

# ANOMALOUS LOW FRICTION COEFFICIENT IN DENSE SUSPENSIONS

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**Summary** We study the friction coefficient of glass powders in water at low confining pressure, by measuring the pile slope angle in rotating drum flow experiments. We show that, at low rotation rates, the pile angle is about  $10^\circ$ , which is much lower than pile angles observed with larger glass beads in the same conditions ( $\sim 25^\circ$ ). Changing the pH or salinity of the suspension restores the classical high slope angle, suggesting that physical and chemical interactions between particles are responsible for this observation. This result supports a recent scenario for the shear-thickening transition in such non-Brownian systems, where interparticle repulsive forces suppress friction at low confining pressure.

## INTRODUCTION

Shear-thickening consists in a brutal increase in the viscosity of a dense suspension when the shear rate exceeds a critical value  $\gamma_c$ . The most famous example is a suspension of cornstarch in water. This phenomenon was first mentioned by Freundlich and Roder [1] in 1938 but remains ill-understood despite numerous studies. Recently, theoretical and numerical works [2, 3, 4] have proposed a new scenario for shear-thickening in non-Brownian suspensions. They suggest that it is due to a frictional transition induced by a repulsive force between the suspended particles. According to this model, at low confining pressure, repulsive particles should be nearly frictionless.

Testing this scenario would require to measure the friction coefficient  $\mu_p$  between the grains in a suspension. However, this quantity is very difficult to obtain in classical rheological measurements using neutrally-buoyant suspensions. In this study, we use non-buoyant suspensions to indirectly measure  $\mu_p$  through the pile slope angle  $\theta_s$  in rotating drum flow experiments. In the quasi-static regime,  $\theta_s = \arctan(\mu)$ , where  $\mu$  is the macroscopic friction coefficient of the suspension, which itself depends on  $\mu_p$  [5]. Therefore, measuring the pile slope angle  $\theta_s$  should grant access to the interparticle friction at very low confining pressure ( $P \sim \rho_p g d$  where  $\rho_p$  is the grains density and  $d$  their diameter). For repulsive particles and small enough  $d$ , we expect the pile angle to reflect the low frictional state of the system.

## PROTOCOL

We studied the friction properties of glass powder in water. Glass in water is known to have a negative surface charge [6, 7], which should give rise to a repulsive force between the grains. We used small glass spheres, of diameter  $d$  such that  $20\text{ }\mu\text{m} \lesssim d \lesssim 40\text{ }\mu\text{m}$ , immersed in microfiltered deionized water. Larger glass beads ( $d \sim 500\text{ }\mu\text{m}$ ) were also used as a standard granular suspension. For such large beads, the repulsive force is negligible compared to their weight, thus they should flow in a frictional state. The plexiglass rotating drums (diameter  $D = 1.2\text{ cm}$  and width  $W = 3\text{ mm}$  for the glass powder,  $D = 6\text{ cm}$  and  $W = 8\text{ mm}$  for the large beads, figure 1 a) are fixed on a vibration free rotating table controlled by a computer. The angular speed  $\omega$  of the drum can be varied from  $10^{-3}\text{ s}^{-1}$  to  $90^\circ\text{ s}^{-1}$ . Both the light source and the camera used to take pictures are disconnected from the table bearing the experiment so they do not cause interfering vibrations. We took care not to contaminate the drum or the mixture. Indeed, the presence of ions dramatically changes the behavior of the system, as we evidenced by conducting the same experiment in salty water ( $1\text{ mol L}^{-1}$ ) and in a  $\text{pH} = 10$  buffer solution. The experimental protocol was as follows: we rotated the drum at high speed ( $90^\circ\text{ s}^{-1}$ ) until the grains were suspended, then we set the angular speed to a chosen value. Time-lapse pictures were taken in order to determine the angle  $\theta$  of the grains-water interface and its evolution in time.

## RESULTS

Figure 1 b) shows the long time evolution of the interface angle  $\theta$  for small glass spheres in microfiltered water, in a slowly rotating drum. We observe a steady regime with a low pile angle:  $\theta_s \sim 10^\circ$ . This angle seems independent of the angular speed  $\omega$ , which suggests that it is the quasi-static pile slope angle of the suspension. To check the role of chemical and physical interactions between particles in this low angle, we changed the ionic force of the solution by adding salt or changing its pH. Figure 1 c) shows that in both cases, adding ions strongly increases the pile slope angle of the suspension to  $\theta_s \sim 25^\circ$ . This observation suggests that ions screen the repulsive force. The system thus transits from a frictionless to a ‘standard’ frictional granular medium. To test this hypothesis, we measured the pile angle of large glass beads of diameter  $d \sim 500\text{ }\mu\text{m}$  at an angular speed of  $5 \times 10^{-2}\text{ s}^{-1}$ . As we can see (orange line in figure 1 c), they flow with a large pile angle of  $\theta_s \sim 27^\circ$ ,

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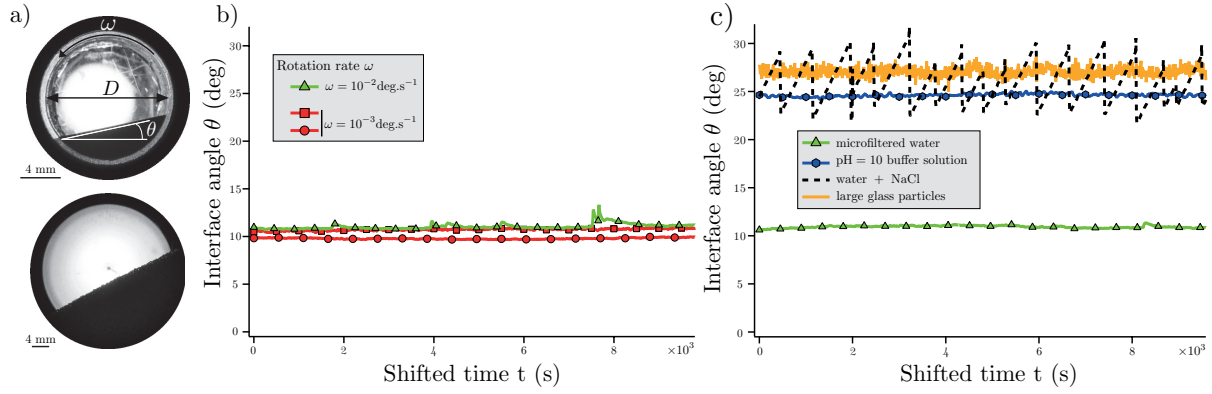


Figure 1: a) Pictures of the two rotating drums used in this study (top: for small beads, bottom: for large beads). Interface angle  $\theta$  versus shifted time  $t$ : b) small ( $20\ \mu\text{m} \lesssim d \lesssim 40\ \mu\text{m}$ ) glass beads in microfiltered water, comparison between two angular speeds, c) small glass beads in different suspending fluids and large ( $d \sim 500\ \mu\text{m}$ ) glass beads in microfiltered water. Time was shifted to simplify the presentation of the data, however this does not influence the discussion of the results.

which is close to that obtained with small beads in ionic solutions. This value is also compatible with previous experiments using large beads ( $d \sim 230\ \mu\text{m}$ ) [8]. This confirms our hypothesis: the small glass beads in microfiltered water are repulsive and subjected to a low confining pressure, therefore they flow with a low pile angle. The small beads in the buffer solution or in salty water, though subjected to a low confining pressure, are no longer repulsive because the presence of ions screens the repulsive force. The system thus becomes frictional. Finally, the large beads are forced into frictional contact by their weight, that overcomes the electric repulsion. They cannot be subjected to a low imposed confining pressure.

## CONCLUSION

By performing rotating drum flow experiments, we demonstrate the existence of anomalous low pile angles of about  $10^\circ$  in suspensions of glass microspheres immersed in pure water. This is much lower than the pile angles observed in classical granular media and indicates an almost vanishing interparticle friction in these systems for low confining pressures. Modification of the ionic properties of the solution suggests that such a frictionless state arises due to short-range repulsive forces between particles that overcome the self weight of the first layers of beads.

This observation gives a first support to the recent scenario for the shear-thickening transition in non-Brownian suspensions, based on a frictional transition induced by short range interparticle repulsive forces. What remains to be asserted is that the glass powder suspension used in this study does shear-thicken in classical rheological configurations, as previously suggested [9]. It will also be interesting to adapt the rotating drum set-up to cornstarch suspensions, to see if a frictional transition occurs in this emblematic shear-thickening medium.

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