Rheology of dry, partially saturated and wet granular materials
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Summary

This thesis is dedicated to the study of the *Rheology of Dry, Wet and Partially Saturated Granular Materials*. Granular media, suspensions, emulsions, polymers and gels are ubiquitous in the chemical and materials processing industry, and despite their very different appearance, the rheology and study of the behaviour of these materials is the key to the large-scale industrial production.

Granular materials are large collections of discrete particles. A granular material is called *dry* if the fluid in the interstices or voids between the grains is a gas, which is usually air. For dry granular media, the dominant interactions are inelastic collisions and friction, which are short range and non-cohesive. If the voids are completely filled with a liquid, the material is called a *saturated granular material*. If there is a liquid in some of the voids, and the rest of the voids are filled with a gas, the material is said to be *partially saturated*. Surprisingly, adding a small amount of liquid to granular matter transforms its properties because the liquid induces a cohesion between the grains. Cohesion in wet granular media arises from the surface tension and capillary effects of the liquid. The mechanical properties at low water contents are determined by the liquid bridges between grains, and those at high water content are determined by the flow of the liquid through the soil pores.

We aim here to study the behaviour of granular materials in different regimes of wetness. We have investigated the flow, stability, optimum strength, time reversibility and other rheological behaviour of these systems (dry, partially granular materials and suspensions) in different experiments.

In the first part of the thesis we study the behaviour of “dry and partially saturated granular materials”. To investigate their mechanical properties, we compared the rheology of wet and dry granular materials near the jamming transition for different sizes of the grains and different volume fractions. Our samples were composed of glass spheres of diameter $d = 140, 250$ and $500\ \mu m$ with and without small amounts of liquid. Partially saturated sand has a much higher yield stress and should therefore have a much higher apparent viscosity for slow flows. For this reason, it is commonly believed that wet sand should show a larger resistance to flow, i.e., more viscous, than dry sand. We found, however, that in two very different setups (a shear cell which quasi-statically pushed the sand and a cup-plate rotational rheometer applying large amplitude oscillatory shear), the energy dissipation of dry sand is larger than that of wet sand. So it is much easier to push wet sand than dry granular matter. We showed that this is due to the fact that the adhesion between the grains decreases the confining pressure and hence decreases the flow resistance. 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 in the absence of gravity and a pure frictional behaviour is observed.
In the next chapter, to obtain a deeper insight into the effects of liquid content on the stability of granular materials, we studied the stability of wet sand columns and the optimum strength of these systems. This allows, amongst other things, to predict the maximum height of a sandcastle. A column becomes unstable to elastic buckling under its own weight. To verify this experimentally, beach sand with an average radius of 100 \( \mu \text{m} \) was mixed with a small amount of deionized water. We found that the maximum height of the sand column, increases to the 2/3 power of the base radius of the column. Measuring the elastic modulus of the wet sand, we found the optimum strength of sand versus the liquid volume fraction.

In the second part of the thesis, we investigate the behaviour of completely “wet granular materials”, non-Brownian suspensions with different volume fractions of particles were studied in our measurements.

We find that the particle motion becomes irreversible when the particles are subjected to a large-amplitude oscillatory shear, when the deformation exceeds a critical value. The origin of the irreversibility is still debated. By a combination of MRI experiments and classical rheology, we uncover the origin of the irreversible behaviour in an oscillatory flow of granular suspension. These methods can probe the homogeneity of the suspensions and reveals an irreversible migration of particles from high-into low shear rate regions. Also we found that above a critical deformation, large normal forces appear in the suspensions. The onset of frictional behaviour can then account for the existence of such a critical strain as evidenced by the sudden increase in normal stresses that strongly depend on the volume fraction. Such contacts also lead to irreversibility in the motion of the particles, and in addition give a quantitative criterion for the onset of irreversibility that agrees with the experiments.

In the last chapter we study the rheology of dense suspensions of non-Brownian particles in a confined geometry under imposed gap. Dense suspensions exhibit a behavior known as shear thickening in which the viscosity jumps up dramatically. Measurements were performed with a rotational rheometer and a cup-plate geometry. The suspensions are made of spherical polystyrene beads with diameter 20 \( \mu \text{m} \) suspended in aqueous solutions. Our results show a transition at low shear rate from viscous to a shear thickening behaviour with shear stresses proportional to the shear rate squared, as predicted by a scaling analysis.