Tiny 'bridges' help particles stick together

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It happens outside your window every time it rains: The soil gets wet and may form sticky mud. Then it dries. Later it might rain again. Each wetting and rewetting affects the structure and stability of the soil. These changes are taken into account when, for example, architects and engineers design, site, and construct buildings. But more broadly, the science of how particles stick together and then pull apart touches fields as diverse as natural hazards, crop fertilization, cement production, and pharmaceutical design.

Uniting these disparate fields, a team at the University of Pennsylvania has found that when particles are wet and then allowed to dry, the size of those particles has a lot to do with how strongly they stick together—and whether they stay together or fall apart the next time they are wetted.

What lends these sticky aggregates strength, the team found, are thin bridges formed when particles of the material are suspended in a liquid and then left to dry, leaving thin strands of particles that connect larger clumps. The strands, which the researchers call solid bridges, increase the aggregates' stability 10- to 100-fold.

The researchers reported their findings in the journal *Proceedings of the National Academy of Sciences*.

"This solid bridging phenomenon may be ubiquitous and important in understanding the strength and erodibility of natural soils," says Paulo Arratia, a fluid mechanics engineer in Penn's School of Engineering and Applied Science, and a coauthor on the study.

"We found that a particle's size can outweigh the contribution of its chemical properties when it comes to determining how strongly it sticks to other particles," adds Douglas Jerolmack, a geophysicist in the School of Arts and Sciences and the paper's corresponding author.

The research team was led by Ali Seiphoori, formerly a postdoc in Jerolmack's lab and now at MIT, and included physics postdoc Xiao-guang Ma. The current work spun out from investigations they had been pursuing in conjunction with Penn's Perelman School of Medicine on asbestos, specifically how its needle-like fibers stick to one other and to other materials to form aggregates. That got them thinking more generally about what determines the strength and stability of an aggregate.

The group took an experimental approach to answering this question by creating a simple model of particle aggregation. They suspended glass spheres of two sizes, 3 microns and 20 microns, in a droplet of water. (For reference, a human hair is roughly 50 to 100 microns in width.) As the water evaporated, the edges of the droplet retreated, dragging the particles inward. Eventually the shrinking water droplet transformed into multiple smaller droplets connected by a thin water bridge, known as a capillary bridge, before that too evaporated.

The team found that the extreme suction pressures caused by evaporation pulled the small particles so tightly together that they fused together in the capillary bridges, leaving behind solid bridges between the larger particles, to which they also bound, once the water evaporated completely.

When the team rewet the particles, applying water in a controlled flow, they found that aggregates composed solely of the 20 micron particles were much easier to disrupt and resuspend than those composed of either the smaller particles, or mixtures of small and larger particles.

"We found that if aggregates composed of only particles larger than 5 microns were rewet, they collapsed," Jerolmack says. "But under 5 microns, nothing happens, the aggregates were stable."

In further tests with mixtures of particles of four different sizes—more closely mimicking natural soil composition—the researchers found the same bridging affect occurring at different scales: The largest particles were bridged by the second largest, which were in turn bridged by the third largest, which themselves were stabilized by bridges of the smallest particles. Even mixtures that contained only a small fraction of smaller particles became more stable thanks to solid bridging.

How much more stable? To find out, Seiphoori painstakingly glued the probe of an atomic force microscope to a single particle, let it set, and then quantified the "pull-off force" required to remove that particle from the aggregate. Repeating this for particles in aggregates of both big and small particles, they found that particles were 10 to 100 times harder to pull off when they had formed a solid bridge structure than in other configurations.

To convince themselves that the same would be true with materials besides their experimental glass beads, they performed similar experiments using two types of clay that are both common components of natural soils. The principals held: the smaller clay particles and the presence of solid bridges made aggregates stable. And the reverse was also true: When clay particles smaller than 5 microns were removed from the suspensions, their resulting aggregates lost cohesion.

"Clay soils are thought to be fundamentally cohesive," says Jerolmack, "and that cohesiveness has usually been attributed to their charge or some other mineralogic property. But we found this very surprising thing that it doesn't seem to be the fundamental properties of clay that make it sticky, but rather the fact that clay particles tend to be very small. It's a brand new explanation for cohesion."

These new insights about the contribution of particle size to aggregate stability open up new possibilities for considering how to enhance stability of materials like soil or cement when desired. "You could envision stabilizing soils before a construction project by adding smaller particles that help bind the soil together," Jerolmack says.

In addition, the production of a variety of materials, from medical devices to LED screen coatings, relies on thin film deposition, which the researchers say might benefit from the controlled production of aggregates that they observed in their experiments.

More information: Ali Seiphoori et al, Formation of stable aggregates by fluid-assembled solid bridges, *Proceedings of the National Academy of Sciences* (2020). DOI: 10.1073/pnas.1913855117

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