Rheological Characterization of Oil-Based Drilling Fluids – Effect on Barite Sag

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ABSTRACT

Rheology is one of the key drilling fluid properties for controlling sag. Yet, the current understanding of the sag-rheology relationship is limited to a few general guidelines for reducing sag in the field. This paper reviews current understanding of sag and describes the initial stage of work aimed at finding a correlation between fluid rheology and sag performance under laboratory conditions.

INTRODUCTION

In oilfield terminology, "sag" describes the settling of weight material, which results in significant drilling fluid density variations seen at the flow line. Barite sag is usually observed when circulating the fluid out of the hole after the fluid column has been static for some time.

Barite sag can occur over a relatively wide fluid density range, 1400-2400 kg/m^3, and can lead to density variations as high as 480 kg/m^3. Sag can occur in both oil-based and water-based drilling fluids, but it is experienced more often in oil-based fluids. Occurrence of sag can lead to potential drilling complications such as well-control problems, lost circulation, induced wellbore instability, and stuck pipe.

Sag occurs through dynamic and/or static settling. In an inclined hole, sag may result in the slumping of barite bed[1]. The fact that the density variations are most commonly seen after static periods had previously led to the belief that static settling was the main mechanism for barite sag. However, flow loop tests and field experience have shown that while some static settling may occur, it is less likely to produce the large scale density variations seen frequently at the flow line. Hanson *et al.*[2] and Jefferson[3] emphasised the potential for dynamic sag occurring while circulating the drilling fluid, and observed that prevention of dynamic sag is more difficult than static sag. The overall potential for barite sag is highest when the drilling fluid experiences low shear rates[2,4]. Flow loop data and field observations suggest that severe sag (>120 kg/m^3) occurs under the combined influence of low viscosity and low annular velocity.

Well-control and hydraulics considerations often require the drilling fluid pressure to exceed formation pore pressure (to prevent the influx of formation fluids) and to be less than the fracture gradient (to avoid fracturing of formation and drilling fluid losses). These requirements place operating windows on flow rate and/or fluid rheology that may actually create conditions that promote barite sag. Sag may be particularly problematic in extended reach wells where the margin between pore pressure and fracture gradient is small. In flow loop tests, Bern *et al.*[4] and Dye and Greg[5] identified a critical mean annular velocity of 100 ft/min above which barite bed formation was minimised.

Accelerated settling can occur in an inclined wellbore through the well-known

Boycott effect. This can lead to "slumping" which is the sliding downward of a bed of solids deposited on the lower side of an inclined wellbore. For well angles 50-80°, which are subjected to most of the sag problems, low flow rates will make low density fluid accelerate upwards while the high density fluid is forced downward along the low side of the well creating a slumping barite bed. The barite bed may be disturbed by high annular velocities and with drillpipe rotation. Flow loop tests and field experience shows that sag is worst when drillpipe is stationary[4].

Barite sag is related both to the drilling fluid properties and the drilling conditions and practices indicated above. The fluid properties affecting sag include rheology, solids content, particle-size distribution (PSD), and the chemistry of the fluid system.

It is a commonly held view that the low-shear-rate (LSR) rheology of the fluid and its linear viscoelastic properties affect the sag performance of the fluid[4]. An increase in the LSR rheology is thought to be beneficial for mitigating dynamic sag[4,6]. The LSR rheology has been variously defined by the low-shear-rate viscosity (*LSRV*), yield stress or gel strength. The shear rate to which *LSRV* should correspond can typically be thought of as the shear rate created by the particle as it settles under gravity in an otherwise quiescent fluid. This may be estimated from Stokes' Law:

$$V_S = \frac{\Delta r\, g\, d^2}{18m} \qquad (1)$$

$$\dot{g}_{LSRV} = \frac{2V_S}{d} \qquad (2)$$

For a typical barite particle size and density (d = 50 μm, s.g. = 4.25), fluid density (s.g. = 1.4), a given *LSRV* (say, m = 20 Pas), and with g = 10 ms^{-2}, the $\dot{g}_{LSRV}$ is estimated to be around 0.008 s^{-1}. Dye, *et al.*[7] suggested that the viscosity value at a shear rate of 0.5 s^{-1} could be used as sag indicator. However, there is evidence to suggest that considerably lower values in the range 10^{-2} –10^{-3} s^{-1} may be more appropriate[6,8]. Thus, conventional oilfield viscometers such as the Fann 35, which has a low-shear-rate restriction of 5.1 s^{-1}, are inadequate for direct *LSRV* measurements[6]. Further, such low shear rates generate very small torque values which are below the acceptable accuracy limits of many conventional oilfield-type viscometers.

Herzhaft *et al.*[6] investigated the LSR characteristics of oil-based drilling fluids. They identified two distinct regimes: a regime at very low shear rates where the fluid exhibited quasi-Newtonian behaviour and a regime at higher shear rates where the fluid had shear-thinning characteristics. The transition between the two regimes appeared to occur at a "critical" shear rate which increased with increasing temperature. Their cryomicroscopic observations suggested that interaction of organoclay (usually used in the formulation of oil-based muds for rheology control) with emulsion droplets is responsible for a solid-like structure at very low shear rates. This structure is rapidly destroyed upon shearing of the fluid.

Dye and Greg[5] used a field viscometer, capable of measuring at shear rates as low as 0.0017 s^{-1}, to characterise the LSR properties of several oil-based drilling fluids. From this data and dynamic sag measurements in a flow loop, they produced a Sag Prevention Window of viscosity vs. shear rate. The viscosity limits are imposed by the constraints of poor sag performance (lower viscosity limit) and formation fracture pressure (upper viscosity limit). However, details are not provided in their paper and it is difficult to substantiate their claims.

The question of the existence of a true yield stress is of interest both academically and in the field. If rheological measurements and qualitative observations such as those made by Hezhaft[6] suggest the existence of a structure at very low shear rates, then definition of a yield stress for practical

purposes becomes permissible. The yield stress required for preventing sag of a barite particle in a quiescent fluid can be estimated from a balance of buoyancy and viscous forces:

$$t_y = \frac{1}{6} d \Delta r g \qquad (3)$$

For a 50-μm barite particle suspended in the drilling fluid of the previous example, a yield stress of 0.24 Pa is required. Accurate measurement of the yield stress is achievable only with sophisticated rheometers capable of operating in the controlled stress or creep modes. Without such instruments, only estimates of the yield stress can be produced. Bern, *et al.*[4] suggest the Herschel-Bulkley yield value t_y, and predict that sag may be eliminated if t_y > 3.5 Pa. For field application, they define an alternative low-shear-rate yield point (LSRYP) as the minimum yield stress required to prevent sag. This value is estimated from the 6 and 3 rpm data on the Fann 35 viscometer (shear rates of 10.2 and 5.1 s^{-1}, respectively):

$$\text{LSRYP} = 2\theta_3 - \theta_6, \qquad (4)$$

where θ is the Fann 35 reading in Pa. Based on available data, they suggest a value of 3.5 – 7.5 Pa for LSRYP.

Viscoelastic behaviour may also be important for reducing sag[4]. In particular, static sag is thought to be related to the viscoelastic properties of the fluid[9]. Herzhaft, *et al.*[6] performed oscillatory measurements on a number of oil-based drilling fluids and found that, while G" was not affected by pre-shearing and did not evolve with time, the elastic modulus G' was strongly affected by pre-shear and continued to rise with time after shear was removed. They concluded that, at rest or in the absence of appreciable shear, the viscoelastic properties of the fluid may influence sag. These and many other observations point to the possibility of structure formation in the fluid at ultra-low shear rates, and hence to the existence of a gel strength. Bern *et al.*[4] observed that static settling can be controlled by appropriate development of gel strength and suggested this as the reason why clay-type products are more effective at sag reduction than fatty-acid rheology enhancers.

Jamison and Clements[10] studied the static settling of barite in an inclined tube. They observed a tendency of increased sag potential with reduced viscosity or gel strength. The significant scatter in their data led them to conclude that it was not possible to relate static sag to plastic viscosity, yield stress, or the gel strength as measured on the Fann 35 viscometer.

Hindered settling in a concentrated suspension of particles has been the subject of many studies, most of which have treated the effect of the solids as an increase in the bulk density and rheology of the continuum. The effect of high solids content in the mud is to increase the resistance towards settling motion. In oil-based drilling fluids, the settling is further reduced if gel structure develops and improves suspension[2].

The chemistry of the fluid system may also influence barite sag in oil-based 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[4,8].

To summarise, barite sag in OBM is related both to the mud properties and the drilling operation and, as such, they should not be treated independently of one another. However, understanding the effect of each variable on sag will help define an appropriate course of action to minimise sag. From the standpoint of drilling fluid properties, rheology is a key parameter for controlling sag.

The studies reported to date have produced useful guidelines for reducing sag in oil-based fluids, nevertheless there is still a need for a clearer understanding of the link between sag and fluid rheology. This paper

describes the initial stages of work aimed at determining the effect of rheology on barite sag. To achieve this, dynamic sag is measured under viscometric flow conditions so that rheological properties become the dominant parameter in the sag process.

MATERIALS

A number of oil-based drilling fluids are used in this study differing only in the type and concentration of the rheology control additive. All fluids are formulated to the same oil-water ratio, density and brine phase salinity, and hot rolled at 121ºC for 16 hours. The concentration of the rheology additive is adjusted to produce a Fann 35 reading of 8 – 10 at 3 rpm (equivalent to 4 – 5 Pa at 5.1 s^{-1}).

Table 1. Oil-based drilling fluid formulation used in the tests.

Product	Kg/m^3
Mineral base oil	478
Invert emulsifier	13
Wetting agent	13
Lime	22
Rheological additive	10 – 30
Brine	190
Barite	870

METHODS OF MEASUREMENT

Rheology.

Rheological measurements are performed on a Bohlin Instrument C-VOR rheometer. These consist of steady shear controlled-stress and dynamic oscillatory measurements in the linear viscoelastic region.

The test fluids are stabilised by a 5-minute shearing on a high-shear mixer prior to transfer of the required volume to the measuring geometry. The measurement protocol includes shearing at 1000 s^{-1} for 5 minutes, followed by a 5-minute equilibration time before measurements begin.

A concentric-cylinder geometry is used for both types of measurements in preference to the conventional cone-plate geometry, in order to avoid any disturbance due to the presence of barite particles. The surface of the rotating component is roughened to minimise slip.

For each fluid, the steady shear measurements are performed over a shear stress range that cover shear rates in the range 1000 s^{-1} to 10^{-3} s^{-1}. Shear stress is both ramped down and up.

Dynamic oscillatory measurements consist of a strain sweep to establish the linear viscoelastic region, followed by a frequency sweep to measure the storage and loss moduli. The measurements cover frequency range 0.01 – 100 Hz.

Rheological measurements are performed at 20ºC and at 50ºC to correspond to temperatures of the sag measurements.

Dynamic sag.

Laboratory measurement of dynamic sag is commonly performed in one of two ways; by a viscometer sag test[3] device where the sag performance of the fluid is investigated in a relatively well-defined shear field (where the dominant effect is that of fluid rheology), or in a flow loop where other parameters such as flow rate, eccentricity, pipe rotation and inclination are also effective.

Available data show that the viscometric sag results are often different from the flow loop results, and that the sag performance of fluids in a flow loop is close to how drilling fluids perform in the field[5]. Nevertheless, to investigate the effect of rheology on dynamic sag, and to exclude all other effects, it was decided to perform the sag test under conditions where rheological properties are the dominant factor, *i.e.* in a well-defined, or viscometric, shear field.

Two viscometric sag devices are used in this work. The first is a modified version of the viscometer sag test device (VST) developed by Jefferson[3]. It utilizes the measuring geometry of the Fann 35 rotational viscometer to apply shear at a fixed rate of 170.3 s^{-1} (100 rpm). Dynamic sag is

measured as the change in fluid density after 30 minutes. The modifications are similar to those made by Dye and Greg[5], who allowed the fluid in the heating cup to be circulated through a densiometer for continual density and temperature measurements.

A drawback of the VST device described above is that it has two distinct fluid volumes experiencing different shear rates[5]. A high-shear volume of about 10 cm^3 between the cup and bob where the fluid is sheared at 170.3 s^{-1}, and a low-shear volume of 117 cm^3 between the sleeve and the heating cup where the fluid is sheared at about 39 s^{-1}. This duality in shear fields makes it difficult to determine which is the main contributor to the measured sag. The uncertainly increases to some extent in the modified version of the VST, as the design introduces added volume and different shear fields in the densiometer, the pump and the connecting tubing.

The second device utilised in this work was developed at Schlumberger Cambridge Research, UK. This device eliminates the uncertainty in shear rate of the conventional VST in the region between the rotating sleeve and the heating cup. The sheared fluid consists solely of the volume between a rotating inner cylinder and a stationary cup. The bottoms of the inner cylinder and the cup are conical and form a funnel-shaped gap of the same width as the vertical cylindrical gap. Samples of the fluid are removed for density measurements from a port drilled into the tip of the conical base. Dynamic sag is measured after the fluid has been subjected to a shear rate of about 12 s^{-1} for 30 minutes.

EXPERIMENTAL RESULTS

As mentioned before, this paper describes early stages of the work and, as such, a limited amount of data is available to date. These are presented and discussed below.

Rheological measurements. All test fluids show a degree of time dependency in the steady shear measurements the extent of which depended on the type of rheology additive used. Fig.1 is an example of a flow curve for a conventional organoclay-type additive. The waiting time per point varies from 1.2 s to 6 s. The rheology appears to have stabilised at the longer delay times. The difference between the flow curves is more pronounced at lower stress values, suggesting the existence of some structure in the fluid.

In Fig. 1, transition to a shear-thinning behaviour is clearly evident at a shear stress of around 4 Pa. At lower stress values, the fluid exhibits a quasi-Newtonian behaviour, which becomes more evident at the longer waiting times. A similar behaviour seems to emerge again at higher stress values. This is in agreement with previous observations, including those reported by Herzhaft[6]. Interestingly, a shear-thickening behaviour seems to emerge at the lowest stress values. Saasen[8] suggested the existence of such behaviour for simple invert emulsions. More work is needed to confirm this behaviour in fully formulated oil-based fluids.

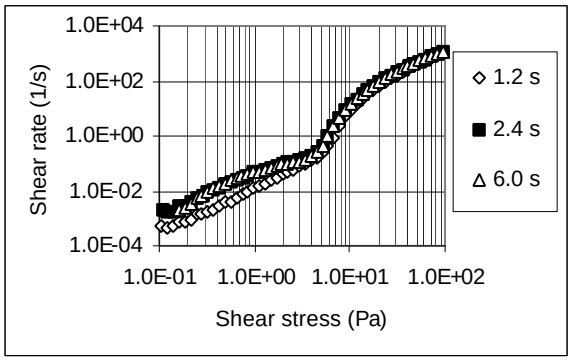

Figure 1. Effect of waiting time on the flow curves of clay-based fluids.

Fig. 2 shows flow curves for an oil-based fluid with a polymeric rheology additive. There are two notable differences with the flow curves of Fig.1. The transition to shear-thinning behaviour is less well defined, and the stress values increase with waiting time. For the fluid with the organoclay rheology additive, at each shear rate, stress decreases with increasing time, whereas for the fluid with polymeric additive the opposite is true. The former is consistent with the existence of

a structure formed by the organoclay particles and water droplets, whereas the latter may be indicative of the evolution with time of the viscoelastic properties similar to those observed by Herzhaft[6].

Some of the test fluids, particularly those containing more than one type of rheology additive, exhibit stronger time-dependencies. It is found that a 2-minute waiting time at each point was sufficient for all fluids to reach equilibrium.

Fig. 3 shows the viscosity profiles for a number of the test fluids. Although the fluids are formulated to produce a 3-rpm Fann viscometer reading of 4 – 5 Pa, the profiles are very different. The differences become more significant at shear rates below 1 s^{-1}. This is due to the fact that a wide range of clay-type and polymeric rheological additives are used, with some fluids containing both types of additives. Some of the fluids exhibit a relatively sharp transition to shear-thinning behaviour, while for others, the shear-thinning behaviour extends to lower shear rates than that shown in Fig. 3.

For each fluid, the linear viscoelastic region is determined by performing a strain sweep at 1 Hz. Fig. 4 illustrates typical plots obtained for the clay-based and polymer-based test fluids.

Both types of fluid produce a linear response below 1% strain. The viscoelastic properties of the fluids vary from more elastic at very small deformations to more viscous at larger deformations. The polymer-based fluids become more liquid-like at smaller deformations than the clay-based fluids.

The frequency sweeps for an oil-based drilling fluid with a clay-type rheology additive is shown in Fig. 5. The fluid has the characteristics of a viscoelastic material – it behaves like a viscous liquid at lower frequencies, and develops elastic properties at higher frequencies. The oil-based fluids of these tests vary in the values of G' and G", and in the frequency of the crossover point, or the relaxation time.

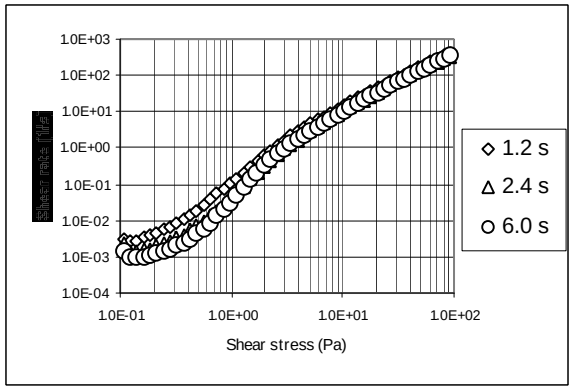

Figure 2. Effect of waiting time on the flow curve of an oil-based drilling fluids with polymeric rheology additive.

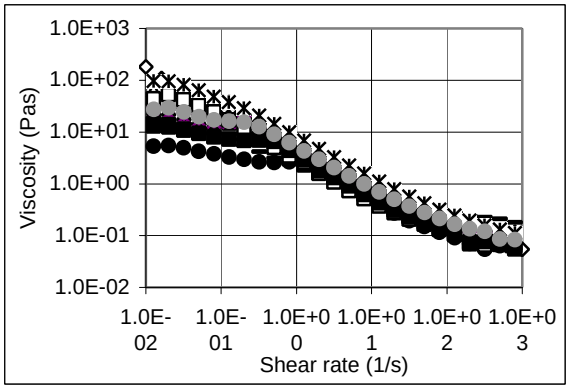

Figure 3. Viscosity profiles of a number of test fluids at 20°C.

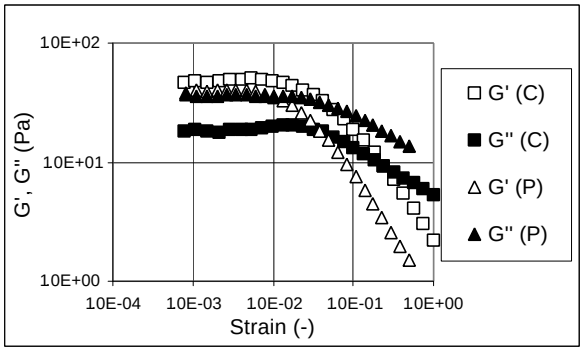

Figure 4. Typical strain sweeps for oil-based fluids with clay-type (C) and polymeric (P) rheology additive.

Sag measurements.

A summary of the dynamic sag measurements made to date is shown in Fig.6. Both methods show a large variation in the sag performance of the fluids. This is despite the fact that the fluids are formulated to a 3-rpm Fann viscometer reading of 4 – 5 Pa. The sag values measured by the two methods are different. This is due to a combination of temperature, shear rate and, in particular, the volume of sheared fluid. It is found that the VST values would approach those of the SCR method if the duration of the test is increased to two hours or longer. As seen in Fig. 6, the two methods show different sag trends for the test fluids. The reason for this is not clear at present. More tests are needed to establish the cause.

Since the test fluids are formulated to a 3-rpm Fann reading of 4 – 5 Pa, there is insufficient difference in the 3 and 6 rpm readings of the fluids to plot against the sag data. The same is true of the LSRYP as given by Eq. 4. However, the readings at 100 rpm, which is the rotational speed of the VST method, show more variation and are more accurate. These are plotted against the VST sag results in Fig. 7.

There is too much scatter in the data of Fig. 7 to obtain a correlation. But the apparent trend (*i.e.*, lower sag values at higher viscosities) suggests that there may exist an aspect of rheology that influences sag directly. This study aims to explore this possibility by looking for a correlation between sag and low-shear-rate rheological properties of the fluids. These will be various parameters extracted from carefully constructed, controlled-stress flow curves.

A similar scatter is evident when the sag data are plotted against G'. Fig. 8 and Fig. 9 show the measured density variations vs. G' at 1 Hz for the two test methods. Both plots show significant scatter, but there is a definite trend in the variation of density change with G' at 1Hz.

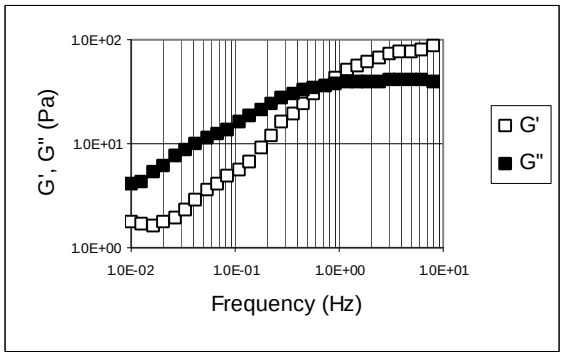

Figure 5. Frequency sweep for a clay-based test fluid at 25°C.

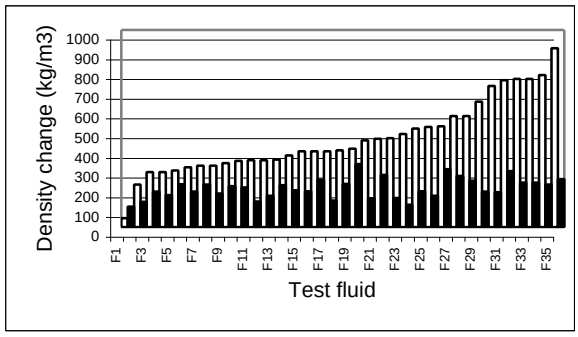

Figure 6. Density variations measured by the modified Jefferson VST method at 50°C (black bars) and the SCR device at ambient temperature (white bars).

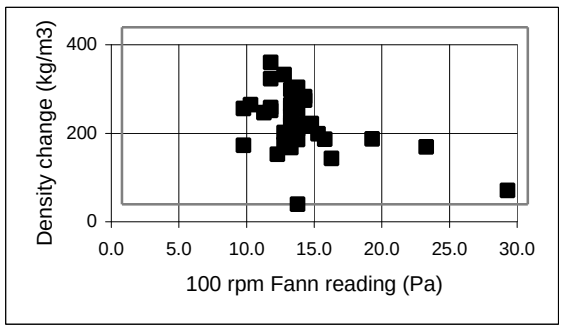

Figure 7. Dynamic sag results measured by the VST method.

The comparisons shown here are only the first step in investigating the relationship between sag and viscoelastic properties. It is perhaps likely that the frequency dependence of G' may be a factor to consider when correlating sag with viscoelastic properties.

Other possibilities are that the relative values of the elastic and viscous moduli or the relaxation time of the mud systems may be of importance. Detailed investigation of these and other possibilities is underway.

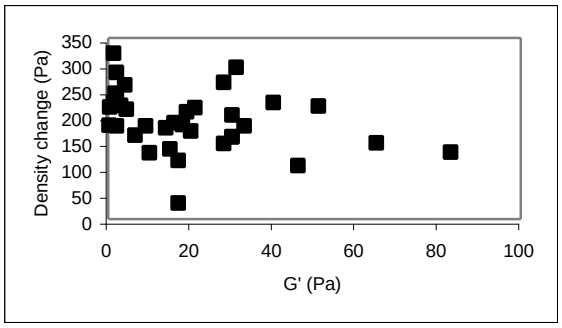

Figure 8. Sag results for the VST measurements at 50°C.

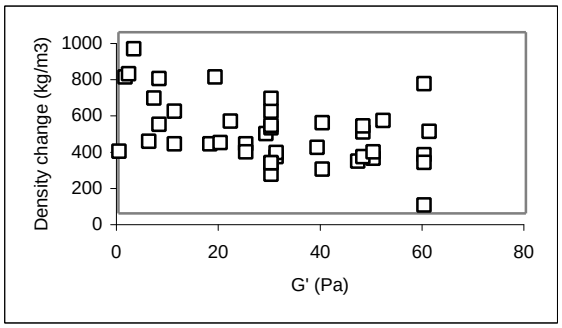

Figure 9. Sag results for the SCR measurements at ambient temperature.

From the experimental perspective, there are two important points to note:

1) Utmost care is required to perform accurate viscoelastic and steady low-shear-rate measurements on oil-based drilling fluids. The stability of the invert emulsion and its homogeneity are critical for the accuracy of the measurements.

2) Dynamic sag measurements of the type described here tend to show relatively poor reproducibility. Several repeat tests are required to ensure that measurements are representative of the sag performance of the fluid.

CONCLUSIONS

The initial stages of a study to find a link between barite sag and fluid rheology are described. Data obtained to date show that a trend exits between dynamic sag and rheology, but the data are too scattered to suggest a correlation. The oscillatory measurements, in particular, are promising. It is expected that refinement of the measurement techniques and a more detailed study of the data may lead to finding a correlation between sag and rheology.

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