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Behaviour of Suspensions and Emulsions in Drilling Fluids

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ABSTRACT

Drilling fluids are multi-component fluid systems that are designed to perform several functions during drilling for oil or gas under varying conditions of temperature and pressure. They are suspensions of solids in an aqueous or invert-emulsion suspending medium. This paper reviews performance areas where fluid rheology plays a dominant role.

INTRODUCTION

Drilling for oil or gas is facilitated by the drilling fluid which is designed to perform a number of functions during the drilling operation. It cools and lubricates the drill bit, provides hydrostatic pressure to stabilise the wellbore and transports the drill cuttings to the surface. Generally, drilling fluids are suspensions of solid particles in an aqueous or non-aqueous suspending medium. Water-based fluids are suspensions of weight material in water, but also contain a number of additives to control fluid properties such as rheology, fluid loss, shale inhibition and lubricity. The carrier liquid in non-aqueous fluids is an invert emulsion of a brine (aqueous solution of sodium chloride, calcium chloride, etc) in an organic liquid such as mineral or synthetic oil, or diesel. The brine phase, which is dispersed in the non-aqueous phase as fine droplets, helps to reduce drilling fluid cost and contributes to fluid density and rheology. The salinity of the brine phase is adjusted to minimise shale hydration by balancing the water activity of the formation being drilled. In addition to the weight material for density control, invert-emulsion fluids contain emulsifiers and oil-wetting agents as well as additives for rheology and fluid loss control.

Although fluid loss, shale inhibition and lubricity are important properties of the drilling fluid, they are outside the scope of this paper and will not be discussed here. The remainder of this paper describes the significance of rheology in drilling fluids and the manner in which it is generated in different fluids, and discusses the aspects of fluid performance that are dominated by rheology.

RHEOLOGY OF DRILLING FLUIDS

Rheology is a key property which influences different aspects of the drilling operation. It affects the pressure drop in the drill-pipe and the annulus, with direct impact on the pumping requirements. It influences the ability of the fluid to carry drill cuttings to surface and to keep solids suspended when flow stops, thus affecting hole cleaning in the annulus It determines the degree of turbulence achieved and the impact speed of the fluid on the rock as the fluid issues through the bit nozzles, thus affecting the rate of penetration. It can also affect the flow of fluid in porous media, thus controlling loss of drilling fluid to high-permeability formations or where there are natural or induced fractures in the rock.

During its cycle of flow through the well, the drilling fluid experiences a wide range of shear rates. Shear rates of order 10^3 s^{-1} are prevalent in the drillpipe, while rates as high as 10^5 s^{-1} may develop at the bit nozzles. The wider cross-sectional area of the annulus has a shear field of order 10^2 s^{-1}. Thus, the drilling fluid has to be capable of delivering the rheological requirements of all the shear fields. The rheological parameters of significance are the high-shear viscosity, the yield stress and the gelling properties of the fluid. High-shear viscosity (*HSV*) affects the frictional pressure drop as the mud flows down the drillpipe and up the annulus. This, in turn, determines the pumping requirements at the surface. High pressure drops require high pumping pressures and run the risk of inducing fractures in weak formations and causing severe mud losses downhole. High *HSV* also limits the pump rate that can be used for effective hole cleaning.

Yield stress is a measure of the solids suspending capacity of the fluid, particularly when drilling is interrupted and the fluid becomes stationary. Equally important are the gelling properties of the fluid. These give some indication of how quickly the fluid gels to prevent, or significantly reduce, the settling of solid particles. High gels values and progressive gels are not desirable as they make it difficult to re-mobilise the fluid after a break in the drilling operation.

The standard weight material is API barite with D_{50} of 15-20 μm. There are also non-standard weight materials with considerably finer particle size, which generate low rheology and are used in some high-density and/or slim-hole applications. Examples of these are micro-fine barite, which may or may not be treated, with D_{50} of 1.8 μm or manganese tetroxide with very narrow particle size distribution of 0.47-1.0 μm.

The liquid phase of drilling fluids generally contains a number of additives to control the various required properties of fluids, including one or more rheology additives to suspend the weight material. Thus, fluid rheology is generated partly by the suspended solids and partly by the rheology additives. Although there are many equations for estimating the bulk viscosity of suspensions of solids, they generally apply to mono-disperse spherical or regular-shaped particles in a Newtonian carrier fluid. The poly-dispersity and the irregular shape of the weight material, make estimation of its contribution to suspension rheology very difficult.

Drilling fluids are treated as pure liquids, or continuum, with a yield stress. They are commonly described as Bingham fluids for oilfield calculations, although there is a tendency now to use yield-power law relationships such as Herschel-Bulkley[1] and Casson[2], for hydraulics calculations:

$$\text{Bingham: } \tau = YP + PV\,\dot{\gamma}, \tag{1}$$

$$\text{Herschel-Bulkley: } \tau = \tau_Y + k\dot{\gamma}^n, \tag{2}$$

$$\text{Casson: } \tau^{1/2} = k_0 + k_1\dot{\gamma}^{1/2}, \tag{3}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate; *PV* and *YP* are Bingham plastic viscosity and yield point, respectively; τ_Y, k and n are the Herschel-Bulkley yield stress, consistency and flow indices, respectively; and k_0 and k_1 are the Casson constants. Fig. 1 shows an example of the deviations of the above models from the measured data. It is clear that at low shear rates the Bingham model gives poor predictions.

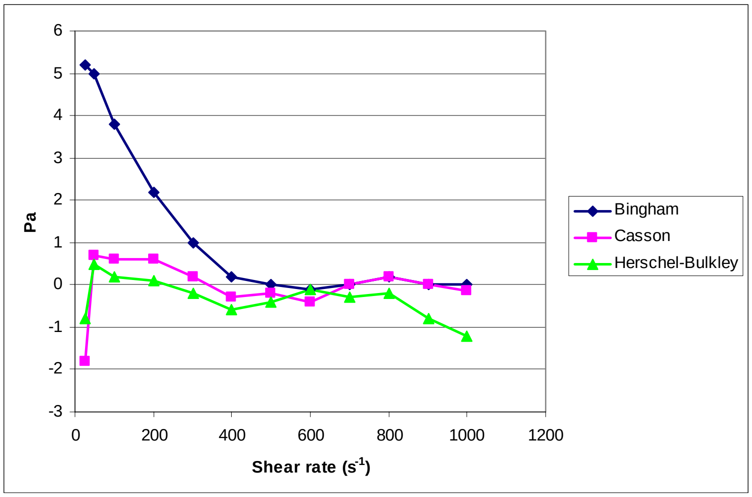

Figure 1. Comparison of rheology models for a water-based drilling fluid.

RHEOLOGY MEASUREMENT IN DRILLING FLUIDS

The standard oilfield measuring device for drilling fluid rheology is the Fann-35 viscometer, a Couette-type concentric cylinder device with fixed rotational speeds. The Fann-35 viscometer has six fixed rotational speeds of 3, 6, 100, 200, 300 and 600 rpm, which with the standard concentric cylinders (R1-B1 combination) produce shear rates ranging from 5.11 to 1021.8 s^{-1}.

The dimensions of the annular gap and the rotational speeds of the Fann viscometer are chosen such that the high-shear viscosity and the yield stress can be approximated for a Bingham fluid (Eq. 1) by simple relationships giving *PV* (plastic viscosity) and *YP* (yield point):

$$PV = \theta_{600} - \theta_{300}, \tag{4}$$

$$YP = 2\theta_{300} - \theta_{600}, \tag{5}$$

where θ is the Fann dial reading at different rotational speeds, *PV* is in units of centipoise (or mPa.s) and *YP* is expressed in oilfield units lb/100ft^2 (equivalent to 0.48 Pa).

As shown in Fig. 1, *YP* can significantly overestimate the shear stress above which the fluid undergoes plastic deformation, *i.e.* the yield stress. To produce a closer estimate of the yield stress, a low-shear yield point *LSYP* has been defined[6] which uses the Fann data at low rotational speeds:

$$LSYP = 2\theta_3 - \theta_6 \tag{6}$$

WATER-BASED FLUIDS

Conventional water-based fluids may be polymer- or clay-based systems. The former use polymeric materials to generate rheology, while the latter use bentonite, and possibly other charged particulates, to create a fluid with structure at low shear rates and low viscosity at higher rates.

Polymer-based fluids use biopolymers, or synthetic polymers for high-temperature applications, to viscosify the aqueous phase. In clay-based systems, the differing surface and edge charges of clay platelets lead to formation of a gel-like network of particles at low shear rates that helps support the weight material and the drill cuttings. At higher shear rates the network breaks down and the fluid flows with low viscosity. This thixotropic characteristic is an optimum type of rheology for drilling fluids provided that the time scales for breakdown and buildup of structure are small.

The thixotropic behaviour of clay-based fluids has been modelled by using a simple rate equation for structure breakdown and buildup:[3]

$$\frac{d\lambda(t)}{dt} = a\,(1 - \lambda(t)) - b\,\lambda(t)\,\dot{\gamma}\,, \qquad (7)$$

where λ is a time-dependent structure parameter with values from 0 (purely viscous fluid with no structure) to 1 (fully gelled state), and a and b are rate constants determined from stress relaxation experiments. Incorporation of λ in the Herschel-Bulkley equation can yield a relationship that relates shear stress both to shear rate and time:

$$\tau(t) = \lambda(t)\,\tau_Y + [\mu_\infty + c\,\lambda(t)]\,\dot{\gamma}^{\,m} \qquad (8)$$

Eq. 8 was used to predict the hysteresis loops that are produced when a thixotropic fluid is subjected to shearing by repeated ramping up and down of the shear rate. The test fluid was an unweighted suspension of bentonite (6.43% by weight) in tap water. The suspension was hot rolled for 48 hours at 100ºC and its pH adjusted to 9.5. The Bohlin VOR rheometer was used for all the rheology measurements. Controlled-stress measurements gave τ_Y=16.0 pa. The remainder of the parameters in Eqs. 7 and 8 were determined by shear rate step-change measurements and were found to be: μ_∞ = 0.0198 Pa.s^m, c = 0.20 Pa.s^m, m = 0.81 and b/a = 5.44 x 10^{-4} s. The experimental hysteresis loops were obtained by ramping the shear rate up and down over the range 11.6 – 1460 s^{-1}. The cycle was repeated five times. Measurements were made at 20 shear rates in each direction, with a ramp time of 48 minutes. The experimental results and the predicted hysteresis loops are shown in Fig. 2. The results show that the model gives poor prediction for the first cycle, when the fluid is not in an equilibrium state, but the predictions improve as the cycles are repeated and the system approaches equilibrium. This example demonstrates the time-dependence of structure development (gel formation) in drilling fluids. In oilfield practice, an alternative and much simpler technique is used to obtain similar information. This is achieved by measuring the shear stress of the fluid at a low shear rate after different periods of rest, referred to as 10-second and 10-minute gels.

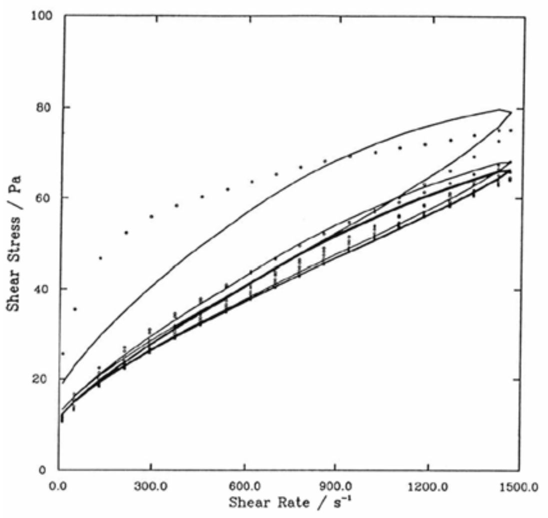

Figure 2. Experimental and predicted hysteresis loops.

A common problem with rheology measurements of suspensions and structured fluids is wall slip. Fig. 3 shows rheograms obtained for a bentonite water-based fluid by using different measuring geometries. The fluid shows slip across the entire range of shear rates as indicated by very large increase in measured stress on moving from a smooth to roughened cup and bob (C&B) geometry. The smaller difference between the four-bladed vane and rough C&B data could also be slip.

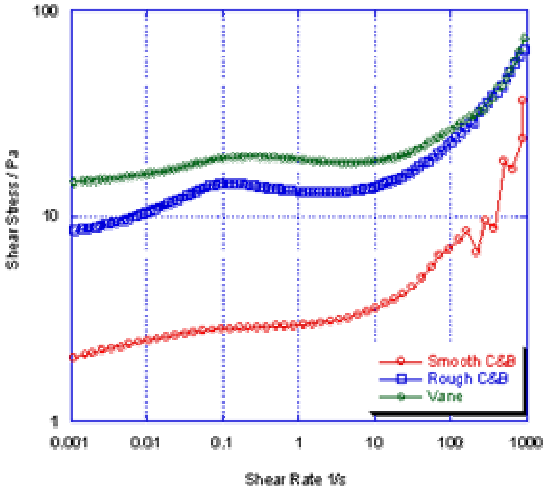

Figure 3. Wall slip in bentonite water-based mud.

OIL-BASED FLUIDS

In most oil-based drilling fluids, the rheology required for solids suspension is generated by organically modified clays. Organoclays are bentonite or hectorite clays made hydrophobic by treatment with quaternary ammonium salts containing long alkyl chains and/or aromatic rings. It is thought that the clay particles interact with emulsion droplets to form a weak structure that enhances fluid rheology.

The emulsion droplets behave as fine solid particles and make a contribution to rheology. As a result, oil-based fluids with higher brine content (*i.e.*, lower oil-water ratio) have higher rheology. In recent years, oil-based fluids with micro-fine weight material have been introduced which allow formulation of high-density fluids without the consequent high rheology usually obtained if standard weight material (API barite) were used. The micro-fine weight material may be produced as a slurry of treated particles in oil. The treatment provides the barite with steric stabilisation that reduces the need for higher rheology as a means of suspending the particles. The fluid provides excellent settling resistance and low friction pressures. The latter allows higher pump rates for better hole cleaning.

Effect of temperature on the rheology of drilling fluids is of particular concern in high-temperature applications and in drilling in deep water. In deep-water drilling, large variations in temperature from low at sea bed (around 1-2ºC) to high values downhole cause significant changes in fluid rheology. This has major implications for the hydraulics of the drilling operation, including hole cleaning, barite sag and hole stability. The desired "flat-rheology" fluid is one with relatively stable yield stress and high-shear viscosity over a wide temperature range. In recent years, a synthetic-based fluid has been developed which uses a combination of high-performance polymeric additives and emulsifiers to generate a temperature-stable rheology. The fluid has been used successfully in many field applications where significant differences were seen between the rheology-temperature profile of this fluid and a conventional SBM of similar density.[4]

RHEOLOGY AND HOLE CLEANING

To illustrate the effect of drilling fluid rheology on particle settling, we consider the settling of a single particle (drill cutting) in a deviated well. To prevent the settling of the particle and formation of a cuttings bed in the long horizontal section (diameter *D*, length *L*), the particle must reach the near-vertical section before it has time to settle out. The time to settle out (T_S) and the time to transport out (T_T) are given by:

$$T_S = \frac{D}{V_S}, \qquad \text{and} \qquad T_T = \frac{L}{V_T}, \qquad (9)$$

where V_S and V_T are the settling and the flow-driven translational velocities of the particle. The condition for the particle to leave the horizontal section before settling out is:

$$T_T << T_S \quad \text{or} \quad V_S << \frac{D}{L} V_T , \tag{10}$$

where the settling velocity V_S may be estimated from Stokes' equation:

$$V_S = \frac{\Delta\rho\, g\, d^2}{18\mu_m} \tag{11}$$

In Eq. 11, μ_m is the viscosity of the continuum, d is particle diameter, $\Delta\rho$ is the density difference between particle and the continuum and g is the gravitational acceleration. Combining Eqs. 10 and 11 gives,

$$\mu_m >> \frac{L}{DV_T} \frac{d\,\Delta\rho\, g}{18} \tag{12}$$

For $V_T = 1$ m/s, $L = 1000$ m, $D = 20$ cm, $d = 1$ mm, $\Delta\rho = 1200$ kg/m^3, and $g = 10$ m/s^2, the required viscosity would be $\mu_m >> 3.3$ Pa.s. For a non-Newtonian fluid, however, viscosity is a function of shear rate. The effective shear experienced by the particle is the net result of the shear induced by the translational flow of the fluid and that induced by the gravitational fall of the particle. The dominant component of shear, however, is that due to fluid flow, which is of order $4V_T/w = 80$ s^{-1} (w is the width of the annulus between the drillstring and the wellbore, say 5 cm), corresponding to 47 rpm. In terms of the Fann-viscometer dial readings, this is equivalent to about 550 lb/100 ft^2 (or 264 Pa), which is an unrealistically high value for drilling fluids. In practice, the settling velocity, thus the required rheology, would be lower than that predicted above because of the hindering effect of other particles in the fluid. Nevertheless, this simple example shows that rheology alone cannot be utilised to prevent particle settling during flow, and that other means such as higher flow rates and/or pipe rotation must be used to prevent buildup of cuttings-beds.

To prevent settling of cuttings when flow is interrupted, the gravitational force acting on the particle must be balanced by viscous drag:

$$\tau_y \times 4\pi \left(\frac{d}{2}\right)^2 = \frac{4}{3}\pi \left(\frac{d}{2}\right)^3 \Delta\rho\, g \tag{13}$$

For a 1-mm particle with $\Delta\rho = 1200$ kg/m^3, this gives $\tau_y = 2$ Pa, which is the "true" yield stress of the fluid. Analysis of a large body of field-mud data[5] has shown that the ratio of "true" yield stress to *YP* is in the range 0.3 – 0.7. Thus, the *YP* required for suspending the 1-mm particle is 2.8 – 6.7 Pa, equivalent to about 6 – 14 lb/100 ft^2. This is a realistic value for drilling fluid rheology and shows that fluids can be designed to support solid particles during non-flow periods of drilling.

RHEOLOGY AND BARITE SAG

Barite sag is the settling of weight material during the drilling operation, which may result in significant density variations in the fluid return line at the surface. Sag can occur in both water-based and invert emulsion fluids, but is more severe in the latter. Barite sag can lead to drilling complications such as well-control problems, lost circulation, induced wellbore instability, and stuck pipe.

Sag occurs both through dynamic and static settling, but evidence suggests that the overall potential for sag is highest when the drilling fluid experiences low shear rates.[6-8] The low-shear-rate (LSR) rheology has been variously defined by the low-shear viscosity (*LSV*), yield stress or gel strength. The LSR environment can typically be thought of as the shear rate created by a particle as it settles under gravity in an otherwise quiescent fluid.

This may be estimated from Stokes' equation (Eq. 11) and the following definition:

$$\dot{\gamma} = \frac{2\,V_S}{d} \qquad (14)$$

For a typical barite particle (d = 50 micron, S.G. = 4.25), fluid density (S.G. = 1.40), a given *LSV* (say, μ_m=2 ×10^4 mPa.s), and with g = 10 m/s^2, Eq. (14) predicts:

$$\dot{\gamma} = 0.008\ \text{s}^{-1} \qquad (15)$$

Dye, *et al.*[9] suggested that the viscosity value at a shear rate of 0.5 s^{-1} could be used as sag indicator, while others (e.g. Herzhaft, *et al.*[8], Saasen[10]) argued that considerably lower values in the range 10^{-2} to 10^{-3} s^{-1} may be more appropriate. Thus, a conventional oilfield viscometer such as the Fann 35, which has a LSR restriction of 5.1 s^{-1}, is inadequate for direct *LSV* measurements.

Tehrani, *et al.*[11] investigated the effect of rheology on dynamic sag for a large number of oil-based fluids formulated with different organoclays and polymeric rheology additives. Although the fluids were formulated to produce 3-rpm Fann readings of 4-5 Pa, they showed significant differences in their LSR rheology. The more common types of organoclays, *i.e.* modified bentonite and hectorite, showed evidence of two Newtonian regimes, at very low and at high shear rates. These regimes were followed, or preceded, by two shear-thinning regions that were separated by a quasi-Newtonian region at intermediate shear rates, Fig. 5. For fluid OB2 the first Newtonian regime occurred at shear rates below 0.0005 s^{-1}, while the second regime emerged above 100 s^{-1}. In the intermediate region the fluid exhibited evidence of several structural changes. For most of these fluids the quasi-Newtonian region occurred in the 0.01–1 s^{-1} shear-rate range. The structural changes are likely to be due to a strong interaction between the organoclay particles and emulsion droplets. Fluid OA2, with needle-shaped organoattapulgite, and P5/1, with polymeric additive, show much weaker structural changes.

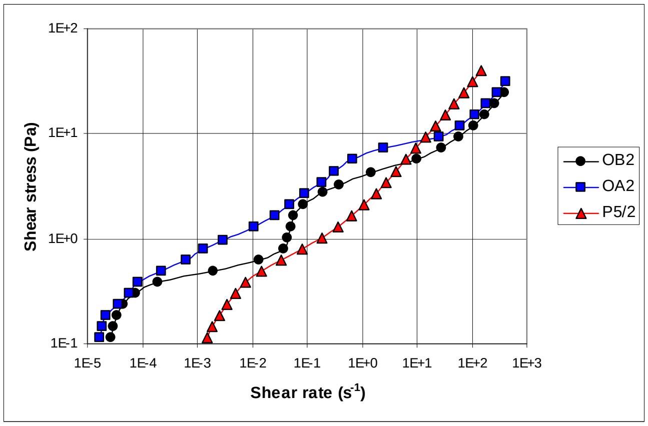

Figure 5. Flow curves for oil-based fluids containing: organophilic bentonite (OB2), organophilic attapulgite (OA2), polymeric viscosifier (P5/2). (Data at 50ºC)

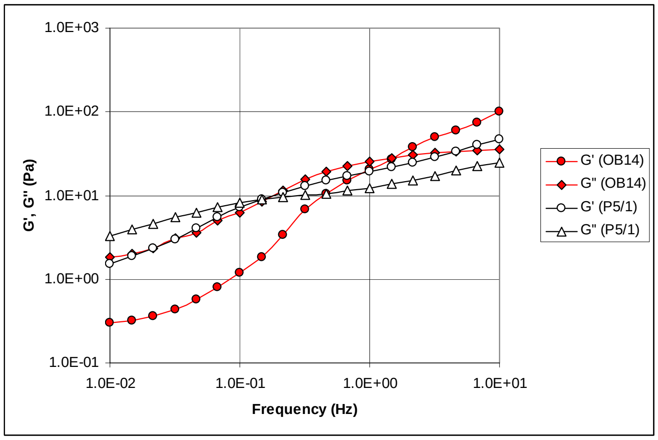

Figure 6. Viscoelastic responses of oil-based fluids containing: organophilic bentonite (OB14) and a polymeric additive (P5/1). (Data at 50ºC)

Tehrani, *et al.*[11] also performed viscoelastic measurements on the same fluids. The frequency sweep of Fig. 6 compares an organophilic bentonite fluid

OB14 with fluid P5/1 containing a block copolymer. The results show that Fluid P5/1 has a lower crossover frequency and higher G' at lower f than OB14, giving it more prominent viscoelastic properties.

Dynamic sag of the above fluids was measured by a modified version of the VST method developed by Jefferson[12]. The device uses the heating cup of the Fann-35 viscometer to apply shear at a fixed rate of 170.3 s^{-1} (100 rpm). Dynamic sag was measured at 50ºC as the change in fluid density after 30 minutes. The measurements showed a wide variation in the sag performance of the fluids. Barite sag was higher in the polymer-based fluids than in fluids containing organoclays. This was attributed to the low LSR rheology and the absence of structure in polymer-based fluids. It also suggests that viscoelastic properties may not play a prominent role in dynamic sag. For organoclays, dynamic sag showed good correlation with viscosity at low shear rates down to 10^{-2} s^{-1}. This is illustrated in Fig. 7 for measurements made at 50ºC.

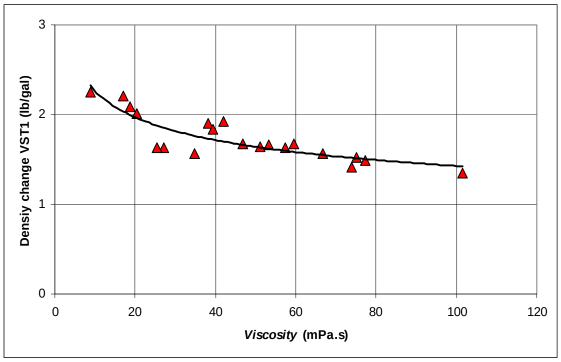

Figure 7. Dynamic sag vs. *LSV* at 10^{-2} s^{-1}.[Data obtained at 50ºC.]

Viscoelastic properties of the drilling fluid are also thought to affect barite sag.[8,11,13] Tehrani, *et al.*[11] showed that barite sag correlated well with complex viscosity V^*. The trends were considerably stronger when only the clay-based fluids were considered, Fig. 8.

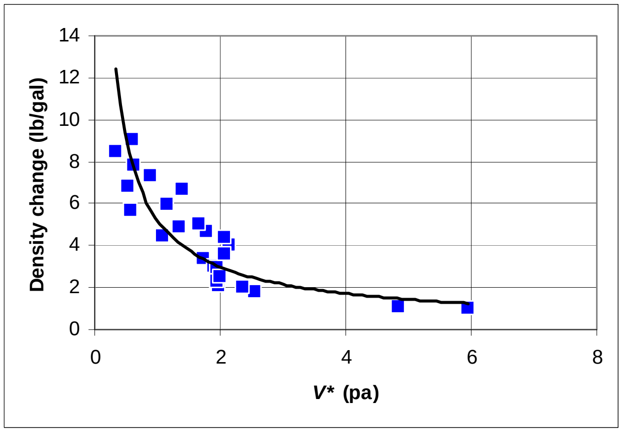

Figure 8. Dynamic sag vs. complex viscosity. [Data obtained at 5 Hz, 20ºC.]

Other properties of the drilling fluid also affect barite sag. The interfacial chemistry of the dispersed phases, *i.e.* the solids and emulsion droplets, can also influence barite sag in invert drilling fluids. The type and concentration of the emulsifier and wetting agent affect emulsion stability and the wettability of the solids, including organoclays, and may have an effect on sag.[6,10,14]

CONCLUSIONS

1. Drilling fluids are important examples of industrial suspensions and emulsions. They serve many different functions during the drilling operation.
2. The rheology of drilling fluids affects many aspects of their performance and is critical to the safe and successful execution of a well. Drilling hydraulics, hole cleaning and barite sag are areas where rheology plays a dominant role.
3. Drilling fluids are complex multi-component systems whose rheology depends on the concentration of the various phases and on the interactions of different components. Low-shear

rheology and presence of a structure appear to play an important role in solids suspension.

4. Although a significant amount of work has been done to understand the mechanisms of rheology generation in drilling fluids, the complexity of the systems and the physico-chemical interactions involved mean that there is more to be done.
5. Future efforts should lead to better control of existing fluid systems and to the development of new ones that meet the current and future challenges of more demanding drilling scenarios and stricter environmental controls.

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