The “Fifty Cent” Rheometer-Effect of Slip, Speed of Lift and Stability on Measurement of Yield Stress

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ABSTRACT

Most researchers in the field of engineering accept the yield stress of a fluid as a useful engineering parameter. With the need for pumping and stacking mineral paste at higher concentration the focus has shifted towards its measurement. Since Pashias and Boger in 1996 first published the use of the 50 cent rheometer for measuring the yield stress on site, a number of authors have continued with this work. The slump cone originally developed to measure the workability of fresh concrete was the first of such measuring instruments. All the subsequent cones and cylinders including the cylindrical 50 cent rheometer have all been hand lifted. The Flow Process Research Centre at the Cape Peninsula University of Technology has developed a mechanical slump meter where the speed of lift can be controlled and lateral movements eliminated. Cones and cylinders made of stainless steel and PVC were fitted to the slump machine. In addition the 50c rheometer was also used. Tests have been conducted using laponite, kaolin and a mineral tailing with different concentrations to ascertain whether the speed of lift and slip has an influence on the value of the yield stress measured. The results from each test set are compared with each other, the standard vane test, and with three published predictive approaches. From the results obtained, no consistent trends can be identified and it would appear that hand lifting can produce adequate results.

1 INTRODUCTION

In recent years there has been much debate over the existence of the yield stress Barnes and Walters (1985). However, many researchers accept the yield stress as a useful engineering parameter, and focus has shifted towards its measurement (Murata, 1984; Schowalter and Christensen, 1988; Pashias et al., 1996; Jewell et al., 2002; Hallbom, 2005).

There are various ways in which the yield stress can be determined depending on the application. In civil engineering, the slump cone has long been used to establish the workability of fresh concrete (BS 1881: Part 102: 1983; AS 2701.5: 1984; SABS 862-1: 1994). The model used for measuring the yield stress from a conical slump was first published by Murata in 1984 and was later corrected by Schowalter and Christensen (1988). Pashias et al. (1996) adapted this for a cylindrical geometry and published their paper on the fifty cent rheometer. Using the cylinder, which could be a drink can, with cut off bottom and top, has since then been used successfully to determine the yield stress of paste-like suspensions (Schowalter and Christensen, 1988; Jewell et al., 2002; Hallbom, 2005).

The cones and cylinders used have, up to now, been lifted by hand, and the objective of this work is to assess the effect of this by controlling lift speed and eliminate lateral movement. The Flow Process Research Centre (FPRC) at the Cape Peninsula University of Technology has developed a mechanical slump meter to achieve this.

Different yield stress fluids have been tested in various size cones and cylinders, with different rates of lift. The yield stress values will be compared with those measured with a hand-lifted fifty cent rheometer, as well as the vane test. The slump meter will be described and initial results will be presented.

2 LITERATURE AND THEORY

In most comparisons found in the literature and where data are analysed the two main parameters namely yield stress and slump height are non-dimensionalised as follows:

$$s' = s/H \tag{1}$$

$$\tau' = \tau_y/\rho g H \tag{2}$$

where:

s' = dimensionless slump height.

H = height of cylinder (m).

τ_y = yield stress (Pa).

τ' = dimensionless yield stress.

ρ = density (kg/m^3).

s = slump height (m).

g = gravitational constant (m/s^2).

Pashias et al. (1996) adapted the analytical model which was developed by Murata (1984), which related yield stress to slump height for a cylindrical geometry. The relationship between dimensionless slump and dimensionless yield stress is as follows.

$$s' = 1 - 2\tau'_y\left(1 - \ln\left(2\tau'_y\right)\right) \tag{3}$$

The same authors provide an approximation of the above implicit equation, in terms of the dimensionless yield stress.

$$\tau'_y = \frac{1}{2} - \frac{1}{2}\sqrt{s'} \tag{4}$$

Halbom (2005) presented a semi-empirical model that extended the correlation range of the cylindrical model. This lump model uses the height of the lump (L) instead of the slump. The reasoning for using the lump height is that ‘it is conceptually easier because it trends in the same direction as most of the variables of interest’. That is, both shear and compressive yield stress increase with increase of lump. The author also mentions the fact that it simplifies the non-dimensionalisation when the container height is not used. Hallbom investigates the modification of the cylinder model by including the von Mises maximum-distortion energy yield criterion. The von Mises failure criterion is as follows:

$$\frac{\tau_y}{\sigma_{cy}} = \frac{1}{\sqrt{3}} \tag{5}$$

where σ_{cy} being the stress required to produce yielding along a shear plane due to an applied compressive force.

The lump model incorporating the von Mises failure criterion in dimensionless form is as follows:

$$\tau' = \frac{1}{2} L' e^{\sqrt{3}(L'-1)} \tag{6}$$

where L' being the dimensionless lump (L/H).

The lump model in dimensionless slump form in a similar form to the cylinder model is as follows:

$$s' = \frac{1}{\sqrt{3}} \ln\left(\frac{2\tau'_y}{1 - s'}\right) \tag{7}$$

When using a rotating cylinder geometry, slip is always an issue and that has led to the adaptation of a rotating vane device to measure yield stress (Keentok, 1982 and Nguyen and Boger, 1983). The vane consists of a number of blades attached at equal angles around a shaft. The vane is immersed in the fluid and the torque-time response is recorded. By fixing the rate of rotation, the torque-time curve for a yield stress fluid will show a definite peak after the linear elastic deformation region. (Nguyen and Boger, 1983). The yield stress can be determined directly from the maximum torque measurement and the vane dimensions as follows (Nguyen and Boger, 1992):

$$T_m = \frac{\pi}{2} d^3 \left(\frac{L}{d} + \frac{1}{3} \right) \tau_y \tag{8}$$

where:

T_m = maximum torque (N)

d = diameter of vane (m)

L = length of vane (m)

The point where the slump is measured is of vital importance because the top of the slumped material is not an even surface. Concrete slump measurements are taken at the highest point of the slump cone (SABS 1994). In the tests conducted by Pashias et al. (1996), the centre position of the slump cone height was measured. Gawu and Fourie (2004) use an average of the lowest three points of the slump cone.

These three models will be compared with the test data. The vane test has been extensively used in the paste and tailings industry to measure the yield stress, and is used as the reference standard (Barnes and Nguyen, 2001; Jewell et al., 2002).

3 EXPERIMENTAL PROCEDURE

3.1 Equipment

The slump meter was developed at the FPRC and is depicted in Figure 1. The gear drive ensures a constant lift speed which can be adjusted by a variable speed control. Lift speeds are between 4-30 mm/s. Another feature of the machine is that the lift motion is horizontally constrained by three vertical rods. This ensures that the lifting motion is perfectly vertical, and lateral movement is eliminated. One of the objectives of this research was to see whether the stability of the lifting motion had an effect on the yield stress.

The cylinder size is 100 mm diameter by 100 mm high. Two materials were used for the cylinders, namely stainless steel and PVC. The hand held slump meter is a stainless steel pipe of size 73 mm diameter by 75 mm high. Figure 1 depicts the slump meter.

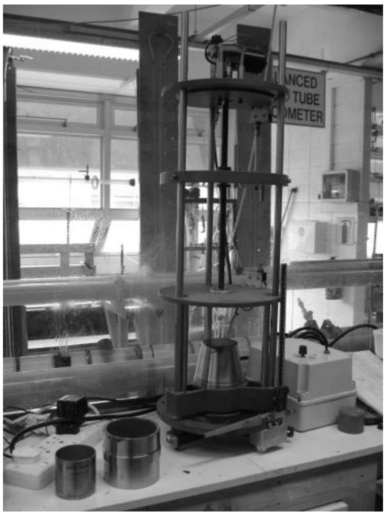

Figure 1 **The new slump meter with lift speed control**

For the vane tests a Paar Physica MC-1 rotary viscometer was used with a four bladed vane. The vane was inserted in a large container to eliminate end and side effects that may have occurred in a standard cylinder configuration. The rotary viscometer setup is depicted in Figure 2.

Figure 2 **Rotary viscometer with vane attachment**

3.2 Tests Conducted and Materials Used

The following materials were tested; kaolin suspension at 14, 16, 18 and 20%v/v; laponite suspension at 4, 5, 6 and, 7% v/v, and a mineral tailings at 20, 24, 27 and 30% v/v.

Each test consisted of 4 lift speeds using the PVC and stainless steel cylinder, the hand-held slump meter and the vane test. The slump was measured in the middle of the measuring device with a digital depth gauge to an accuracy of 0.5 mm. The lift speed was measured with a stop watch and depth gauge for every measurement over the lift distance which cleared the material.

Tests were conducted with dry surfaces as well as surfaces sprayed with a thin layer of silicon. This was to see whether the effect of slip could be established.

The slump height was measured at different positions on top of the slump cone to establish what the effect of height variation would have on the value of the yield stress.

4 RESULTS

4.1 Effect of Lift Speed

The lift speed in the range tested did not have a significant effect on the value of the yield stress. An example is given in Figure 3. The same trend was seen with most of the results. In some cases a slight downward trend in the slump height with lift speed could be seen but it was within the experimental error of measurement.

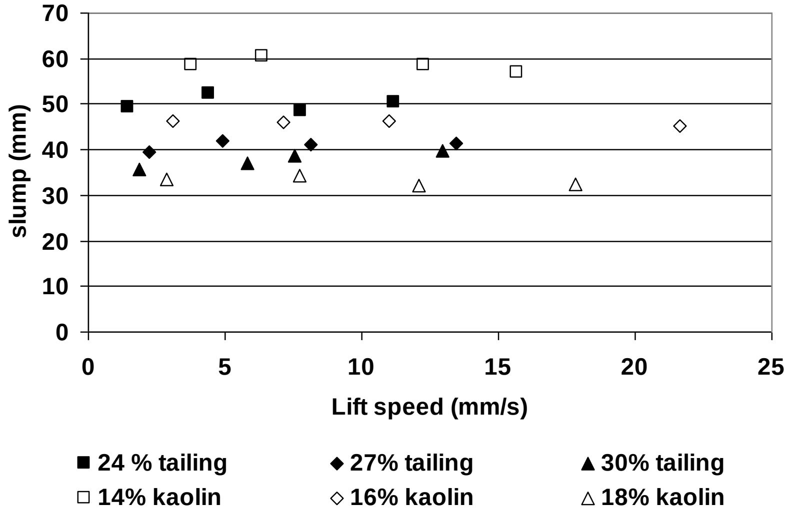

Figure 3 **Effect of lift speed on slump for stainless steel cylinder**

4.2 Effect of Slip and Slump Meter Material

In Figure 4, two material cylinders with and without spray are compared to try and evaluate the effect of slip. From the results (evaluated using the lump model) it seems that both cylinders with sprayed surface have a slightly higher yield stress value. It does not seem as though the material of construction matters. Values taken with the PVC and stainless steel cylinder are very close and no consistent trend is apparent. The error bars give an indication of variation between results with the vane test being the standard.

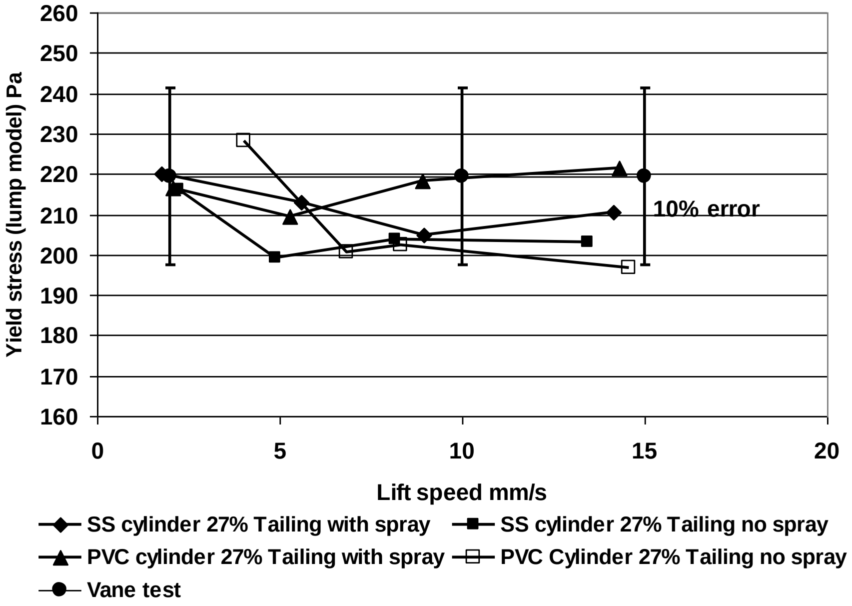

Figure 4 **Effect of spraying surface on yield stress**

4.3 Comparison of Models

In Figure 5, all the stainless steel data using the mechanical slump meter as well as the stainless steel hand held slump meter are presented for 27% kaolinite tailing. The three models discussed namely the approximate cylinder, exact cylinder and lump models are compared. As can be seen in Figure 5, at most lift speeds, the approximate cylinder model over predicts, and the exact cylinder model slightly under predicts the values of yield stress when compared to the vane test. In this test the hand held slump meter for the approximate cylinder is the closest to the vane tests. For most of the tests however the lump model was closer to the vane results than the other. The approximate cylinder results were always higher and the exact cylinder results lower that the lump model.

In Figure 6, the dimensionless yield stress obtained from the vane test for all the materials tested is compared to the dimensionless yield stress determined from the three models. The lump test equally over and under predicts the vane yield stress whereas the exact cylinder solution generally over predicts and the approximate cylinder generally under predicts.

In Figure 7, the dimensionless slump height is plotted against the dimensionless yield stress for the three models. Over the range of concentrations the lump model seems to predict the yield stress better than the cylinder model.

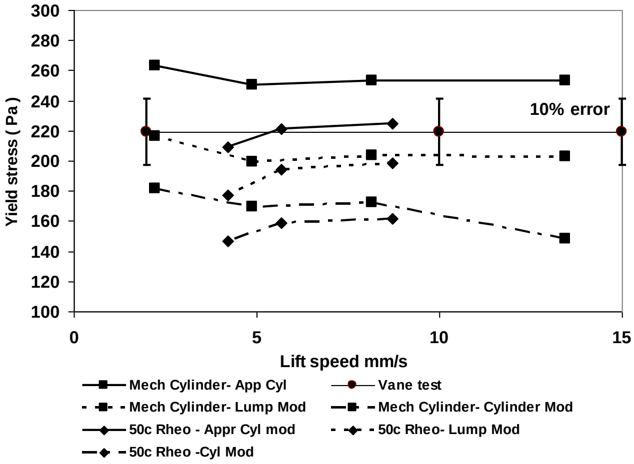

Figure 5 Vane measured yield stress compared with slump calculated yield stress

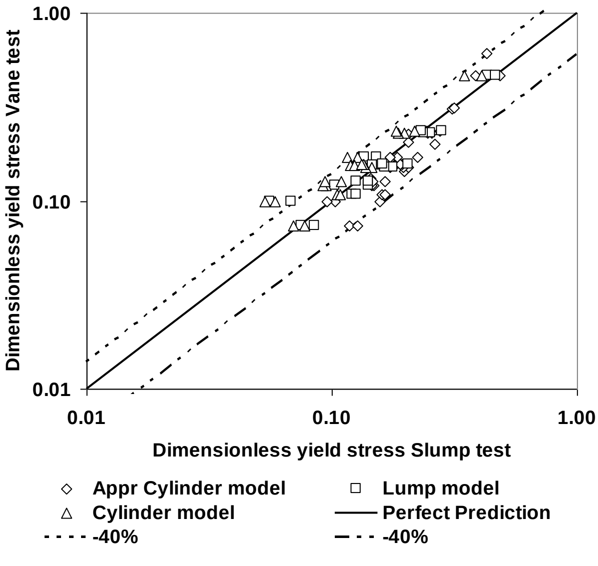

Figure 6 Vane measured yield stress compared with slump calculated yield stress

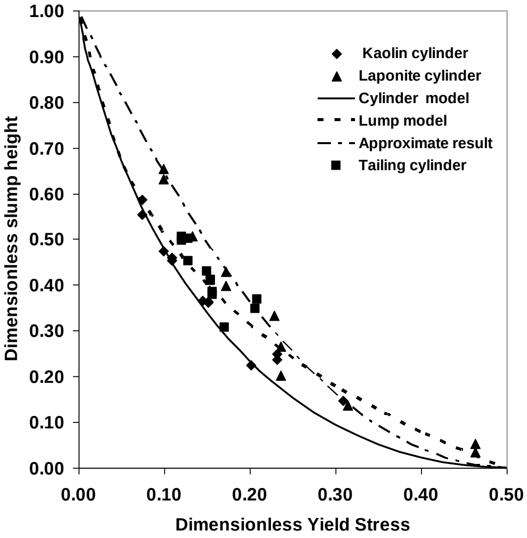

Figure 7 Comparison of different slump models with data

4.4 Effect of Position where Slump is Measured

The position where the height is measured on the slump cone does differ as was discussed in Section 2. The difference between the highest point and the lowest point measured can exceed 10 mm. A typical slumped cone using the kaolinite tailing is shown in Figure 8.

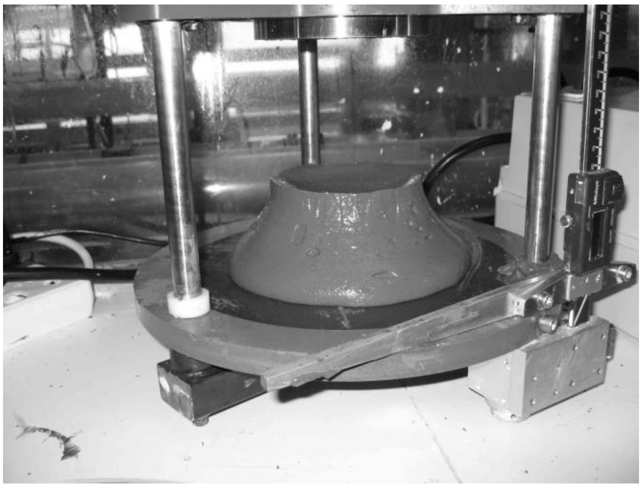

Figure 8 Typical slumped cone formed by kaolinite tailing

For the tests done in this project the middle of the cone was used. A few tests were done where the highest and lowest heights were measured.

A typical example is the 30 % kaolinite tailings where for the 100 mm cylinder the minimum value of slump was 38 mm and the maximum value 48 mm. This corresponds to a maximum yield stress of 278 Pa and a minimum of 238 Pa which is a difference of 17%. For the 22 % kaolinite tailing the difference was 24%.

5 DISCUSSION AND CONCLUSIONS

The effect of speed of lift is not conclusive. Within the accuracy of the experimental setup no effect of lift speed is discernable.

The effect of slip is also not conclusive. There are some indications that surfaces sprayed with a silicon spray produce slightly higher values than those without spray. This will have to be investigated in more detail.

Where the measurement of the slump height is taken on the slump cone can have a significant effect on the value of the yield stress calculated. A difference of 24% has been observed.

The effect of the model used however seems to have a greater effect. The lump model for most of the tests predicts the yield stress better over the range of materials and concentrations tested. The approximate cylinder model generally gives a higher yield stress value than the lump model and the full cylinder model a lower value. In some cases however the results could shift up or down slightly relative to what the value of the vane tests results are which was always taken as the reference. When compared with the vane test all three models predict the yield stress within 40%. There is no significant difference between the hand-held and the mechanical slump meters or whether the material used is PVC or stainless steel.

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