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# Dissipation in quasistatically sheared wet and dry sand under confinement

J. E. Fiscina,[1,2,3,*] M. Pakpour,[4,5] A. Fall,[5] N. Vandewalle,[2] C. Wagner,[1] and D. Bonn[5,6,†]
[1]*Experimental Physics, Saarland University, D-66123, Saarbrücken Germany*
[2]*GRASP, Physics Department B5, University of Liège, B-4000 Liège, Belgium*
[3]*Gravitation Group, Tata Institute of Fundamental Research, 1 Homi Bhabha Road, 400005 Mumbai, India*
[4]*Institute for Advanced Studies in Basic Sciences, P.O. Box 45195-1159 Zanjan, Iran*
[5]*van der waals-Zeeman Istitute, University of Amsterdam, Science Park 904, Amsterdam, the Netherlands*
[6]*Laboratoire de Physique Statistique de l'ENS, 24 Rue Lhomond, 75231 Paris Cedex 05, France*
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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.

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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, in spite of the fact that the handling and flow of granular materials are responsible for roughly 10% of the world's energy consumption [2] and in many cases the humidity in the air is sufficient for liquid bridges to form between sand grains. In addition, the few existing studies were done either in a rotating drum [3,4] or in standard rheometric setups [5], in which shear banding (localization) and avalanches will strongly influence the apparent rheology, and so it is not evident that results for a given setup can be translated to a generally applicable conclusion.

For dry sand, a major step for describing the rheological properties was the introduction of the Coulomb friction approach [6–8]. This relates the shear stress to the confinement pressure via a friction coefficient that depends on the dimensionless inertial number [9]. 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. This approach was applied successfully to different flow configurations [6]. However, it was realized recently that for describing the system near the jamming transition the model is too simple and therefore not applicable [10].

On the other hand, wet (partially saturated) granular materials have been studied mostly in the geophysics literature since soils are a typical example of such a system. Here, the characterization of flow properties is very different; these materials are reported to exhibit a mixed behavior of elasticity, viscosity, and plasticity. The system starts to flow when the externally imposed stress exceeds the interaggregate contact forces [11]. The mechanical properties at lower water content are determined by the liquid bridges between grains, and those at higher water content are determined by the flow of the liquid through the soil pores [12].

In this Rapid Communication we compare the properties in incipient flows of wet and dry granular materials near the jamming transition. 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 [5,13]. For this reason, it is commonly believed that wet sand should show a larger resistance to flow, i.e., more "viscous," than dry sand [14–16]. 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. We even think that these results explain why the ancient Egyptians poured water on the sand to facilitate the pulling of very heavy stone sculptures [17].

Our study was inspired by an apparatus invented by the authors of refs. [18–20]. Their work focused on the regime below the yield point; here we study the yielding behavior itself. Our "sand" was composed of glass spheres of diameter $d = 140$–$150\ \mu$m with and without additional deionized water. The content of water $w$ is defined as the ratio between the liquid volume and the volume occupied by the grains. We carried out experiments with the shear cell described in Refs. [18–20]. The use of this device makes it possible to shear the granular materials homogeneously over the sample volume. In short, the granular material is put into an acrylic cylindrical cell [Fig. 1(a)]. The sides of the cell are sealed with thin latex membranes of 300 $\mu$m, which are flat at the beginning of the experiment; we gently pour dry sand into the cell and tap and add sand until $\phi = 0.63$. The cell also is filled with wet sand with $0.01 \leqslant w \leqslant 0.3$ and $\phi = 0.63$. 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. The syringe pistons are connected to spindles that can be moved with a step

*j.fiscina@mx.uni-saarland.de
†d.bonn@uva.nl

 

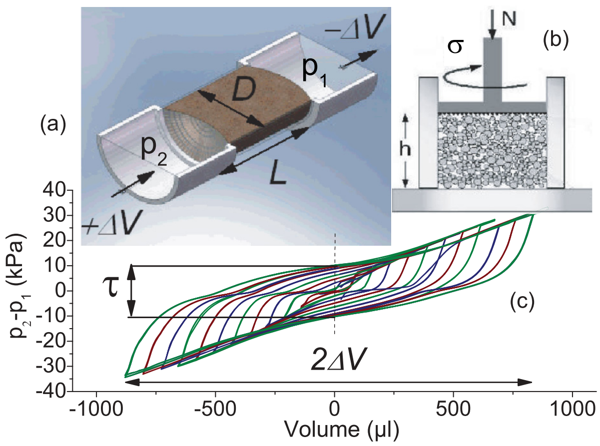


FIG. 1. (Color online) (a) Tube experiment's measurement cell containing granular matter (dark red); a volume change $\Delta V$ provokes a difference between $p_1$ and $p_2$, the pressures in the adjacent chambers; $D$ and $L$ are the cell diameter and length, respectively. (b) Cup-plate rotational rheometric setup. (c) Differential pressure curves with increasing shear amplitudes for wet sand. The measured parameters for each curve are $\tau$ and $\Delta V$.

motor. The pistons move at the same speed as each other but in the opposite direction. 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 (with respect to atmospheric pressure) in both 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 are shown in Fig. 1(c). It is worth mentioning that for a given shear amplitude, the hysteresis loop is stable during as many cycles. We carried out a few tests which were one week in duration and found that the opening of the loop for different shear amplitudes remains constant (we made sure that all our data were taken in such a steady-state situation). We also tested shear rates $\dot{\gamma}$ between 0.0002 and 0.1 s$^{-1}$ without observing differences in the hysteresis loop. The measured quantities for each differential pressure curve are the opening of the loop at zero shear $\tau$ (a measure of the yield stress) and the volume $\Delta V$. The imposed profile permits us to estimate the equivalent for the wall shear strain for the cylindrical cell as $\gamma_{max} = 32\Delta V/\pi D^3$ [21].

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 [22]. Therefore for the same overall deformation, the dissipated energy is much smaller for the wet than for the dry sand.

Figure 3 shows $\tau$ 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 [16,23].

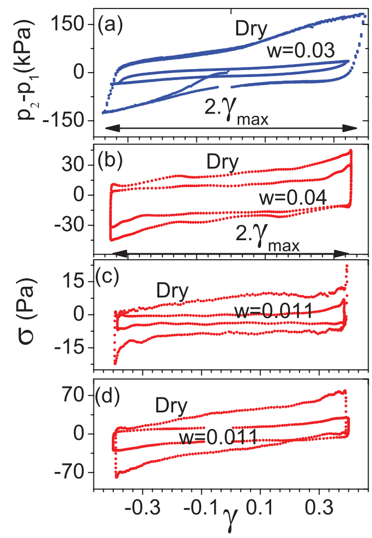


FIG. 2. (Color online) (a) Differential pressure curves for dry and wet sand measured with the setup of Fig. 1(a). In blocks (b)–(d) Lissajous characteristics are shown for polystyrene beads with and without silicon oil under confinement measured with the standard rheometric setup of Fig. 1 for bead diameters (b) 250, (c) 500, and (d) 140 $\mu$m. The liquid content $w$ indicates the wet loop. The strain amplitude $\gamma_{max}$ is indicated in (a) and (b).

Accordingly, the inset of Fig. 3 shows the range $\gamma_{max} < 0.1$, from which we get a mean value $\langle\tau\rangle = (1.2 \pm 0.4)$ kPa for the wet sand and $\langle\tau\rangle = (0.4 \pm 0.4)$ kPa for the dry sand. For the wet sand this value keeps constant in the range of existence of the liquid bridge network $0.01 \leqslant w \leqslant 0.03$; in good agreement with Ref. [24]. The onset of dissipative flow occurs for deformations larger than about $\gamma_{onset} \sim 0.1$ in all cases; this suggests that it is the size of the grains rather than the presence or absence of the network that sets this strain scale.

Further, $\tau$ grows more strongly for the dry than for the wet sand (Fig. 3), this means that one needs less energy to push the wet sand through the tube. To quantify this, we note that

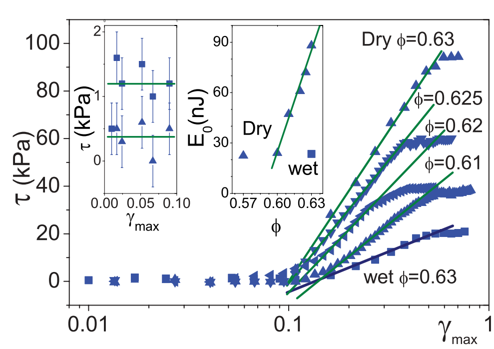


FIG. 3. (Color online) Studies with the tube experiment, $\tau$ vs $\gamma_{max}$ behavior and corresponding fit for the dissipative flow range for dry sand with different packing fractions $\phi$ and wet sand ($0.01 \leqslant w \leqslant 0.03$, $\phi = 0.63$). The inset shows the corresponding range $\gamma_{max} < 0.1$. The second inset shows the characteristic energy $E_0$ vs the packing fraction $\phi$ (triangles) compared with the wet sand (squares).

beyond the yield point in Fig. 3, the data show an exponential dependence of the deformation on the stress:

$$\frac{\gamma_{\max}}{\gamma_{\text{onset}}} = \exp\left(\frac{\tau}{\tau_0}\right). \tag{1}$$

A fit with Eq. (1), applied, for example, for dry and wet sand with $\phi = 0.63$, yields a constant $\tau_0 = 55$ and 14.7 kPa and onset values $\gamma_{\text{onset}} = 0.1$ and 0.14, respectively; with $\nu$ the volume of a grain, we define $E = \tau\nu$ and $E_0 = \tau_0\nu$, so it is possible to rewrite Eq. (1) as

$$\frac{\gamma_{\max}}{\gamma_{\text{onset}}} = \exp\left(\frac{E}{E_0}\right), \tag{2}$$

where $E_0$ is an intensive property of the granular assembly, which in a mean-field picture includes all the interactions and possible configurations of the grains [25]. From the fits we then find $E_0 = 88$ and 23 nJ for the dry and wet granulate with $\phi = 0.63$, respectively. It has been proposed [25–28] to interpret $E_0 = k_B\Theta$, a "noise temperature." It is difficult to estimate the value of $\Theta$ for dry sand since the energy loss is sensitive to, e.g., microscopic roughness and topology. We measure for increasing packing fraction $\phi$ a range of $\Theta$ until around 6 PK (peta Kelvin) as shown in the inset of Fig. 3, which is in agreement with previous measurements [26–28].

For the wet sand, $\Theta$ can be related directly to the liquid bridges. By considering the coordination number $N = 6$, the characteristic energy per bridge is $E_0/N = (4 \pm 2)$ nJ, which is in agreement with an estimate for the energy loss during bridge formation and rupture $\Delta E_{\text{cap}} < \pi\gamma_w d^2/2 = 2.4$ nJ [20,23].

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 $\phi \simeq 0.63$ [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. Figures 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. Figure 4 shows the energy for deformations beyond the yield point for both experiments. The comparison of Figs. 4(a) and 4(b) shows that the results are very similar qualitatively, but that a quantitative

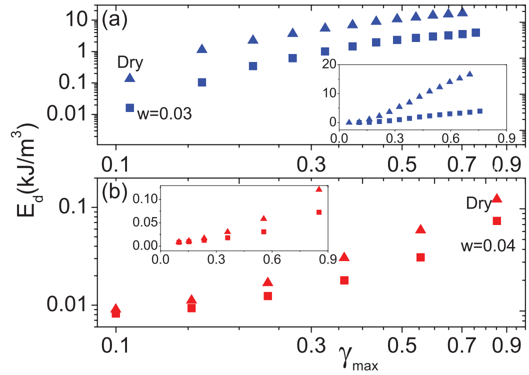


FIG. 4. (Color online) Dissipated energy per unit volume $E_d$ vs strain amplitude $\gamma_{\max}$: (a) for the range $\gamma_{\max} > 0.1$, calculated from the area of the differential pressure curve loop; and (b) integrating $E_d$ from Lissajous loops for polystyrene beads. In both figures, squares represent wet sand, triangles dry sand. The insets show the same graphs in linear scale.

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. 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 $\tau$ varies inversely with the diameter of the beads and also depends on the surface tension [18]. 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.

The question remains then, why is this so? One possible explanation is the following: the sand should behave as a frictional granular system in the regime beyond yielding. It is well known that for such systems, the shear stress under flow is directly proportional to the normal stress, i.e., the confining pressure. The capillary bridges are an adhesive force that hold the granular system together, and thus should reduce the tendency of the system to dilate under flow, thus reducing the confining pressure.

In the tube experiment a measure of the confining pressure is the mean value of the sum of the pressures at maximum shear $p = (|p_1 + p_2|_{-\gamma_{\max}} + |p_1 + p_2|_{\gamma_{\max}})/2$ is shown in Fig. 5(a). The advantage of the rheometric setup is that it provides us with a direct measurement of the confining pressure. In the rheology experiments, which were done at a fixed gap of the cup-plate geometry, the confining pressure is directly the normal stress measured by the rheometer during the deformation. Figure 5(b) shows the measured normal stress as a function of the deformation for dry and wet sand. It is evident that the normal stresses are much larger for dry sand: the dry sand is much more dilatant. This provides a direct explanation of why the wet sand flows more easily than the dry sand. Both systems

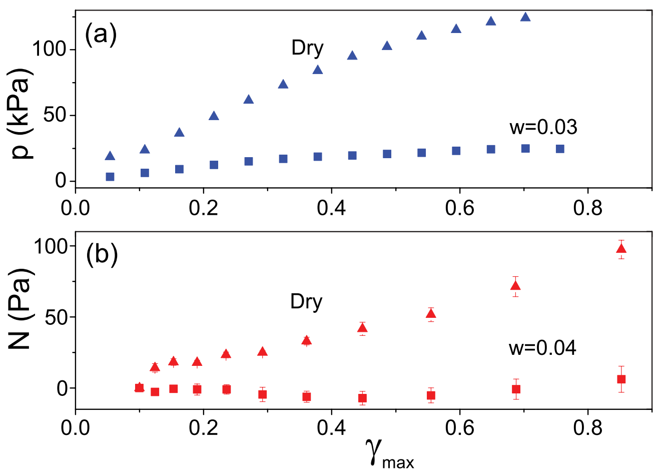


FIG. 5. (Color online) (a) Confinement pressure vs strain amplitude for the tube experiment. (b) Normal stress vs strain amplitude for the cup-plate rheometric setup.

are expected to have a friction coefficient that is constant and somewhat smaller than unity. Since the friction coefficient is nothing more than the ratio of normal to shear forces, for frictional systems, a smaller normal stress immediately implies a smaller shear stress, in line with the results presented above.

In 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.

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