

What keeps sandcastles standing?

Any child playing on the beach knows that the physical properties of wet and dry sand are very different. Wet sand can be used to build sharp-featured sandcastles that would be unstable in dry sand. We have now quantified the effect of adding small quantities of liquid to a granular medium. Nanometre-scale layers of liquid on millimetre-scale grains dramatically increase the repose angle (the steepest stable slope that the substance can form) and allow the development of long-range correlations, or clumps.

Moisture-induced changes in granular media are primarily caused by adhesive forces associated with interstitial liquid bridges between grains. Such effects are significant in industries as diverse as pharmaceuticals, construction and agriculture. Liquid-induced forces also affect experimental studies of the physics of granular media^{1–4}. Previous studies of moisture in granular media have examined only relatively large quantities of water added to highly irregular, porous or water-soluble materials such as coal^{5,6}, sugar⁷, seeds or rock chips^{8,9}. The resulting data are difficult to analyse and do not aid understanding of the physics of wetted granular media.

We have studied the effects of the addition of small quantities of corn oil and vacuum-pump oil (which both have low vapour pressures) to spherical polystyrene beads, which are insoluble in these oils. We measured the angle of repose by the draining-crater method¹⁰, with varying draining apertures and liquid content. Our maximum liquid content, (40 times less than the minimum moisture content of previous studies) corresponds to a liquid coating thickness (t_{liq}) of less than 50 nm on the spheres. We found an enormous increase of the angle of repose (Θ_R) with t_{liq} (Fig. 1a). One surprising feature is that Θ_R seems to increase linearly with t_{liq} up to the point where clumping occurs. The results are independent of oil type and aperture (except for the largest t_{liq}), and Θ_R at $t_{liq}=0$ agrees with previous measurements by this method¹⁰.

In dry sand, Θ_R is determined by the shape of the grains and by the friction forces. In wet sand, the attractive forces due to interstitial liquid bridges increase the stability of the

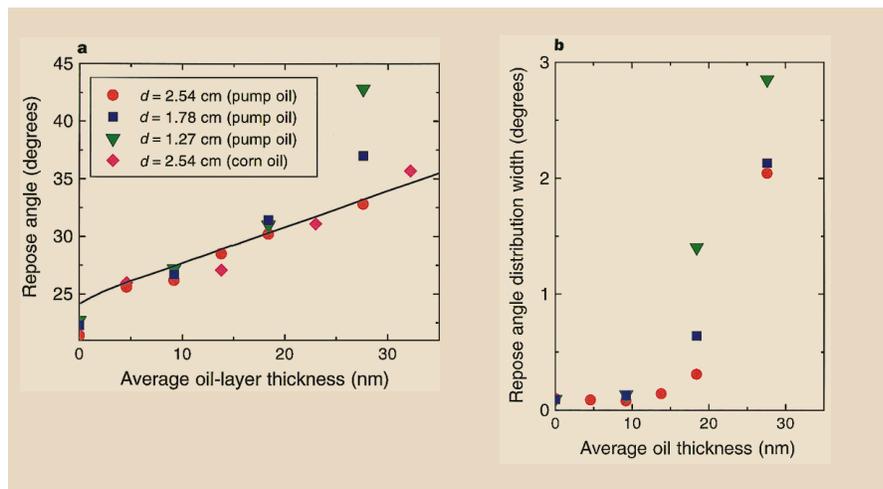


Figure 1a, The angle of repose (Θ_R) as a function of the average liquid-layer thickness on spheres (750 g samples, sphere diameter 0.8 ± 0.2 mm). Draining apertures, d , are listed. Data have been corrected for changes in relative humidity (40–50%) which had a small ($\sim 1^\circ$) effect on Θ_R . Experimental uncertainty is thus roughly 1° . Solid curve, one-parameter theoretical fit. Deviation from the theoretical values for small apertures and large t_{liq} , is due to clumping. **b**, The distribution width of measured Θ_R as a function of pump-oil layer thickness. Width corresponds to variations in roughness of the crater surface, which increases with cluster size, as seen with larger t_{liq} .

surface particles and hence Θ_R . Taking into account the observed surface roughness ($\sim 1 \mu\text{m}$) of the spheres, we calculated the interparticle adhesive force as a function of liquid content¹¹. We then calculated the angle of repose for the wet material using a method based on the stability of the surface particles¹². This model fits the data with a single free parameter corresponding to the volume of liquid in a typical bridge. The fit indicates that the typical volume of a liquid bridge is $\sim 3 \times 10^{-17} \text{ m}^3$ for our maximum t_{liq} , implying that 99.9% of the liquid does not contribute to the adhesive force, possibly because of the surface roughness.

As liquid was added to the spheres, correlated particle clusters (clumps) formed, the size of which increased with liquid content. The presence of such clusters leads to the appearance of an aperture dependence in Θ_R for the largest values of t_{liq} . The development of clustering is also shown by increases in the width of the distribution of values of Θ_R with increasing t_{liq} (Fig. 1b). The width corresponds to variations in the roughness of the crater surface (for $t_{liq} \geq 20$ nm the craters were noticeably asymmetrical whereas for smaller t_{liq} the surfaces were essentially conical with roughness equivalent to a few sphere diameters).

The development of such clusters appears to be rather sudden, suggesting a transition from a situation where the bulk properties are associated with the dynamics of individual grains to a situation where long-range correlations dominate. Our apparatus entirely failed to drain for larger

t_{liq} (≥ 40 nm) when the size of the clusters approached the aperture size.

Small quantities of wetting liquid can thus dramatically change the properties of granular media, leading to a large increase in the repose angle, clustering and correlation in grain motion. Our results indicate that interstitial liquids can alter many aspects of pattern formation, self-organization^{1–4} and segregation¹³ in granular materials, potentially leading to new physical phenomena not encountered in dry matter.

D. J. Hornbaker, R. Albert, I. Albert A.-L. Barabási, P. Schiffer

Department of Physics,
University of Notre Dame, Notre Dame,
Indiana 46556, USA
e-mail: peter.schiffer.1@nd.edu

- Jaeger, H. M., Lui, C.-H. & Nagel, S. R. *Phys. Rev. Lett.* **62**, 40–43 (1989).
- Alonso, J. J. & Herrmann, H. J. *Phys. Rev. Lett.* **76**, 4911–4914 (1996).
- Umbanhowar, P. B., Melo, F. & Swinney, H. L. *Nature* **382**, 793–796 (1996).
- Jaeger, H. M., Nagel, S. R. & Behringer, R. P. *Rev. Mod. Phys.* **68**, 1259–1273 (1996).
- Standish, N., Yu, A. B. & He, Q. L. *Powder Technol.* **68**, 187–193 (1991).
- Wolf, E. F. & von Hohenleiten, H. L. *Trans. Am. Soc. Mech. Eng.* **67**, 585–599 (1945).
- Craik, D. J. & Miller, B. F. *J. Pharm. Pharmacol.* **10**, 136T–144T (1958).
- Fowler, R. T. & Wyatt, F. A. *Aus. J. Chem. Eng.* **1**, 5–8 (1960).
- Pilpel, N. *Manufact. Chem. Aerosol News* **41**, 19–22 (1970).
- Brown, R. L. & Richards, J. C. *Principles of Powder Mechanics* (Pergamon, Oxford, 1970).
- Eremenko, V. N., Nadich, Yu. V. & Lavrimenko, I. A. *Liquid-Phase Sintering* (Consultants Bureau, New York, 1970).
- Albert, R., Albert, I., Hornbaker, D. J., Schiffer, P. & Barabási, A.-L. *Phys. Rev. Lett.* (submitted).
- Makse, H. A., Havlin, S., King, P. R. & Stanley, H. E. *Nature* **386**, 379–382 (1997).

