Dissipation in quasistatically sheared wet and dry sand under confinement

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Abstract: *We investigated the stress-strain behavior of sand with and without small amounts of liquid under steady and oscillatory shear. Since dry sand has a lower shear modulus, one would expect it to deform more easily. Using a new technique to quasistatically push the sand through a tube with an enforced parabolic (Poiseuille-like) profile, we minimize the effect of avalanches and shear localization. We observe that the resistance against deformation of the wet (partially saturated) sand is much smaller than that of the dry sand, and that the latter dissipates more energy under flow. This is also observed in large-amplitude oscillatory shear measurements using a rotational rheometer, showing that the effect is robust and holds for different types of flow.*

Capillary forces between single grains are the cause of the stiffness of sculptured wet sand in a sand castle, as opposed to dry sand which can hardly or not support its own weight [1]. Not many studies, however, on the flow behavior of partially saturated sand have been undertaken yet. For dry sand, a major step for describing the rheological properties was the introduction of the Coulomb friction approach [2]. This relates the shear stress to the confinement pressure via a friction coefficient that depends on the dimensionless inertial number [3]. The inertial number is suited to characterizing the granular flow from void-hopping at low shear rates to inertial flight at high rates; it is given by the ratio of the inertial time scale (i.e., the shear rate) and the time scale of the rearrangement process. Wet (partially saturated) granular materials have been studied mostly in the geophysics literature since soils are a typical example of such a system. These materials are reported to exhibit a mixed behavior of elasticity, viscosity, and plasticity. In this paper we compare the properties in incipient flows of wet and dry granular materials. Partially saturated sand has a much higher yield stress (allowing the construction of a sand castle) and should therefore have a much higher apparent viscosity for slow flows [4]. For this reason, it is commonly believed that wet sand should show a larger resistance to flow, i.e., more viscous, than dry sand [5,6]. We will show, however, that in two very different setups, the energy dissipation, i.e., the viscosity of dry sand is larger than that of wet sand. We show that this is due to the fact that the adhesion between the grains decreases the confining pressure and hence decreases the flow resistance. Our sand was composed of glass spheres of diameter d=140–150μm, with and without additional deionizedwater. The content of water is defined as the ratio between the liquid volume and the volume occupied by the grains. We carried out experiments with the shear cell [7] and the granular material is put into this acrylic cylindrical cell (Fig. 1(a)). The sides of the cell are sealed with thin latex membranes of 300 μm, which are flat at the beginning of the experiment; we gently pour dry sand into the cell and tap and add sand until $\varphi=0.63$. The cell also is filled with wet sand with $0.01 \le \omega \le 0.3$ and $\varphi=0.63$. Chambers filled with water are attached to both sides of the cell, adjacent to the membranes. It is possible to inject and extract water into and out of the chamber through tubes via a syringe which is connected to spindles that can be moved with a step motor. The acrylic glass tube we used for this experiment has a length equal to its diameter L=D=24 mm. The deformation of the membranes is approximately parabolic and imposes a Poiseuille-like profile within the sample; thus, avalanching and arching can be kept to a minimum. Piezoresistive sensors measure the pressure chambers. A fixed quantity of water is then injected into or extracted from the adjacent chambers and the differential pressure $p_1 - p_2$ is measured. A family of differential pressure characteristics for increasing shear volumes is shown in Fig. 1(c). It is worth mentioning that for a given shear amplitude, the hysteresis loop is stable during as many cycles.

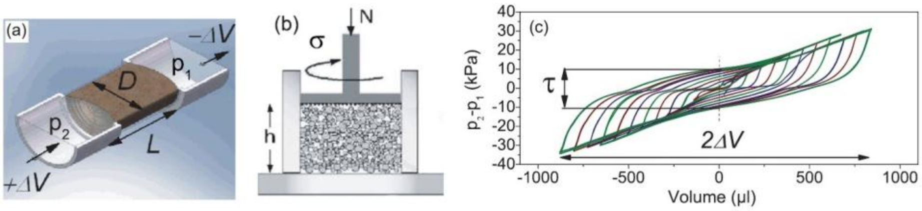

FIG.1. (a) Tube experiment's measurement cell containing granular matter (dark red),(b) Cup-plate rotational rheometric setup. (c) Differential pressure curves with increasing shear amplitudes for wet sand. The measured parameters for each curve are τ and ΔV .

The surprising conclusion from this series of experiments is that the wet sand flows more easily than the dry one. This is evident from the pressure-displacement curves shown Fig. 2(a). The area enclosed by the pressure/strain curve is directly proportional to the work done, i.e., the energy dissipated during the cycle [8]. Therefore for the same overall deformation, the dissipated energy is much smaller for the wet than for the dry sand. Fig. 3 shows τ vs. $\gamma_{\max}$; these measurements were done for samples prepared with different packing fractions and liquid contents w. For small deformations ($\gamma_{\max}$<0.1), we found the dry sand does not resist any stress to within the accuracy of the experiment. On the other hand, the wet sand behaves like a yield stress fluid due to the liquid bridge network [6,9].

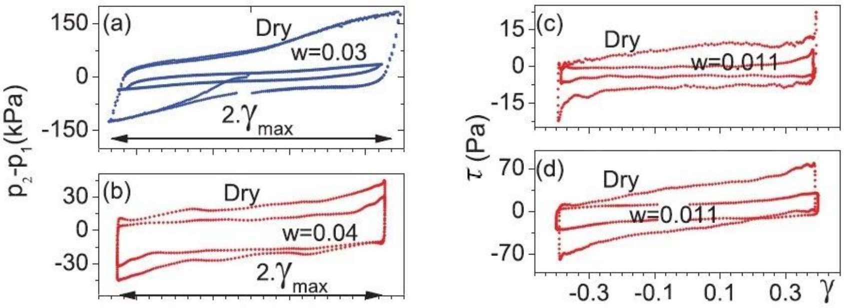

FIG. 2. (a) Differential pressure curves for dry and wet sand measured with the setup of Fig. 1(a). (b)–(d) Lissajous characteristics are shown for polystyrene beads with and without silicon oil under confinement measured with the standard rheometric setup of Fig. 1 for bead diameters (b)250, (c)500, and (d)140 μm.

For a better understanding of the results and to check their robustness, we performed a similar experiment in a completely different geometry. For this, we use a standard rheometer with a geometry that allows a test under confinement. We use a cup-plate geometry (Fig.1(b)) and study polystyrene spheres with different diameters, Dynoseeds, with and without additional silicon oil (*w*=0.04). We use silicon oil rather than water since the polystyrene beads are not wettable by water. The beads are poured into the cup of the rheometer (50 mm diameter and 5 mm bed depth) with a global packing fraction φ=0.63 (Fig. 1(b)). The rheometric equivalent of the differential-pressure displacement curves are the so-called Lissajous curves, where one plots the stress as a function of the deformation for a single oscillation cycle of the plate. Typical Lissajous characteristics are shown in Figs. 2(b)–2(d) for the dry and wet polystyrene beads. Figs. 2(b)–2(d) show that the stress-strain behavior is very similar to that observed in the tube experiment (Fig. 2(a)): again the wet sand flows more easily than the dry one. In addition these results show that this conclusion is general and does not depend on the size of the beads and the liquid content of the wet sand. The energy dissipated per unit volume in a single cycle, $E_d = \oint \sigma \, d\gamma$, can be visualized by the area enclosed by the Lissajous curves. Equivalently, when pushing sand through the tube, one can calculate the energy dissipated in a single cycle as the area of the differential-pressure curve loop. Fig. 3 shows the energy for deformations beyond the yield point for both experiments. The comparison of Figs. 3(a) and 3(b) shows that the results are very similar qualitatively, but that a quantitative difference occurs in the measured dissipated energy. The differences in order of magnitude for E_d between the two experiments can be understood from both the differences between the two setups and those between the granular media. The tube experiment is conceived in such a way that the deformation remains homogeneous throughout the sample.

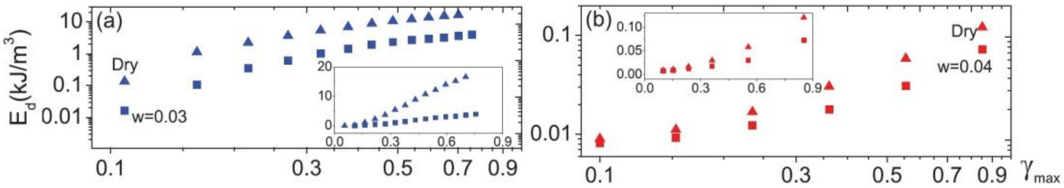

FIG. 3. Dissipated energy per unit volume vs strain amplitude: (a) for the range $\gamma_{max}>0.1$, calculated from the area of the differential pressure curve loop; and (b) integrating E_d from Lissajous loops for polystyrene beads. Squares represent wet sand, triangles dry sand. Insets: the same graphs in linear scale.

In the rheology setup, on the other hand, for the larger deformations there is undoubtedly shear localization (banding) which in general happens because this is the easiest way for the system to deform, i.e., the deformation that minimizes the dissipated energy. On the other hand, additional experiments for wet sand show that the opening of the loop τ varies inversely with the diameter of the beads and also depends on the surface tension. Thus, although the results from the two setups can only be compared in a qualitative manner, they do confirm the main result that the overall energy dissipation is smaller for wet than for dry sand.

Conclusion: we have found that it is much easier to push wet sand than dry granular matter in a Poiseuille-like profile through a tube. Even if the capillary forces increase the yield stress, the water promotes cluster formation and reduces effective intergrain friction, whereas for dry sand the yield stress is zero and a pure frictional behavior is observed. Finally we find indications that the yield of the system is related to the microscopic size of the grains.

References:

[1] D. Hornbaker, R. Albert, I. Albert, A. L. Barabasi, P. Schiffer, *Nature* **387**, 765 (1997).
[2] P. Jop, Y. Forterre, O. Pouliquen, *Nature* **441**, 727 (2006).
[3] F. da Cruz, *et al.*, *Phys. Rev. E* **72**, 021309 (2005).
[4] P. C. F. Moller, J. Mewis, D. Bonn, *Soft Matter* **2**, 274 (2006).
[5] A. Kudrolli, *Nat. Mater* **7**, 174 (2008).
[6] P. C. F. Moller, D. Bonn, *Europhys. Lett.* **80**, 38002 (2007).
[7] S. Herminghaus, Adv. Phys. **54**, 221 (2005).
[8] R. H. Ewoldt, P. Winter, J. Maxey, G. H. McKinley, *Rheol. Acta* **49**, 191 (2010).
[9] J. E. Fiscina, G. Lumay, F. Ludewig, N. Vandewalle, *Phys. Rev. Lett.* **105**, 048001 (2010).