Formation of stable aggregates by fluid-assembled solid bridges

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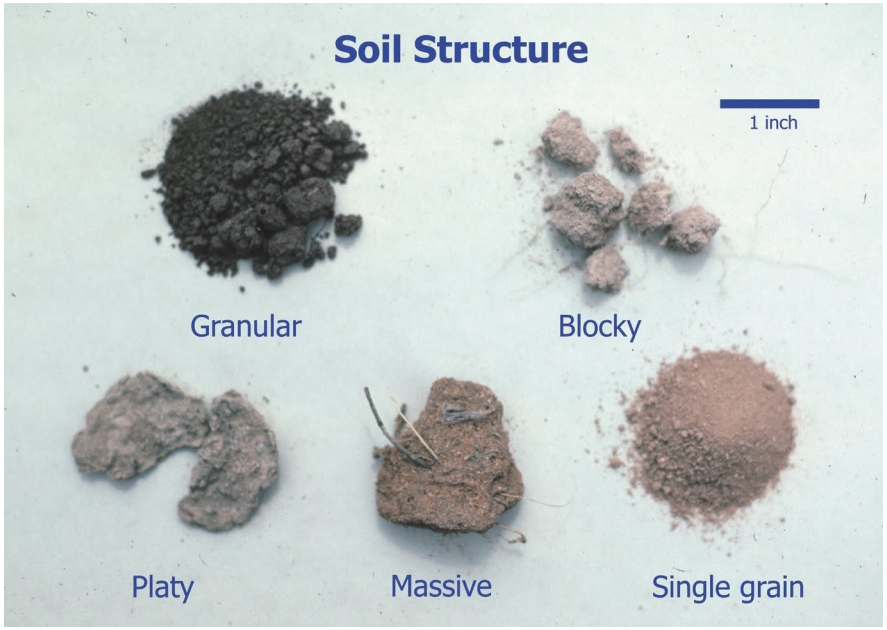
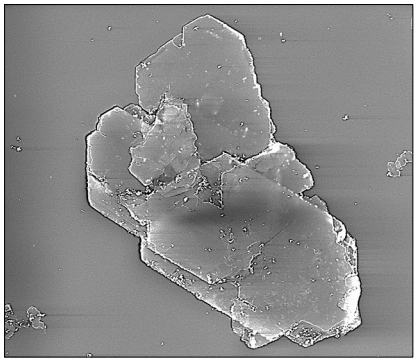
Cohesion dictates (in)stability of soils

Soil aggregates, and what makes them



[Ecomerge]

Paradigm: clay is 'sticky'



Kaolinite particle

In suspension: electrostatic charge determines stability

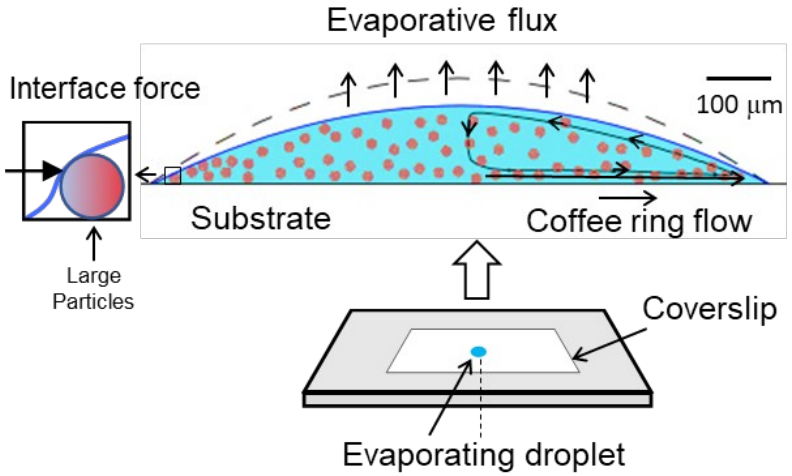
Drying: can drive particles together → overcome electrostatic repulsion

Wetting: hydration effects become important

Can form aggregates when theory says we shouldn't. Are they stable?

Let's make some aggregates by drying

Step 1: Evaporation and aggregation



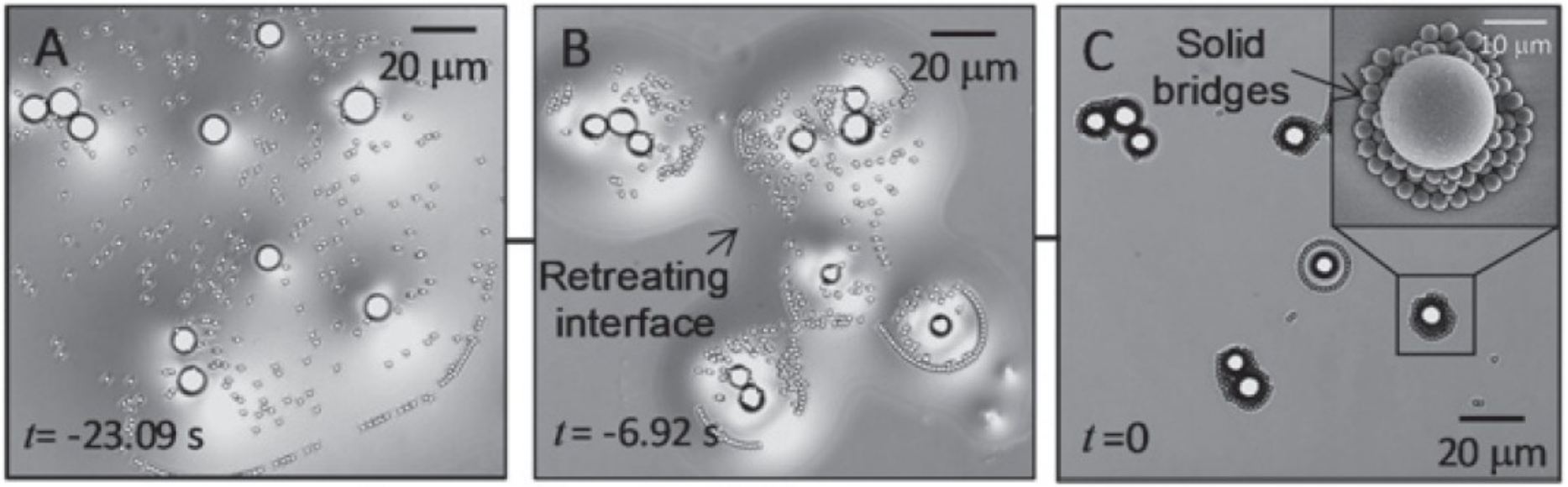
A simple 'synthetic soil':

Water droplet containing 20 micron and 3 micron silica spheres.

Retreating water interface condenses particles.

Droplet breaks into 'islands' around big particles.

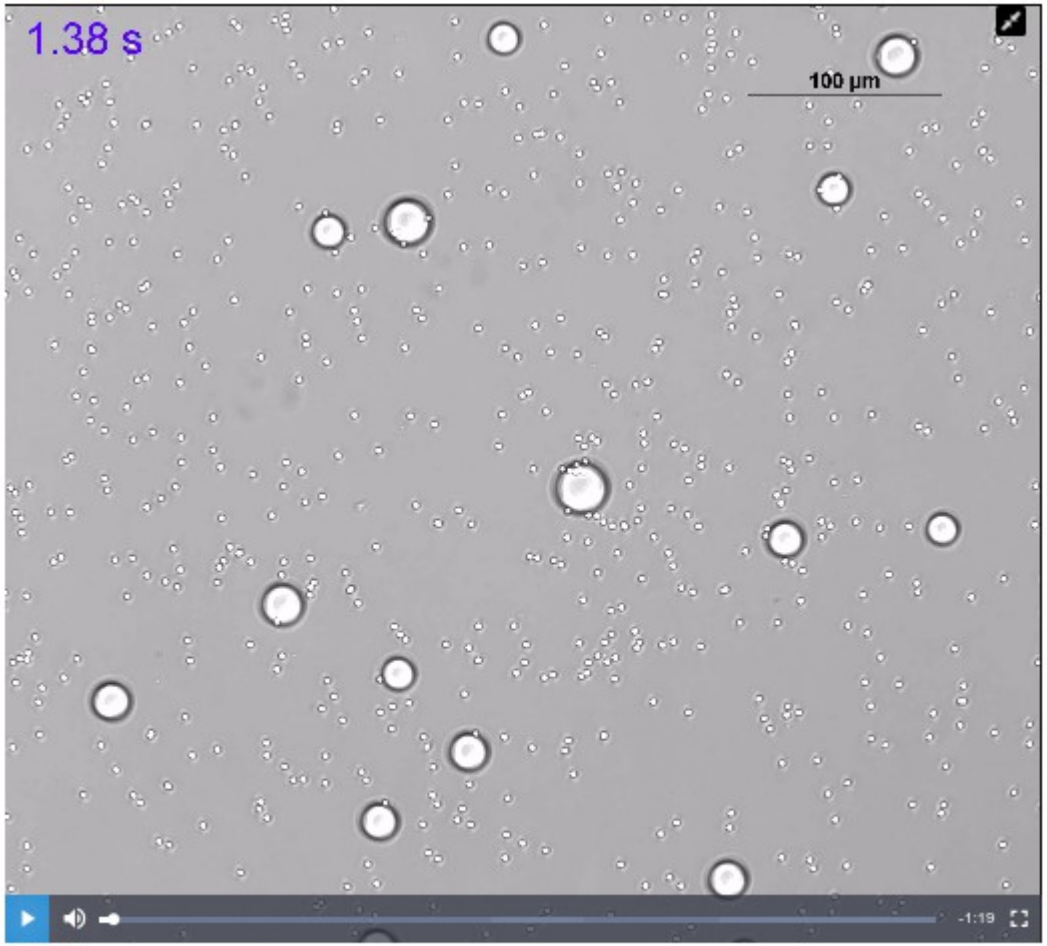
Small particles condense in capillary bridges, are squeezed.



Evaporation of a bidisperse suspension

Relevant movie:

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1913855117/video-2



Movie S2.

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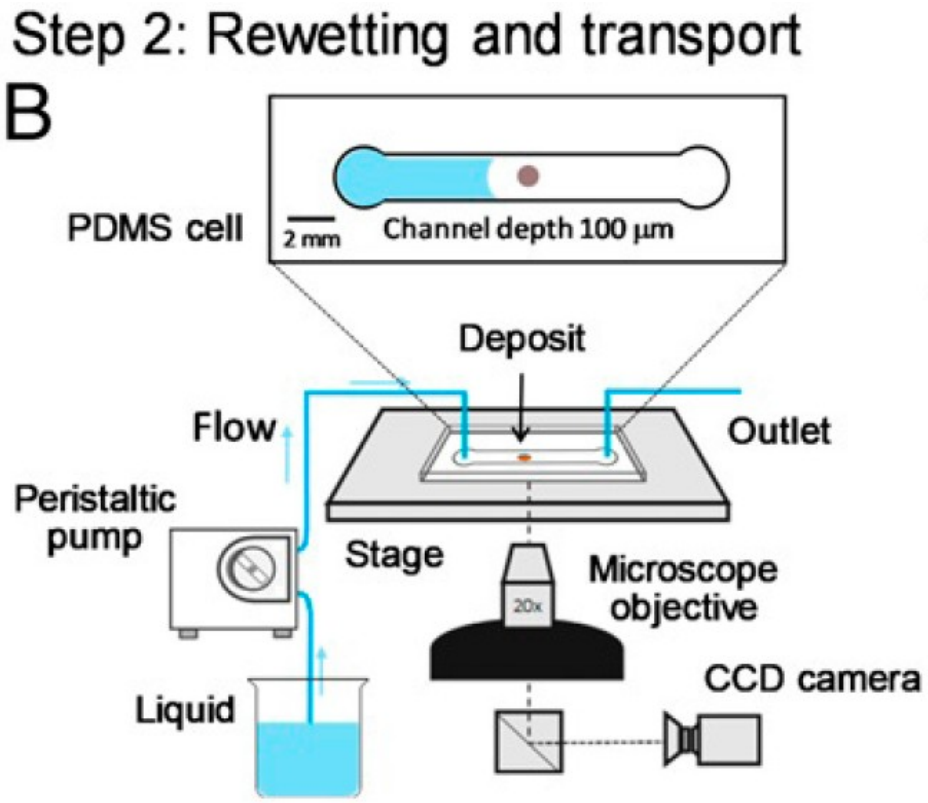
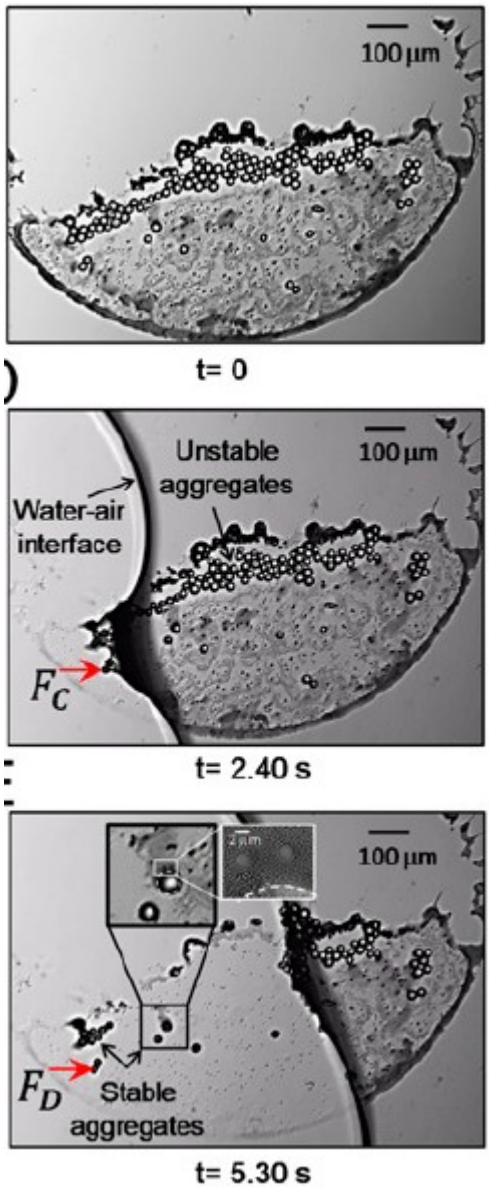
An evaporating suspension of bidisperse silica spheres composed of 20 and 3-*µm* particles on a silicate coverslip substrate. The retreating air-water interface drags 3-*µm* particles and condenses some of them within the meniscus formed between the 20-*µm* particles and the substrate or between adjacent particles. After water is fully evaporated, small particles form 'solid bridges' that connect larger particles to the substrate and to each other to make aggregates.

Evaporation of droplet with 20- and 3-micron particles

Let's (try to) erode some aggregates: a tiny flume





Capillary force of water-air interface pushes particles.

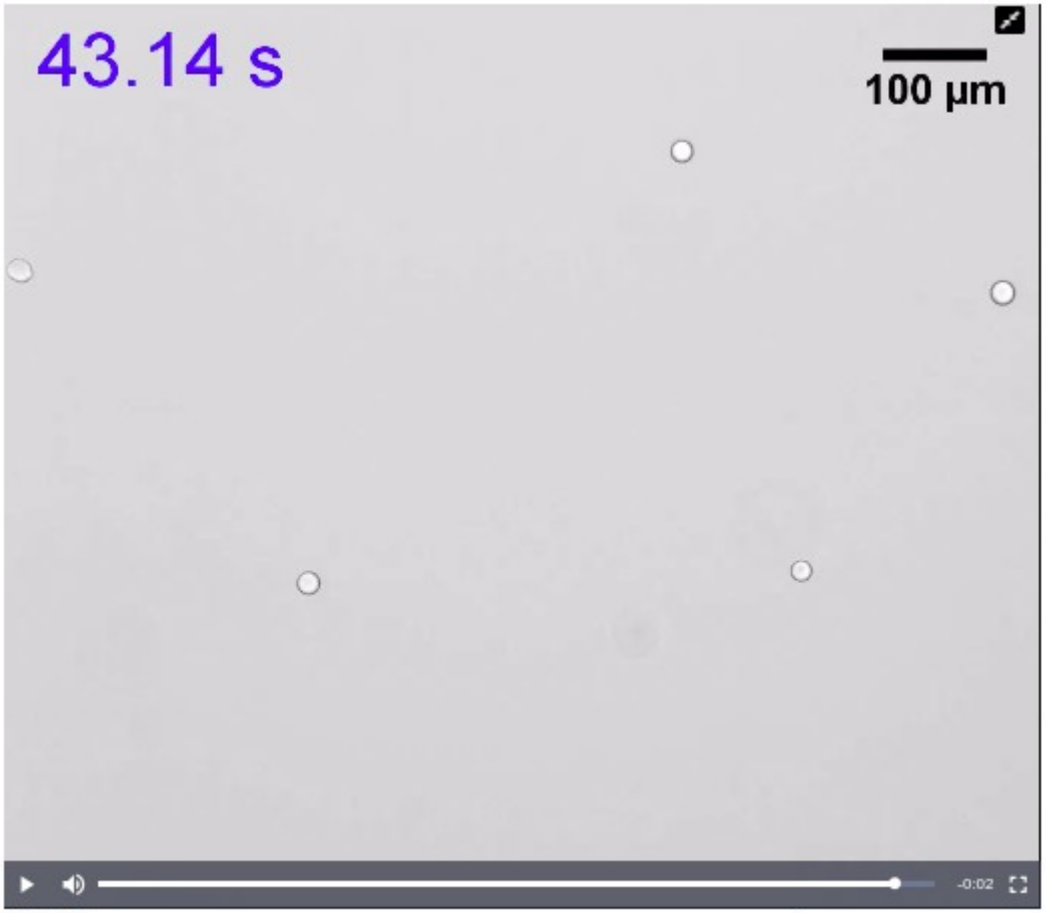
After that, drag force keeps pushing.

Some aggregates are **unstable**, some are **stable**.

What determines stability?

Relevant movie:

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1913855117/video-4



Movie S4.

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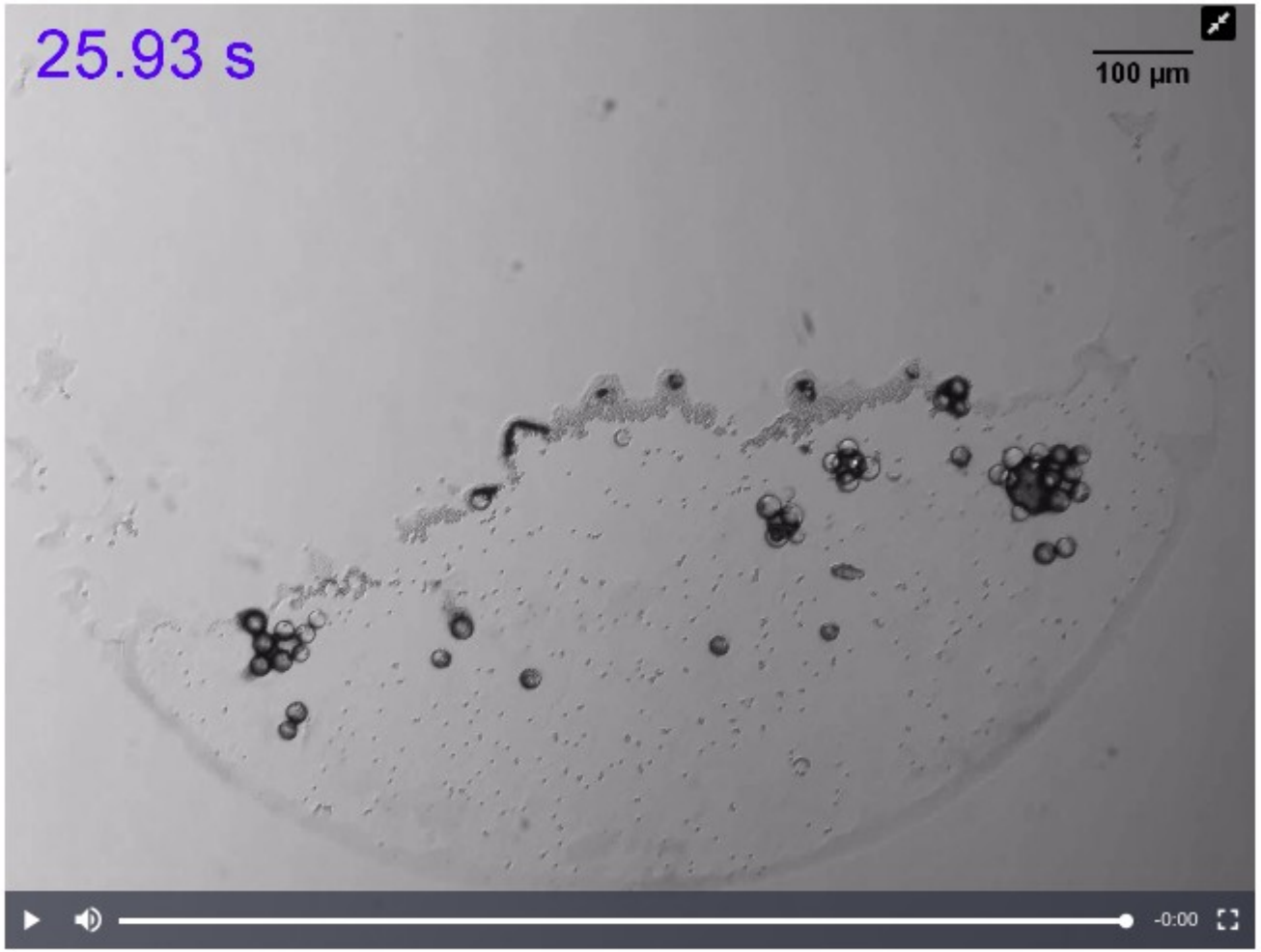
A deposit formed by evaporation from a monodisperse suspension of 20-*µm* particles subject to rewetting, where particles are easily transported due to the absence of solid bridges.

Deposit of 20-micron (large) particles:
UNSTABLE to rewetting

Relevant movie:

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1913855117/video-1



Movie S1.

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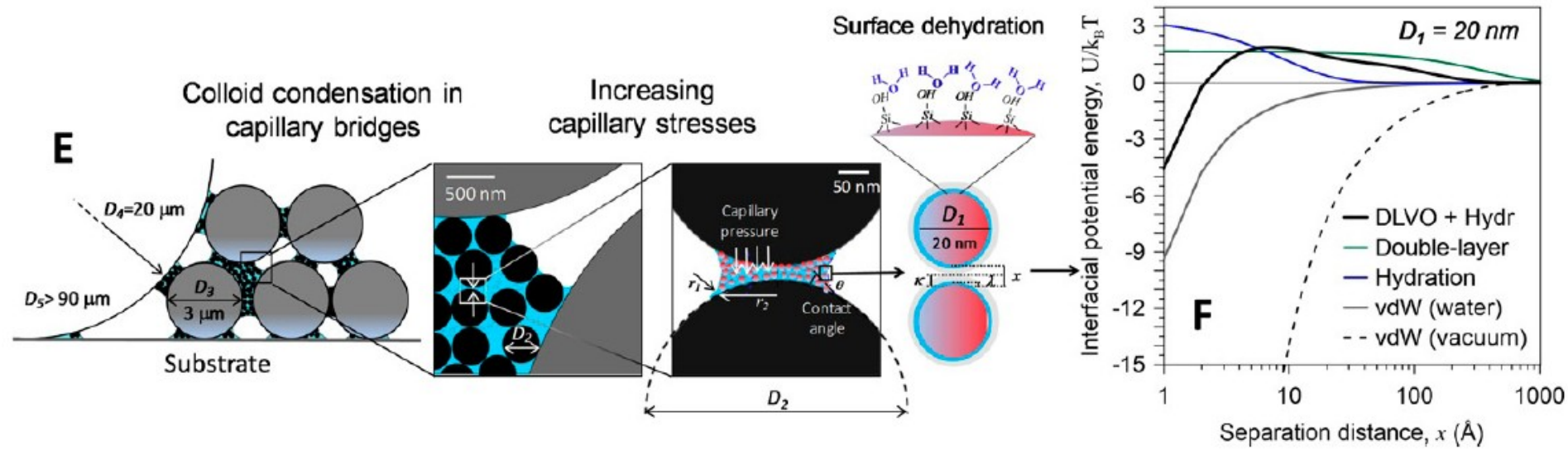
A deposit formed by evaporation from a suspension of polydisperse silica spheres composed of 20, 3, and 0.4-*µm* particles, subject to rewetting and fluid shear in a microfluidic channel.

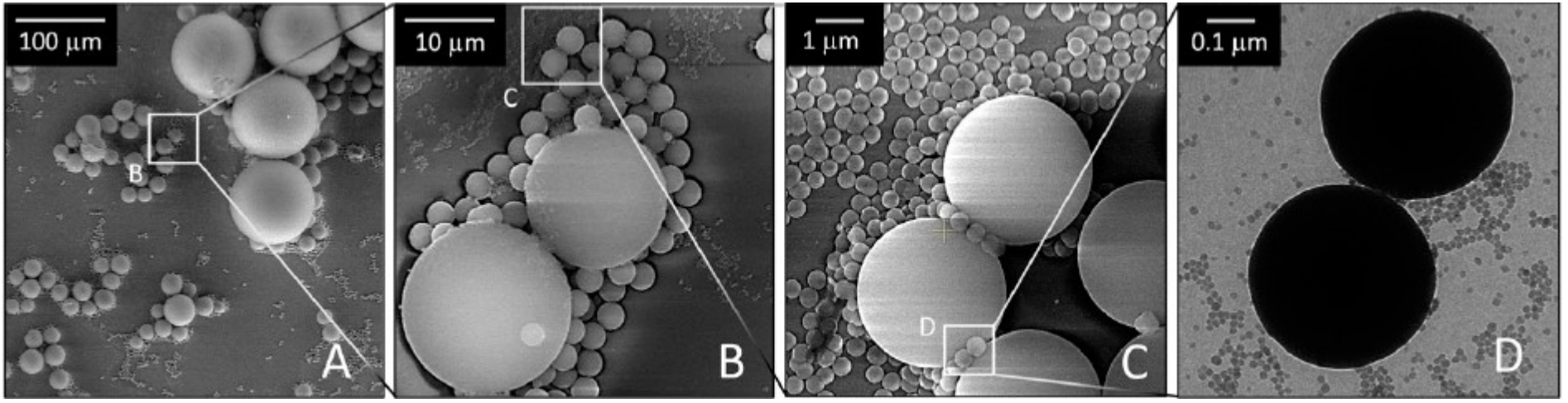
Add some small (3-microns and less) particles:
Bingo-bango, STABLE aggregates!

“Solid bridges” make stable aggregates. How?

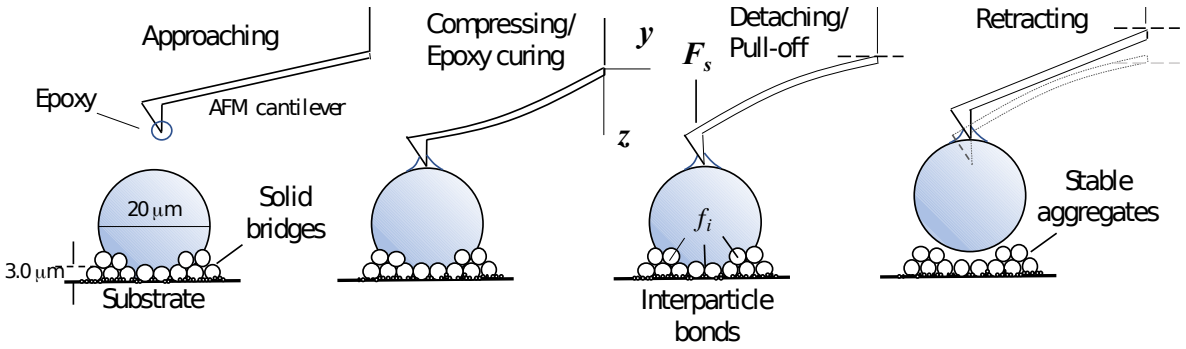


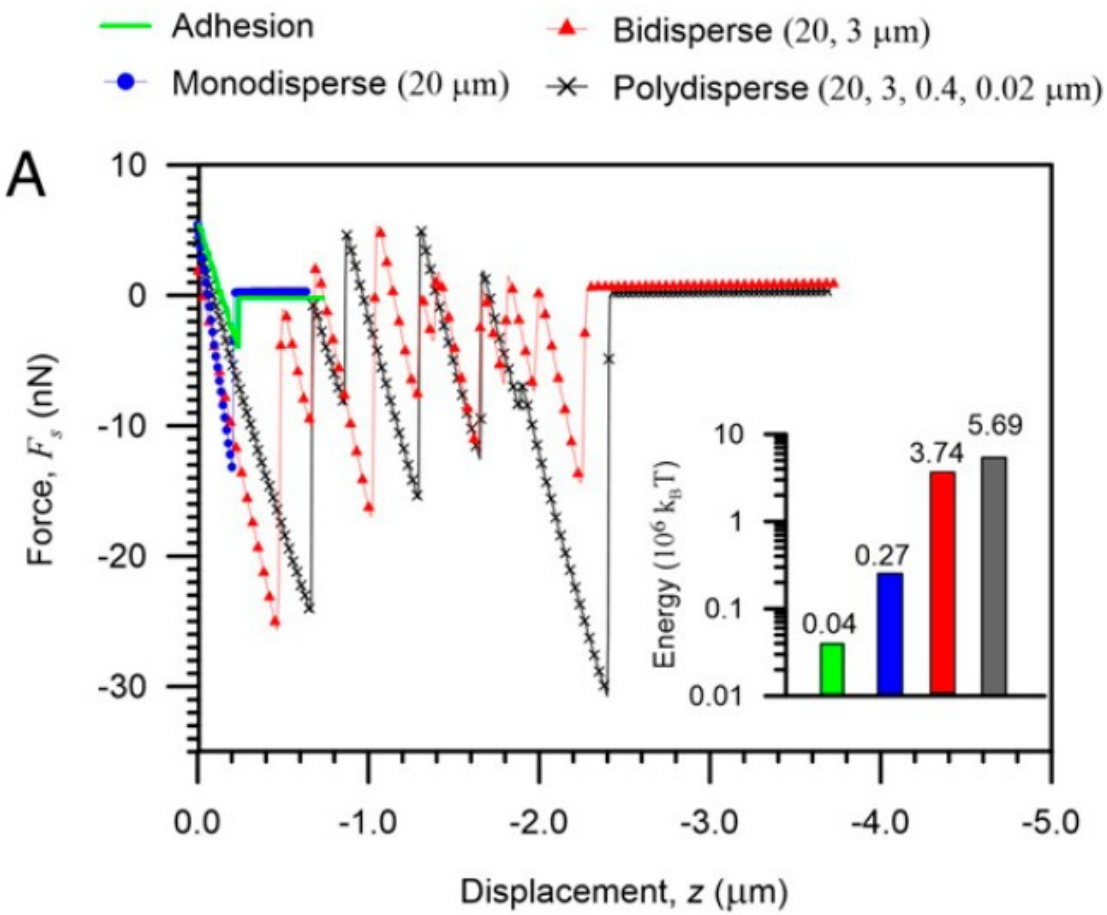
Fluid stress overwhelms electrostatic repulsion:
→ pushes particles into **“van der Waals** well”. **They stick together.**

Experiment with **4** different particle sizes
→ bridges within bridges within bridges. **Fractal aggregates.**



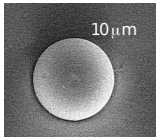
Measuring strength of solid bridges with AFM



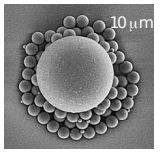


Measure pull-off force (curve), and total pull-off energy (bar chart), for:

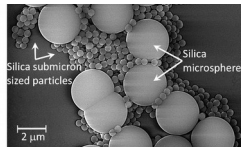
- a **single 20-micron particle**



- a **20-micron particle bonded to 3-micron particles**



- a **20-micron particle bonded to 3, 0.4 and 0.02 micron particles.**

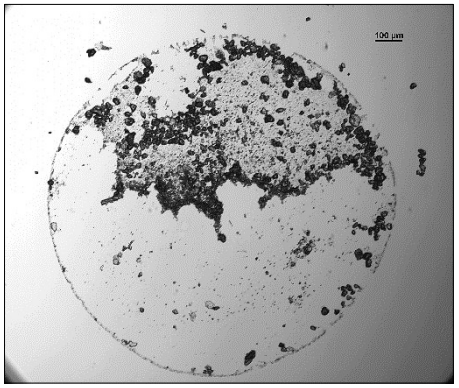


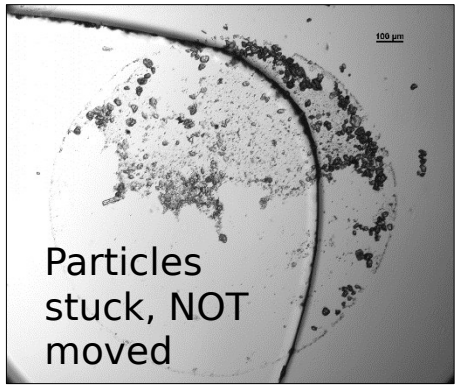
Force jumps: distinct bond breaking events!

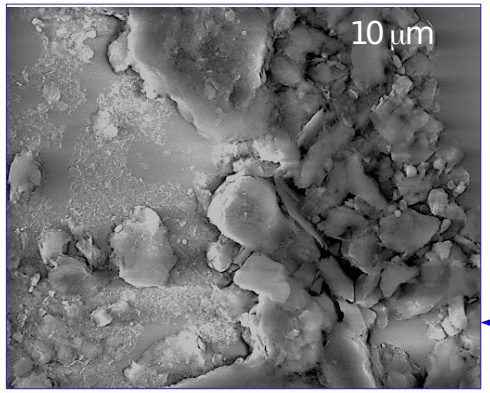
Solid bridging: small particles are bonded by van der Waals.
→ **Small particles make cohesion.**

SIZE, NOT MINERALOGY, dictates cohesion!

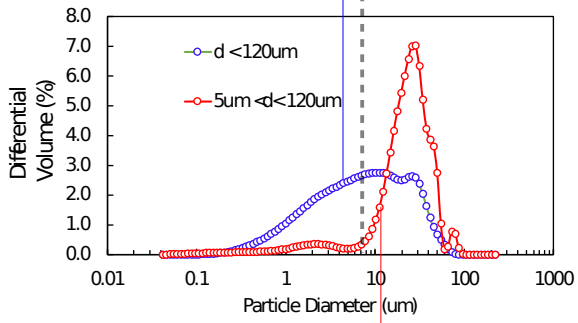
Illite clay particles WITH small particles: STABLE (sticky)



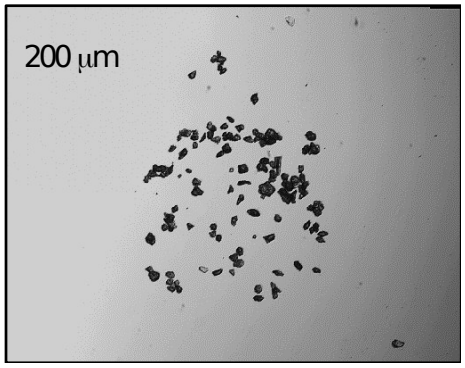


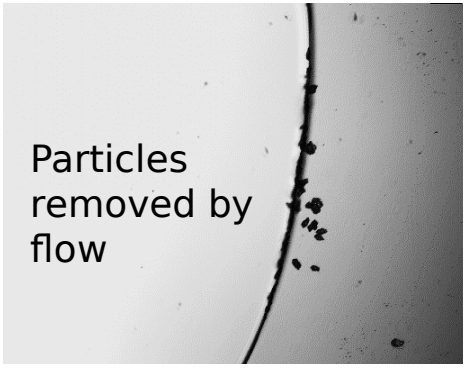


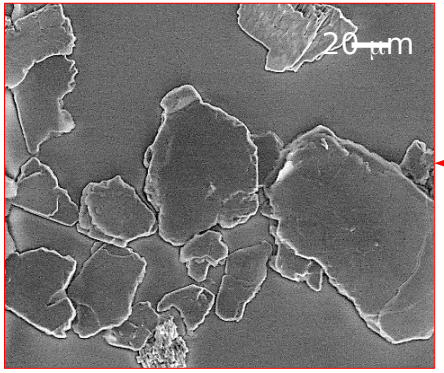
5 microns



Illite clay particles WITHOUT small particles: UNSTABLE



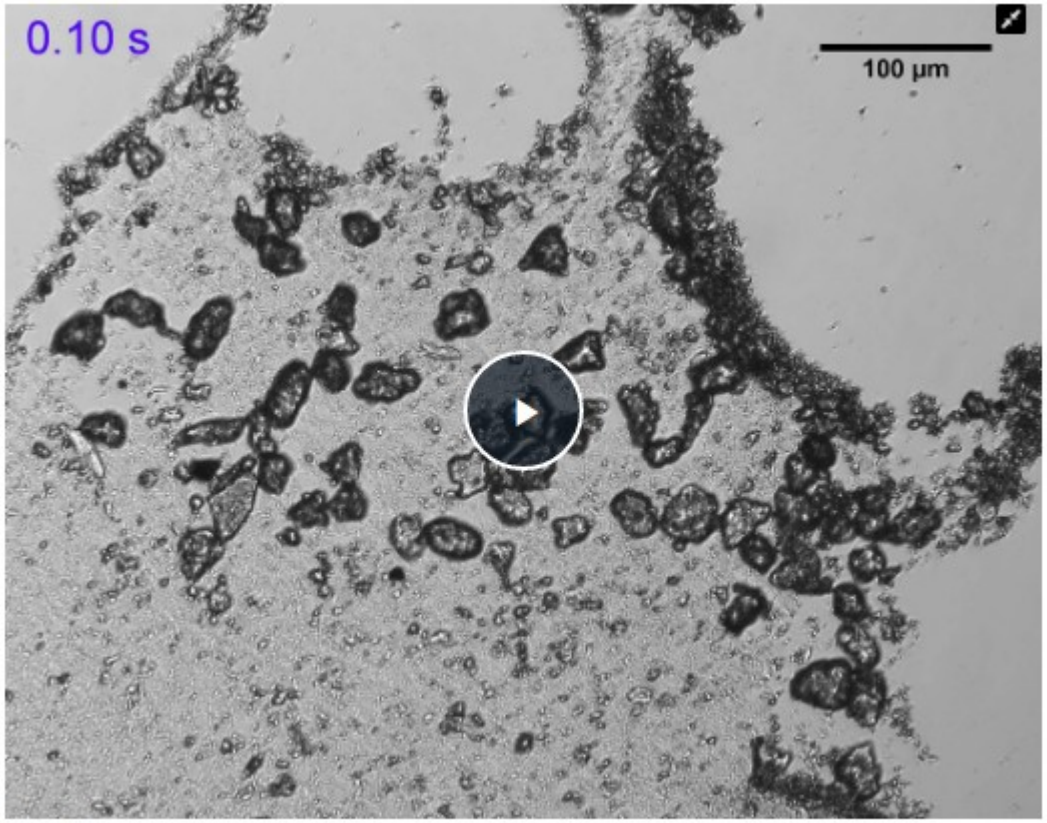




Clay is NOT sticky if you remove particles < 5 microns!!

Relevant movie:

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1913855117/video-5



Movie S5.

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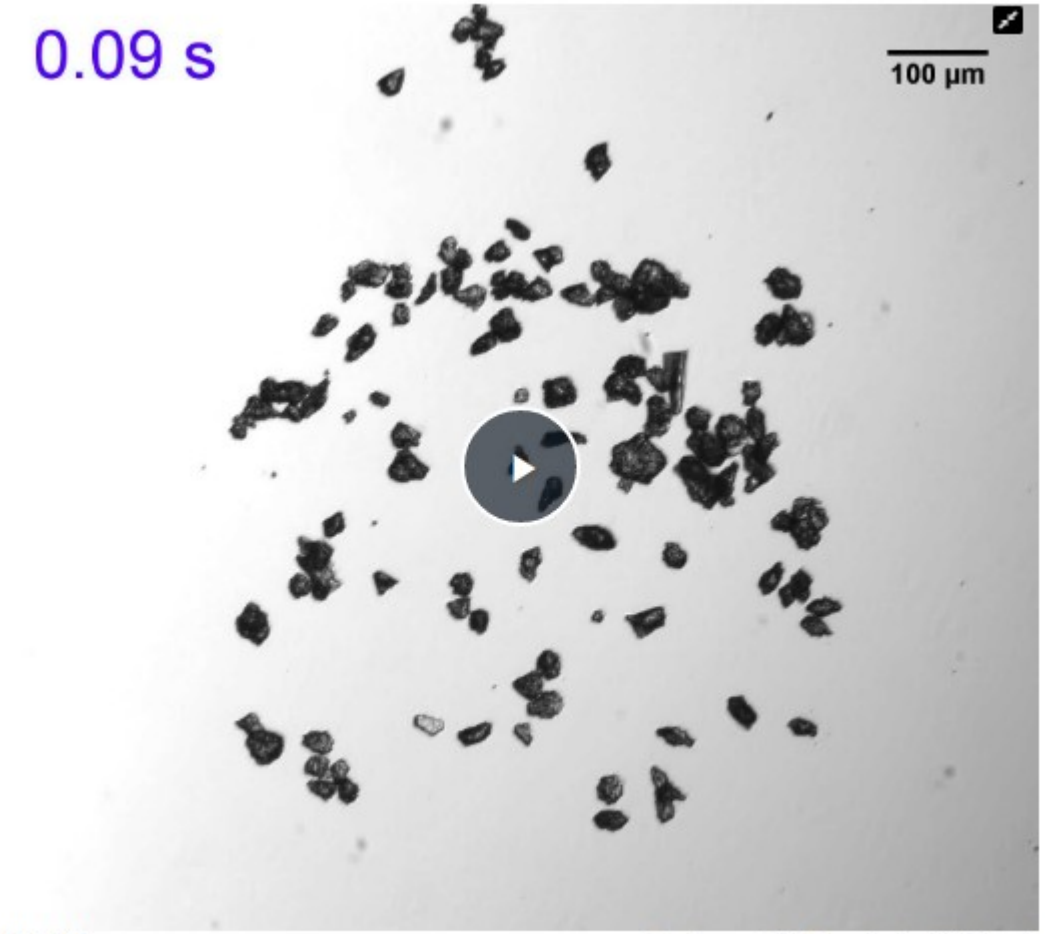
Aggregates formed by evaporation from a suspension of unsieved, polydisperse illite clay particles subject to rewetting. Aggregates are stable due to solid bridges.

Rewetting of Illite mixture (w/ small grains):
STABLE aggregates

Relevant movie:

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1913855117/video-6



Movie S6. Open in new tab | Download original movie

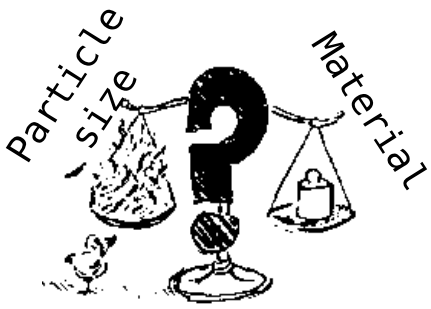
Aggregates of illite clay modified by sieving out particles < 5 *µm* subject to rewetting, and transport of particles due to the absence of small particles and the associated solid bridges.

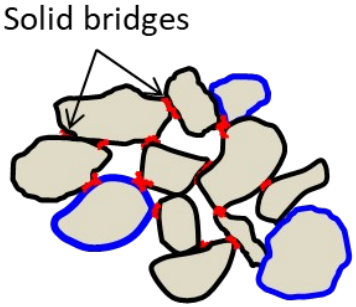
Rewetting of Illite w/ < 5-micron grains REMOVED: UNSTABLE aggregates

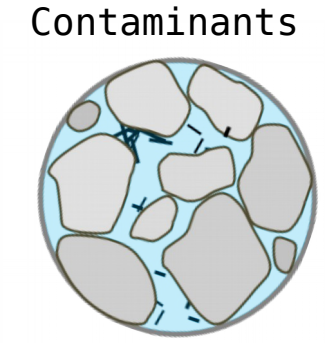
A COHESIONLESS CLAY AGGREGATE!!

WHAT WE LEARNED

- Significance of interfacial capillary forces
- Role of particle size
- Granular origins of cohesion
- Origins of cohesion in natural soils
- New Experimental Avenues
  - Contaminant transport
  - Collapsible soils







Application: stabilization of soils

The unstable monodisperse illite clay aggregates can be stabilized using a small concentration (0.04 wt %) of silica nanoparticles (0.4 μm), through the solid bridging mechanism.