Low Shear Rate Rheology of Drilling Fluids

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ABSTRACT

The flow properties of drilling fluids at low shear rates are important in understanding hole cleaning and suspension characteristics. This paper discusses the evaluation of the flow properties of drilling muds and current approximations of the yield stress using the standard oilfield viscometer. Comparisons are made to results obtained with a controlled stress rheometer using non slip geometry.

INTRODUCTION

The principal device used for measuring the flow properties of drilling muds within the oil industry is the Fann® 35A viscometer, the two speed unit of which is 50 years old this year. Since design changes in 1955, the basic measuring principle and geometry has remained unchanged. The device is a couette style viscometer with a wide gap of 1170 micron and a rotating outer cylinder. The standard rotor and bob (R1/B1) combination have radii of 1.8415 and 1.7245 cm respectively, and the bob length is 3.8 cm. Spring stiffness was increased by 6% to account for any end effects on the flat bottomed bob and rotor.

Initially, two speeds of 600 rpm and 300 rpm were provided and the machine is designed so that the 300 rpm gives a direct reading of the viscosity of a Newtonian fluid in centipoise or mPa.s. The 600 rpm dial reading less the 300 rpm dial reading denotes the plastic viscosity and the 300 rpm dial reading less the plastic viscosity provided a value for the yield point of the mud – assuming the mud behaves as a Bingham plastic. (see Eq. 1.) σ_y is the yield stress and η_p the plastic viscosity.

$$\sigma = \sigma_y + \eta_p\dot{\gamma} \qquad (1)$$

This device was still the main instrument in field use throughout the industry even in 1973. Walker et al[1] amongst others, realised that data at lower rpm (and hence shear rate), could be used to improve the performance and understanding of drilling muds at the lower shear rates prevailing in the wellbore annulus. The laboratory 6 speed viscometer (600, 300, 200, 100, 6 and 3 rpm) slowly replaced the two speed field units during the next 10 years, while 8 speed viscometers (with 60 and 30 rpm control) are sometimes used offshore Norway.

The recognition that drilling muds were not ideal plastic fluids saw the introduction of the Power Law rheological model (Eq. 2.), principally to represent the rheology of polymeric muds such as xanthan-gum treated systems in the late 1960's, and then to annular pressure loss and hole cleaning predictions in the 1970's. K is the consistency factor and n is the consistency index.

$$\sigma = K\dot{\gamma}^n \qquad (2)$$

The desire for greater accuracy in pressure modelling and hole cleaning predictions in the late 1980's resulted from wells becoming deeper and more highly deviated. This, coupled with the advent of inexpensive computers, saw the industry adopt rheological models that could better describe the flow properties of drilling muds as measured on a Fann® viscometer. The most widely used currently are the Herschel-Bulkley (Eq. 3.) and the Robertson-Stiff[2] (Eq. 4.) flow models, although many others have been proposed as suitable and some may fit 6-speed data better than others.

$$\sigma = \sigma_0 + K\dot{\gamma}^n \qquad (3)$$

σ_0 is the Herschel-Bulkley yield stress.

$$\sigma = A(\dot{\gamma} + C)^B \qquad (4)$$

A and B can be considered similar to the power law parameters K and n. C is a fit constant. The term ($\dot{\gamma}$ + C) is the effective shear rate required for a power law fluid to produce the same shear stress.

The concept of drilling muds being plastic fluids that possess a yield point has become ingrained in the industry, probably due to both teaching methodology and the practical application of drilling fluids. Even today, many drilling mud products and systems are primarily evaluated and designed on the basis of their Bingham yield point. The Power Law concepts of K and n have appeared too abstract for use in anything other than pressure loss or hole cleaning modelling.

The adoption of the Herschel-Bulkley rheological model (commonly known as the power law with a yield stress) to describe drilling fluids, requires use of a non linear regression routine, which is not always available in the field. This model is nowadays often applied to the 6 speed (or if available), 8 speed viscometer values. It has been used by some to run and maintain drilling fluids in the field.

For all commonly used drilling fluids, this technique will provide a yield stress value which is obviously lower than the conventional oilfield yield point previously described.

Where this technique is not available, many use another approximation - originally called the Yz or low shear rate yield stress. The Yz is an approximation of a low shear rate yield stress obtained by multiplying the 3 rpm reading by 2 then subtracting the 6 rpm reading.

Recognising that both methods are approximations, a question has to be asked - "does the yield stress exist at all and if so, what are appropriate values for typical drilling muds?"

The existence of a real yield stress has been questioned by many authors in the field of rheology and the excellent review paper by Barnes[3] sums up the situation very well.

When we examine the oilfield method of measuring flow properties we realise that the curve fit technique utilises the data obtained on a down flow curve. The industry standard practice is to take viscometer readings at decreasing rotational speeds, starting at 600 rpm. This method recognises that mud systems in the annulus undergo a transition from a high shear rate region exiting the drill bit nozzles to a lower shear rate region in the annulus.

A mud sample undergoing testing can take several minutes for the viscosity to stabilise at a defined shear rate as drilling muds exhibit time dependency and so are thixotropic. Ground up rock fragments (often clays) will always provide this property to field muds even if initially solids free, and it can also be derived from certain additives and colloidal interactions.

Conventional Viscometer Data

Plotting Fann® data vs. shear rate requires knowledge of the shear rate at the particular rpm. (The industry has typically used Newtonian shear rate values).

Viscometer dial readings for an oil mud were plotted against rpm, Newtonian model shear rate, Power Law model shear rate, Bingham model shear rate, as well as the arithmetic and geometric mean shear rates proposed by Whorlow[4] for wide gap viscometers with time dependent fluids. (These are the first terms of the Mooney (Eq.5.) and Moore and Davies (Eq.6.) formulae

$$\dot{\gamma}_{am} = \frac{R_c^2 + R_b^2}{R_c^2 - R_b^2} * \Omega \qquad (5)$$

R_c is cylinder radius, R_b is bob radius and Ω is the angular velocity

$$\dot{\gamma}_{gm} = \frac{\Omega}{\ln(R_b/R_c)} \qquad (6)$$

Values for yield stress and n value obtained by curve fitting were identical (coefficient of r^2 – 0.9998) using rpm, Newtonian, Power law, Mooney or Moore and Davies shear rate values. The K values were respectively 0.209 $Pa.s^n$, 0.136 $Pa.s^n$ and 0.143 $Pa.s^n$ for both the Mooney and Moore and Davies equations. Use of the Bingham model shear rates in the viscometer gap however, gave a completely different curve fit result (coefficient of r^2 0.982), indicating that these shear rate values are not valid for this mud. By inference this demonstrates that use of the Bingham plastic model and therefore its yield point parameter is not justified.

An example of a best fit plot is given in Fig. 1, where the geometric mean shear rate of Moore and Davies is on the x axis. The Herschel-Bulkley model gave the best fit to the various shear rate values plotted on the x axis, apart from the Bingham shear rate.

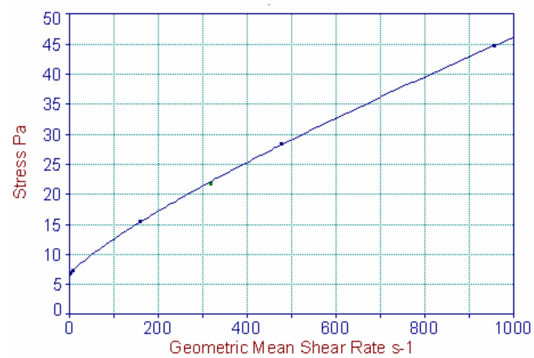

Figure 1: A typical data set from a 6 speed Fann® viscometer. The various parameters are: Yield Stress = 6.24 Pa; n = 0.814; K = 0.143 $Pa.s^n$; Yz = 6.22 Pa; Yield Point 12 Pa.

RHEOMETER EVALUATIONS

Drilling fluids taken from field locations were tested on a controlled stress rheometer (TA Instruments CSL[2]) fitted with non slip crossed hatch parallel plate geometry. This geometry and a brief description of the general composition of oil based drilling muds have been given elsewhere[5].

While up and down flow curves provide some evidence of thixotropy (Fig. 2), it is more easily seen by plotting stress vs. shear rate on log scales as seen in Fig. 3. This shows a good example of thixotropy in an oil mud. Note there is no information below ~ 0.1 s^{-1} and measurement in continuous flow mode ceased well before the stress resolution limits of the rheometer, perhaps due to insufficient angular resolution.

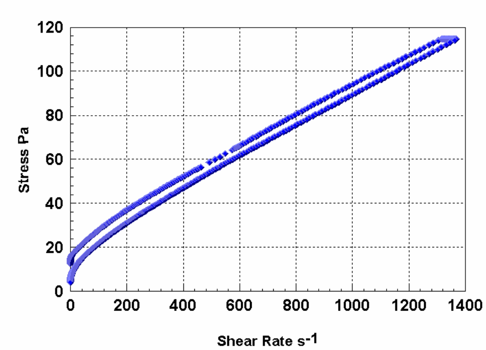

Figure 2. Slight Thixotropy in an oil mud

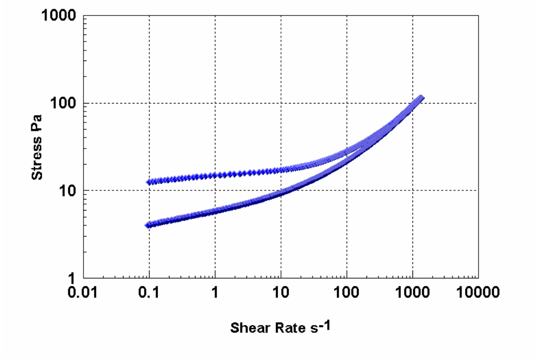

Figure 3. Up curve measurement commenced 10 minutes after shearing.

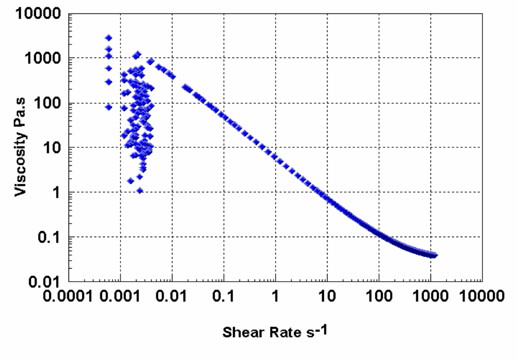

Figure 4. Typical down curve response from a stepped stress test

The use of stepped stress techniques provides a means of obtaining data at lower stresses and shear rates. Resolution can be obtained down to $1e^{-5}$ s^{-1} if care is taken in the experimental set-up, but the applied stress at the end of these experiments is usually well above the minimum the rheometer can apply in creep mode (→0.0283 Pa).

Further tests with the stepped stress technique applied to the downcurve over a data collection interval of one hour, show that oil mud systems begin to form a structure (gel) usually at shear rates between 0.01 and 0.001 s^{-1}. Over a long test period oil mud systems in particular, exhibit syneresis as they structure. The resulting film of oil at the sample surface results in a continuously decreasing viscosity as the (supposedly non slip) geometry slips. Fig. 4 shows a typical result with some of the data scatter removed for ease of viewing.

Stepped stress measurements can also be applied at low stress values and over a narrow range of stress. Fig. 5 shows the results after applying the same increasing stress after equilibrium times of 10 seconds, 10 minutes and 30 minutes to a typical oil mud. The scatter in the data is due to the cross-hatch geometry, but it is obvious that while the viscosity has increased as equilibrium time increases, the system starts to collapse at substantially the same stress.

Some regard the peak as the yield stress measured on the up curve.

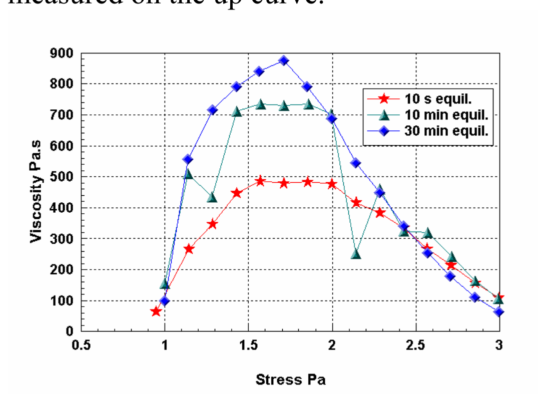

Figure 5. Viscosity responses for various applied stresses.

Plots of shear rate vs viscosity can be seen in Fig. 6. Initially, not all the networks in the system are disrupted by the increasing stress and viscosity increases as the systems continue to structure. At a high enough stress all networks collapse relatively quickly and a decrease in viscosity and an increase in shear rate are seen. Obtaining an apparent yield stress result depends both on the initial stress selected and the time scale of the experiment.

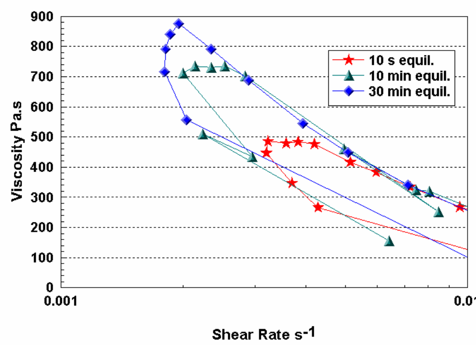

Figure 6. Apparent yield stress

Increasing temperature decreases viscosity and, as one would expect, also results in a decrease in the apparent yield stress. Knowledge of the temperature in the annulus relative to the measurement temperature is therefore quite important.

CREEP TESTS

A creep test run at stress values slightly above the apparent yield stress can still show slight viscoelastic behaviour similar to that seen in Fig. 7. This is probably due to the different time scales of each experiment and the actual values used for the time parameters within the stepped stress test. At slightly higher stress levels, viscoelasticity is not seen. The samples show no elastic recovery as flow is immediate. At certain stress levels some point below the yield stress, there is a significant increase in viscosity and decrease in shear rate values to <1e^{-4} s^{-1}. (Shear rates are derived from a Voigt analysis of the creep retard curves. The procedure is embedded in the rheometer software). Viscosities tend to approach a constant value at these very low shear rates, indicative of an upper Newtonian plateau.

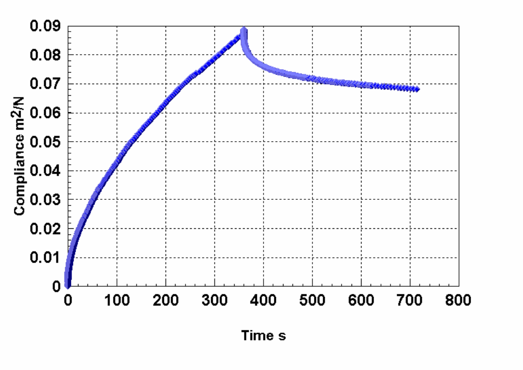

Figure 7. Typical creep response

It can be seen that only a partial recovery in the creep test implies permanent deformation and thus some flow has occurred. Analysis of the retard curve gave a Newtonian viscosity of 6770 Pa.s at a shear rate of 6.2 E^{-4} s^{-1}. Creep ringing analysis of this experiment gave an elastic modulus of 409.7 Pa.

In Fig. 8 the results of a stepped stress test on the upcurve showing a viscosity peak after an equilibrium period of one minute are plotted. The down curve data were obtained by reducing the stepped stress from 4 to 1 Pa. This followed pre-shear at 1000 s^{-1} for 5 minutes, a 5 second equilibrium period then a further 2 minute preshear at 150 s^{-1}. The two highest viscosity data points are from creep experiments. There is no obvious yield stress on this down curve.

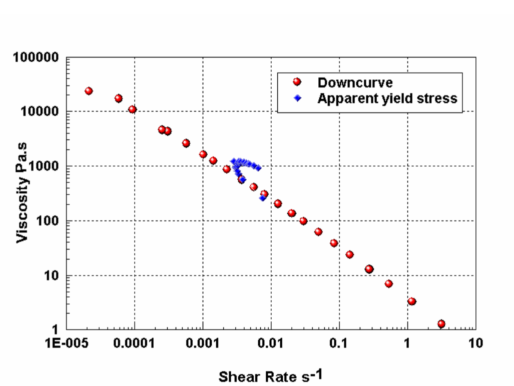

Figure 8. Comparison of stepped stress measurements on the down and up curves

COMPARISON OF DATA

A variety of oil and water-based muds have had their apparent yield stress measured by the stepped stress technique and the data compared to 6-speed viscometer curve fits and Yz values. These parameters were obtained on down curve data.

While this analysis has not been exhaustive, it is quite apparent that both curve fitting conventional viscometer data and the use of the Yz term can under or over predict the yield stress as seen with data in Table 1.

Table 1.
Comparison of oilfield yield point and approximate yield stress values to measured values. (all in Pa)

Term	A	B	C	D	E	F
YP	7.18	9.58	13.9	11.5	15.8	7.18
Yz	3.35	1.44	6.22	4.3	3.35	2.87
Ys CF	3.55	0.96	4.48	3.2	2.9	2.96
Ys M	1.72	0.82	3.9	2.6	3.9	4.1

CF is the curve fit value: M is measured.

RELEVANCE OF YIELD STRESS

During laminar flow in a wellbore annulus, the shear rate tends to be typically <100 s^{-1} at the wall and tends to zero in the centre of the annulus. While a Newtonian fluid exhibits a parabolic velocity profile, a Power Law fluid has a flatter profile. The extent of this flat or plug like region becomes greater the lower n becomes. As the shear rate is at a minimum in this area, the viscosity is also at a very high value compared to that at the wall. This is analogous to the large increase in viscosity found in creep tests as the stress drops below a certain value.

In a Herschel-Bulkley fluid the size of the flat plug like region is defined by both the n value and more importantly the yield stress. This zone with its low shear rates and extremely high viscosities thus dominates hole cleaning and so the effectiveness of the drilling fluid in use.

The downflow curve does not exactly describe the rheological state of flow in the annulus. Mud flow is stopped and re-started at intervals due to pipe connections. Therefore mud systems will have time to partly restructure during these periods of rest.

Use of the Herschel-Bulkley rheological model provided it fits a Fann® data set well enough, will provide more accurate results for pressure loss and hole cleaning calculations than either the Bingham plastic or Power Law models.

Based on the experimental data, the apparent yield stress could be described as the point where an applied stress is sufficient to disrupt enough networks for continuous flow to occur without any immediate elastic recovery should flow cease.

CONCLUSIONS

Curve fits of conventional viscometer data and the Yz term may overestimate or underestimate the upcurve apparent yield stress. Under estimates appear to be associated with muds that have very high concentrations of fine drill solids. Otherwise, these methods will always overpredict the apparent yield stress.

No drilling mud has yet been tested where the apparent yield stress exceeds 7 Pa. Most drilling muds will have apparent yield stresses <4.5 Pa.

The shear rate at which the apparent yield stress occurs is not zero, but in the region of $1e^{-5}$ to $1e^{-2}$ s^{-1} for typical drilling muds.

The industry places far too much emphasis on the Bingham yield point and should consider abandoning the concept of a Bingham plastic fluid for anything other than monitoring of the plastic viscosity.

Mud viscosities in parts of the annulus where shear rates are <0.01 s^{-1} are normally greater than 10^3 mPa.s, not the hundreds usually obtained by simple calculations that ignore the existence of the central plug.

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