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Laboratory Investigation of Barite Sag in Drilling Fluids

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ABSTRACT

Barite sag in drilling fluids is a well-known cause of operational problems in the oil well drilling industry[1,2,3]. As part of an investigation into this phenomenon under the auspices of the American Petroleum Institute, a study of the rheological properties of a series of laboratory-prepared drilling fluids was undertaken to investigate the variations resulting from the use of different measuring equipment and into the degree of reproducibility and repeatability that could be achieved when different laboratories measure the same fluid.

INTRODUCTION

At the rig-site, the rheological properties of drilling fluids are typically monitored in relatively simplistic ways during the drilling process and this, combined with the poorly understood effects of shear, temperature and pressure on these properties, can result in situations where the fluid structure is insufficient to suspend the weighting materials suspended in the drilling fluid. This leads to undesirable density stratification in the drilling fluid, known generically as "barite sag" which can occur under either dynamic or static (non-flowing) conditions. For convenience in this paper, the term "barite sag" will be used to indicate settling of any weighting material used in a drilling fluid, regardless of its chemical composition.

Despite the relative frequency of barite sag incidents during oil-well drilling, there is still some debate within the industry about how best to monitor the rheological properties of drilling fluids to predict or detect the early onset of sag. This situation is made more difficult by the fact that many rheometers are not designed to work in conditions prevailing at the rig-site.

A study involving the measurement of various rheological properties of a series of laboratory-prepared drilling fluids was undertaken to provide some insight into the variations resulting from the use of different measuring equipment and into the degree of reproducibility and repeatability that could be achieved when different laboratories measure the same fluid. In addition, the data collected were analysed in a simple way to determine if there was any particular shear rate at which viscosity could best be measured in order to assess a fluid's potential for barite sag under dynamic conditions. A variety of equipment types, ranging from sophisticated rheometers to oilfield viscometers which are simple in design but robust enough for field use, was used to measure the properties of the test fluids. These fluids were specifically designed to exhibit a range of rheological properties, to include fluids characterised as having low and high dynamic barite sag potential.

SAMPLE DESIGN AND PREPARATION

A non-Newtonian oil-based drilling fluid was used as the model for this study. Such fluids are typically emulsions of calcium chloride brine in mineral oil containing barium sulphate (barite) suspended with a suitable viscosifier. A base fluid was

designed with sufficient viscosity that the barite remained evenly suspended in a standard settling test under static conditions. Samples of this base fluid were diluted with different quantities of oil to lower the viscosity profile by varying amounts such that different degrees of static settling of barite were observed. Test samples of the various fluids were prepared at a single location and then shipped to the participating laboratories for evaluation.

The composition of the base fluid is shown in Table 1. It has a density of 1.68 g/L, an oil to water ratio of 80:20 and an internal phase salinity of 175 g/L chlorides.

Table 1. Base Fluid Composition

Component	(g/L)
Mineral oil	413.6
Emulsifier (polyamide)	30.0
Viscosifier (organophilic clay)	20.0
Water	182.7
Calcium chloride	55.3
Barite	945.5
Simulated drill solids	85.7

Samples of the base fluid were diluted with base oil to varying degrees (3%, 6% and 12% by volume) and sufficient barite was added to each diluted sample to return the density to the original value of 1.68 g/L.

The simulated drill solids were an equal mixture of kaolinitic clay, calcium carbonate and sand.

EQUIPMENT DETAILS

Seven different laboratories participated in the study. The companies involved and the equipment used are detailed in Table 2.

The criteria established for participation in the study in terms of equipment suitability are listed below

- Measurement of viscosity at shear rates of $0.1s^{-1}$ or lower.
- Delivery of accurate and steady shear rate at low speed combined with accurate viscosity measurement.
- Measurement of solids laden fluids (up to 25% by volume suspended solids).
- Measurement of viscosity at 120°F [49.1°C] (drilling fluids industry standard).
- Ability to make continuous viscosity measurements during a shear rate sweep.

Table 2. Companies and Equipment Participating in the Study

Company Name	Equipment
Grace Instrument Company	Grace M3500a-1
Anton Paar	Physica MCR101
Brookfield Instruments	Brookfield PVS
Malvern Instruments	Bohlin Gemini
OFITE	OFI Model 900
Baker Hughes Drilling Fluids	RJF Viscometer
Kelco Oilfield Group	Brookfield PVS

The equipment listed in Table 1 varies considerably in cost and functionality with the machines from Anton Paar and Malvern being identified as generally unsuitable for use on a drilling rig.

RESULTS

Equipment Comparison

The viscosity plots from each instrument were combined into single graphs for each fluid tested. The results for the base fluid are shown in Figure 1 and for the 12% oil dilution in Figure 2. In these and the intermediate cases, there is broad agreement between the different machines, particularly at intermediate shear rates. The shear-thinning nature of these fluids means that recent shear history will affect the viscosity of the fluid and this may account for the variations seen at high shear. Not all laboratories had access to the same mixing equipment and therefore sample preparation could not be standardised.

The variations seen at very low shear rates (<0.1 sec^{-1}) are almost certainly due to

the difficulties of making measurements on solids-laden fluids, particularly when they are prone to some degree of solids settling.

Figure 1. Viscosities of the Base Fluid

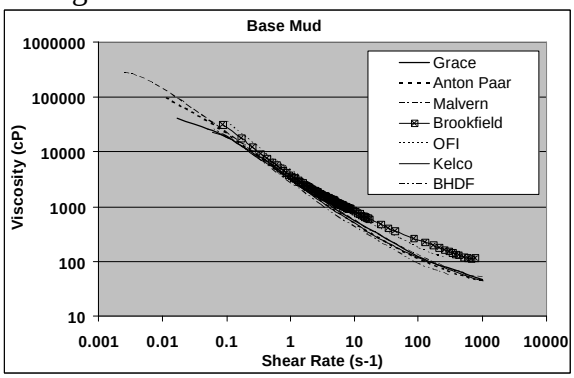
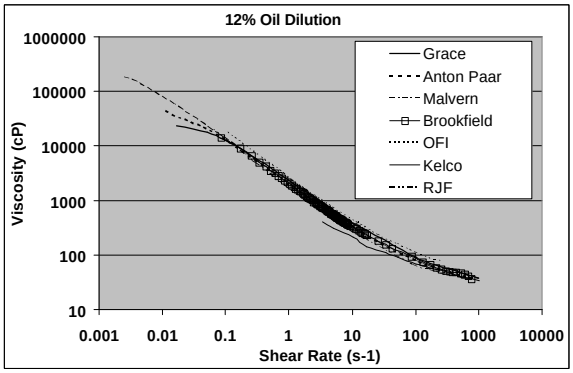


Figure 2. Viscosities of the Base Fluid after a 12% Oil Dilution



Effect of Shear Rate

One of the aims of the study was to attempt to determine whether there was any particular shear rate range at which the differences in sag potential would be most evident in differences in viscosity.

Previous work[4] has identified that the shear rate range 0.17 – 1.7 sec^{-1} is most likely to serve as an indicator for dynamic barite sag potential. These authors identified shear rates corresponding to the onset of dynamic barite sag in flow loop tests, and then developed a correlation between drilling fluid viscosity and dynamic sag potential at equivalent shear rates. Effectively, this model is an indirect test for dynamic barite sag in that the model is based on viscosity levels, at appropriate shear rates, required to manage dynamic sag. At 1.7 sec^{-1}, the ideal viscosity range was proposed to be 1,500-2,500 cP and at 0.17 sec^{-1} it was proposed to be 12,000-20,000 cP[5].

Table 3 shows the percentage drop in viscosity for each of the oil dilution samples relative to the base fluid at 5 different shear rates. Each figure is an average of the different measurements made by different companies with different equipment.

Table 3. Percentage Changes in Viscosity Due to Oil Dilution Measured at Different Shear Rates

	Oil Dilution		
Shear Rate	3%	6%	12%
1000 s^{-1}	-13.4	-22.1	-31.6
100 s^{-1}	-11.4	-20.6	-37.4
10 s^{-1}	-10.7	-20.1	-41.6
1 s^{-1}	-12.6	-19.9	-38.5
0.1 s^{-1}	-17.6	-21.9	-39.9

At all shear rates, the results show the expected trend of larger drops in viscosity being associated with larger dilutions of the base fluid with oil. However, there is no significant difference in degree of viscosity change at any of the shear rates investigated.

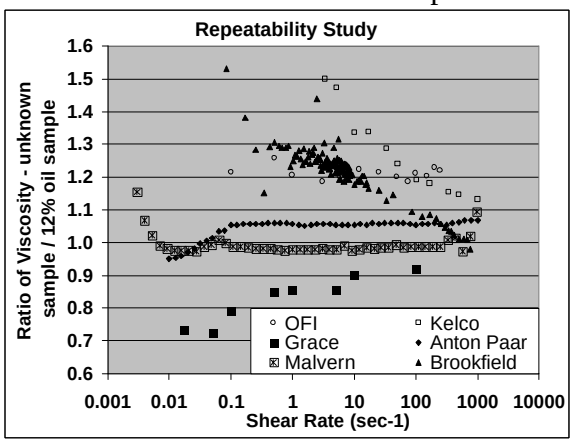
Repeatability

In addition to the four test samples described so far, each laboratory was sent a fifth sample marked as “unknown”. This was in fact identical to the sample which had been diluted with 12% oil and the intent was to obtain an indication of the repeatability of the measurements when the same fluid was measured by the same person on the same equipment following an identical form of sample preparation.

The data collected from six companies was analysed by plotting the ratio of measured viscosity for the unknown sample to the 12% oil dilution sample as a function of shear rate. The results are shown below in Figure 3.

Only two machines produced numbers close to the theoretically expected result over the majority of the shear rate range, these being two of the most expensive and sophisticated machines involved in the study.

Figure 3. Viscosity Ratios for the Unknown and 12% Oil Dilution Samples



These results are not intended to imply criticism of either the operators or the other machines used in the study but they do highlight the difficulty of working with unstable systems. The 12% oil dilution sample was chosen as the unknown as it was the least stable (i.e. most prone to barite sag) and therefore presented the greatest challenge to repeatability testing.

There is an obvious trend of decreasing repeatability as the shear rate is reduced implying that in systems like the one tested, factors affecting the rate of particle settling and consequent loss of homogeneity cannot be readily replicated.

The optimal viscosity ranges for drilling fluids at low shear rates referred to above are based on a ±25% range about the mid point but even with this degree of latitude, it would appear that many machines would not be able to reliably differentiate between fluids inside and outside this range at low shear rates.

Elastic and Viscous Moduli

Measurement of the viscous and elastic moduli in drilling fluids is not common except during research activities and oscillatory rheometers capable of making such measurements are not found in field locations due to the unsuitable working environment. These viscoelastic properties are characterized from non-destructive tests of structural networks developed by drilling fluids at rest. One company involved in the study did make these measurements on all five fluids and the results are shown in Figures 4 and 5.

Figure 4. Strain vs Elastic Modulus

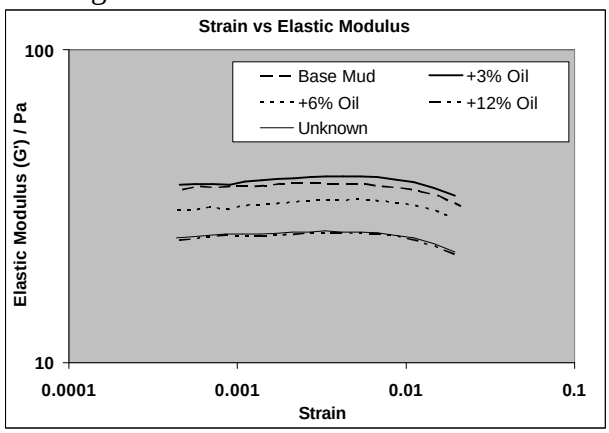
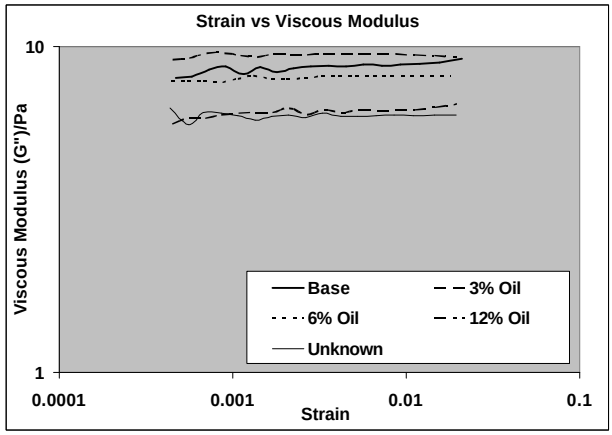


Figure 5. Strain vs Viscous Modulus



Both graphs show the expected trend of decreasing viscosities as the degree of oil dilution increases with the exception of the smallest oil dilution (3%) where there is a small increase in the modulus in both cases. The percentage change in values for the diluted samples with respect to the base is of the same order as the change in conventional viscosity and on this basis, it does not appear

that G' (elastic modulus) or G? (viscous modulus) are especially helpful in differentiating between fluids which do and do not exhibit a significant tendency towards sag.

Other Data

A range of other techniques were also used to analyse the samples of drilling fluid. These included standard 6-speed oilfield viscometer (Fann 35) data, static and dynamic sag testing. The results are shown in Table 4 and the methods used are described briefly below.

The Fann 35 6-speed viscometer has been the oilfield standard viscometer for measuring rheological properties of drilling fluids since the 1950s. It is a concentric cylinder (Couette) device operating at 6 different shear rates between approximately 5 and 1000 sec^{-1}. Standard parameters obtained from the dial reading are plastic viscosity (PV) and yield point (YP) based on the Bingham Plastic model.

Testing was also conducted using the Fann 35 viscometer in conjunction with a "sag shoe". This is a device, designed to produce a direct measure of dynamic barite sag, which is placed in the heating vessel containing the fluid under test and which is designed to accelerate the settling of particles under dynamic conditions and collect them in a "well" at the bottom of the device to assist in sampling. Full details of the sag shoe have been presented in the literature[6]. The test involves making density measurements on two samples of a fluid with the sag shoe in place in the heating vessel after exposure to different shear rates (~1000 and ~170 sec^{-1}) and recording the difference between them.

Static sag testing typically involves aging a fluid in a sealed steel cell for 16 hours. In this study the aging temperature was 250°F (121°C). Samples of fluid are then withdrawn from the top and bottom of the fluid column and the Sag Index is calculated as the bottom density divided by the sum of the top and bottom densities; a value of 0.5 would indicate a perfectly homogeneous fluid.

A proprietary device known as DHAST (Dynamic High Angle Sag Tester)[7] was also employed to measure sag under dynamic conditions. The device is a sealed cell containing a rotating bob to provide shear and the capability to expose the fluid to temperature and pressure. The equipment is mounted on a balance such that it tilts when sag occurs as more material is concentrated to one side of the original centre of gravity. The degree of tilt can be measured and the sag rate (in mm/hr) computed.

Table 4. Miscellaneous Viscosity and Sag Data

		Base	3% Oil	6% Oil	12% Oil	Unknown
Fann 35 data	PV (cP)	43	34	32	29	26
	YP ($lbs/100ft^2$)	22	25	21	14	15
Static Sag testing	Sag Index	0.508	0.508	0.536	0.548	0.504
MI Sag Shoe	Density Difference (g/mL @120°F)	0.958	0.916	1.250	1.899	1.366
	Density Difference (g/mL @150°F)	1.141	0.317	0.475	0.833	1.333
Calculated settling rate	DHAST data (mm/hr)	2.36	2.64	2.84	3.22	3.14

While the general trend of these numbers is the same as was obtained from the various viscosity measurements reported above, i.e. thinner fluids with a higher potential for sag as more oil is added, there are some significant deviations highlighting the difficulty of making measurements relating to barite sag. In particular, the large discrepancy between the 12% Oil and Unknown samples in the static sag testing and the mostly "better" numbers seen when using the MI Sag Shoe at 150°F compared to 120°F were unexpected. In terms of repeatability, only the DHAST device gave a reasonably good correlation between the two identical samples.

DISCUSSION

This study was conducted as part of wider investigation into barite sag being carried out by a small group within the American Petroleum Institute's Executive Committee on Standardisation. The charge of this group is to develop a recommended practice for wellsite monitoring of weight material sag. The work reported here has formed an early part of the above charge by advising on the issues and difficulties of measuring sag in drilling fluids in a way which has not previously been attempted. Whilst much of the equipment involved in this study would not be appropriate for wellsite measurements, a method of validating any new wellsite test that is developed will be needed and the lessons learned from this study will be incorporated into the development of that method. Another phase of the API work will be to make measurements on fluids from the field which have been collected during a sag event. The laboratory analysis of these fluids will also benefit from the information reported here.

These results suggest that sophisticated rheometers can give meaningful results in the investigation of sag in drilling fluids but that this is not guaranteed. Some of the variations in results seen in this study when the same sample is measured more than once are greater than the difference in values between a fluid which is relatively stable and one which exhibits a significant sag tendency. This is particularly true when different laboratories are comparing results. Sample preparation and recent shear history are probably the key variables which the inability to properly control led to the results differing from theoretical expectations. Equally, under the right circumstances, simpler and more field-applicable equipment has also been demonstrated to yield valuable results under the right conditions. No attempt was made to support the conclusions reached by Dye *et al*[1] with regard to the optimum shear rate range for detecting barite sag potential because the equipment required for confirmation was beyond the scope of this study. However, despite the fact that the equipment reported in that paper has been widely used by one company to assist in the field engineering of drilling fluid viscosity to prevent sag incidences occurring[8], neither this equipment (the RJF Viscometer as used by BHDF in this study) nor the other machines demonstrated any enhanced differentiation between the different fluids at the proposed key shear rate range. Clearly this is an area worthy of further investigation, which should possibly include expanding the scope of the study to include flow loop devices capable of characterising static and dynamic barite sag under field conditions that include pipe eccentricity, annular flow and hole angle.

CONCLUSIONS

If the confirmation of problems as a precursor to the development of solutions is viewed as a necessary step then the work reported in this paper can be considered a success. Some, but almost certainly not all, of the difficulties involved in quantifying barite sag in drilling fluids and making rheological measurements on inherently unstable systems have been identified.

The development of a standard method of pre-shearing drilling fluids prior to making rheological measurements is almost certain to yield benefits in terms of reproducibility in any further study involving multiple laboratories and/or equipment. Ensuring that testing is carried out by personnel who are experienced in handling drilling fluids will also help in this regard. With the tightening of procedures that these steps would bring, it is likely that much closer agreement between laboratories and equipment could be achieved but the "holy grail" of a single rheological measurement which can be used to determine a fluid's potential to sag under field conditions of use has still not been identified. The search continues!

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