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A Comprehensive Approach to Barite Sag Analysis on Field Muds

Sharath Savari, Sandeep Kulkarni, Jason Maxey, and Kushabhau Teke, Halliburton

Abstract

Barite or weight material sag remains a poorly understood problem for drilling fluids, and prevention efforts related to drilling fluid properties or drilling practices seem inadequate. This paper presents the analysis of drilling fluid field samples that were in use during the work by major operators. These samples were tested for barite sag behaviour using the Dynamic High Angle Sag Tester (DHAST™) tool and a sequence of rheology tests.

The DHAST tool was used to measure the sag rate of drilling fluids under different non-conventional shear rate conditions chosen to closely match sag-prone shearing conditions in the field. All drilling fluids were compared at the selected low shear rates. Results from this analysis compared well with observations made in the field, in terms of sag potential, at specified shear rate conditions.

Rheological tests (flow curve analysis, gel strength, oscillatory amplitude, frequency and time sweeps tests) were also performed to understand the structure building/breakdown process and yielding behaviour of the fluids. These provided several good correlations with observed barite sag performance on the DHAST tool. The most applicable for potential field testing was a simple flow curve analysis at low to ultra-low shear rates. A comparison of the slope of viscosity curve as a function of shear stress revealed an excellent correlation with DHAST tool results, with fluids having a lower slope demonstrating increased probability for sag.

Application of this type of comprehensive analyses can be used to design drilling fluids for minimal barite sag and provide understanding of barite sag in the field.

Introduction

Barite sag or weight material sag is a very well known "term" referring to unwanted variation in drilling fluid density after an extended period of static conditions. This topic is addressed at numerous conferences and a substantial body of literature can be found targeted at deciphering the phenomenon and towards solutions. Papers have discussed barite sag in detail covering topics such as historical understandings, currently available measurement techniques, and numerical predictions for estimating the severity of barite sag in drilling fluids.[1,2]

A quick review of literature on barite sag indicates that drilling fluid rheological properties under high temperature-high pressure (HTHP) conditions and drilling operational practices need to be carefully evaluated in order to understand the occurrence of barite sag in first place or to propose any practical solution to deal the same. The advanced methods of rheological analysis of the drilling fluids to estimate visco-elastic properties,[3] thixotropy and yield stress[4,5] provide detailed information about structural properties of the fluids; these properties are anticipated to be strongly correlated with their sag performance.[6]

Sometimes, putting better efforts and resources into understanding the problem itself may provide a solution that can prevent sag from occurring in the first place. To gain a fundamental understanding of this topic, it is useful to apply a new dimension[7] and consider things other than drilling fluid rheological properties and operational practices. This new perspective is an investigation into the effect of particulates (size and concentration) on the settling of barite.

The objective of this paper is to explore the potential benefits of combining the existing methods of measuring barite sag[8, 9] and drilling fluid's advanced rheological measurements to better understand/monitor sag.

Dynamic Barite Sag Measurements

There have been numerous attempts to measure dynamic barite sag, both in the lab and the field, under HTHP conditions. For the purposes of this paper, the Dynamic High Angle Sag Tester (DHAST) tool was used to measure barite settling rates in tested drilling fluids. In brief, the DHAST setup consists of two test chambers with identical conditions. Each test chamber has a test cell that consists of a hollow tube which holds the shear shaft. Both ends of the tube are closed with the end caps. The test cell is filled with the drilling fluid. During the course of the test, the shear shaft can rotate at different RPM which correspond to different shear rates. The rotation is carried out with the help of a motor to simulate dynamic conditions. The sample cell is enclosed inside the test chamber assembly which allows the heating to simulate bottom hole temperatures and also maintain the other test conditions such as pressure and wellbore angle (typically 45°). More detailed discussion about this sag measuring instrument can be found elsewhere.[8, 9]

Advanced Rheological Measurements

An Anton Paar advanced rheometer was used to perform non-Newtonian rheological measurements on the drilling fluids tested. The various rheological tests performed are described below.

Flow Curve Analysis

In this test, similar to a standard check on a VG meter, the sample was pre-sheared for two minutes before a shear rate sweep from high rates to low rates was performed.[10] Data from the smooth bob was used at rates above ~1-s^{-1} and data from the vane was used at rates below ~5-s^{-1} (above this, turbulence between the vanes creates errors in measurements). The data from the smooth bob and vane are presented as a single, continuous curve.

Gel Strength (by Transient Flow Inception) Test

For this test (which is analogous to the standard gel strength test on a VG meter), the sample is initially pre-sheared for 15 minutes at 100 s^{-1}, followed by a 10-second cessation of flow to allow microstructural bonds to form and an instantaneous step in shear rate (occurring in < 1-millisecond) to 0.1 s^{-1}, held for two minutes, in order to observe the transient start-up flow behavior of the gelled mud. Following this, the mud sample is again sheared at 100 s^{-1} for 5 minutes (breaking down any microstructure in the fluid), followed by 10 minutes of flow cessation and gel growth, and transient step-rate step at 0.1 s^{-1} for two minutes. Finally, the mud sample is sheared at 100 s^{-1} for 5 minutes, allowed 30 minutes of flow cessation and gel growth, and a transient step-rate step at 0.1 s^{-1} for 15 minutes.

Oscillatory Amplitude Sweep

Unlike the previous tests, which are conducted as rotational tests, this test uses sinusoidal oscillations which allow testing of the microstructure without disturbing/breaking the structure. In this test, the sample is pre-sheared at 500 s^{-1} for two minutes followed by flow cessation and microstructure growth for 10 minutes. After this a series of oscillations at constant frequency (1-rad/sec) and increasing strain amplitude (from 0.001% - 1000%) are applied. From this test the extent of the linear viscoelastic region (where measured properties are invariant with strain) is determined for use as a parameter in other tests. This test was performed with the sandblasted plates.

Oscillatory Frequency Sweep

This test uses sinusoidal oscillations at small strain amplitudes (within the linear viscoelastic region) and examines the contributions of microstructure on fluid rheology. The sample is pre-sheared at 500 s^{-1} for two minutes followed by flow cessation and microstructure growth for 10 minutes. After this, a sinusoidal strain is applied over a range of frequencies and the material response recorded. A comparison of the G' (the storage modulus, a measure of the elastic storage of energy in the system), G'' (the loss modulus, a measure of the viscous dissipation of energy in the system) and the complex viscosity is then made to evaluate differences in microstructure. This test was performed with the couette geometry.

Oscillatory Time Sweep

This test uses sinusoidal oscillations at small strain amplitude (within the linear viscoelastic region) and constant frequency, and examines the growth of microstructure in fluid over time. Like the amplitude and frequency sweeps, the sample is pre-sheared at 500 s^{-1} for two minutes; however, no gel growth period is allowed before testing and dynamic rheological properties are measured as the microstructure forms in fluid. The test was carried out for a 2-hour period in order to observe the growth and possible changes in microstructure over time. This test was performed with the couette geometry.

Current Work

Five different non-aqueous based drilling fluid samples were procured from the field for the purpose of the above tests. The samples are labeled as Field Sample 1, 2, 3, 4 and 5 for comparison between the tests. All these samples are conventional organophillic clay-based fluids with varying densities, oil/water ratio (OWR) and base oil type. Below are some of the details of the fluid samples that are used in the sag measuring device and also the differences between the tested fluid samples (**Tables 1-5)**.

Table 1 – Field Sample 1 Properties

Mud weight, ppg	**16.7**
OWR	**83/17**
Base Fluid	**Mineral Oil 1**
ASG	**3.94**
Salt Conc. (wt %:)	**20**

Table 2 – Field Sample 2 Properties

Mud weight, ppg	**17.4**
OWR	**80/20**
Base Fluid	**Mineral Oil 1**
ASG	**3.94**
Salt Conc. (wt %:)	**20**

Table 3 – Field Sample 3 Properties

Mud weight, ppg	**17.2**
OWR	**80/20**
Base Fluid	**Mineral Oil 1**
ASG	**3.87**
Salt Conc. (wt %:)	**16.6**

Table 4 – Field Sample 4 Properties

Mud weight, ppg	**17.5**
OWR	**80/20**
Base Fluid	**Mineral Oil 2**
ASG	**4**
Salt Conc. (wt %:)	**23.6**

Table 5 – Field Sample 5 Properties

Mud weight, ppg	**16.3**
OWR	**74/26**
Base Fluid	**Mineral Oil 1**
ASG	**3.94**
Salt Conc. (wt %:)	**20**

Tests were performed on the above drilling fluid samples, as received, on the sag measuring instrument at 266 °F and 2000 psi. The conditions were selected to closely simulate field conditions. All advanced rheometry tests were conducted at 120°F using either a couette with smooth bob or sandblasted parallel plates (average roughness R_a~3.5 µm). The smooth bob was used for a majority of tests; sandblasted plates were used for repetition of flow curves at low shear rates.

Objective

The objective of the study, sag measurement and rheometry tests, was to relate the behavior of the fluid samples between the two test devices in the lab and in the field.

Results and Discussion

Dynamic Sag Analysis on Fluids

Figure 1 presents the comparison between the sag rates (propensity of tested fluids to sag) of the field samples at tested conditions, 266°F and 2000 psi. All the sag rates reported are from duplicate data to help ensure the reliability of the test data.

Field Sample 2 showed highest initial sag amongst all tested fluids. From the results in Figure 1, Field Sample 4 would exhibit low sag, at tested conditions.

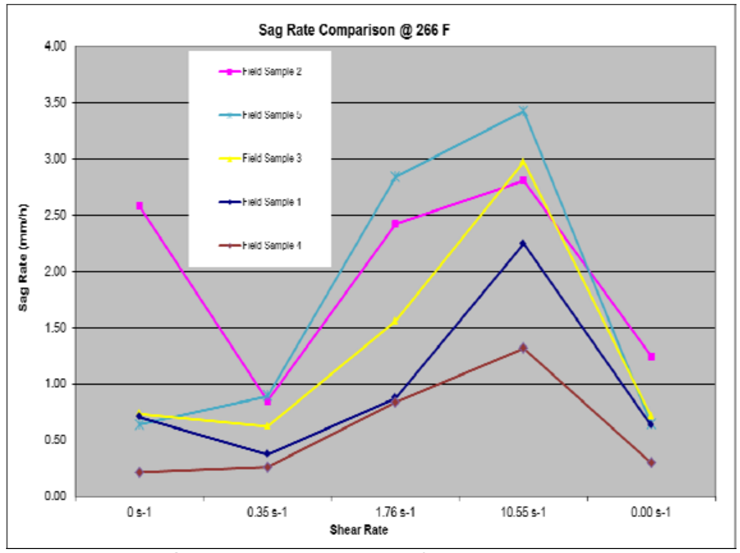

Figure 1: Sag rate comparison on field mud samples.

Advanced Rheological Measurements

Flow curve analysis. From viewing the flow curves as viscosity versus shear stress in **Figure 2**, some significant differentiation between the fluids can be made. First, the slope of the viscosity rise observed in the samples varies, with Field Sample 4 and 1 exhibiting very similar slopes, and the slope for the Sample 5 only slightly lower. The slopes for the Field Samples 2 and 3 were significantly lower.

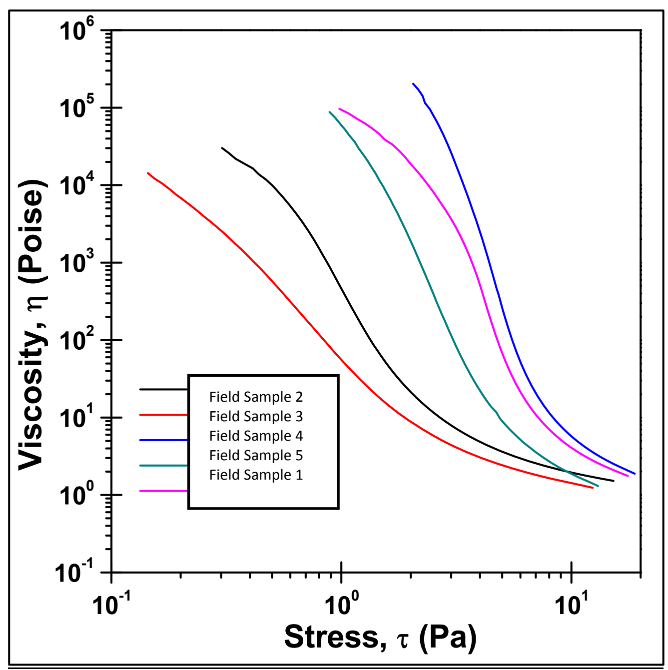

Figure 2: Flow curves from sandblasted parallel plates, presented at viscosity as a function of shear-stress.

This correlates well with the observed sag potential of the samples, with the exception of the Sample 3 which performed slightly better than Sample 2 in sag tests but slightly worse here. In general, it can be observed that the rate at which viscosity increases as the shear stress approaches a yield point is likely a good indicator of the probability of sag events being observed with a fluid.

Gel strength test analysis. Another set of tests performed were the gel strength tests and structural breakdown analysis. The response of the sample to flow initiation in gel strength tests after rest periods of 10-minutes and 30-minutes are presented in **Figure 3**. Only the first 100 seconds of data is shown, as the samples were predominantly at a steady state flow stress at this point. The samples generally followed a rise to peak – the gel strength as commonly reported by API standards – and then an exponential decay over time. Analysis of that decay can be useful in determining the behavior of the mud system. As a note, these tests were performed using the smooth couette geometry. Had more time for testing been available, a cleaner set of data (and thus more accurate comparison of model fits) could have been obtained if the sandblasted plates had been used for these tests. This is due to the error generated by wall slip in the region of the shear rate used for this testing. Nevertheless, good comparisons can be obtained.

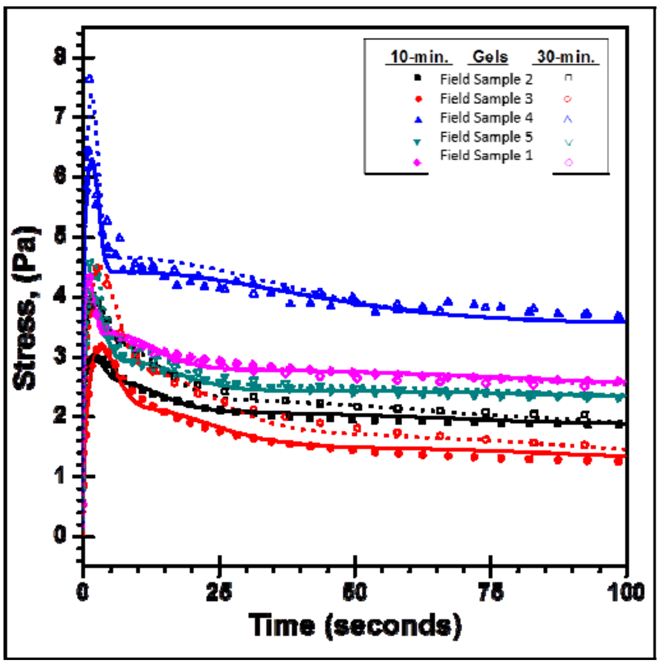

Figure 3: Gel strength tests for the five samples at 120°F after 10-minute (solid symbols) and 30-minute (hollow symbols) gel growth periods. Model fits are presented as solid lines for 10-minute gel tests and dotted lines for 30-minute gel tests.

In order to bring an estimation of the shear history applied to a fluid, a common ***work integral*** function, $\int_0^t \dot{\gamma}(t)dt$, is introduced to all potential forms of a gel breakdown model. The work integral is an integral of the transient shear rate experienced by the fluid as flow is initiated and gel structure is broken down, thus describing a cumulative amount of work which has been performed on the fluid in order to break the gel structure and return to steady state flow conditions. Inclusion of the work integral into a gel breakdown model has the following advantages:

- Parameters for gel breakdown are found to be invariant.
- The same parameters and gel breakdown model can be used in conditions when shear is variable (e.g., when the flow rate changes when gel structure is incompletely broken).
- The effects of shear induced by pipe rotation can be included in the work integral.

Multiple forms of the model could be chosen to do this in order to calculate invariant parameters for gel decay. For this, a combined gel growth and multiple exponential decay model was selected to account for the start-up stress increase due to inertial and motor action and the structural contribution after periods of microstructural growth. The form of the model is as follows:

$$\tau(t) = P_1\left(\int \dot{\gamma}(t)\,dt\right)^{P_2}\left(\sum_i A_i e^{-\left(t/k_i\right)\int \dot{\gamma}(t)\,dt}\right) + \tau_{SS}\left(1 - e^{-k_{SS}t}\right)$$

where k_i are the structural decay constants and can potentially be attributed to microstructural mechanisms for gel formation, and A_i are the weighting functions for each decay mechanism.

The first term in this model, with P_1 and P_2, can be related to structural growth; here it is taken as independent of time, but work could be done to relate this to measured growth of gel strength with increasing rest time. The τ_{SS} term is the steady state flow stress at the test shear rate, and k_{ss} is related to motor inertial response.

Table 6 – Model parameters for the combined stress growth and multiple exponential decay of sample fluids in gel strength tests.

	Fluid Sample 2	Fluid Sample 3	Fluid Sample 4	Fluid Sample 5	Fluid Sample 1
τ_{SS} (Pa)	1.86	1.17	3.52	2.18	2.40
P_1 (10-min / 30-min)	3.01 / 5.67	4.37 / 7.28	9.10 / 11.92	5.22 / 6.64	6.28 / 6.25
P_2	0.44	0.46	0.41	0.46	0.33
A_1	0.65	0.74	0.83	0.81	0.73
k_1	1.07	2.94	0.45	1.10	0.18
A_2	0.30	0.21	0.14	0.16	0.21
k_2	17.31	46.48	18.21	25.43	8.28
A_3	0.06	0.05	0.04	0.03	0.06
k_3	379.75	813.50	683.35	858.32	320.04
k_{ss}	∞	1.84	5.60	4.73	6.07

The values for model parameters for each fluid are presented in **Table 6** above. For this, the test data for a fluid at 10-minute and 30-minute gel growth periods were fit with all parameters in common, with the exception of P_1 which is recognized as a function of rest time which is not accounted for in this model. The parameters were held common because the decay parameters should be invariant and independent of the test, with the same decay followed from a varying peak (gel strength) in the same manner no matter the rest time

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Oscillatory amplitude sweep test analysis. Strain amplitude sweep, the complex modulus, G* (the geometric average of the storage modulus, G', and loss modulus, G'') is examined as a function of stain amplitude (**Figure 4**). This has been previously identified as a possible correlation to probability for barite sag to occur, and indeed a general trend similar to that observed in the viscosity/stress flow curves is observed, with a higher G* in the linear viscoelastic region (LVE, where G* is not a function of strain amplitude) correlating with better static sag behavior in sag testing while G* in the nonlinear region correlating with dynamic sag.

Again, the Fluid Sample 4 clearly exhibits the highest value of G* over the entire test region, while exhibiting the best sag behavior in sag testing. Fluid Samples 1 and 2 are similar in the LVE, slightly lower than Fluid Sample 4; however, G* for the Fluid Sample 2 decreases quickly in the nonlinear region indicating a likely higher probability for dynamic sag. By this measure, Fluid Sample 3 is the worst performing, with G* low in both the LVE and nonlinear regions. Another interesting measure from this test is looking at the point where the fluid leaves the linear viscoelastic region and begins to behave in a nonlinear manner. The stress at this point is often called the dynamic yield stress, τ_0^*, and has also been noted as having correlation with barite sag.

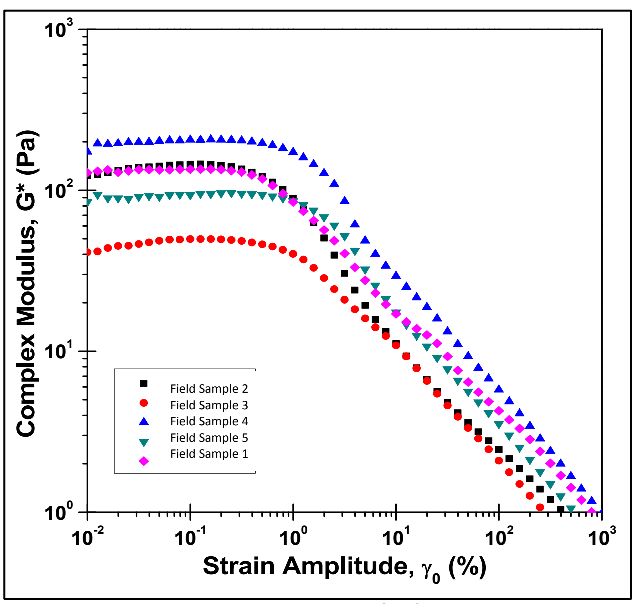

Figure 4: The complex modulus, G*, from oscillatory strain amplitude testing at 120°F.

The data for the LVE transition point is presented in **Table 7** below for the five mud samples, and the dynamic yield stress is again observed to follow the same general trend as the sag performance from sag testing. Fluid Sample 4 has by far the highest dynamic yield stress. The mid-range values for the Fluid Samples 1, 3 and 5 are relatively similar and would require additional measures to interpret. The dynamic yield stress observed for the Fluid Sample 2, however, stands out for its low value as much as the fluid Sample 4 stands out for its high value. This helps to explain the poor sag performance in sag tests of the fluid Sample 2, which requires relatively low stresses to begin behaving in a nonlinear manner, leading to the breakdown of structural dominance in the fluid and less ability to support solids.

Table 7: Extent of linear viscoelastic region and dynamic yield stress for mud samples in oscillatory strain amplitude testing at 120°F.

Sample	LVE Strain, $\gamma_{0,\,LVE}$ (%)	Dynamic Yield Stress, τ_0^* (Pa)
2	0.0889	0.0909
3	1.37	0.38
4	0.545	1.03
5	0.798	0.671
1	0.292	0.404

Oscillatory frequency sweep test analysis. Another measure commonly referred to when relating rheological properties to dynamic sag behavior is the value of the damping function, tan(δ), which is the ratio of G'' to G' and indicative of the degree of elastic or viscous behavior in a material. When tan(δ) is less than unity, the material behavior is dominated by elastic contributions, while a value greater than unity indicates viscous dominance in the system.

For a drilling fluid to provide support of solids in suspension (both drilled cuttings and barite) under near stagnant conditions (when hydraulic transport is negligible) then the fluid should be elastically dominant. Comparisons of this are presented for oscillatory frequency sweeps (**Figure 5**) and oscillatory time sweeps (**Figure 6**). Results in general were similar over both frequency and time domains, with tan(δ) of the Fluid Samples 3 and 2 significantly higher than the other three mud samples. This compares well to the results from sag tests, which indicated that the Fluid Samples 3 and 2 were most likely to experience a sag event. This is not directly reflected in the complex viscosity observed for the samples, where the Fluid Sample 2 is observed to develop the second highest value of η* for the samples. This is strongly indicative that mechanisms other than viscosity controlled Stokes law behavior of the sedimentation process are significant.

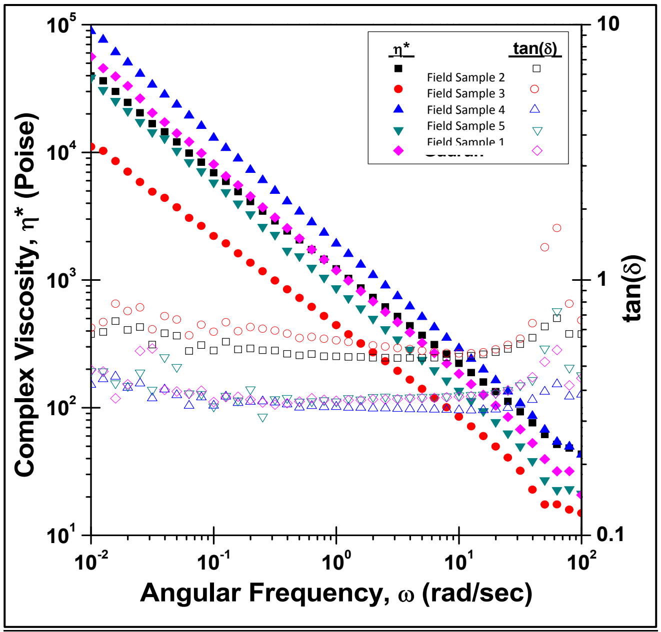

Figure 5: The complex viscosity, η*, and damping function, tan(δ), from oscillatory frequency sweep testing at 120°F.

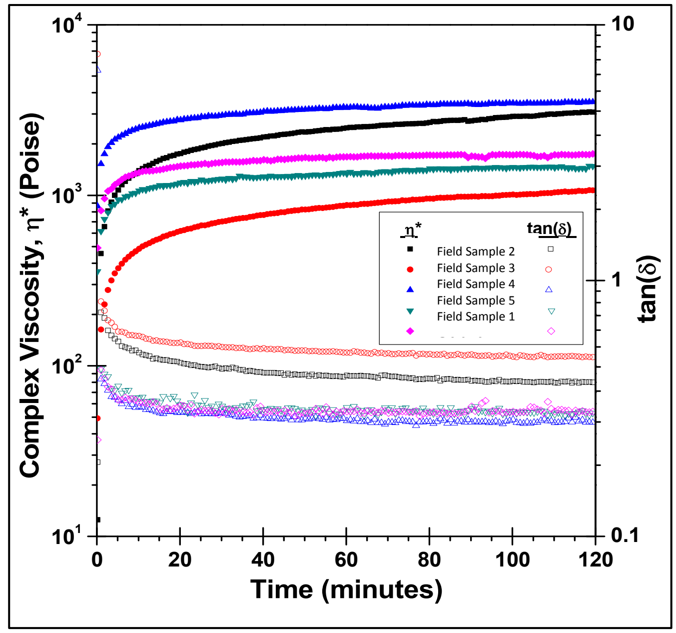

Figure 6: The complex viscosity, η*, and damping function, tan(δ), from oscillatory time sweep testing at 120°F.

Oscillatory time sweep test analysis. An additional observation from the oscillatory time sweep is the rapidity of structural growth and long term stability of the fluid. Structural growth is observed through the initial exponential decrease in tan(δ), coincident with an exponential rise in η*, where the formation of microstructural bonds results in increasing elastic behavior and increased complex viscosity.

Again, these samples were differentiated by how quickly a steady-state gel structure (plateau in tan(δ)) is achieved. Fluid Samples 2 and 3 initially show rapid structural growth, but before a large decrease in tan(δ) is observed microstructure formation begins to slow and actually continues over a very long timeframe. This could be seen as exhibiting progressive gel behavior, yet without achieving significant structural/elastic dominance. For the remaining samples, the microstructural formation occurs rapidly, and then plateaus after ~20 minutes. Corresponding to this, the complex viscosity for Fluid Samples 2 and 3 nearly reaches a plateau, continuing to increase over time – again, this is done without providing significant increases in microstructure – while η* in the Fluid Samples 4 and 1 plateau quickly and Fluid Sample 5 plateaus after a slightly longer time.

Conclusions

- Rigorous rheological measurements and sag testing performed on the drilling fluid samples in tandem could help understand the fluid's propensity towards sag.
- This kind of sag analysis during the fluid design phase could help minimize sag or provide solutions in the event of sag.

Fluid Ranking			
Sag Testing	Flow Curve Analysis	Gel Strength Analysis	Oscillatory Sweep Analysis
4	4	4	4
1	1	1	1
3	5	5	2
5	2	2	5
2	3	3	3

Acknowledgments

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Nomenclature

DHAST = *Dynamic High Angle Sag Tester*
LVE = *Linear Viscoelastic region*

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