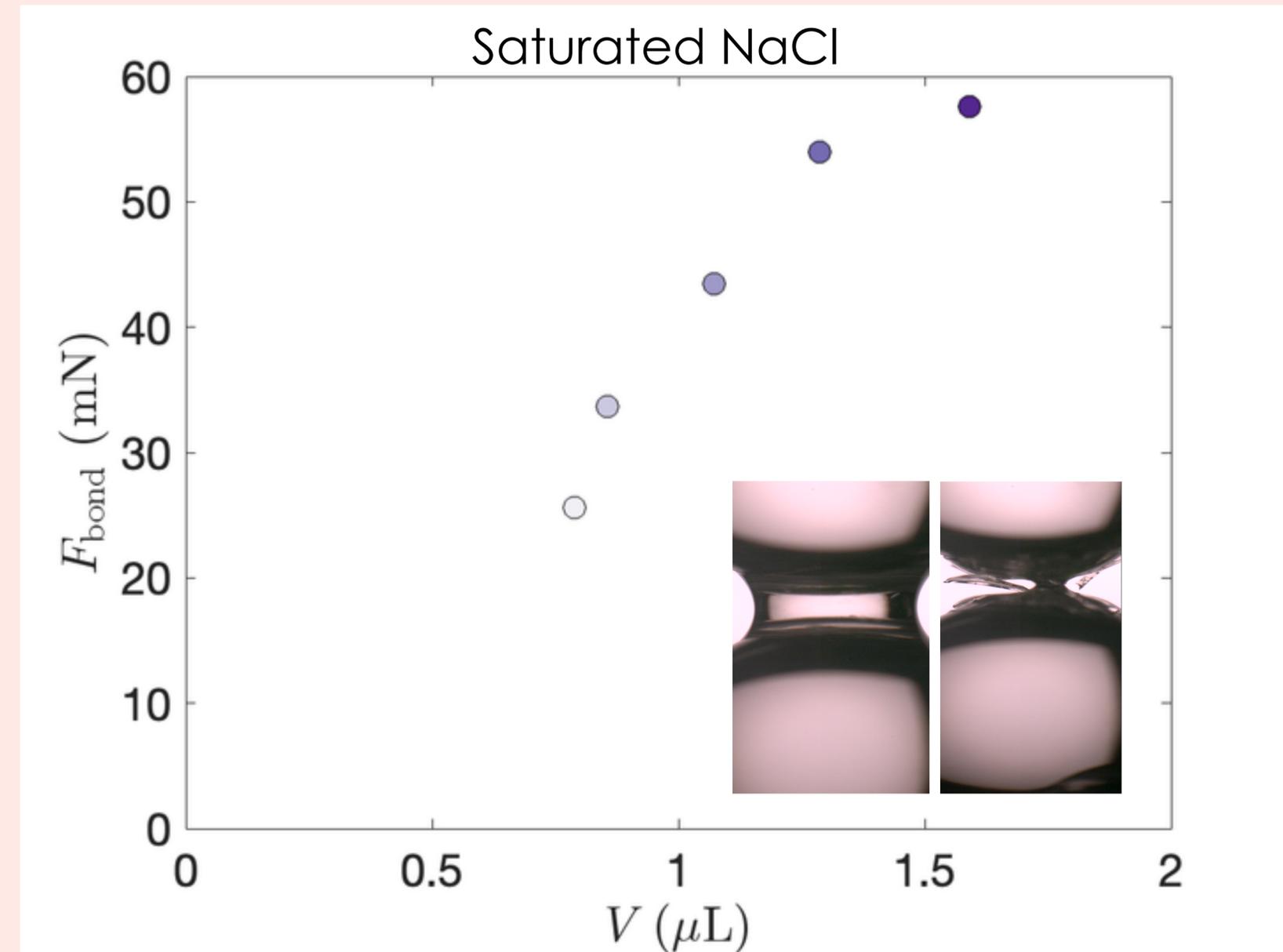
Measuring bulk cohesive stresses:

Powders: measuring forces not feasible at the scales of particles — a bulk description of cohesion strength is often used
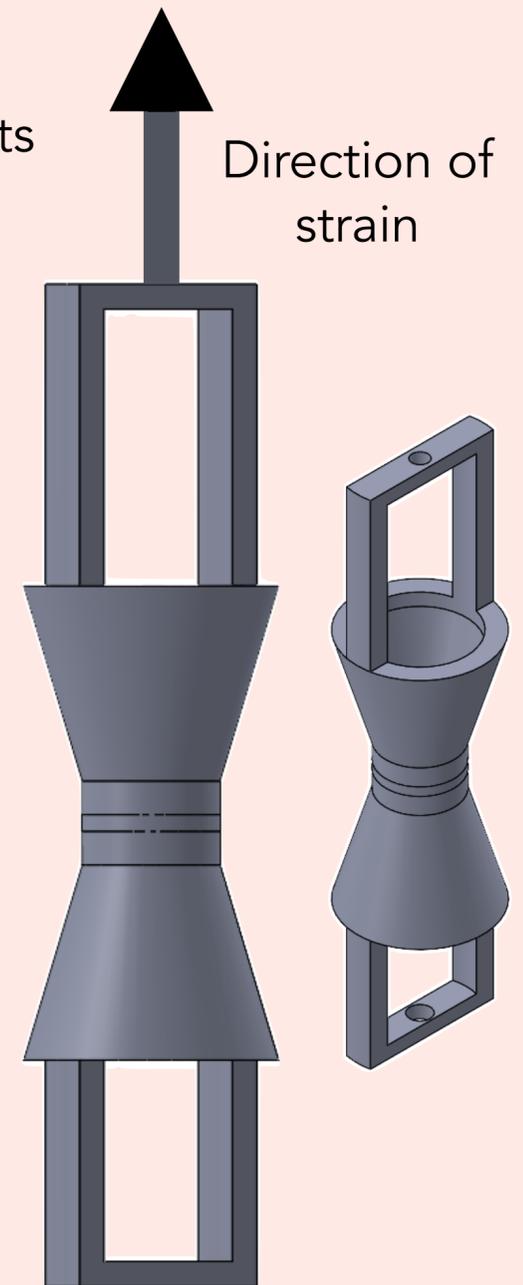
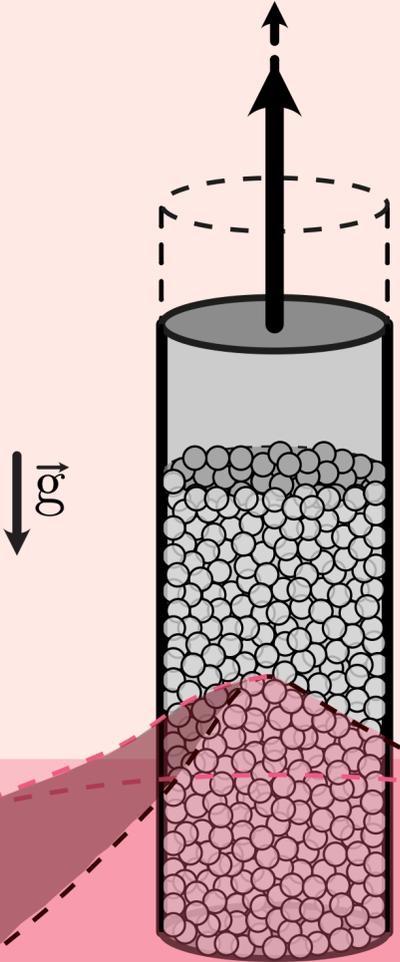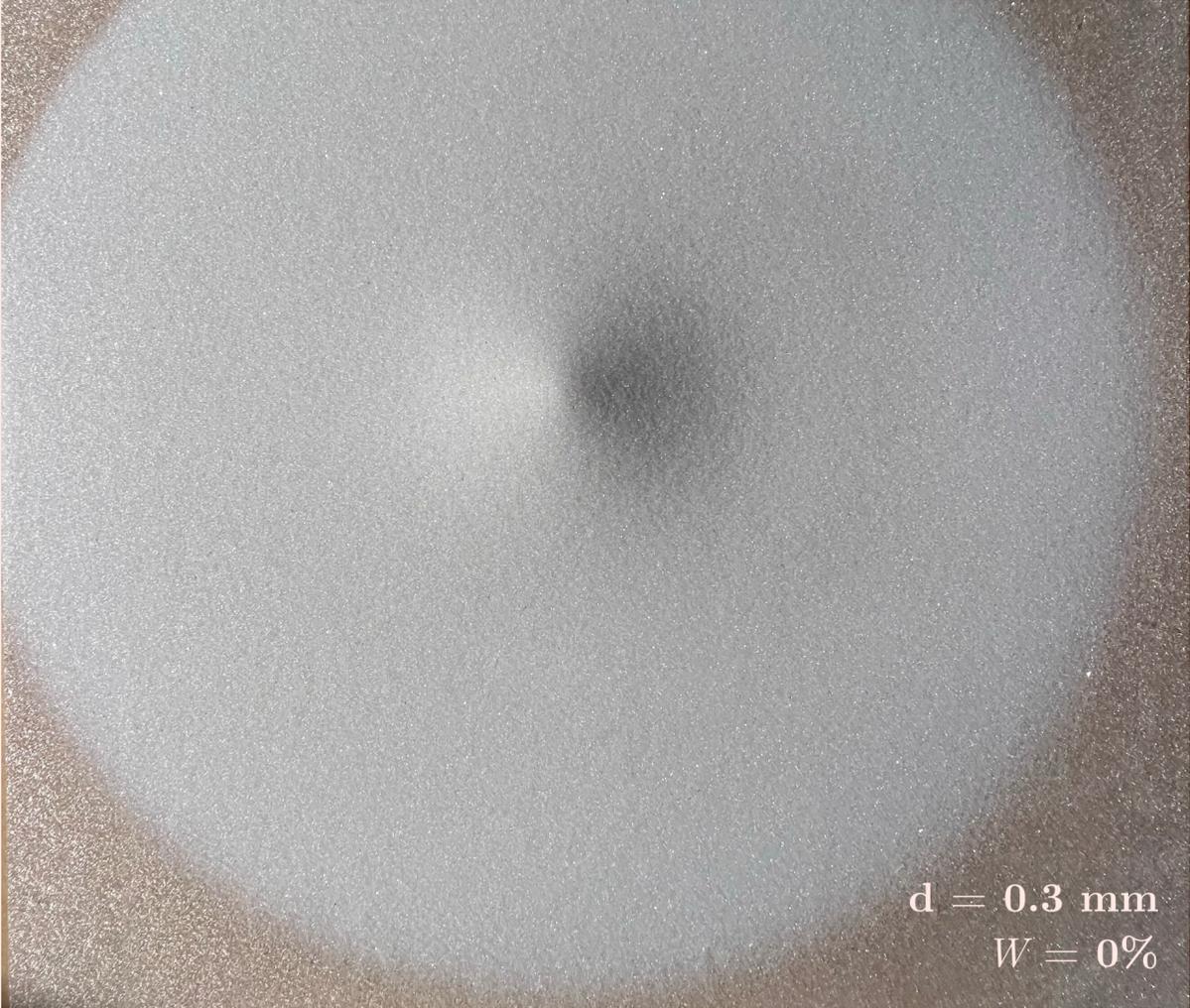Reformable bonds: Shear strength measurements using an Anton Paar ring shear cell

Mohr-Coulomb:

$$\tau \geq \mu\,\sigma + \tau_c \quad \tau_c = \mu\,\sigma_t$$
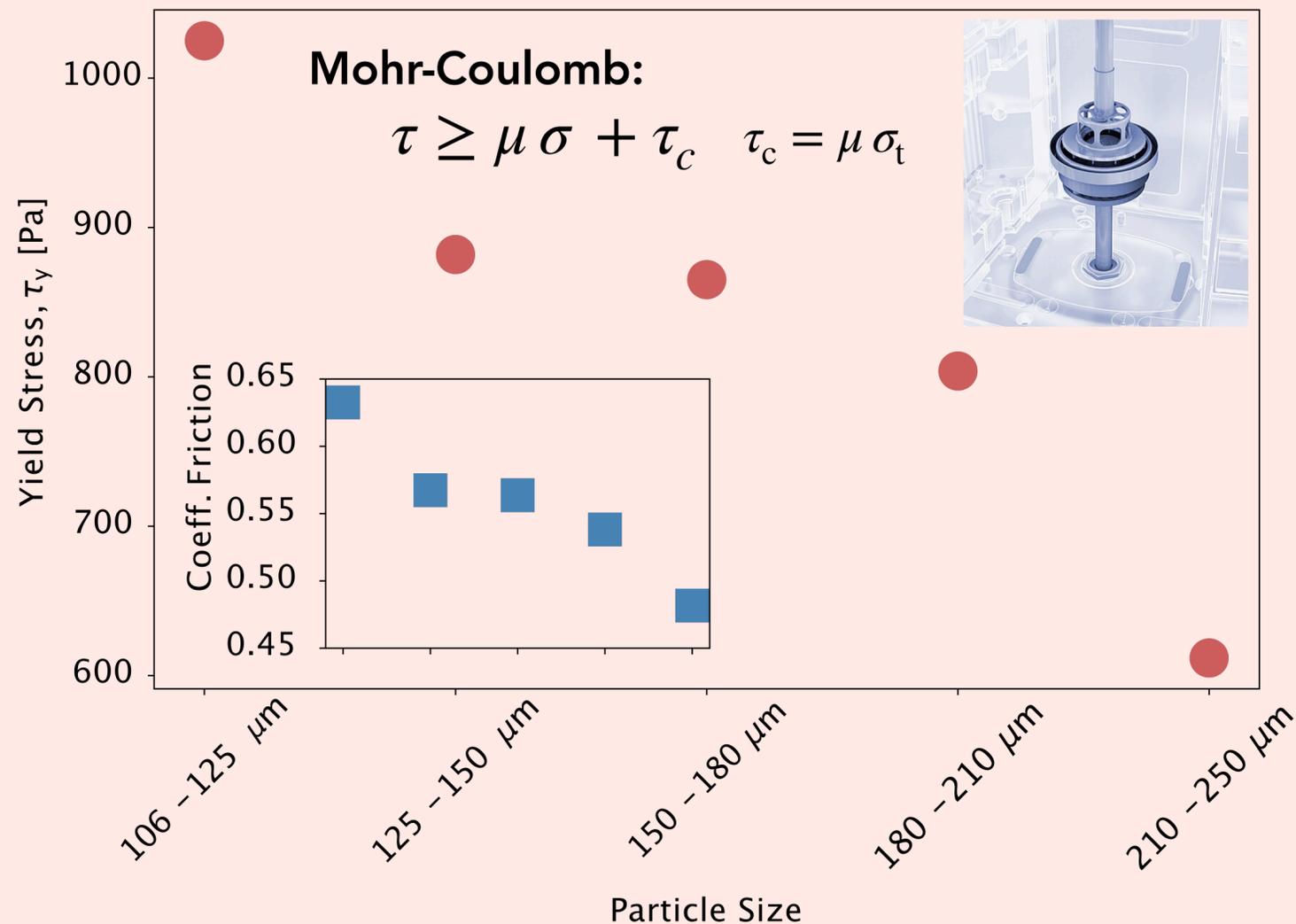
Solid bonds: Tensile strength measurements from an Inverted Cone setup

Direction of strain

45-90 μm glass beads with 5% NaCl

Collaboration: Abhi Shetty (Anton Paar)

Measuring bulk cohesive stresses: aside

$\vec{g}$

$1d$ roughness

$$d = 0.3 \text{ mm}$$
$$W = 0\%$$

$$d = 0.3 \text{ mm}$$
$$W = 0.5\%$$
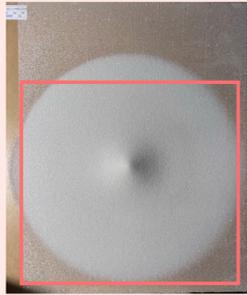
For bulk scale processes, details of the source of cohesion can be ignored in favor of a bulk description.

Sharma, R.S., *et al.*
Effects of inter-particle cohesion on the collapse of granular columns.
Physical Review Fluids. 9, 074301 (2024)

Imerys Calcium Carbonate vs Glass Beads: Comparative Analysis

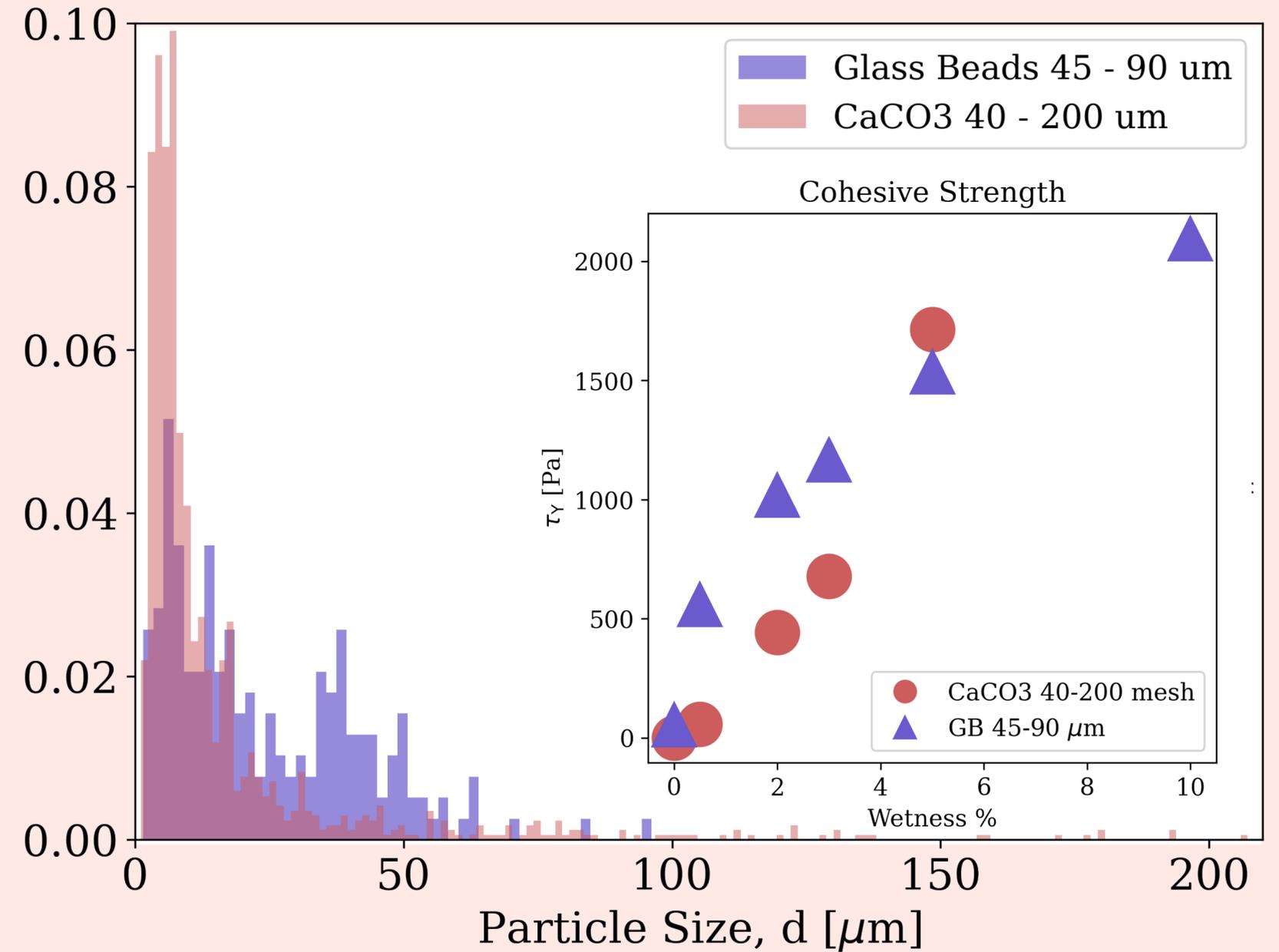Comparison of 40-200 Mesh Imerys CaCO$_3$ and 45-90 µm glass beads:

- Similar size distribution results in similar yield stress.

- Yield stress saturates with wetness for glass beads, but appears to increase significantly for CaCO$_3$
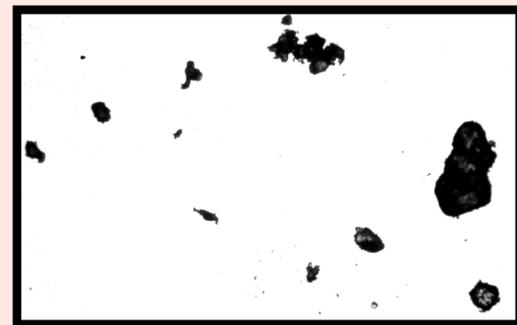
40 - 200 Mesh
Imerys CaCO$_3$

45 - 90 µm
glass beads

Measuring cohesion in drying particles: recap

Particle Scale: Experiments of separating individual grains and model expressions

Bulk Scale: Experiments of static failure in shear cells

The description used to quantify cohesion is based on the scale of process

Rumpf's relation: $\sigma_t \sim F_{adh}/d^2$ **Richefeu-Rumpf:** $\sigma_t = \dfrac{d}{4}\phi Z \rho g \dfrac{F_{adh}}{F_w}$

Capillary bridges   → drying →   Brittle bonds

In the *pendular* state, most liquid is constrained to such bridges ($W \lesssim 5\,\%$ by mass)

Solid bonds prepared from a pendular state followed by a drying process, in the presence impurities & precipitates

$F_{adh} \sim d$ $F_{adh} \sim d^2$

Adhesion can reform after the breakage of any bond

Adhesion is present only till the breakage of link

Transient agglomerates that depend on the stress-state
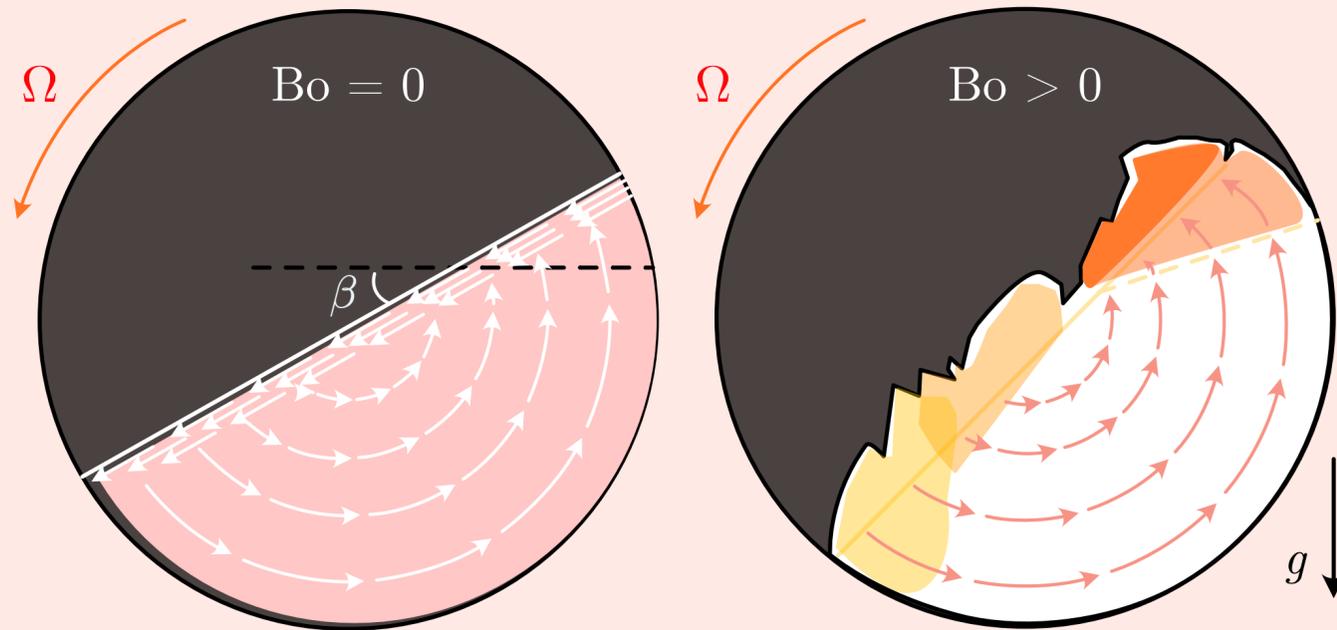
Fixed agglomerates by the drying process, that undergo subsequent breakage

Capillary bridges

drying

Brittle bonds

An approach to understand agglomerate evolution through model experimental geometries and stress conditions
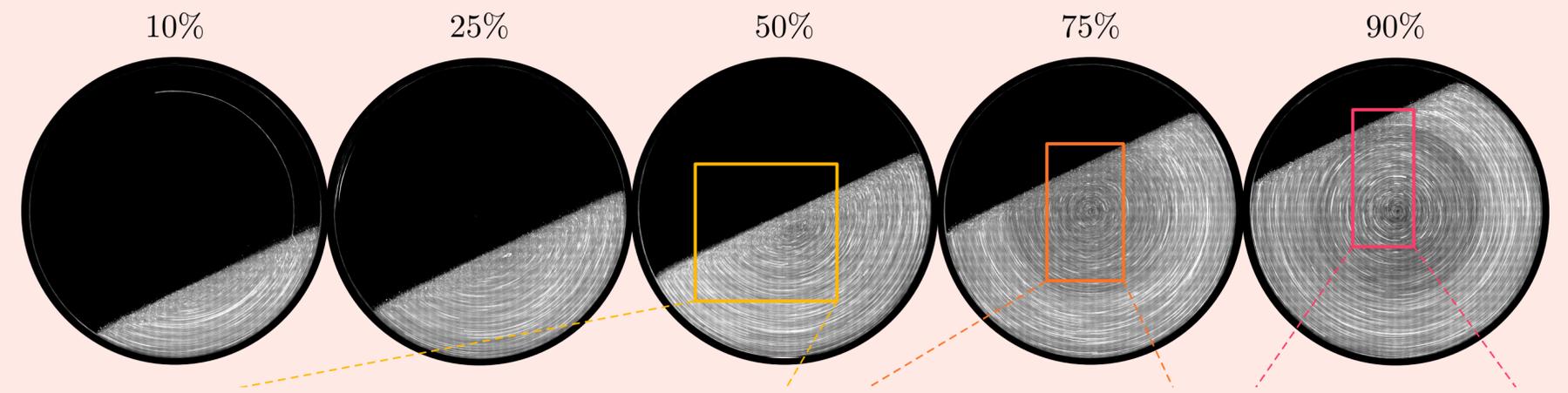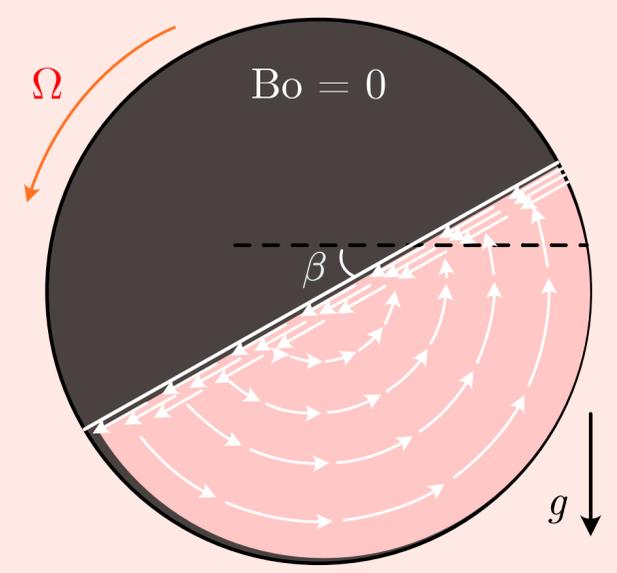
$\text{Bo} = 0$

Ω

β

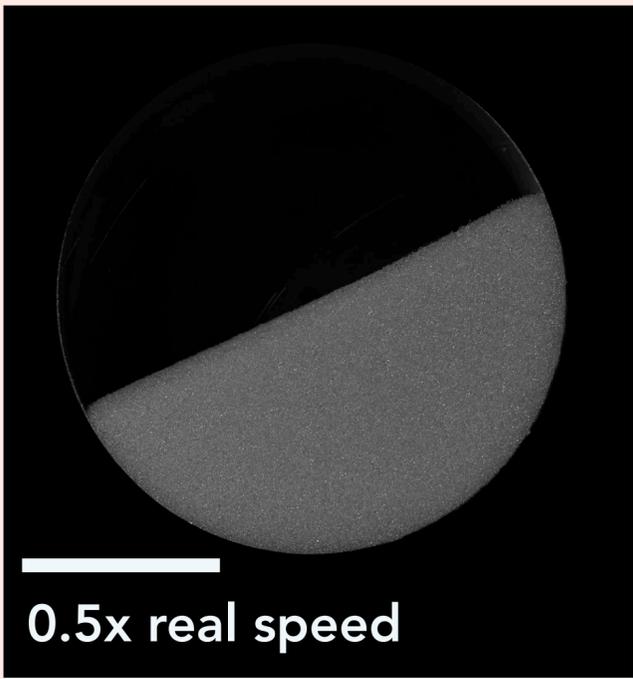$\text{Bo} > 0$

Ω

g

U_J

Low stresses: rotating in a drum

High stresses: impinging turbulent jet

Transient/ system-defined agglomeration in reforming cohesive systems
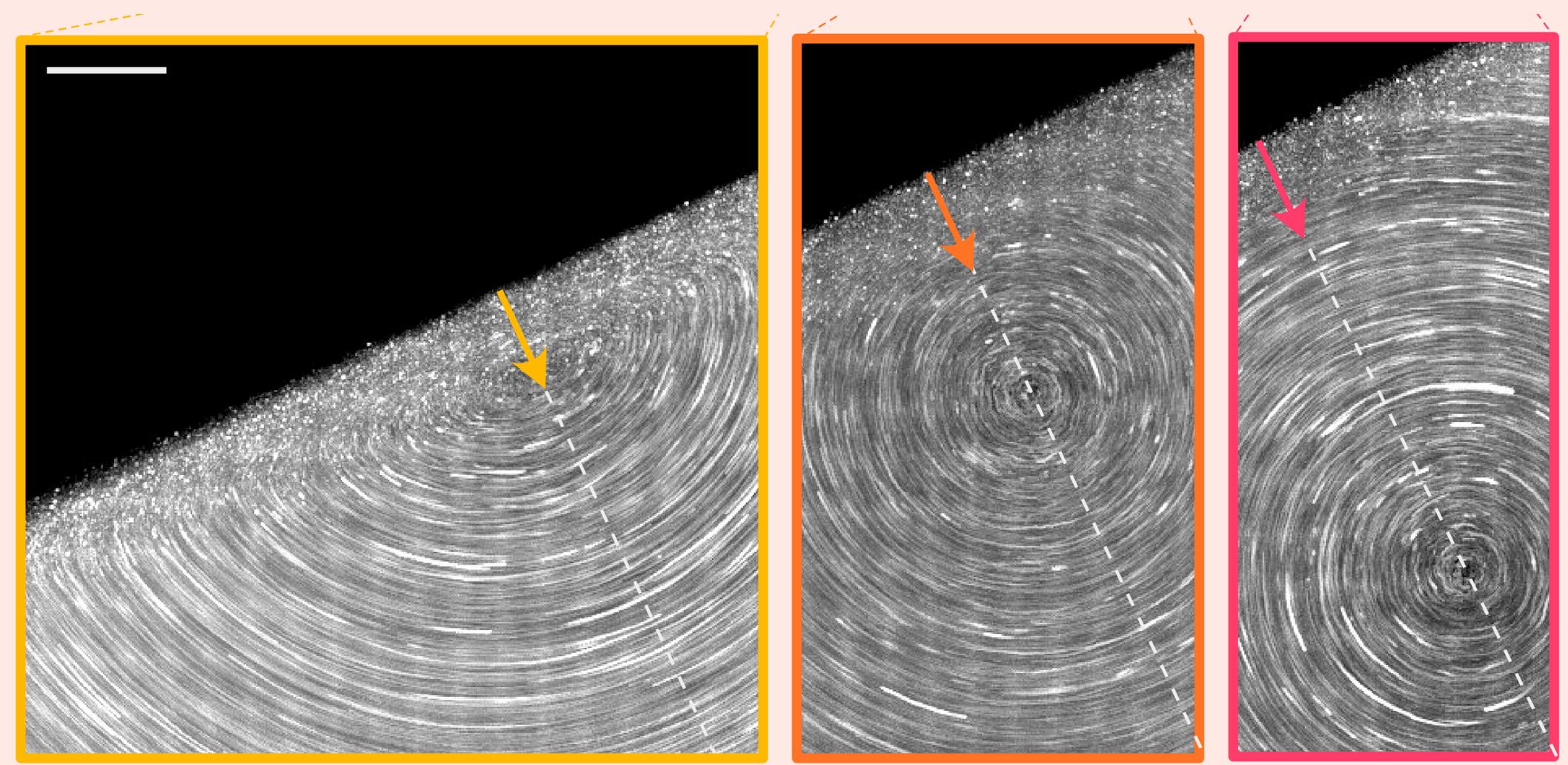
Imposed agglomerates in brittle cohesive systems

0.5x real speed

Ω Bo = 0 β g

10%   25%   50%   75%   90%
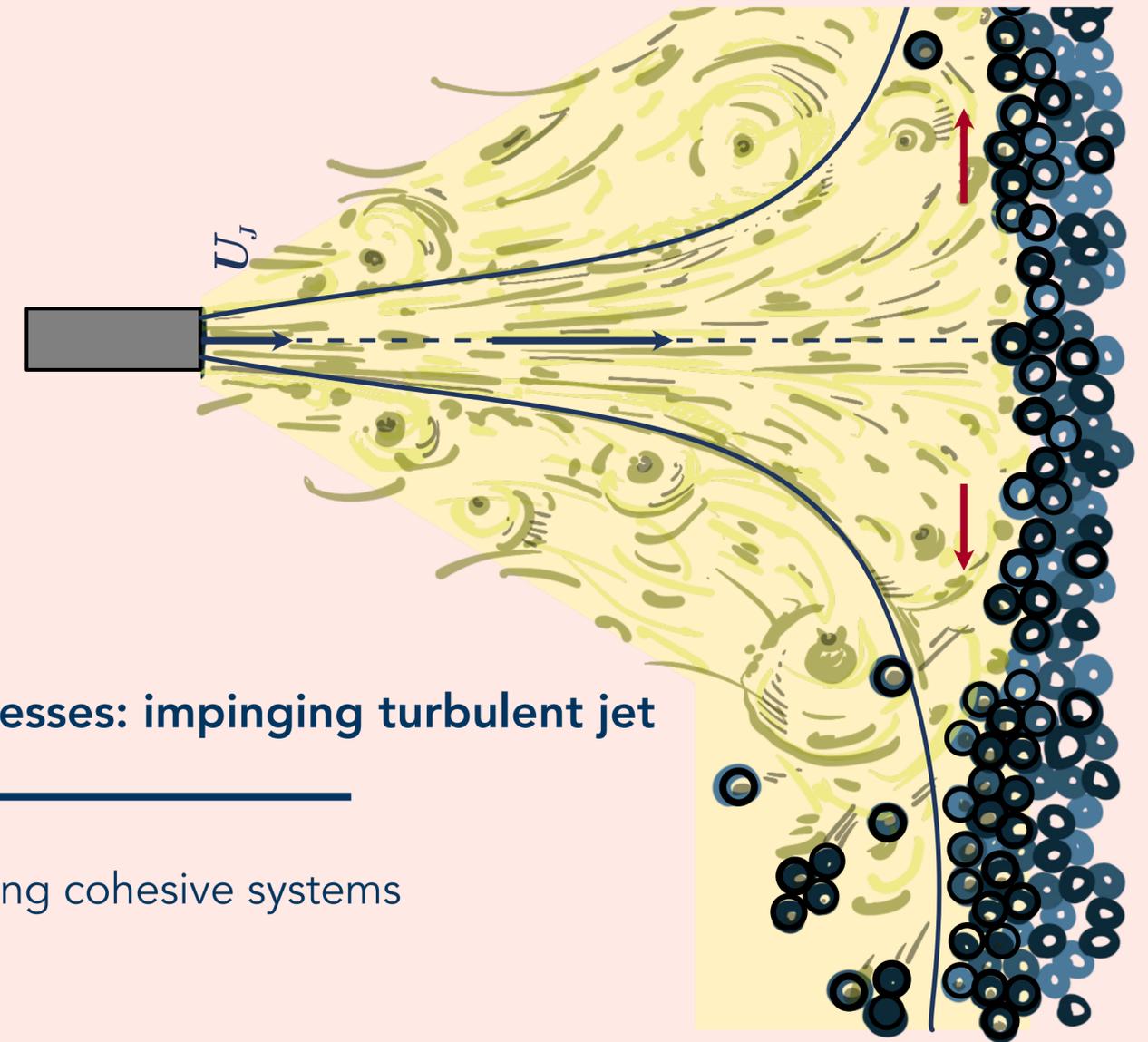
Cohesionless grains: quick recap

$$\dot{\gamma} \simeq \frac{1}{2}\sqrt{\frac{g}{d_{\mathrm{p}}}} \sim 20\,\mathrm{s}^{-1} - 500\,\mathrm{s}^{-1},$$

For our range of particle sizes and fill:

$$h_0 \simeq \sqrt{\frac{2\Omega}{\dot{\gamma}}\left(R^2 - R_0{}^2\right)}$$

$d = 0.5$mm
Cohesionless

0.5x real speed

When slowly tumbled, model reforming cohesive grains display regular structure on the free surface of the system

Besides a point of **re-attachment**, there is a distinct point of **separation** between the grains and the boundaries. Strength due to cohesion maintains structure, before regular **failure** events.

These failure events set the dominant agglomerate scale for observed roughness [Quantification ongoing]

Failure

Separation

0°

Re-attachment

5 cm

$d = 0.5$mm
Polymer coated grains
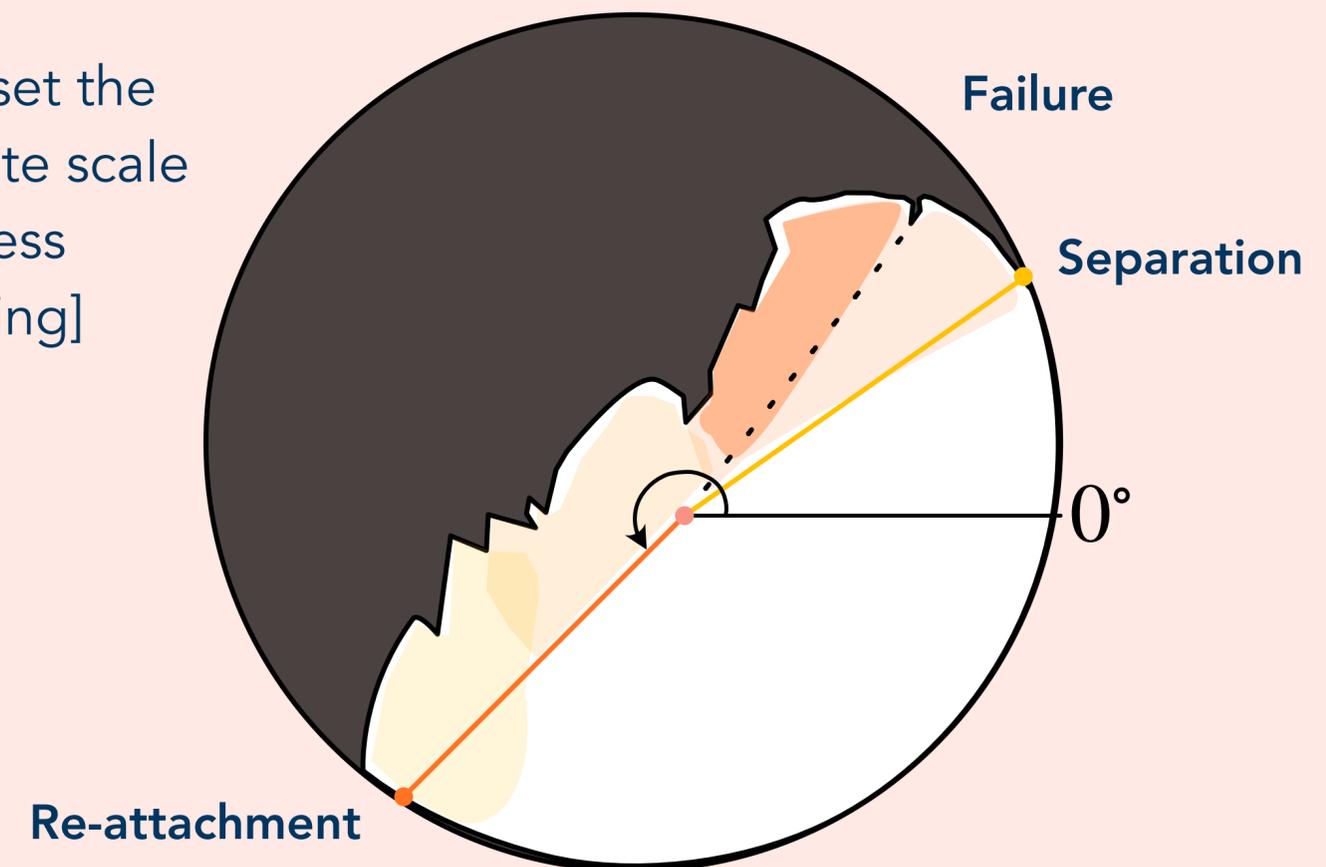
Dominant agglomerate scales for cohesive grains a rotating drum
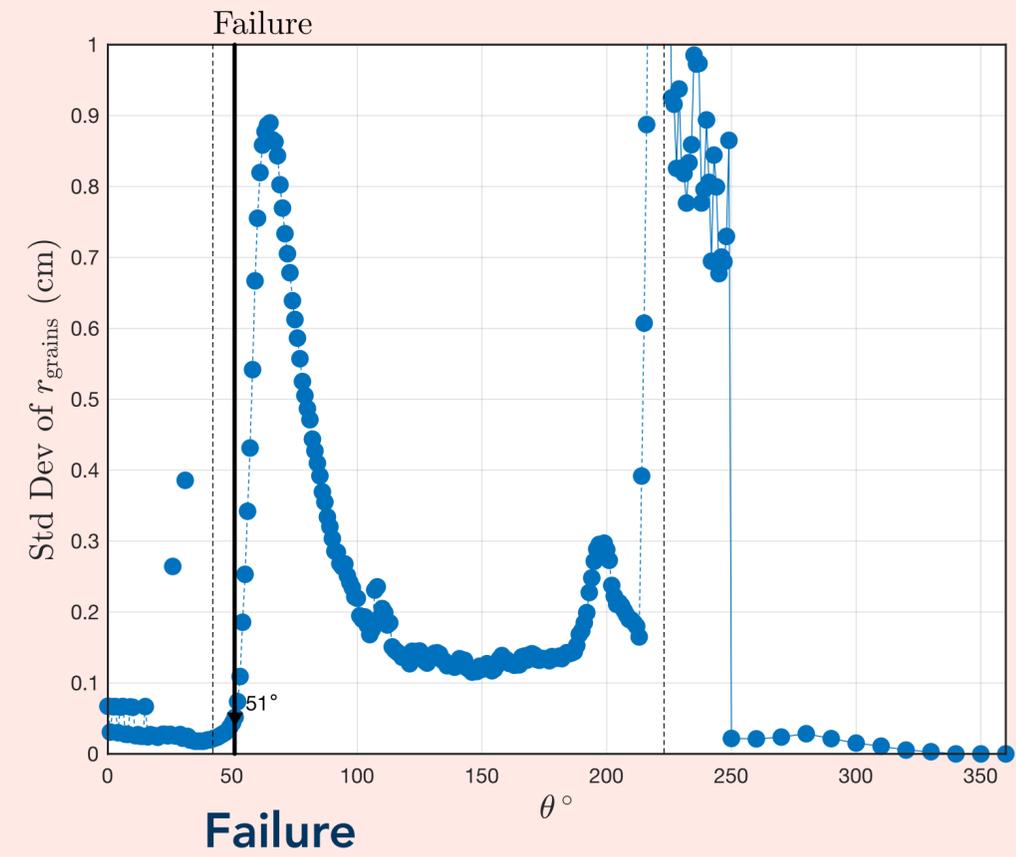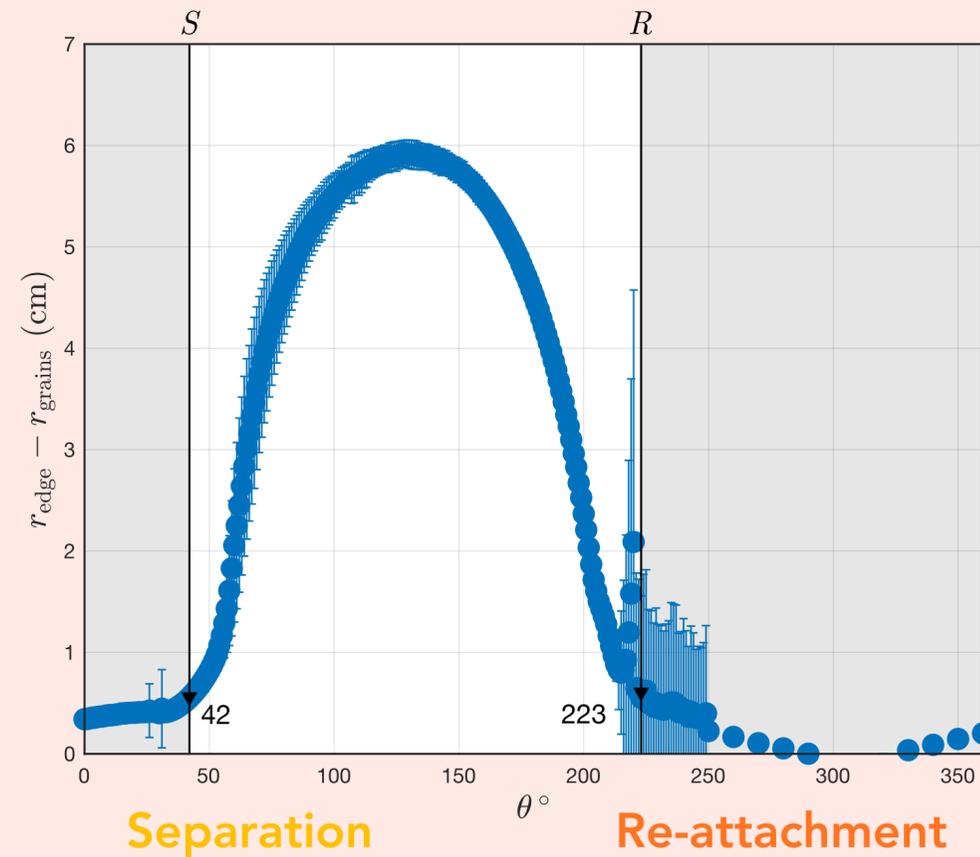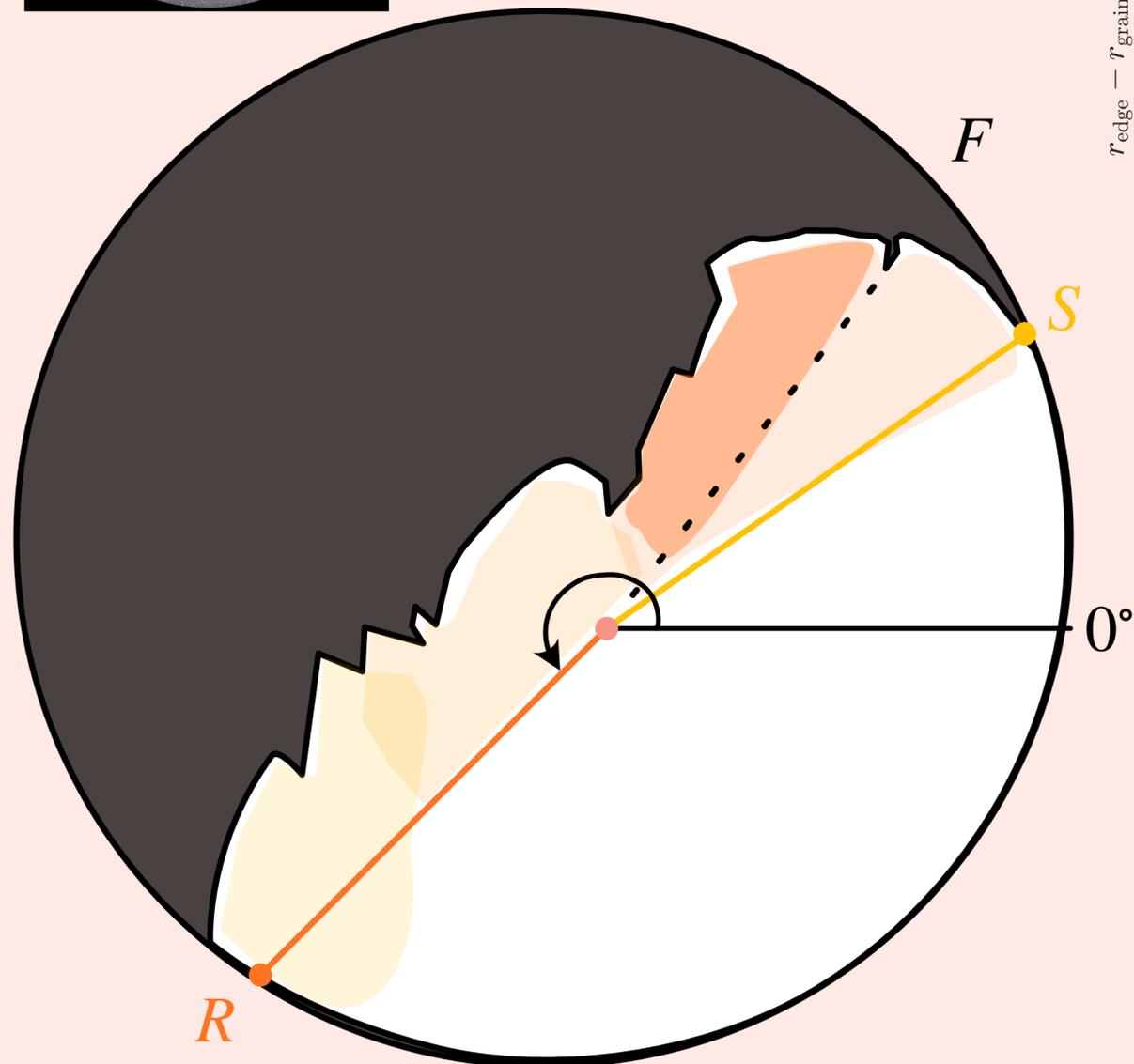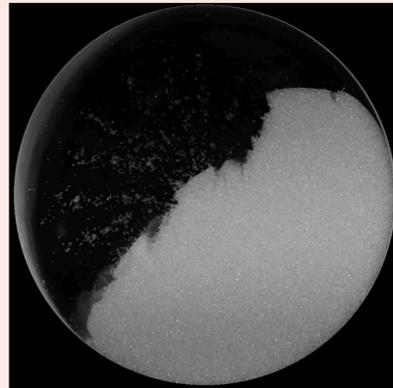
Origin defined at the base of flowing layer, about which material tumbles, CCW is positive.

Angles corresponding to **separation** and **reattachment** from time averaged profiles compared with the distance to edge of drum
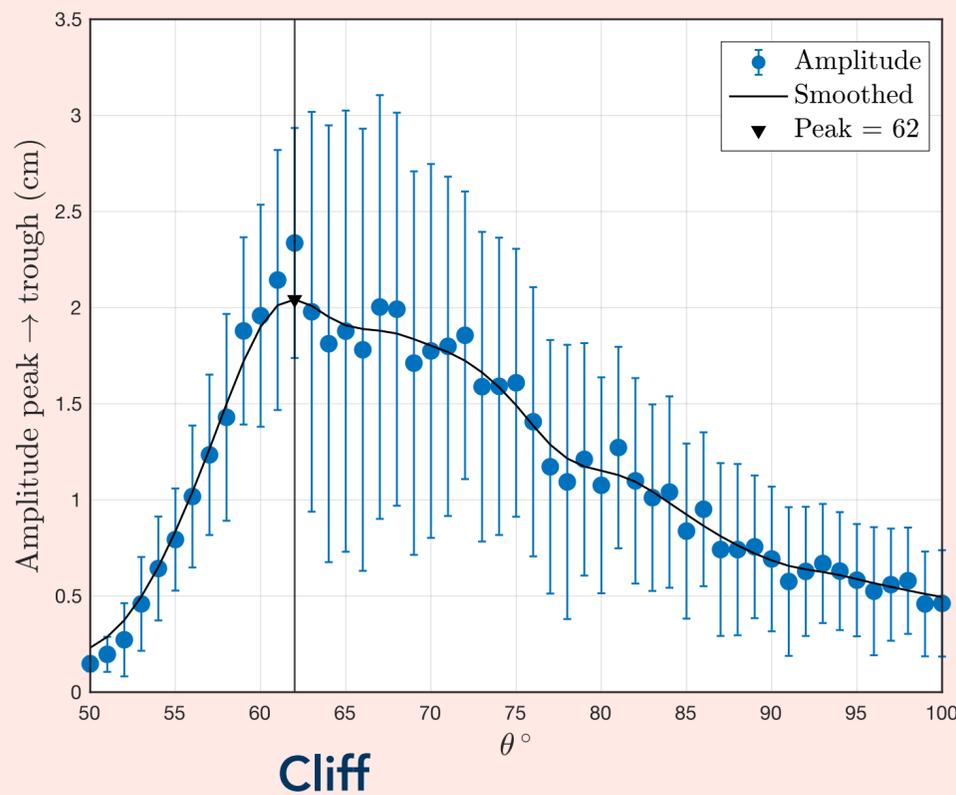
Angle of **failure** determined by where std. deviations in radius become measurable (above noise)

Dominant agglomerate scales for cohesive grains a rotating drum
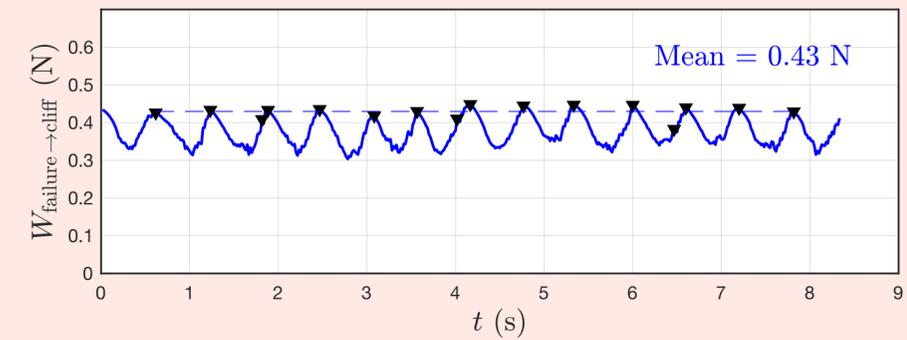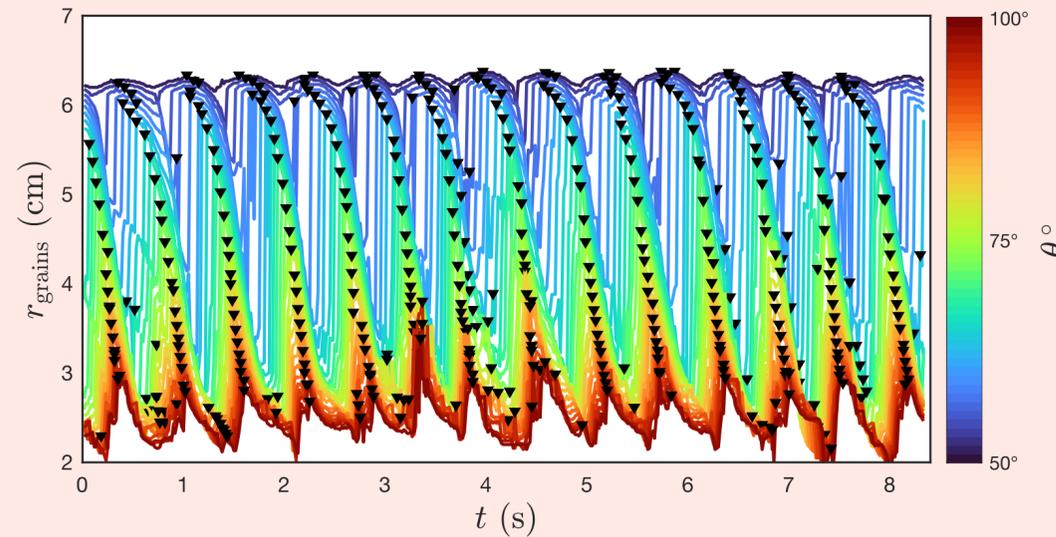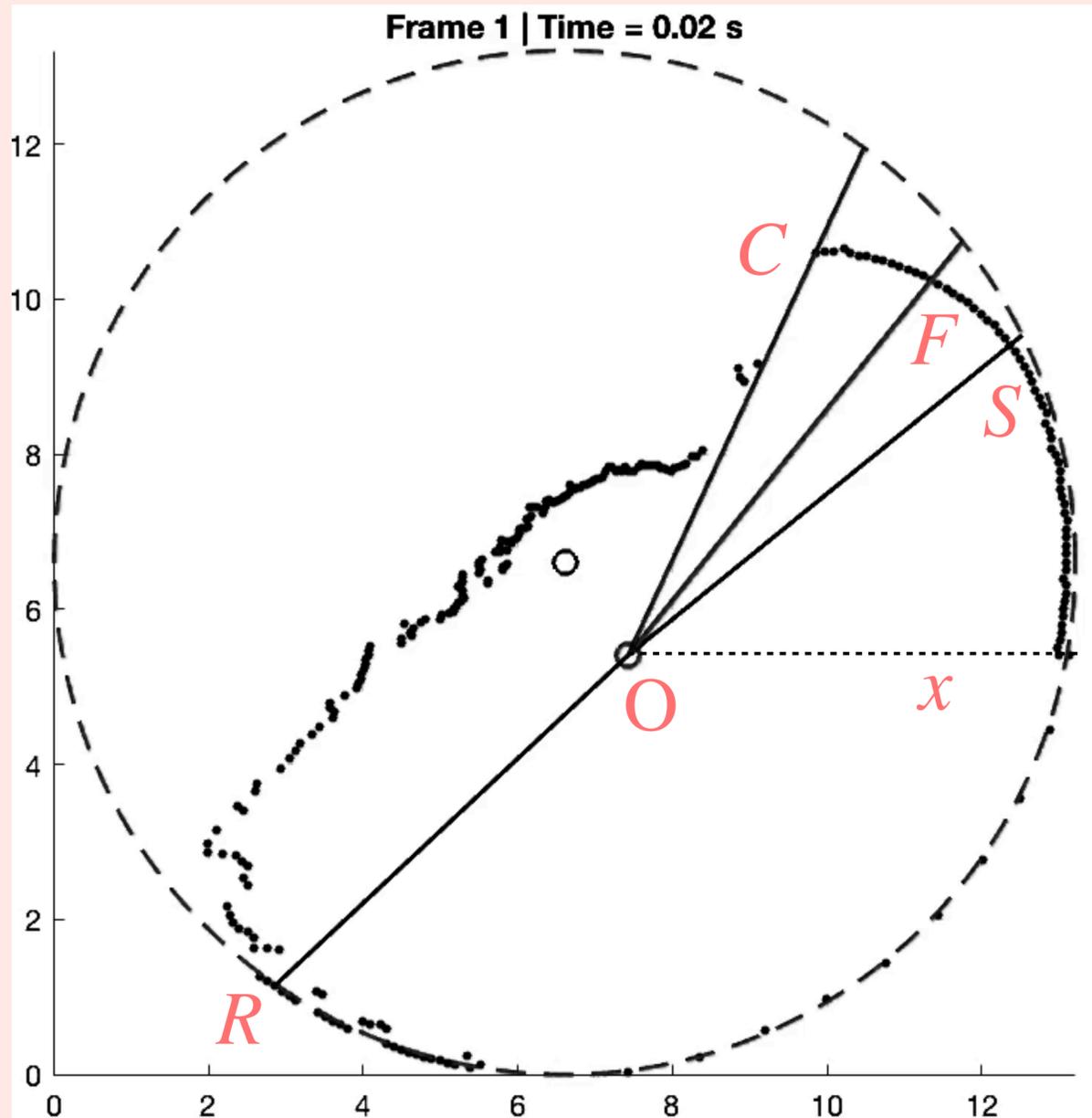
Failure → Cliff:

dominant agglomerate scale

Since we can determine the plane of failure, $\overline{OF}$, and the size of the wedge above $\wedge FOC$

Using only imaging techniques, estimate σ and τ at failure, thereby build a tool to estimate cohesion

Ongoing: Dominant agglomerate scales for cohesive grains a rotating drum

$\Omega +$
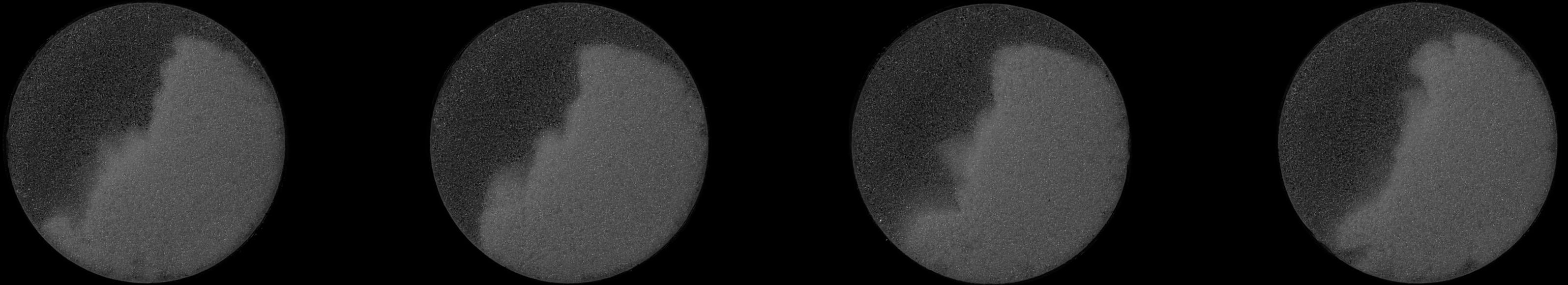
Ongoing: Effects of Ω, drum size and cohesion source on surface roughness

Can a simple rotating drum geometry be used to measure cohesion strength?

Reforming bridges → Brittle bonds

Controlled agglomerates

Sample Preparation

Sample Preparation

‣ Initial size distribution controlled using a grid template.

‣ Agglomerates: dried with 25% wt NaCl solution (200 g/L): 5% wt NaCl in the powder.

Experiment

The agglomerates are kept in the rotating drum for 24 hours and extracted for analysis.

10 mm

Sample Preparation

10 mm

Sample Preparation

▸ Initial size distribution controlled using a grid template.
▸ Agglomerates: dried with 25% wt NaCl solution (200 g/L): 5% wt NaCl in the powder.

Experiment

The agglomerates are kept in the rotating drum for 24 hours and extracted for analysis.

Force undergone by aggregates

Stress driving the erosion/break up (collision): $\tau \propto \rho\, g\, d_{\text{agg}}$

Force of order $F \sim \tau\, d_{\text{agg}}^2 \sim 10\,\mu\text{N} - 1\,\text{mN}$

Aggregate size analysis

The system is first sieved into three bins:

▸ Bin 1: $d_{\text{grain}} < 0.425\,\text{mm}$, m = 185.5 g
▸ Bin 2: $0.425\,\text{mm} < d_{\text{grain}} < 2\,\text{mm}$, m = 23.6 g
▸ Bin 3: $d_{\text{grain}} > 2\,\text{mm}$, 7.3 g
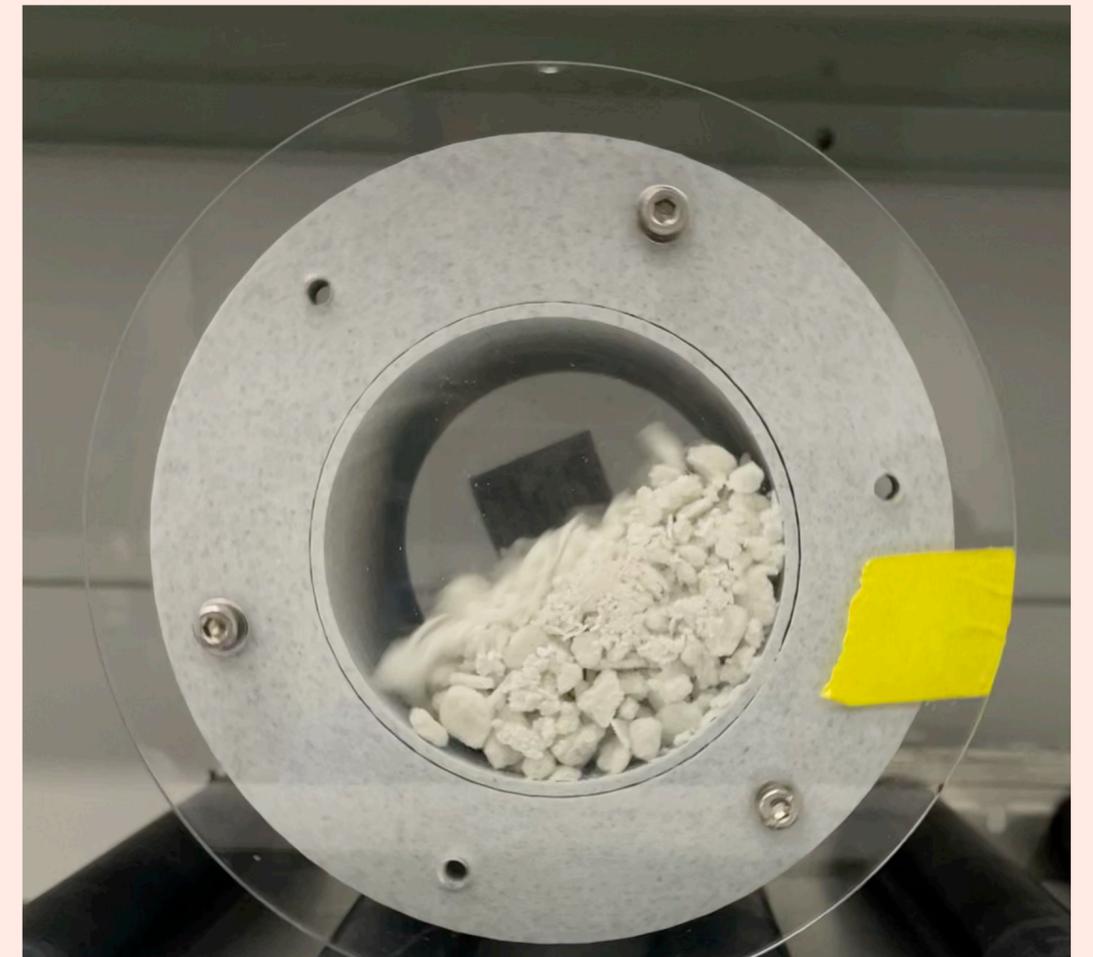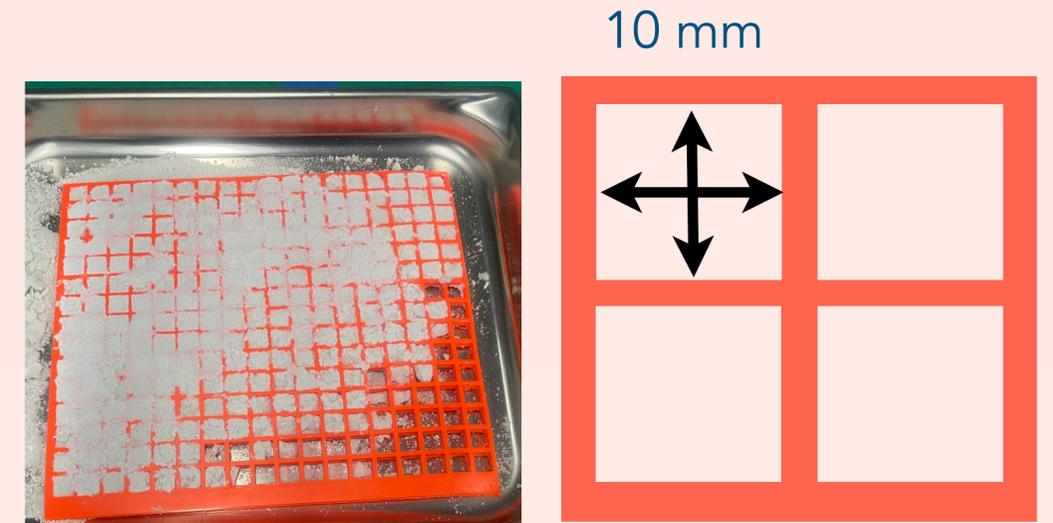
Size Distribution: 180 - 210 Micron

Dry GB 180 - 210 um

$$\left\langle d_{\text{agg}} \right\rangle = 1.6 \, \text{mm}$$

$$\dot{\gamma} \simeq 40 \, \text{s}^{-1}$$
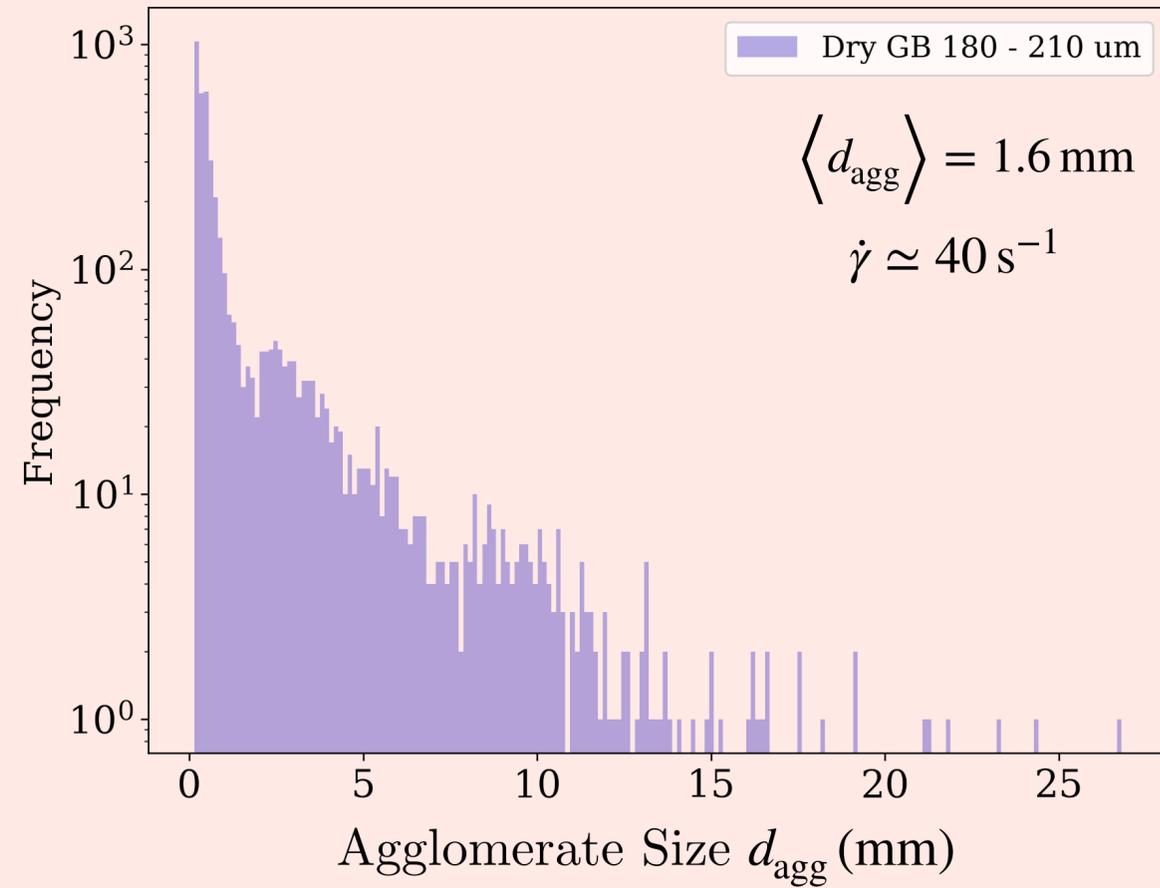
▸ For Bin 2: $0.425 \, \text{mm} < d_{\text{agg}} < 2 \, \text{mm}$, we use the microscope:
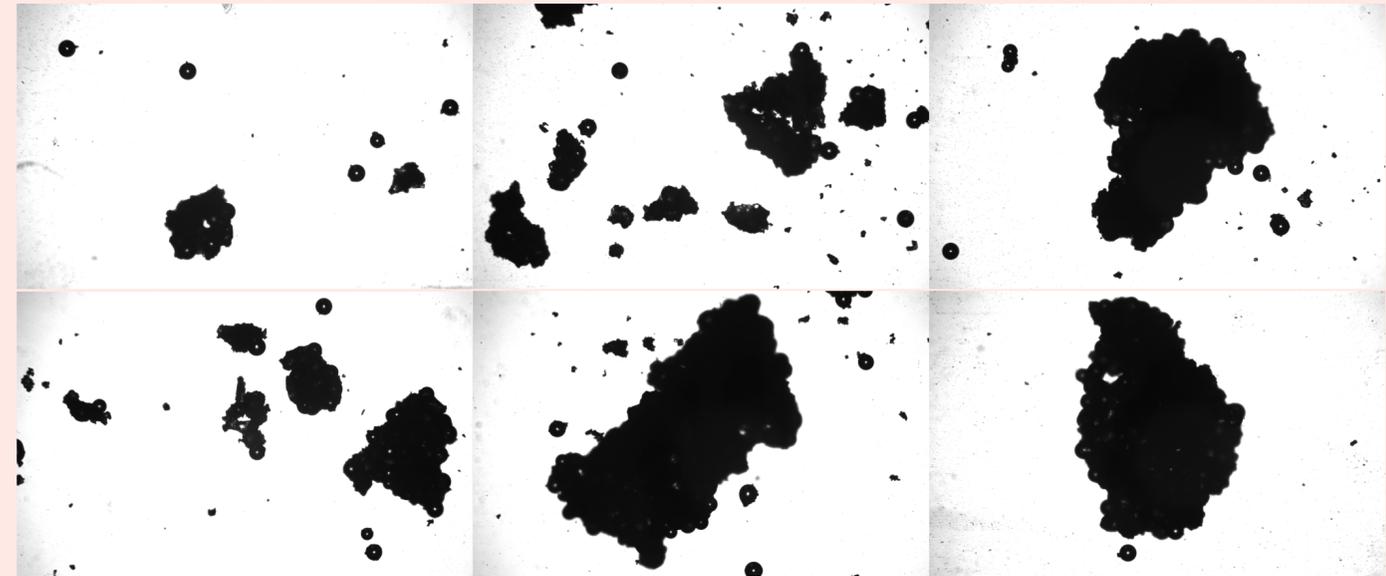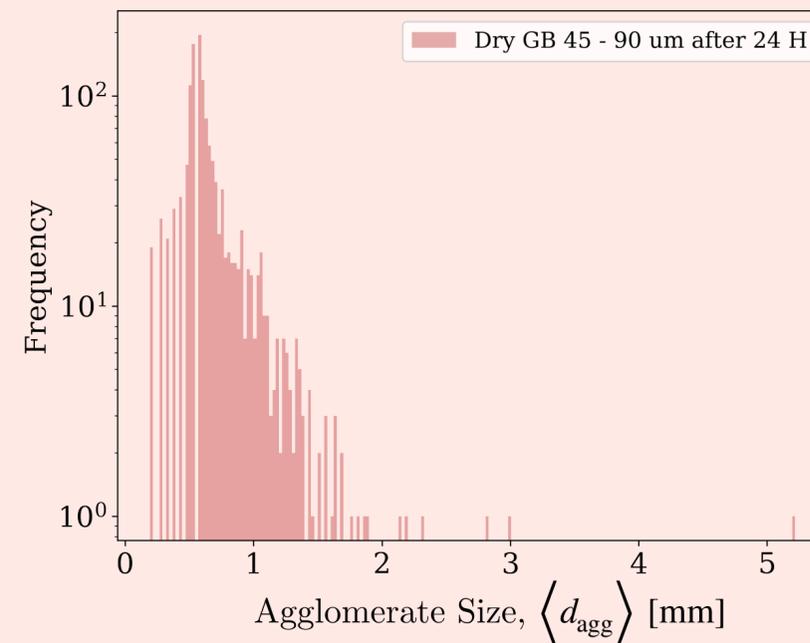

▸ For Bin 3: $d_{\text{agg}} > 2 \, \text{mm}$

After 24 h in the drum

85%

% Mass

11%

3%

Dry GB 180 - 210 um after 0 H
Dry GB 180 - 210 um after 24 H
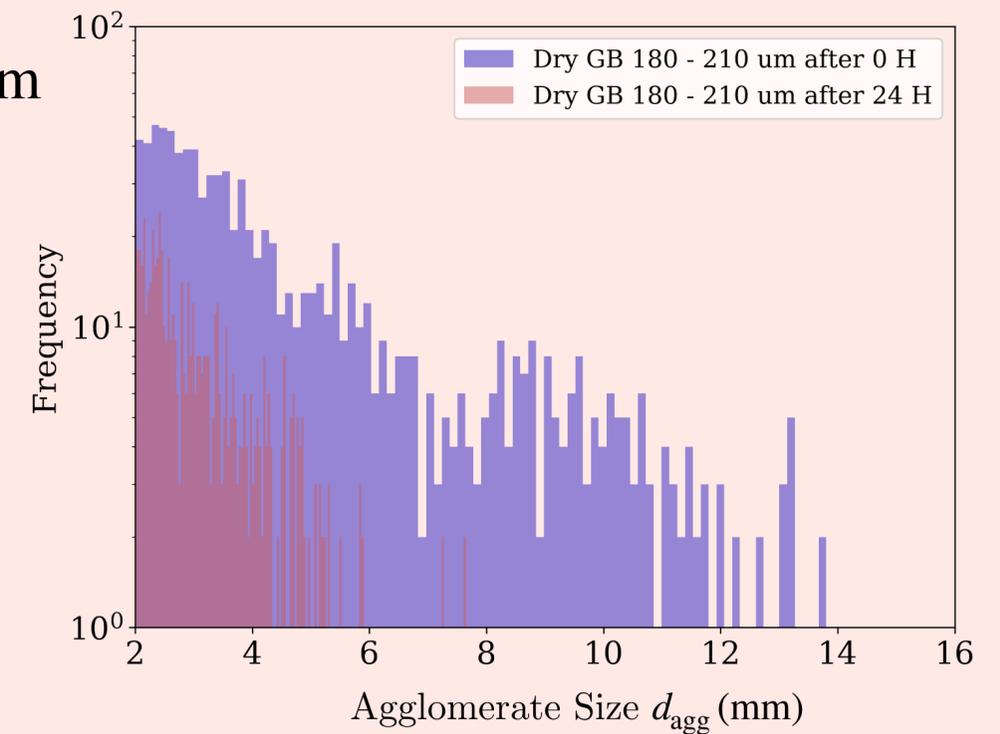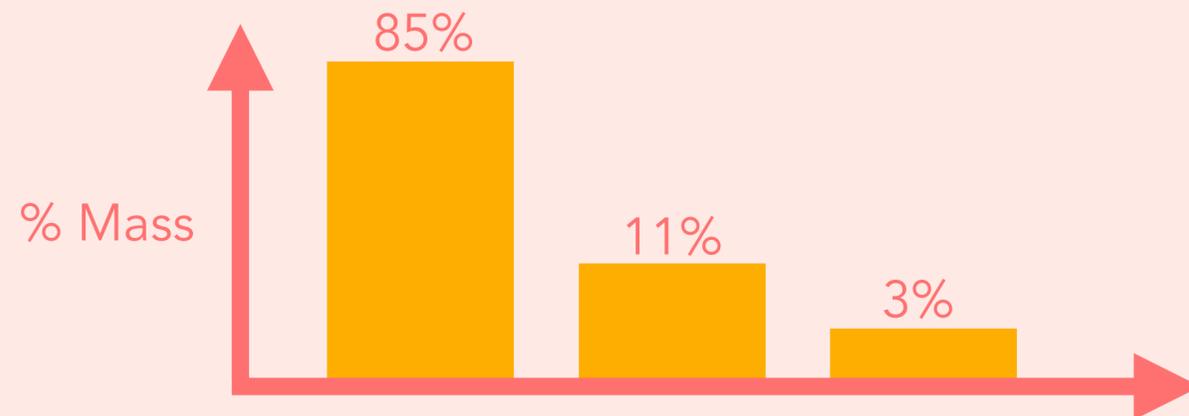
SIZE DISTRIBUTION: 45 - 90 MICRON

$\langle d_{\text{agg}} \rangle = 0.76\,\text{mm}$
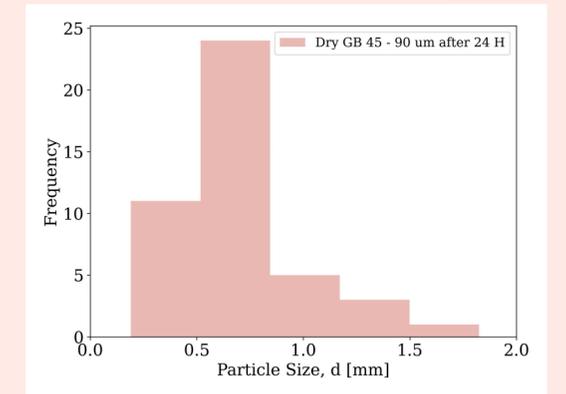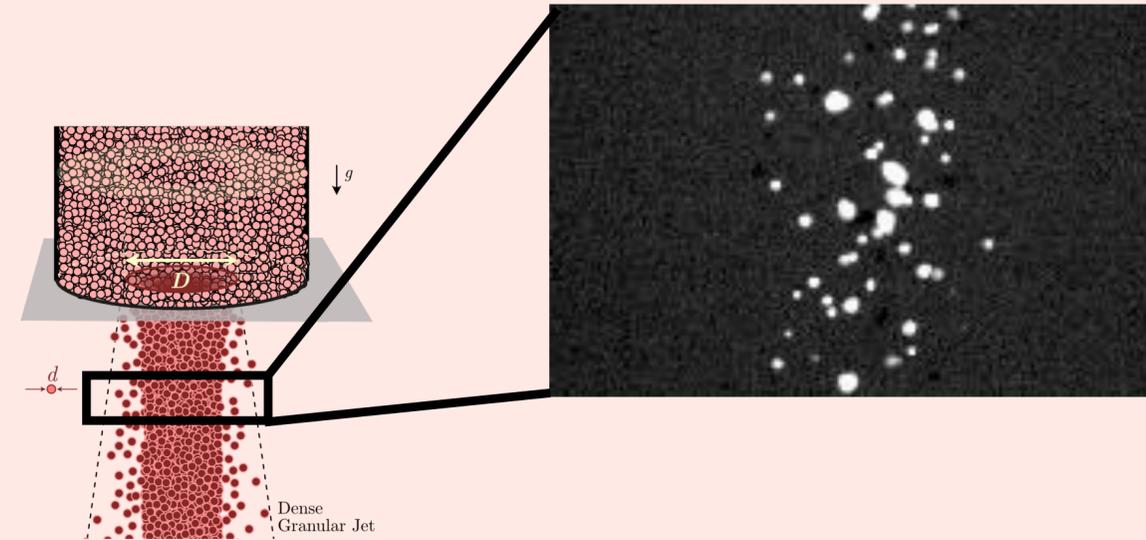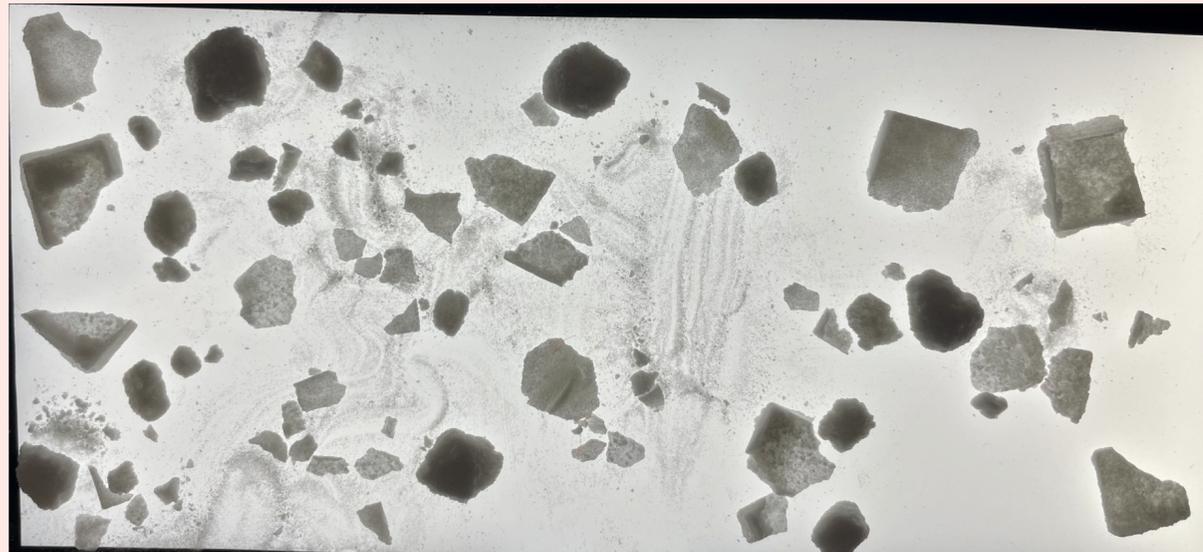
Solid agglomerates prepared using 45-90 μm glass beads before any shear input.

For Bin 2: $0.425\,\text{mm} < d_{\text{agg}} < 2\,\text{mm}$

For Bin 3: $d_{\text{agg}} > 2\,\text{mm}$
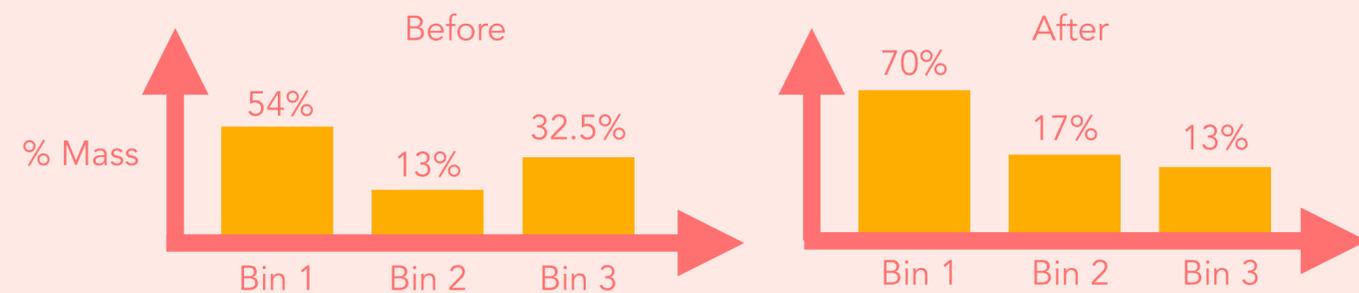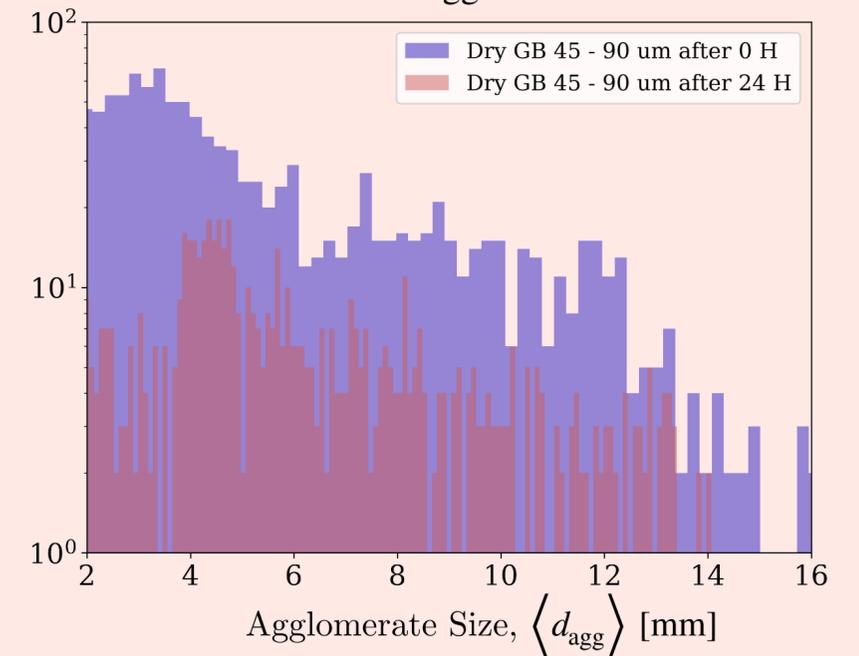
Capillary bridges — drying → **Brittle bonds**

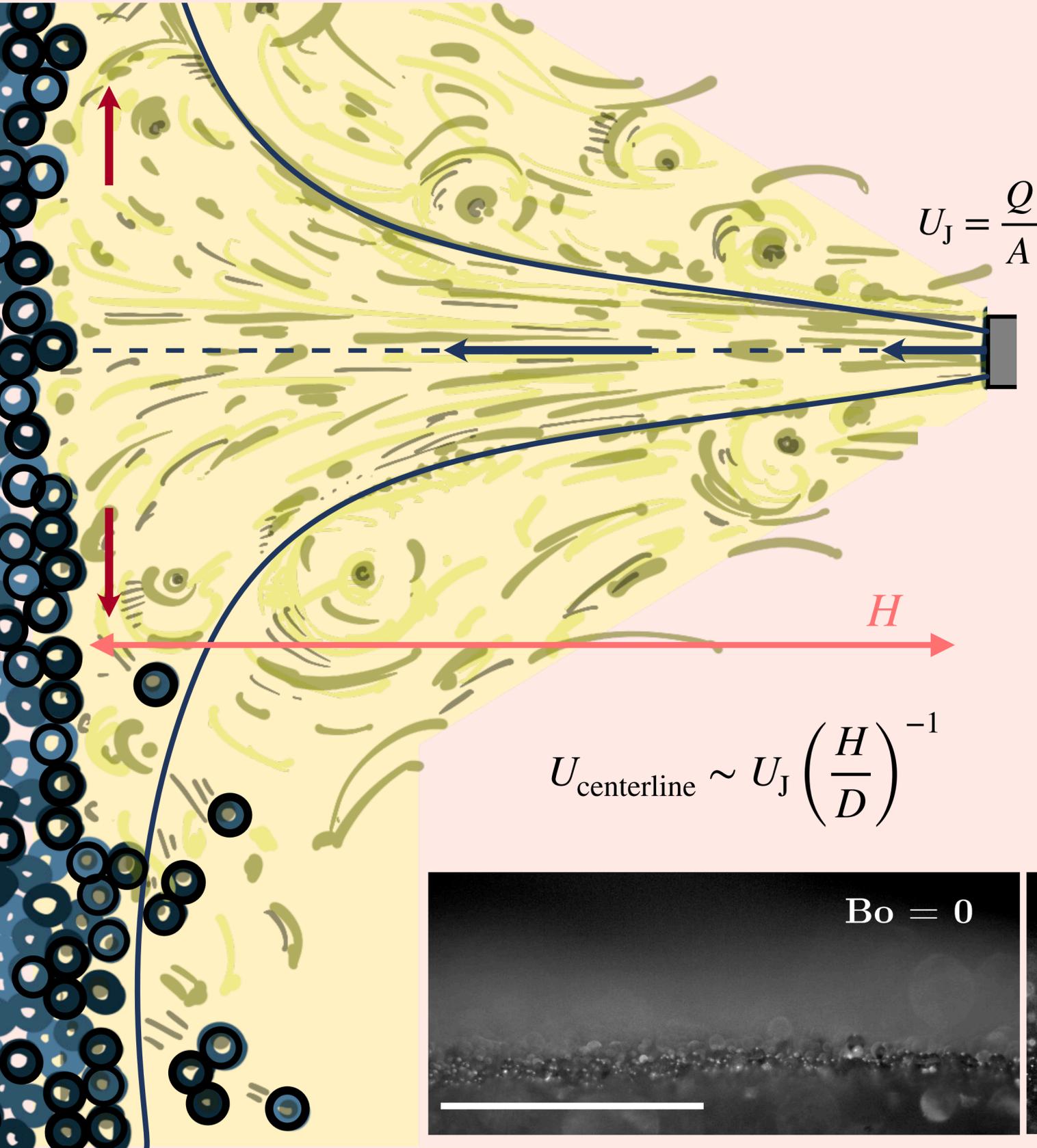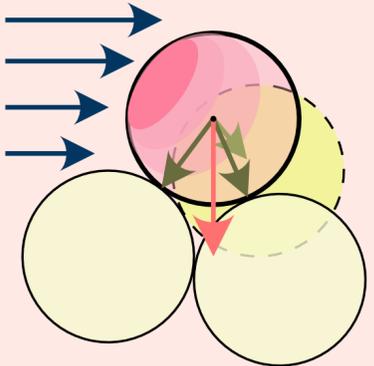An approach to understand agglomerate evolution through model experimental geometries and stress conditions
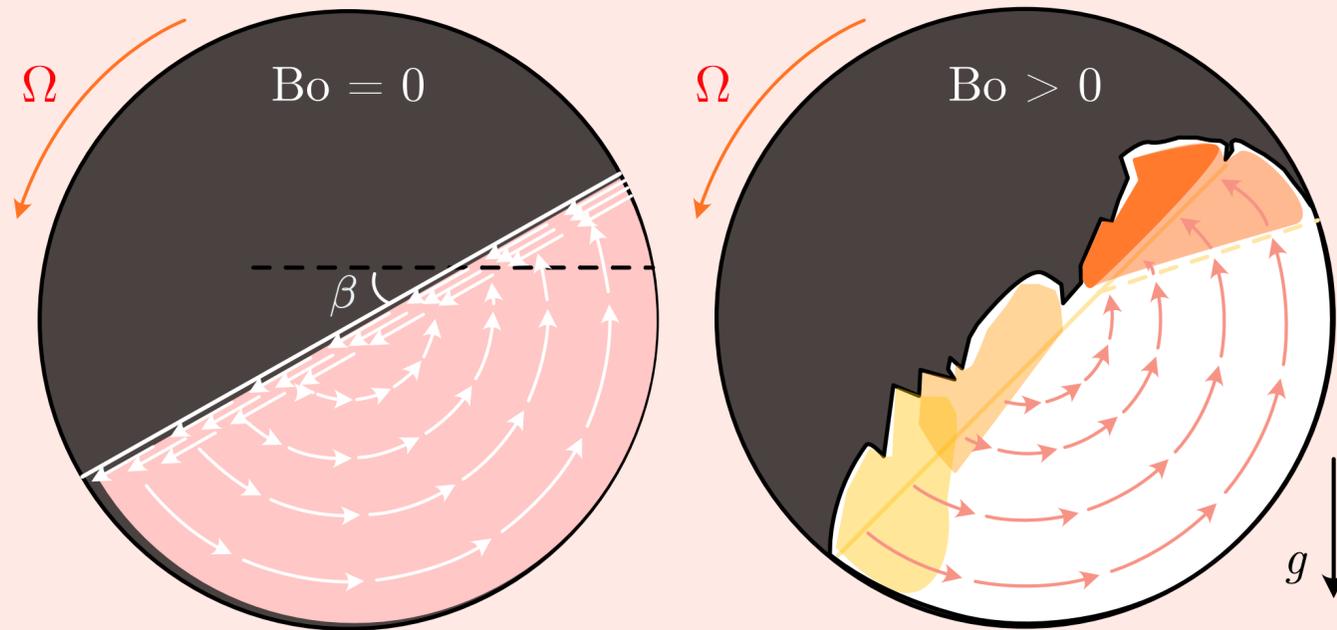
Low stresses: rotating in a drum

High stresses: impinging turbulent jet
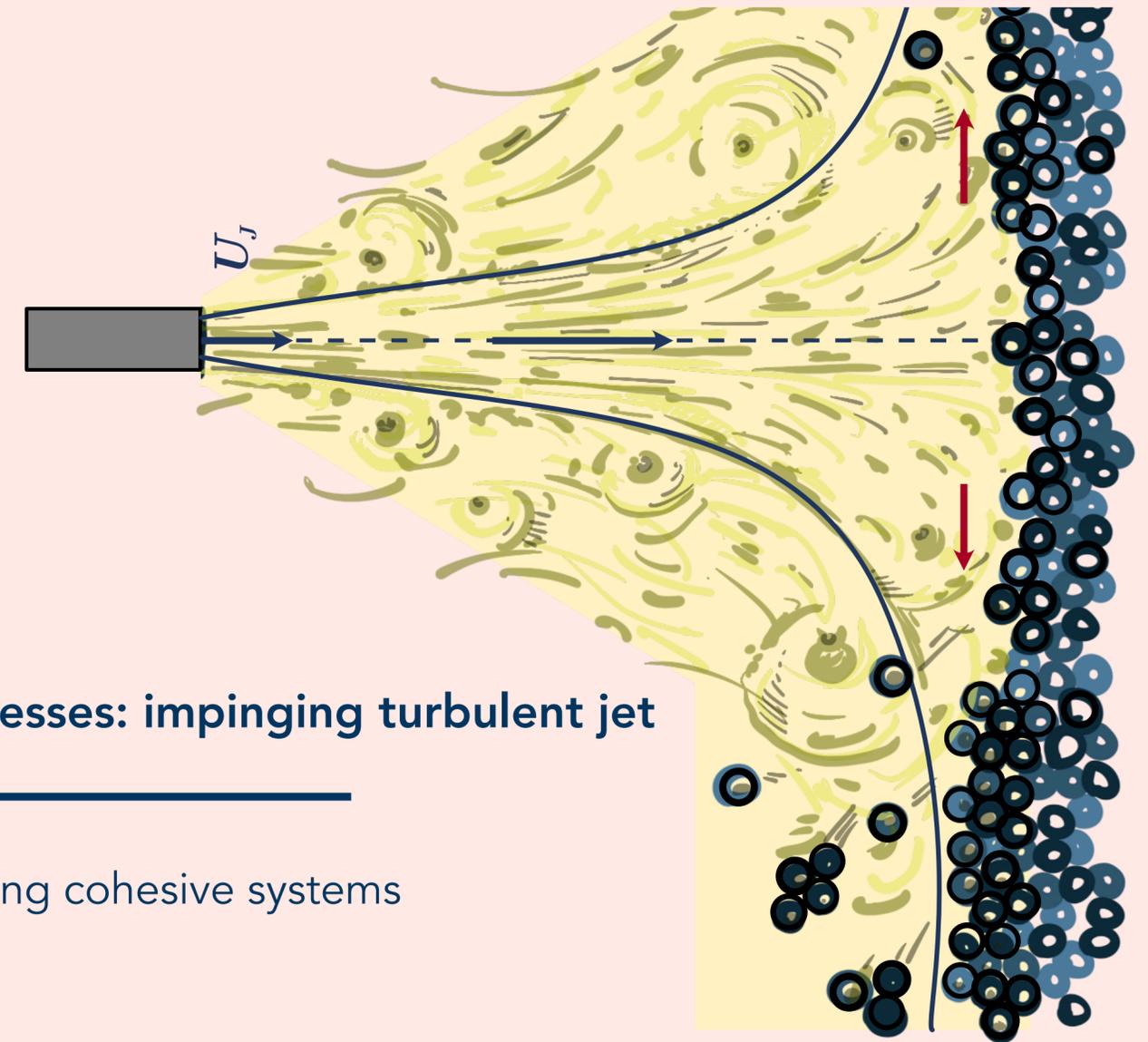
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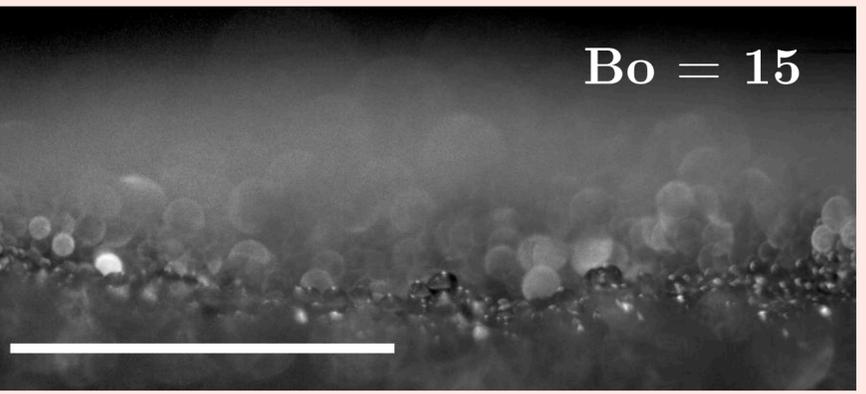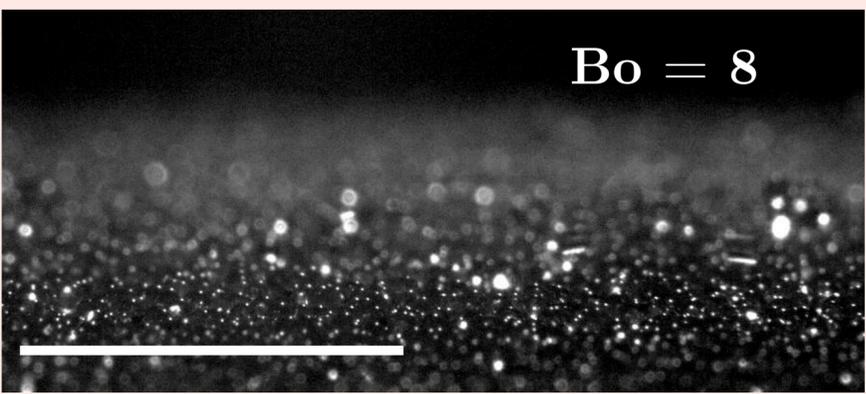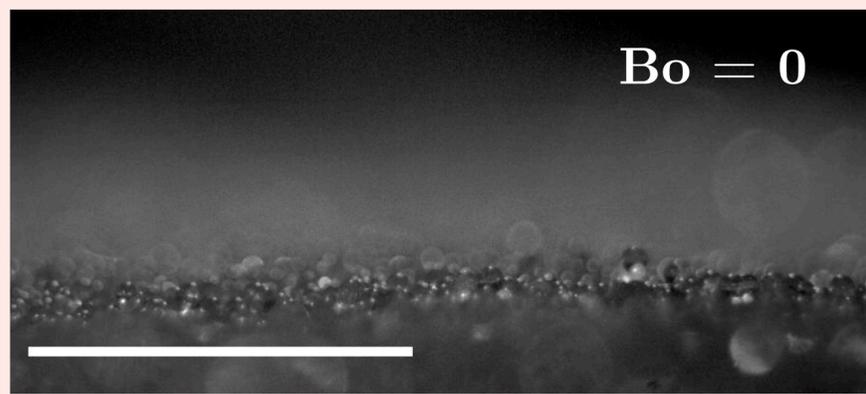
High stresses: impinging turbulent jet

$$U_{\mathrm{J}} = \frac{Q}{A}$$

$$A = \pi \left(\frac{D_{\mathrm{nozzle}}}{2} \right)^2$$
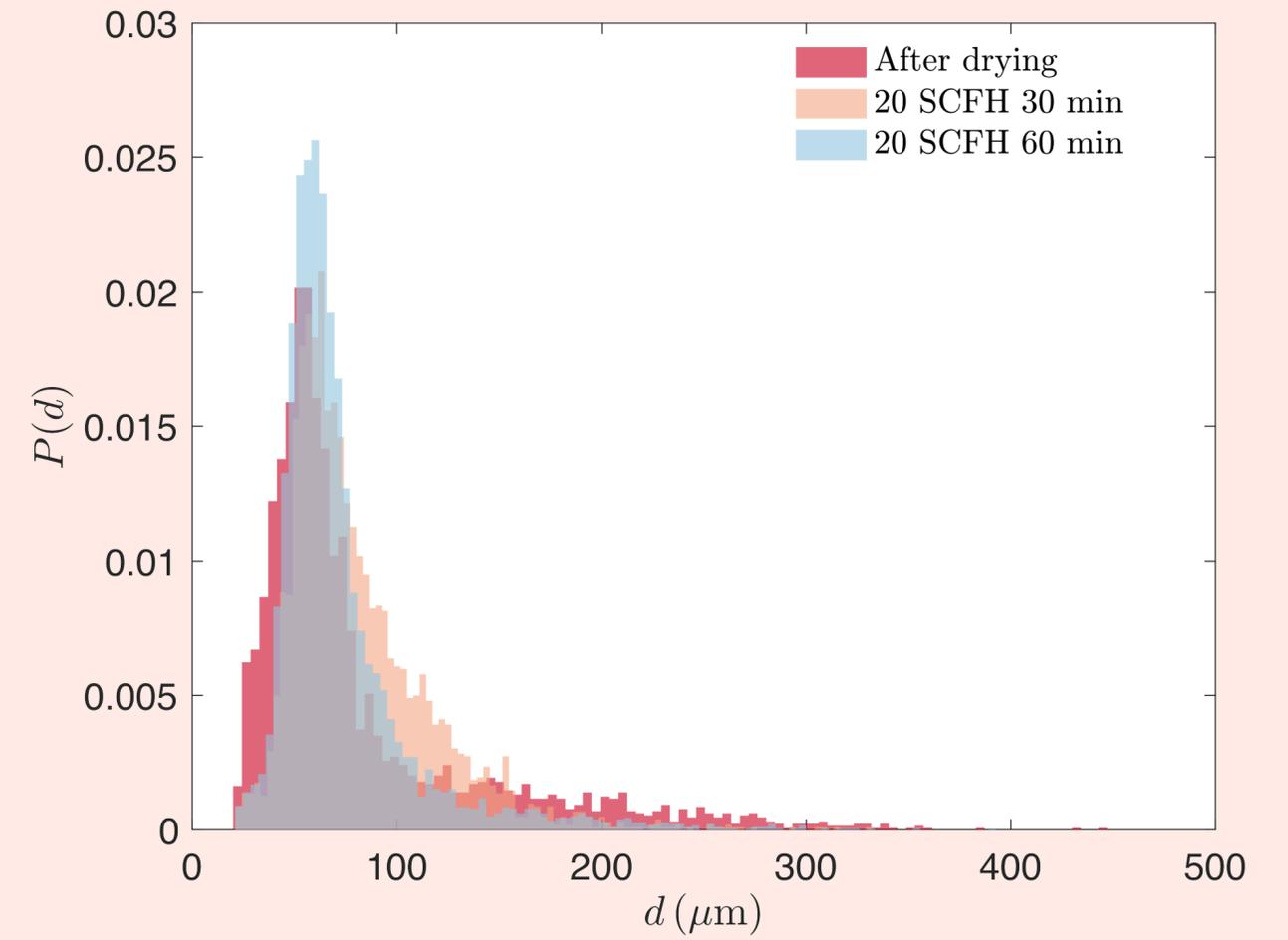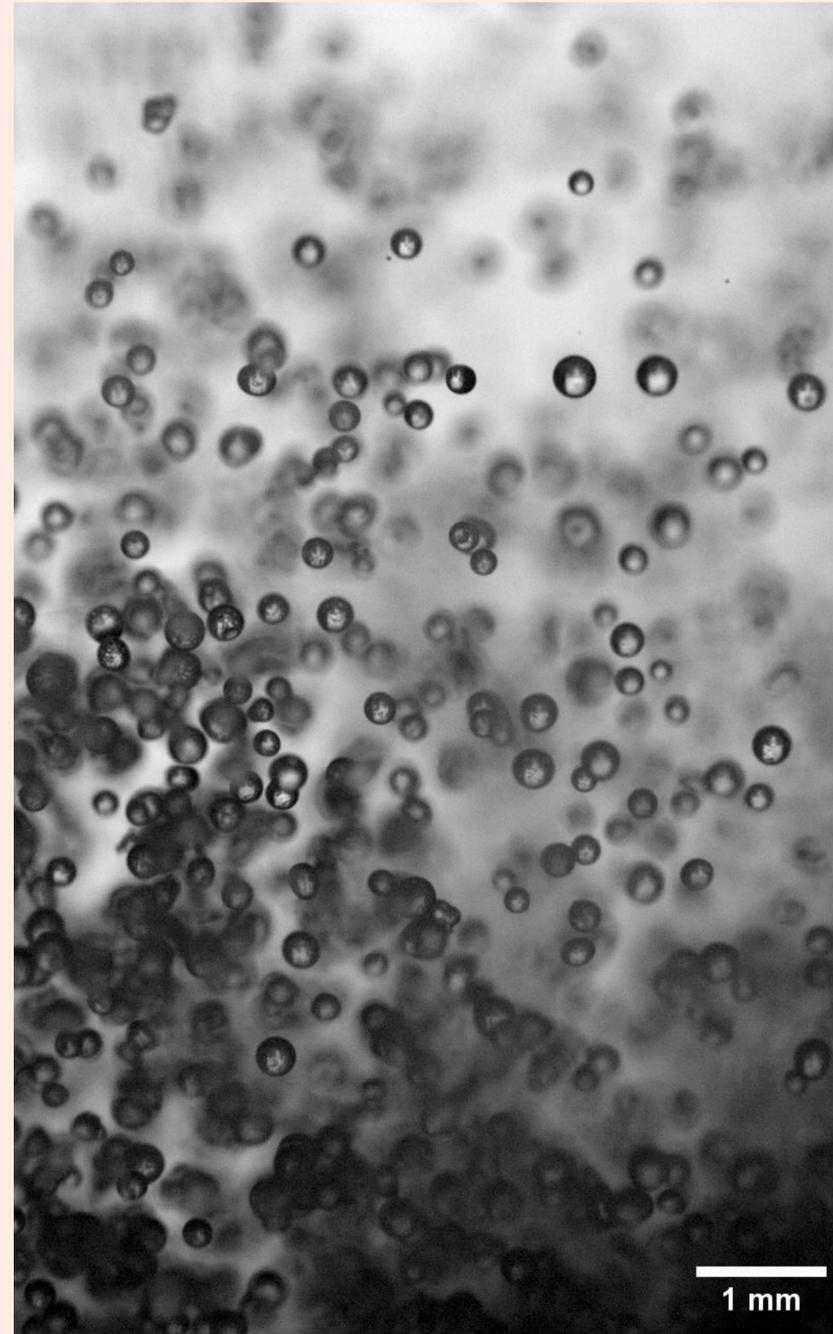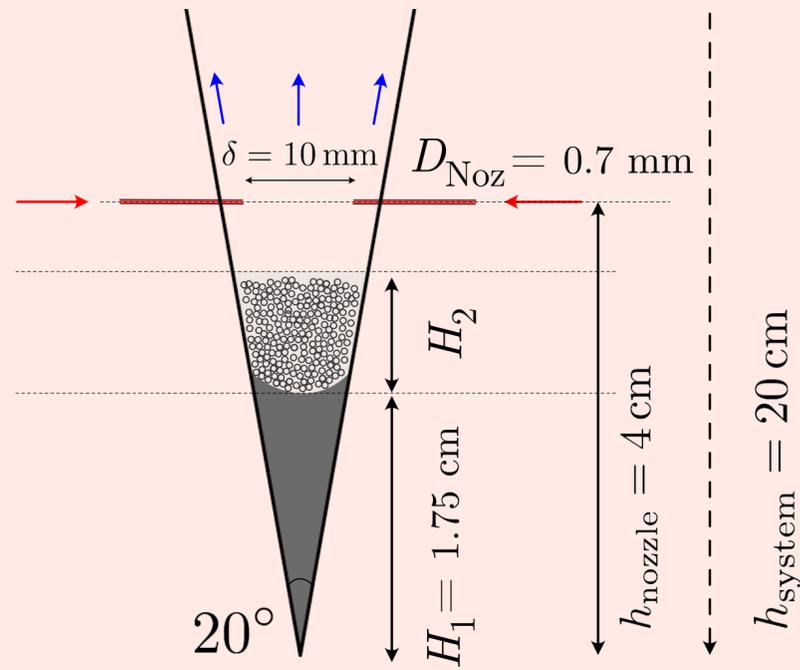
$$U_{\mathrm{centerline}} \sim U_{\mathrm{J}} \left(\frac{H}{D} \right)^{-1}$$

H
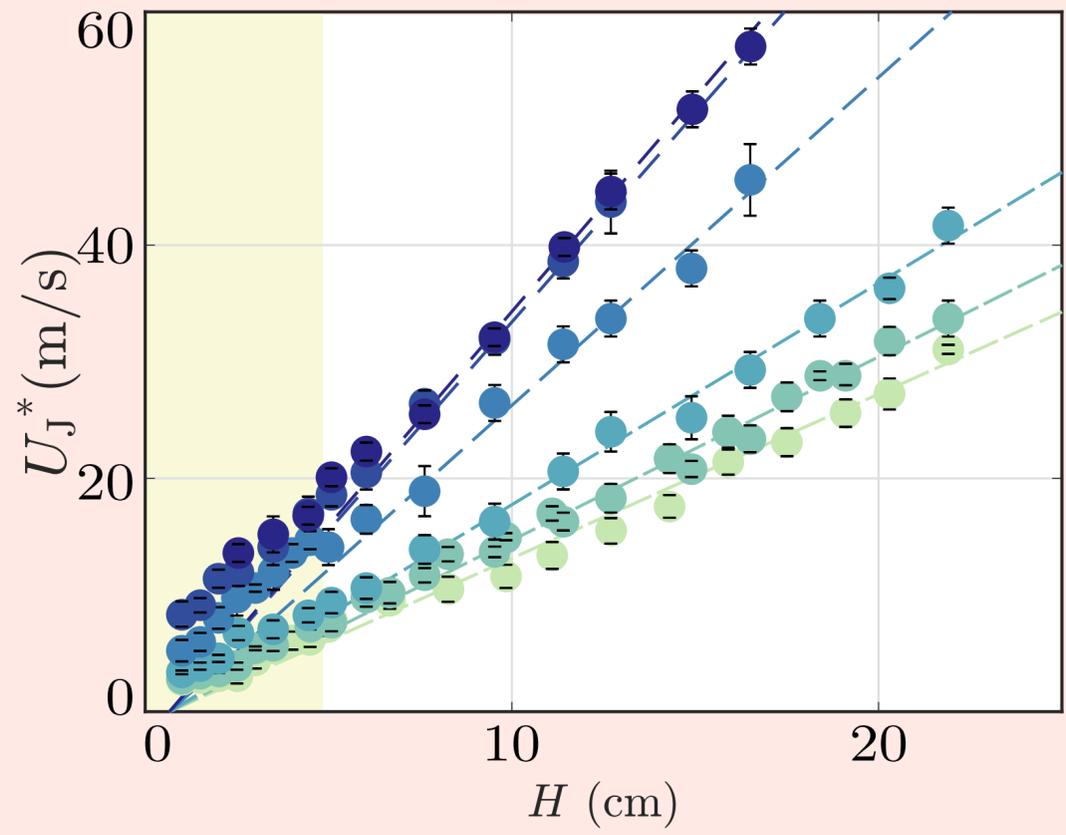
Sharma, R.S., *et al.*
Erosion of cohesive grains by an impinging turbulent jet
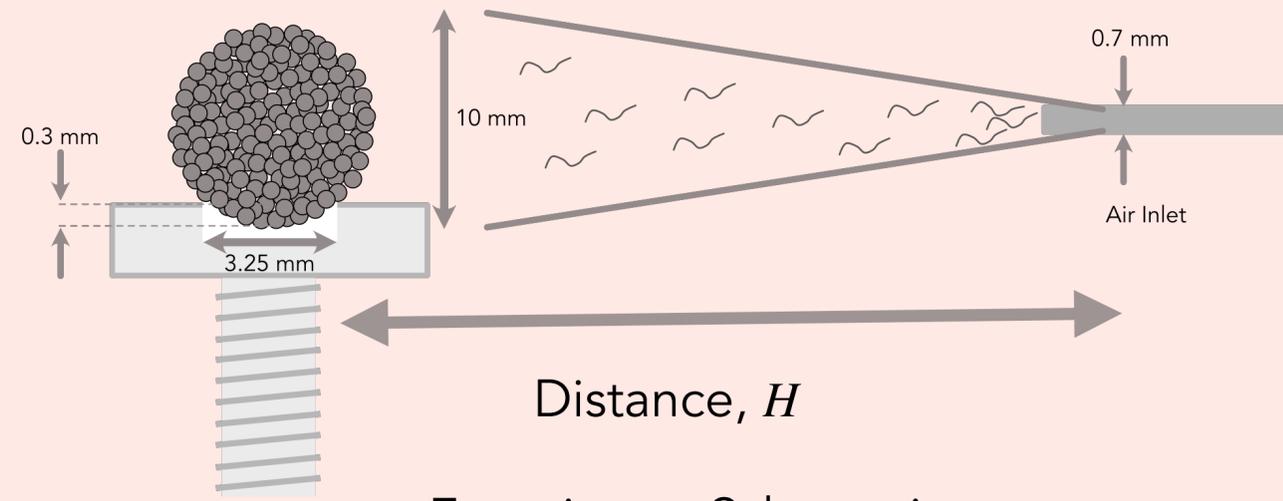**Physical Review Fluids. 7**, 074303 (2022)

Bo = 0 **Bo = 8** **Bo = 15**

High stresses: impinging turbulent jet

$$\tau_{\max} \sim [30\,\mathrm{Pa},\, 200\,\mathrm{Pa}]$$

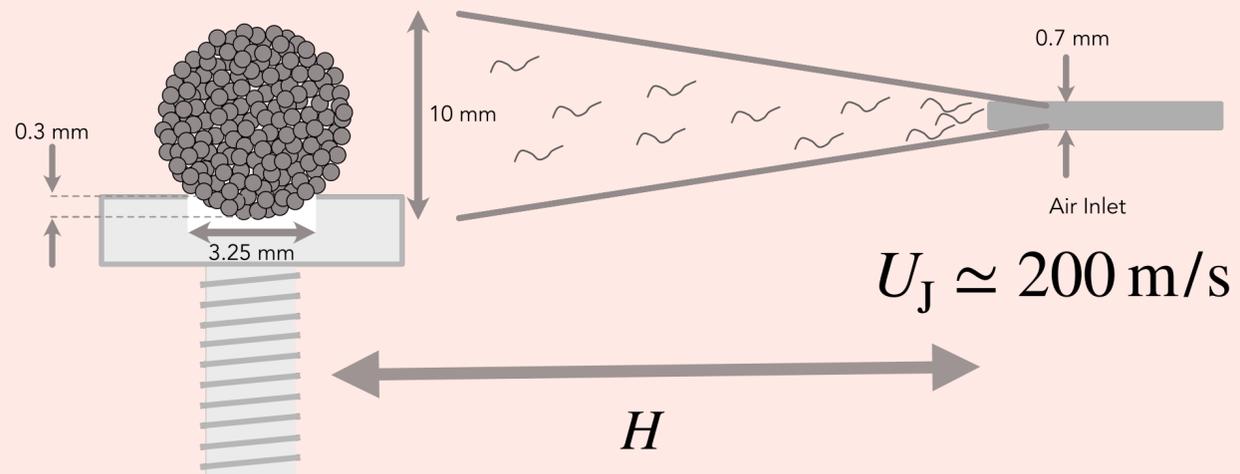# Agglomerate Breakup under a Turbulent Jet

Experiment Schematic
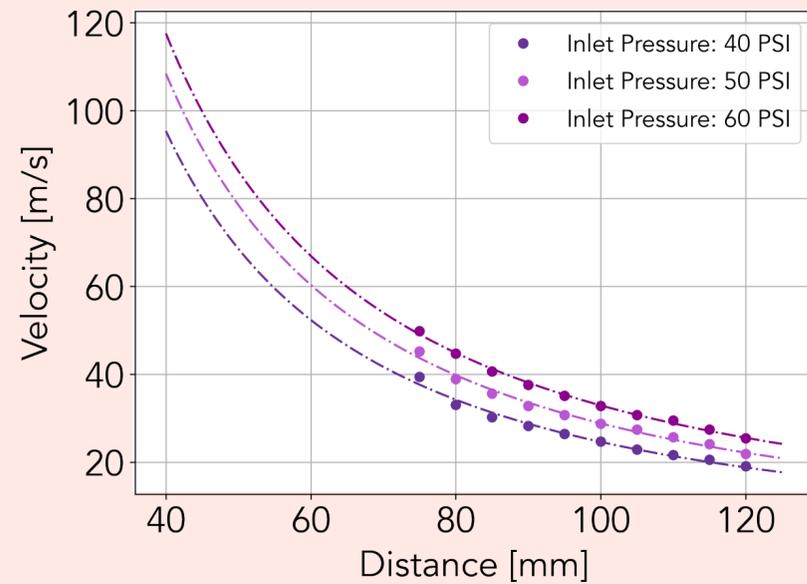
$$U_c(z = H, r = 0) = \kappa\, U_J\, (H/D)^{-3/2}$$

Measured jet velocity profile as a function of distance H

Agglomerate of yield-stress $\tau_c = 0.89\,\text{kPa}$

Agglomerate Breakup under a Turbulent Jet

$U_J \simeq 200\,\mathrm{m/s}$

The local velocity near the agglomerate is:
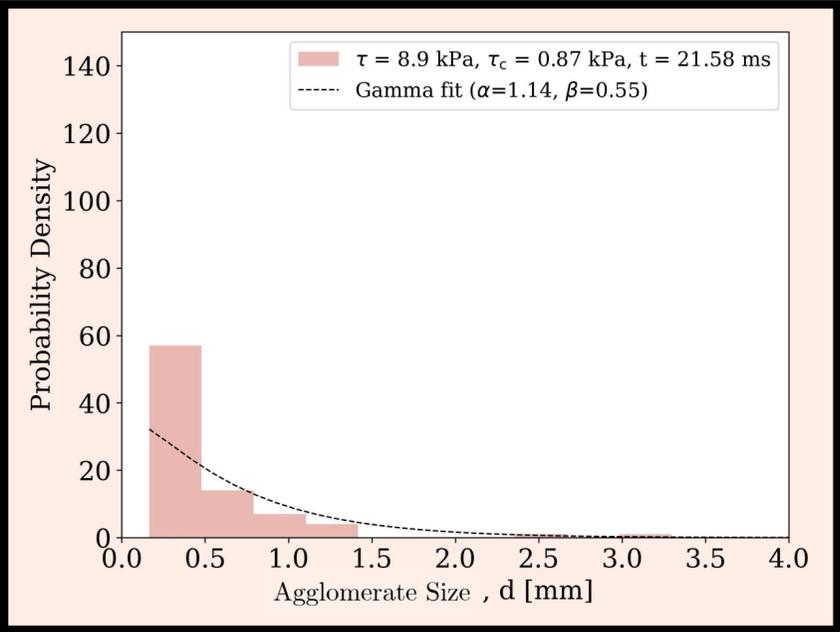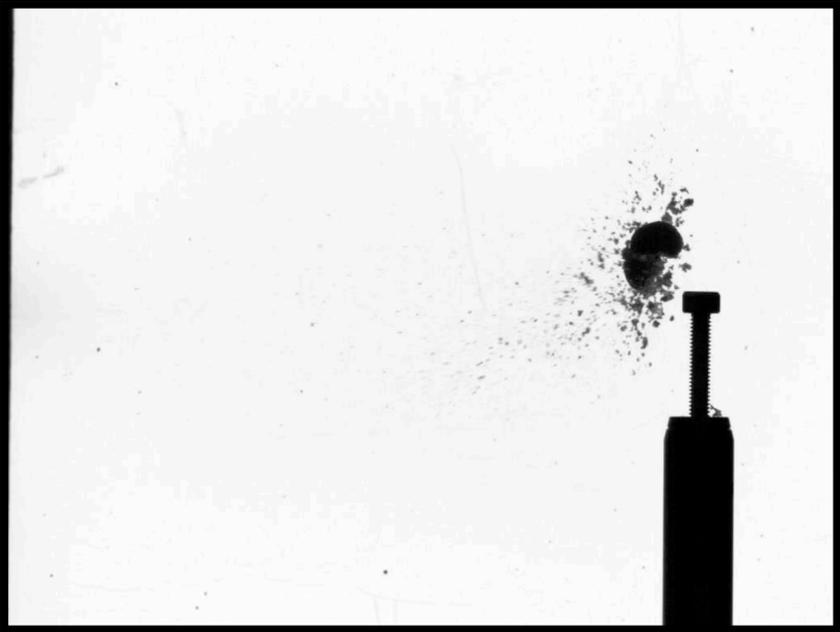
$$U_c = 60 - 100\,\mathrm{m/s}$$

$$\rho U_c^2 = 4.3 - 17.3\,\mathrm{kPa}$$
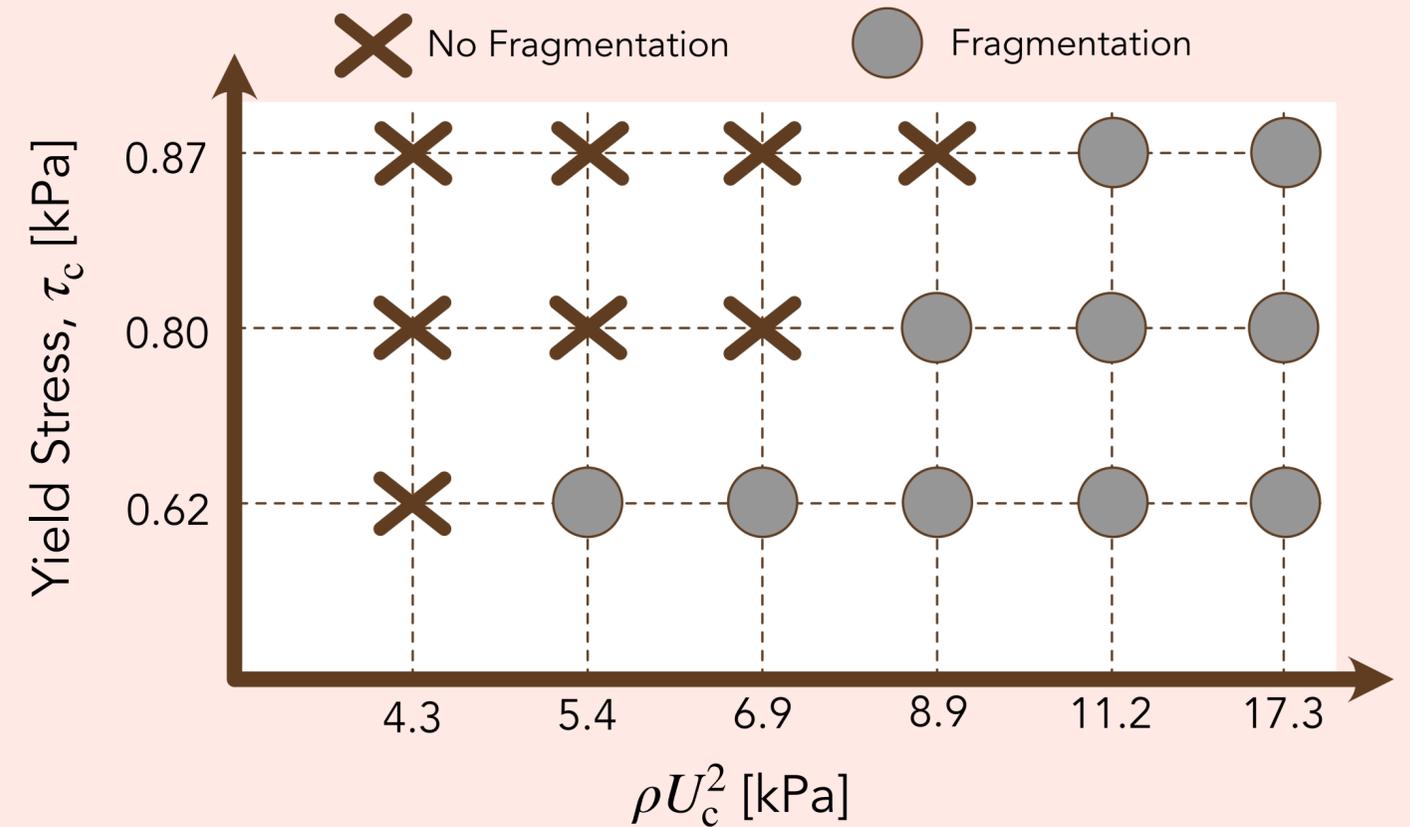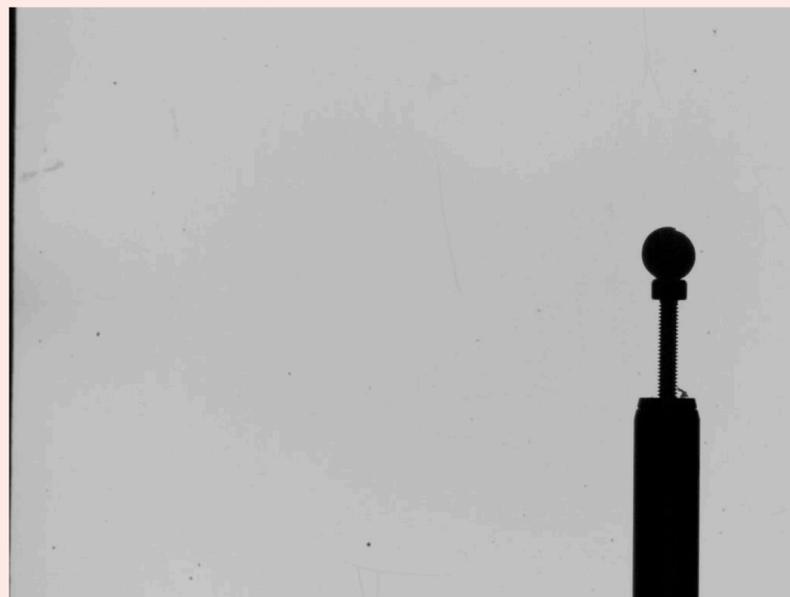
Regime map for no fragmentation / fragmentation under different shear-stress τ

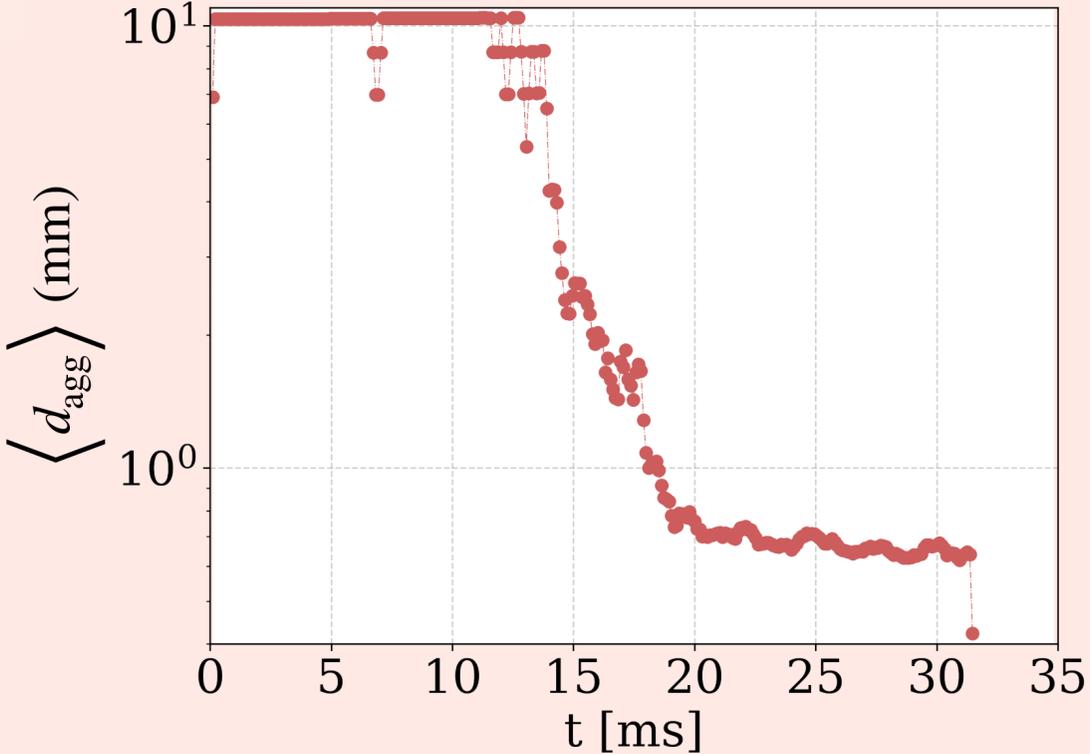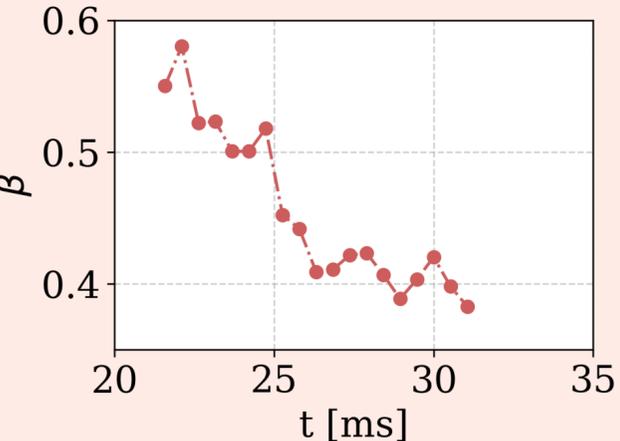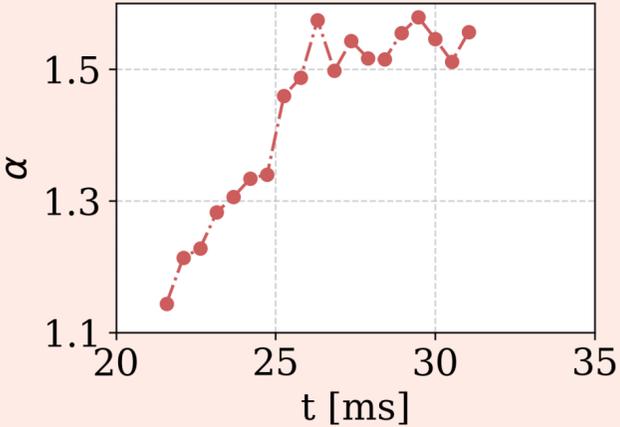# Agglomerate Breakup under Turbulent Jets

Evolution of PSD with time

$$f(d, \alpha, \beta) = \frac{\beta^\alpha d^{\alpha-1} e^{-\beta d}}{\Gamma(\alpha)}$$
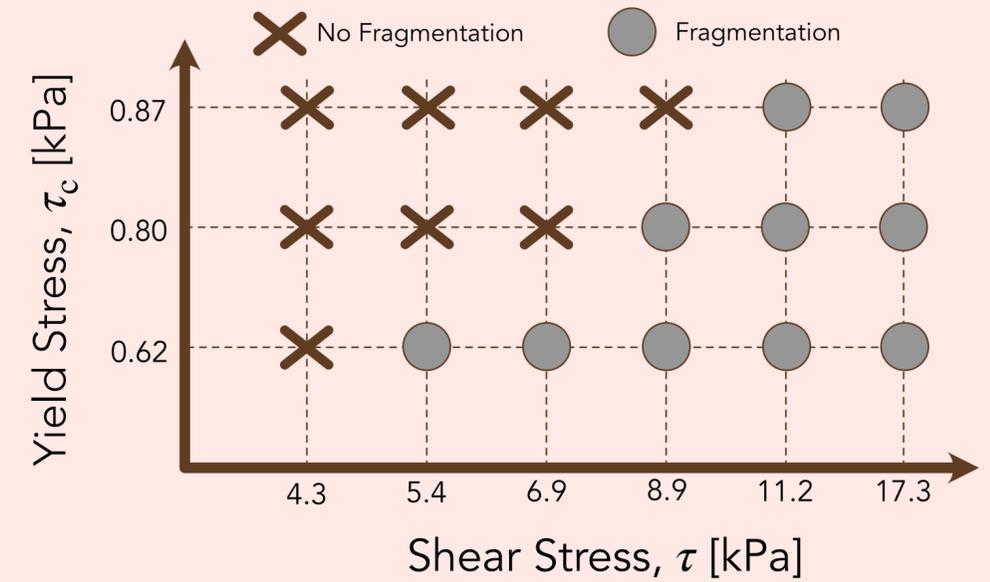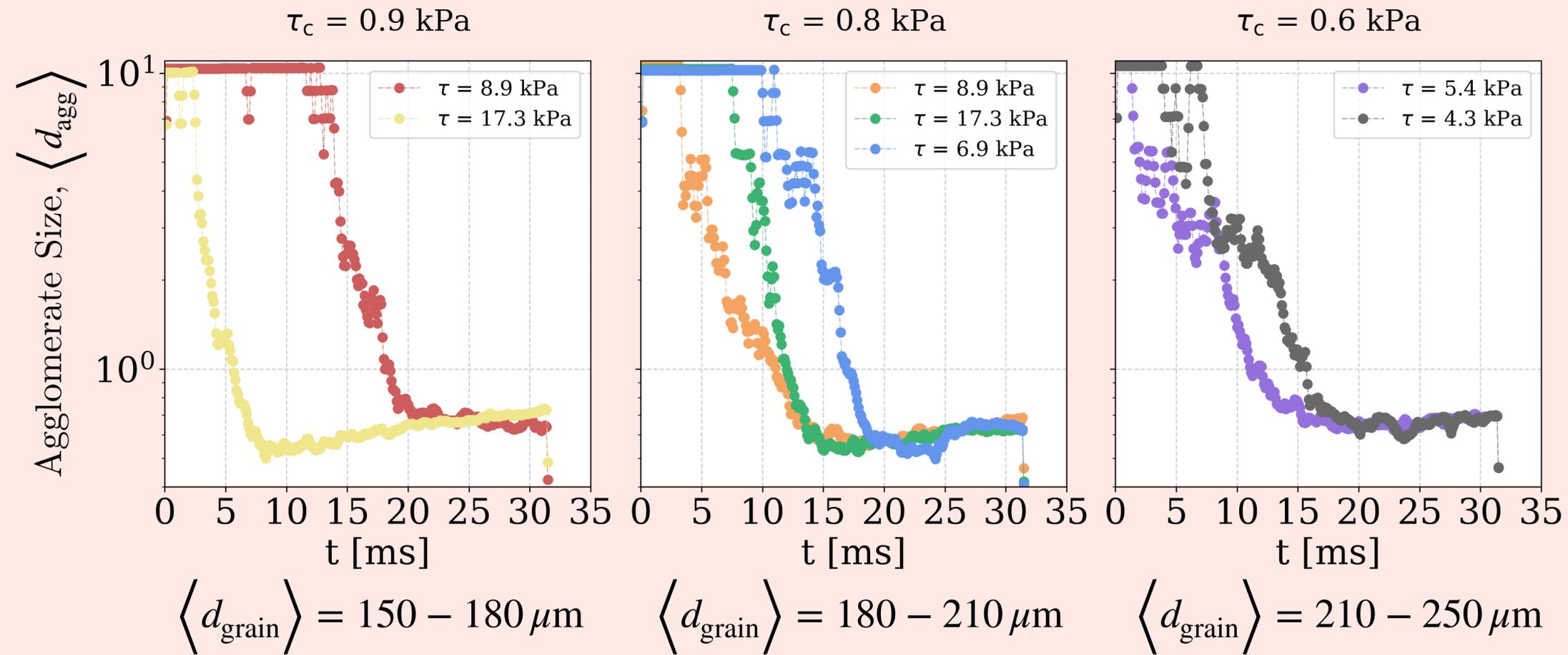
α: Evolution of d_{agg}

β: Evolution of rate of d_{agg}

Agglomerate Breakup under Turbulent Jets

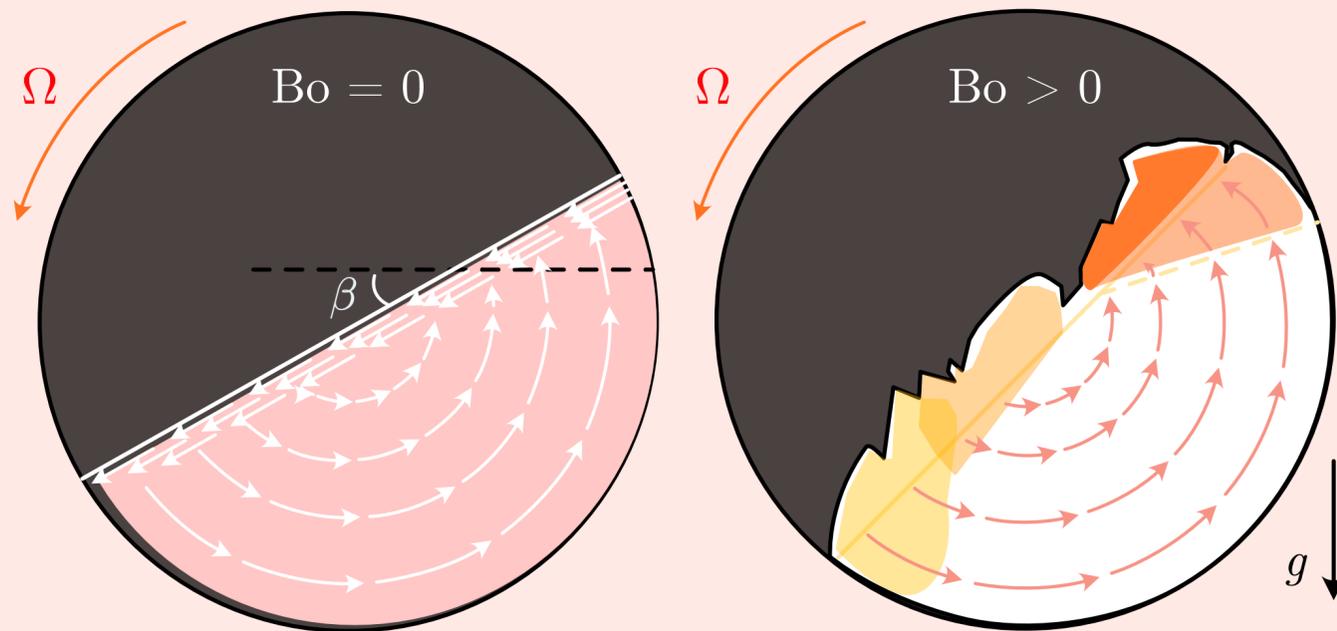Evolution of PSD with time for different grain diameters:

Capillary bridges → drying → Brittle bonds

An approach to understand agglomerate evolution through model experimental geometries and stress conditions

Low stresses: rotating in a drum

High stresses: impinging turbulent jet