Yield strength determination from slump tests

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In this work measurements of the final slump geometry are used to obtain accurate determinations of mud yield strength. The final profile of the mud deposit is captured using photography, and theoretical expressions are adjusted to the profile. Simultaneous measurements of mud yield strength using the proposed technique and a conventional vane rheometer showed very good agreement. Possible advantages of the proposed technique are presented and discussed.

Introduction

The slump test consists of filling a bottomless container resting on a horizontal plane, and lifting the container allowing the material to slump over the surface. The final shape of the deposit is then used to characterize certain rheological properties of the material. For example, the slump test is routinely done for fresh concrete quality control (ASTM, 2003); in this case, a standardized truncated cone without top or bottom is used. Similar tests are applied for quality control and sample comparison in the mining, food, and pharmaceutical industry.

The yield strength can be determined using conventional rheological equipment such as a cone or vane rheometer. However, these rheometers present limitations when used with highly heterogeneous materials (mixes of mud and gravel or shells, for example). Furthermore, rheometers are in general delicate pieces of equipment, which are not easy to carry into the field. The slump test based technique presented here may be useful for these particular conditions.

Theory

The material response to external forcing is determined by a constitutive equation that relates stresses with deformations and their rate. For example for a visco-elastic material, when a small shear stress τ is applied an elastic response of the material may be observed. However, when the shear stress overpasses a certain threshold, the material may respond as a viscous fluid. Similarly the material flow would stop if the shear stresses get below a certain threshold. Here these two thresholds are considered to be equal and are defined as the yield strength of the material (τ_Y). When τ is equal to τ_Y, the material is said to be on 'failure state'.

Murata (1984) proposed the use of the slump test to estimate τ_Y. The comparison of slump results from different materials and moulds is not easy to achieve. Some researchers (Roussel and Cousset, 2005; Balmforth *et al.*, 2006; Dubash *et al.*, 2009;) studied the dynamics of the movement and determined correlations among the deposit final shape, the material density ρ, and the yield strength τ_Y.

Near the end of the slump test, the accelerations of the material are very small and the quasi-equilibrium approximation may be applied. Assuming that the material is incompressible, that the solid plane over which the material flows is a slip plane, that a rotational symmetry solution exists, and that the material is at 'failure state' at every point, the shape of the deposit can be computed. Roussel and Coussot (2005) presented two asymptotic solutions, for when the slump height H is much larger/smaller than the slump radius R. On the other hand Dubash *et al.* (2009) used perturbation analysis to obtain an analytical expression for the final profile. The first order approximation of the profile is given by the following expression

$$h(r)^2 = \frac{2\tau_Y}{\rho g}(R-r), \quad (1)$$

where h is the height of the profile, g is the acceleration of gravity, and r is a radial coordinate. The small quantities H/R and $\tau_Y/\rho g H$ are assumed to be of the same order and are used as a single perturbation parameter in order to obtain higher order approximations to the solution.

Methodology and experiments

Restricting the analysis to zones where the final shape solution is applicable ($r >> h$), and excluding problematic regions (the centre of the 'cake' and the nose of the profile), it is possible to fit the observed geometry with the proposed theoretical profile given by Equation (1). This fitting allows to determine the ratio between τ_Y and ρ.

In order to obtain high resolution measurements of the final profile, the deposit was sliced over radials planes with a pre-wetted metallic plate, and the slump profile was captured using a 12.1 Megapixel digital camera (Panasonic Lumix DMC-ZR1). The images were rectified, and the profiles digitalized. A least squares fit of Equation (1) to the data was performed, determining τ_Y/ρ, and once ρ was independently determined, τ_Y was computed (Fig. 1). Several simultaneous yield strength measurements were performed using the proposed technique and a vane rheometer (Brookfield DV-III Ultra). Fig. 2 shows the obtained results for China clay.

Fig. 8. Photo of the slump test used to measure the final profile, original (left) and after rectification (right). On the far right a digitalized profile (o) and its least square fit (solid line) is shown over the selected zone (between the vertical dashed lines).

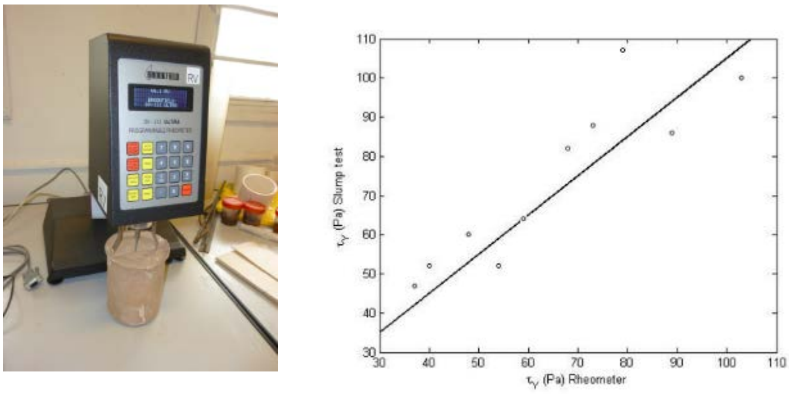

Fig. 9. On the left a photo of the rheometer is shown. On the right the comparison of both determinations of yield strength τ_Y.

Conclusions

The proposed technique is simple and could be used in the field to determine the yield strength *in situ*. The technique can be applied to non-homogenous materials, where the analysis of a large sample is needed in order to obtain a global measurement. The yield strength values determined using the proposed technique compared very well with the ones determined using a vane rheometer. The use of the deposit profile, instead of global dimensions like the total slump and/or the maximum radius, gives more accurate results and it is not affected by the roughness of the slip plane.

References

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