Title: Effect of moisture on the flowability of non-cohesive granular materials

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The objective of the project is to quantify the effect of moisture on the flowability of a granular material.

For the engineering design of a storage unit, e.g. silo, bin or hopper, the Jenike criterion [1] of flow-no flow is widely used. It requires the knowledge of "flow factor" and "flow function" of a material to determine the critical outlet dimension of the storage unit. The flow factor depends on the geometry of the silo or hopper and the flow function is obtained from the yield locus of the material. We have studied the effect of moisture on the yield locus of the powder.

In case of wet granular materials the presence of moisture introduces capillary forces. If there is no geometric ordering of the system, Rumpf [2] has shown that these capillary forces introduce an isotropic compressive stress or isostatic tensile stress (ITS) into the system. The yield locus of a wet material is shifted to the left of that of the dry specimen by a constant value equal to the compressive isostatic stress due to pendular bridges. When the yield locus is approximated by a straight line, the shift of the yield loci is found to be : $\Delta\sigma = \Delta T(1+\sin\phi)/2\sin\phi$; where ΔT is the difference between uniaxial tensile strengths of the two samples and ϕ is the angle of internal friction.

We used a simple shear tester (similar to one used by Hiestand [3] for the testing of pharmaceutical powders) to determine the yield locus and a Parfitt tensile tester for the tensile strength measurements. Tensile strength data can be then combined with the yield locus to obtain a better understanding of the flow characteristics of a powder.

The tensile strength test will be useful only if it is carried out at the same bulk density as in the shear test. For bulk density measurements, the sample was consolidated in the shear tester and travelling vernier calipers were used to measure the thickness of the bed. From the volume and weight of the bed, the bulk density of the sample was calculated. For the tensile strength test, the powder was compacted to a known height in the Parfitt tester to obtain the same bulk density as in the shear test and the maximum force required to fracture the sample was measured.

Shear tests conducted on glass beads (93 μm and 180 μm has shown that the shift theory holds well. Glass beads represent an "ideal" system due to the spherical shape and a narrow distribution of size of the particles. The shift theory was also tested using other powders. Test were performed on crushed limestone with sieve size 88 μm- 180 μm, Super D catalyst, 104 μm in diameter and Leslie coal with sieve size 88 μm- 212 μm in order to determine the yield locus of the dry material. Experiments were also conducted on samples at different moisture contents.

The yield loci for the dry and the wet material were drawn on the same graph. It was found that, for the dry glass beads, consolidation had no significant effect on the shear data. The consolidation had modest effect on the yield loci of the wet glass beads (Figure 1). For the other three powders, yield loci were obtained at a consolidation pressure of 28.8 g/cm^2. The yield loci were nearly parallel to each other and the horizontal distance between them was almost constant over the entire range of normal stress (see Figure 2 for the yield loci of the dry and the wet samples of crushed limestone). For Leslie coal, the curvature was more pronounced at the low values of the normal stress.

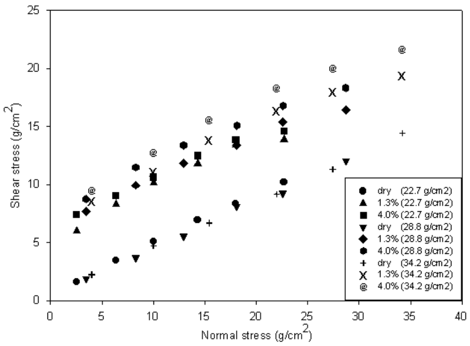

Figure 1: *Effect of consolidation pressure on the yield locus of glass beads (93 μm).*

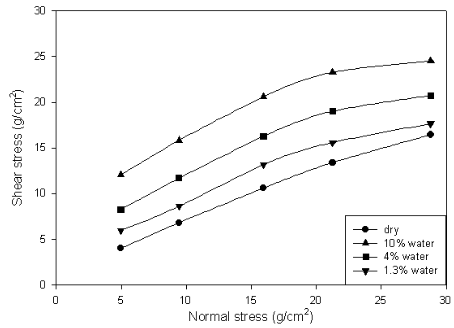

Figure 2 : *Dry and wet yield loci for crushed limestone.*

The separation distance between the dry yield locus and the wet yield loci was measured and above relation was used to predict the shift. Both values are reported on Figure 3 for comparison sake. The line drawn is where the measured and the predicted shift are equal and the agreement is fairly good.

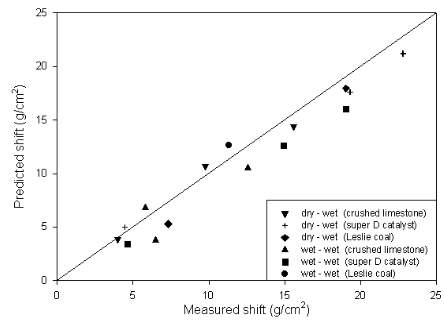

Figure 3 : *Measured shift versus predicted shift between the yield loci for samples wetted with water.*

The above relation assumes that the angle of internal friction does not vary when the moisture content of the material is changed. This appears to be the case for the materials studied, glass beads, crushed limestone, super D catalyst and Leslie coal, powders that do not show tensile strength when dry but may not apply to other materials.

The flow of granular material in a vertical hopper was also studied. Experiments were carried out in a silo of 12 cm diameter with the discharge diameter of 2.54 cm. Glass beads of 2.54 mm diameter were used. Four layers of colored glass beads were introduced as trace particles. The material was discharged slowly. A solution containing 1.5% agar and 0.03% sodium azide was poured into the silo after the discharge and left for solidification.

Table 1 shows the volume of glass beads discharged at the trace layers. It can be seen from the table 1 that there was an expansion wave propagating upwards in the silo. This expansion effect was also seen when glass beads were wetted with water.

	Position of the trace layer before discharge(from bottom), cm	Volume discharged, cm^3
Dry glass beads (2.54 mm)	10.00	46
	10.75	59
	14.00	98
	14.75	110
0.6 mm water / 100 g of glass beads (2.54 mm)	10.10	45
	10.90	70
	13.80	96
	14.55	104

Table 1: *Slow discharge of glass beads from a silo.*

References:

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[2] Rumpf H., in Knepper W. A. (Editor), *Agglomeration*, p. 379. Interscience 1962.
[3] Hiestand E. N., Valvani S. C., Strzelinski E. P. and Glasscock J. F. Jr., *J. Pharm. Sci*., 62(1973), pp. 1513-1517.

Publication:

Pierrat P., Agrawal D. K. and Caram, H. S., *Powder Technology (under review).*