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Annual Report

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SUMMARY OF TECHNICAL PROGRESS:

ABSTRACT:

The strain-stress behavior of a wet granular media was measured using a split Parfitt tensile tester. In all cases the stress increases linearly with distance until the maximum uniaxial tensile stress is reached. The stress then decreases exponentially with distance after this maximum is reached. The linear region indicates that wet solids behave elastically for stresses below the tensile stresses and can store significant elastic energy. The elastic deformation cannot be explained by analyzing the behavior of individual capillary bridges and requires accounting for the deformation of the solids particles. The elastic modulus of the wet granular material remains unexplained.

Introduction:

Figure 1 shows the tensile stress measured in a Parfitt tester against the displacement for 93-micron glass beads with 4% wt. moisture content. As can be seen the force required to pull apart the sample increases with distance to reach a maximum at a separation of about 200 microns or two particle diameters. Figures 2 and 3 show the distance/diameter to a maximum stress for a variety of materials, particle sizes and moisture contents. In all cases a similar pattern is observed, when stretching, with a linear region to the maximum stress followed by an exponential decay of the stress. The objective of this part of the research was to explain and analyze the elastic behavior of the wet granular material on a fundamental basis as it has been done with other mechanical properties. This elastic behavior is unexpected, and difficult to explain quantitatively.

The basis of the cohesive behavior of wet solids is the attractive forces due to the presence of capillary bridges, of a liquid with surface tension a and contact angle d , as the one shown in Figure 4. The force exerted on the particles is, following the notation of Figure 4 [Reference 4], given by:

$$F = a d \left[p \sin(q) \left(\sin(q + d) + \frac{\sin(q)}{4} \left(\frac{1}{r_1^*} - \frac{1}{h^*} \right) \right) \right] \quad (1.1)$$

where the starred variables are given by:

$$h^* = \frac{\sin(q)}{2} + r^* (\sin(q + d) - 1)$$
$$r^* = \frac{1 - \cos(q) + a/d}{2 \cos(q + d)} \quad (1.2)$$

Based on the moisture content it is possible (as discussed in reference [1]) to determine the bridge volume and the filling angle q . It is also easy to show that the filling angle is not sensitive to the separation a between particles as is shown in Figure 5. For a constant filling angle equation

1.1 is plotted in figure 6 for different filling angles and it shows that the value of the interparticle force decreases monotonously with the particle separation a . This is not what the experiments show, with the tensile stress going through a maximum. Several explanations were tried here. The most obvious was to assume that the bridges are not aligned with the direction of displacement as with a combination of vertical and horizontal bridges as is shown in Figure 7. As particle are displaced orthogonal to the vertical bridges the horizontal component goes through a maximum as shown in Figure 8. The maximum, however, takes place at shorter distances than those measured and there is no obvious maximum when the combination of horizontal and vertical bridges is considered. If it is assumed that this model applies to the region after the maximum has been reached it can be seen in figure 9, the decay of the stress is too rapid to justify the model.

The deformation of the solid:

It is also possible that the elastic behavior of the solid is responsible for the elastic energy accumulated. If the solids were elastic, the first part of the deformation would be the unloading of the elastic forces mobilized by the capillary forces as shown in Figure 9. An attractive force F between two elastic spheres, as is shown in Figure 10 will displace the centers toward each other by a relative distance $2c/d$ given by [see reference 2]:

$$\frac{c}{d} = \frac{1}{2} - \left[\left(\frac{1}{2} \right)^2 - \left(\frac{3F}{8d^2} \frac{1-u^2}{E} \right)^{2/3} \right]^{1/2}$$

Where E and ν are the Young modulus and the Poisson coefficient, respectively. If we substitute the capillary force given by equation 1.1 we can obtain the deformation of the material and the distance traveled for the Parffitt tester. The total distance is obtained by multiplying twice the fractional distance by one half the diameter of the enlarged cell (inside diameter 81 mm, height 25 mm) described by Pierrat [3]. Notice that to compute the displacement all of the particles should be unloaded, while for the breakage only one bridge will participate.

Typical values of the parameters of the equations ($\alpha = 0.72$ N/m, $\phi = 30^\circ$, $d = 0^\circ$, $\nu = 0.3$ and $E = 67,660$ MPa). Unfortunately, the deformation predicted is very small compared with the values measured in our experiments. A “fudge” factor of one thousand gives the “theoretical” values shown in Figures 2 and 3. For the large number of experimental conditions, particle sizes and fluids used the trends shown are correct but it is obvious that further work is needed to explain the large deformations observed. Other tests were carried out with fine, cohesive particles (such as starch) in a smaller Parfitt cell. For the instrument used the spatial resolution is estimated to be slightly below one micron. Breakage occurs within that short distance and the very elastic behavior observed in wet solids is not observed.

Future work:

We plan to investigate the effect of the split pillbox size on the measured deformation and compare the results with other methods used to measure the elastic parameters of a wet material. To return to the practical applications we have, earlier in the project, quantified the effect of the most important type of additives, the surfactants, in affecting the yield locus of the wet granular materials. The most dramatic effects, however, were those caused by components, such as silanes,

that render the surface hydrophobic. We will explore alternatives to the very expensive silanes used in our laboratory.

References:

- [1] P.Pierrat, D.K. Agrawal and H.S. Caram, Powder Technology, 99 (1998) 220-227.
- [2] Timoshenko, S. and J.N. Goodier, "Theory of Elasticity", McGraw Hill, New York, (1951), p. 372.
- [3] Pierrat, P., PhD Dissertation, Lehigh University, 1994.
- [4] Heady, R.B. and J.W. Cahn, Metall. Trans., 1 (1970) p. 185

Figure 1: Tensile strength vs. distance (93 micron glass beads, 4% moisture content)

Figure 2: Tensile strength times the diameter vs. the dimensionless distance (experimental and theoretical) for glass beads.

Figure 3: Tensile strength times the diameter vs. the dimensionless distance (experimental and theoretical) for various powders.

Figure 4: Liquid bridge between monosized particles.

Figure 5: Effect of the interparticle distance on the filling angle at fixed bridge volume.

Figure 6: Dimensionless Force (F/da) as a function of filling angle and interparticle distance (contact angle $d=0$).

Figure 7: Fracture plane showing the horizontal and vertical bridges.

Figure 8: Horizontal component of the force exerted by vertical and horizontal bridges as a function of the separation distance.

Figure 9: Comparison of the measured tensile stress normalized to the maximum value with the predictions from the horizontal vertical model.

Figure 9: The elastic force balances the external capillary forces and only when the material has been brought back to the original state the capillary forces can be measured.

Figure 10: Schematic of elastically deformed spheres.