Drilling Fluid Thixotropy & Relevance

Richard Jachnik[1],

[1]Baker Hughes INTEQ, Stoneywood Park North, Dyce, Aberdeen, Scotland, UK

ABSTRACT

Drilling fluid structure and time dependency is reviewed based on rheological data obtained with a controlled stress rheometer. So called gel strength measurements obtained with a standard oilfield viscometer will be discussed and the values obtained shown to be in part a function of the technique.

INTRODUCTION

As H. A. Barnes points out in his extensive review of the subject[1], there are several definitions of the word thixotropy, although he admits a better definition would be "the temporal rheological response of a microstructure to changes in imposed stress or strain rate".

Other definitions such as "the property of gels of showing a temporary reduction in viscosity when shaken or stirred" do not accurately describe the structural changes that can occur in colloidal mixtures while in flow and during the time of measurement.

The existence of thixotropy in drilling muds has been appreciated for a long time especially in early drilling muds that were primarily clay based. This lead to the use of oilfield "gel strength" measurements the idea's being based on the second definition given above. These measurements are obtained after periods of 10 seconds and 10 minutes as a means of determining mud thixotropy[2].

For engineering purposes, drilling mud viscosity is assumed to be time independent and adequately defined by a down flow curve obtained with the standard oilfield rotational viscometer following a shearing period of 10 minutes at 600 rpm (~1022 s^{-1}). In some engineering software programs used to calculate surge and swab effects (where drill pipe is run into or out of the hole), oilfield gel strengths are taken into account. Otherwise they are simply used as an indicator of whether a drilling mud is in "good or bad" shape for treating purposes or for tripping pipe or running in casing. High progressive gels (large differences between 10 seconds and 10 minutes) are seen as "bad" whereas fragile gels (small differences) are seen as "good".

All oil and gas wells experience a temperature gradient and in cases where organic mud systems are in use, pressure effects can also be significant. The generation of a down flow curve at a standard test temperature also has to be viewed with relevance to the temperature and pressure effects being experienced at various points in the well drilling operation.

This paper will present data obtained on a controlled stress rheometer fitted with a non slip serrated parallel plate and discuss standard oilfield measurements.

CONTEXT

Understanding typical time intervals that may be experienced during a drilling phase as well as shear rates in a well annulus are a pre-requisite prior to any laboratory study.

During periods of drilling, flow is usually fairly constant, and the period of flow before cessation is dictated by the rate of penetration as this determines how quickly new drill pipes have to be added. This time frame may typically last between 15 minutes and well in excess of 3 hours. The equilibrium condition in the annulus is then followed by a period of rest during connections which can usually last from 1.5 to 8 minutes before circulation is re-started and structural deformation takes place.

In other well operations such as tripping drill pipes for bit change or running in casing for formation and pressure protection, there are also periods of rest which have similar time frames.

The longest period of rest for a drilling fluid is after the bit has been pulled through a particular depth during a bit change and before a new bit or casing re-passes that particular depth. This period may last for up to 12 hours or more depending on depth.

Growth and then breakdown in structure of drilling fluids during drilling and trips should be viewed in this context of variable time frames and how it may or may not impact operations.

FLOW DATA

For simplicity we will consider laminar flow in an annulus with non rotating concentric pipe. (Laminar flow is the predominant flow type in a well annulus).

Maximum shear rate is experienced at the annulus wall and for drilling fluids this will always be <400 s^{-1}. As the shear rate and so stress decrease to lower values towards the plug zone, a point is reached where the fluid while in flow will begin to structure. At this point (where structural elements overcome deformation stress) there is a dramatic increase in viscosity as can be seen in Fig.1. (All the rheological data presented in this paper were obtained on a typical field oil based mud.)

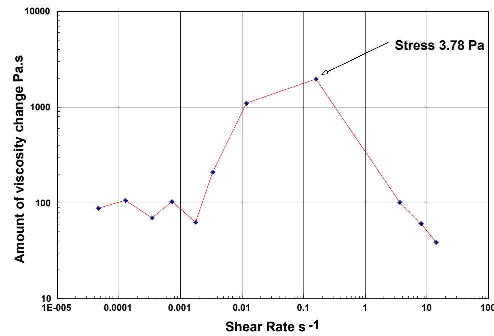

Figure 1. Structure Growth during Linear Decrease of Stress.

Following cessation of flow during pipe connections, the whole system now starts to structure. Two factors should now be considered. The yield stress required to re-initiate flow and the strain required to break the gel structure. The yield stress in Fig.2 is similar in magnitude to the value obtained in Fig. 1 but the values within experimental error may not be exactly the same. (48.9°C is a standard test temperature equivalent to 120°F)

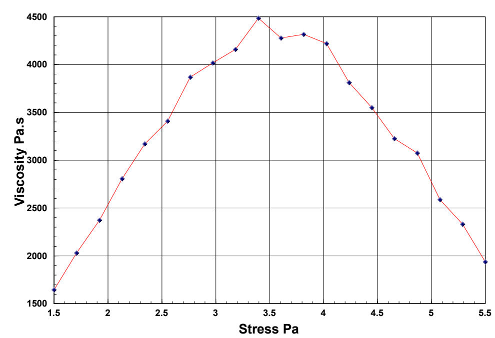

Figure 2. Yield Stress at 48.9°C

As one would expect, the yield stress is temperature (and for organic based muds) pressure dependent as these parameters affect the structure of these systems. The effect of an increased temperature can be seen by the result in Fig. 3 carried out on the same mud sample at 85°C. Data in Figures 1-3 were obtained using a stepped stress technique.

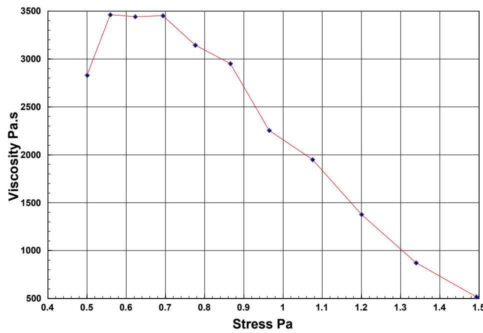

Figure 3. Lower Yield stress with increased Temperature. (Shear rate 1/3rd of that measured in Fig. 2 - 0.00025 s^{-1})

GEL STRUCTURE

The growth in structure during the rest period also depends on the temperature and for organic based mud systems the pressure at any point in the well annulus. The effect of temperature alone for this oil mud can be seen in Fig 4.

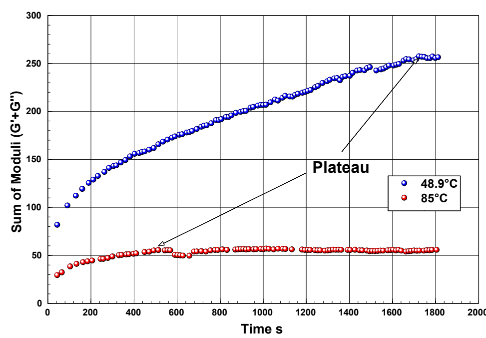

Figure 4. Structural Growth during Oscillation at 0.4% strain

There is quite a large difference between the two results at temperatures of 48.9 and 85°C. At the lower temperature the system takes ~1700 s to reach an equilibrium gel state but only ~500 s at the higher temperature and the system is now 5 times weaker. In many operational instances the time frame of an operation will be less than the time required to reach an equilibrium gel state, so strains required to break the system will be less than those calculated from oscillation tests on gelled systems.

A typical drilling fluid in a good condition shows an equilibrium gel structure similar to that in Fig 5, although actual values for the moduli can vary significantly depending on the temperature and solids content of any particular drilling mud.

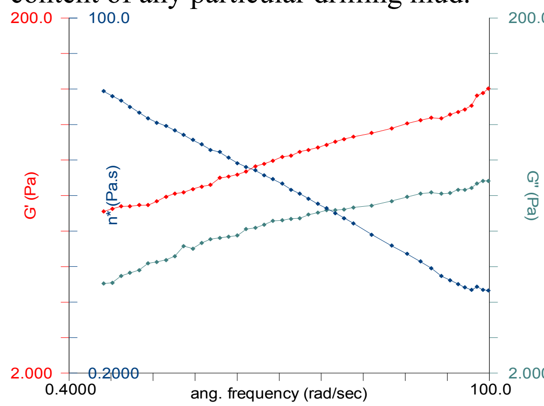

Figure 5. Typical oil mud gel structure measured at 85°C.

As drilling muds are complex mixtures of colloids they would be expected to show a spectrum of different relaxation times. Some organic based systems can be fitted with a 4 parameter Maxwell model although the outputs tend to be biased on the start and end points of the angular frequency chosen for the analysis. Most mud systems appear more complex than can be described by a 4 parameter Maxwell model.

A torque sweep (Fig. 6) run on this mud at the higher temperature indicates that the moduli would intersect by ~8% strain where the system could no longer be described as a gel.

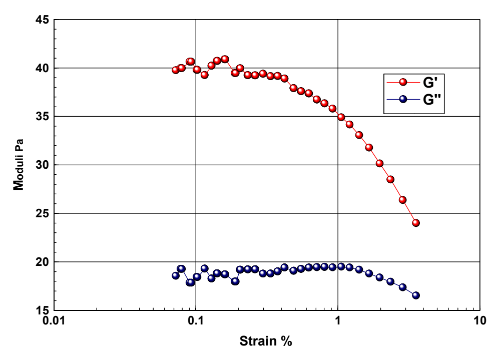

Figure 6. Torque Sweep at 85°C

At lower temperatures it is usually very difficult to obtain G'/G'' crossovers even at very low frequencies with well formulated drilling muds. There is quite a large variability in the structural strength of various drilling muds and all of them become much stiffer as temperatures decrease, so at the standard mud measurement temperature of 48.9°C strains as high as ~30% may be required to fully disrupt the gel networks and these are outside any linear region.

In a drilling perspective, if a 5" diameter pipe in a 12¼" hole moves more than 0.61"it will exceed 25% strain. Therefore any gel structure developed by drilling muds will be broken around the drill pipe by this small amount of movement. This value agrees with comments made by Lal[3] in his paper on Dynamic Surge and Swab modelling. Indeed, in another paper[4] comments were made after some hydraulic tests with a high density oil based mud in a deep HP/HT well, that no overpressure due to mud gels was detected when moving or rotating pipe. (Attributed by the authors to "flat gels" and with a low value)!

The pressure spikes seen when mud pumps are started up quickly or when pipe is run very quickly into a well are due to a significant increase in the Deborah number as the process time decreases. With oil muds the compressibility of the organic phase would also contribute to this pressure spike.

THIXOTROPY

Flow loop tests where the stress is decreased from a fully sheared state down to the approximate yield stress and then increased, can be used to show the magnitude of structural change during the wait time between the down and up curves.

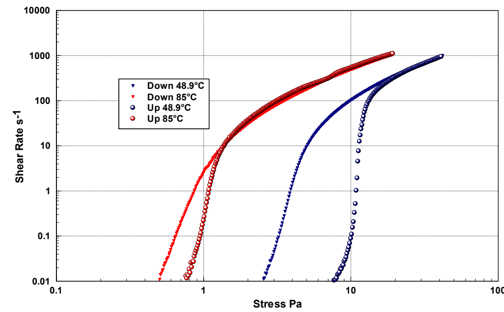

Figure 7. Effect of temperature on Thixotropy of an oil mud

In Fig 7, a cut-off was made in the shear rate at 0.01 s^{-1}. (While some data was collected below this value the rheometer had run out of resolution). The time taken between the 85°C and 48.9°C curves was 677 s and 994 s respectively. The mud viscosity has increased in both cases and based on the data in Fig 4, the 85°C up curve has reached an equilibrium value whereas that at 48.9°C has not. This time dependent increase in viscosity is limited to shear rates below 10 s^{-1} in the case of the higher temperature and ~300 s^{-1} for the lower temperature example. The 85°C flow curves also crossover above 20 s^{-1} which indicates solids (barite) settling during the test cycle.

OILFIELD GEL MEASUREMENT

The standard viscometer used in the western oil industry uses the peak value obtained when 3 rpm is immediately applied to the mud sample to determine the initial 10 second and 10 minute "gel strengths". Robinson et al[5] pointed out that this represents a strain rate far in excess of that required to break any gel. It is also apparent that the use of 3 rpm as the rotational speed is completely arbitrary. If the 6 rpm value is used, the response would be a higher value and if 1 rpm was available to be used a lower value would result. So what do these values represent?

The initial value is the standard 3 rpm rotational value plus any structural growth that occurs in the sample in 10 seconds including a strain effect. This also holds true for the 10 minute gel value although as the system has now structured more, a greater part of the value is due to the application of the high strain rate than at 10 s.

The oil mud used as an example fluid in this paper had Fann® viscometer gels of 12/26 lb/100 ft^2 at 48.9°C and a 3 rpm value of 8. If we assume that the ratio of the 10 s to 10 min Fann® gels represents the increase in apparent hardness seen by the high strain and if we assume that the true structural growth in 10 s will be quite small (assume 0.5 for this example. For low values it will be zero and for higher values perhaps 1-2) then we get

12-8.5 = 3.5 the strain effect at 10 s

3.5*26/12 = 7.6 the strain effect at 10 min

Approximate (and realistic) thixotropy values at 10 s and 10 min are then 8.5 and 26-7.6 = 18.4 (all in lb/100 ft^2). These represent the increase in viscosity with time at the shear rate equivalent to 3 rpm - not any gel structure, and agree with experimental data.

CREEP TESTS

A series of creep tests were conducted on the mud sample to illustrate the points made above. In the first test a stress was applied equivalent to the initial gel.

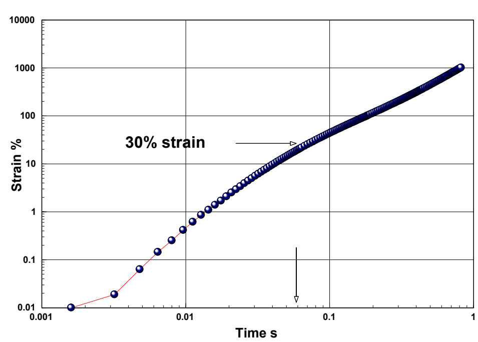

Figure 8. 30% strain exceeded in <0.1 s when a stress of 12 lb/100 ft^2 (5.74 Pa) is applied.

The full creep run shows the sample in flow and exhibiting no viscoelasticity at this high stress level.

At half of this stress the sample still flows although the sample is slightly stiffer. Fig. 9 shows the sample after a 10 minute wait when only 6 lb/100 ft^2 (2.88 Pa) is applied and now some viscoelasticity is apparent on the recovery.

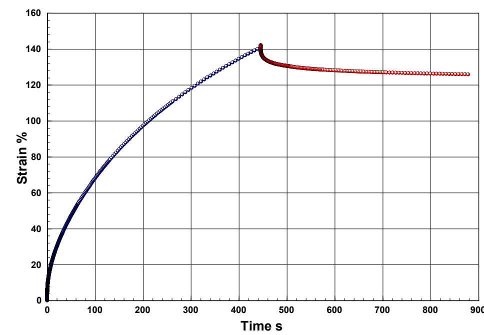

Figure 9. Viscoelasticity after a 10 minute rest period with a lower applied stress

PRACTICAL USE

The standard Fann® viscometer gel strength values can be modified for strain effects and then plotted as stress values on a standard stress/shear rate graph.

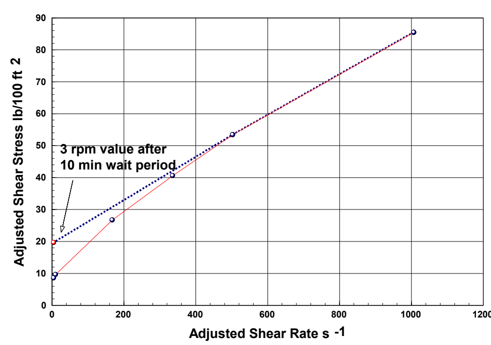

Figure 10. Fann viscometer values adjusted for shear rate and shear stress with adjusted 10 minute gel value added.

The down flow curve points obtained at 600 rpm and 300 rpm can be used with the adjusted gel value to obtain a new flow curve more representative of start up flow properties after a wait of 10 minutes. The stress value obtained from the methodology described above is also the value of the oilfield Bingham yield point which draws a straight line through the 600 rpm and 300 rpm readings.

This is probably co-incidental for this sample as it is expected that values from both methods will fluctuate slightly around each other due to the variability of drilling muds and viscometer accuracy.

It does mean however that the oilfield Bingham yield point used as a stress value at $\sim 5.1\ s^{-1}$, more accurately represents the viscosity of muds after a rest period of 10 minutes than it does the true yield point of drilling muds!

Should the wait time during connections be less than 10 minutes then a simple linear correlation can be made between the standard down curve readings and the adjusted 10 minute gel value.

As mud systems shear down relatively quickly once circulation has re-started, for practical purposes during drilling, the effect of thixotropy will be short lived.

The greatest effect will be felt where muds have lain undisturbed for sufficient time to have developed full structure. As this time frame in some cases may exceed 10 minutes depending on temperature and pressure, it would be advisable to use a longer time frame for the "gel peak" and then adjust this to the true 3 rpm value.

Use of accurate measurements with high temperature high pressure viscometers (not easy) or mathematical predictive techniques can give a better idea of how the 3 rpm values are affected by temperatures and pressures and whether there should be any need for adjustment.

CONCLUSIONS

Fann viscometer gel strength values are a measurement of thixotropy and include a strain effect caused by the rotational speed. They do not measure the gels of drilling fluids per se.

The values obtained on the viscometer can be adjusted to a more realistic thixotropic stress value and used in conjunction with the 600 rpm and 300 rpm readings to generate a new flow curve that reflects time dependency.

Alternatively, the standard oilfield derivation of the Bingham yield point can be used as the 3 rpm value to generate a flow curve that reflects structure growth after ~10 minutes.

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