

Rheological Analysis of Static and Dynamic Sag in Drilling Fluids

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ABSTRACT

Methods exist for evaluation and mitigation of barite sag in drilling fluids; however, the increased use of non-traditional weighting agents and systems presents increased challenges for fluid design. An indirect evaluation of sag is presented for various types of fluids, using viscometry and oscillatory testing, with and without superimposed shear.

INTRODUCTION

Management of sag in drilling fluids is recognized as a critical problem throughout the drilling industry. While traditionally we speak mostly of barite sag, the issue of suspension of all solids is of equal importance. A drilling fluid must be equally able to suspend the large-diameter cuttings and the much smaller weighting agents used, and fluids have been designed with that in mind.

However, as newer weighting materials, such as hematite, ilmenite, and manganese tetraoxide, find more application the traditional fluid formulations must be changed to accommodate their different physical and chemical interactions in the fluid system. By studying the structural properties of the fluids under oscillatory flow, the suspension of solids may be indirectly evaluated.

Sag has been observed to be more severe in invert emulsion drilling fluids and can occur over a wide range of fluid densities.

The occurrence of sag can lead to multiple drilling complications, including mud weight fluctuations, well-control problems, downhole mud losses, induced wellbore instability, and stuck pipe.^{1,2} These complications lead to increases in both the monetary and environmental costs incurred during the drilling process.

Sag is often observed when circulating the fluid out of the hole after the fluid column has not been circulated for some time, leading to the belief that static settling was the main mechanism for barite sag. However, dynamic sag is more likely to produce large variations in fluid density.^{1,3}

Sag continues to be a difficult phenomenon to measure and control, primarily due to the lack of suitable, industry-accepted test methods for quantifying sag in fluids. Static tests in laboratories are often used, but are time consuming and do not evaluate dynamic sag potential. Additionally, few direct methods for testing static or dynamic sag are employable in the wellsite environment. Low shear rheological properties are often used as indirect measures of potential for dynamic sag (primarily the low-shear viscosity, with some consideration of the storage modulus and loss modulus at low frequency).^{1,3,4,5,6} As a result, control of low-shear rheological properties of the fluid has been found to influence the dynamic sag potential of a drilling fluid.

OSCILLATORY TESTING OF DRILLING FLUIDS

The investigation of the structural properties of drilling fluids through oscillatory testing has been previously reported. Tehrani et al.¹ examined the statistical relationship between the storage modulus and damping function at selected frequencies and the observed dynamic sag of invert emulsion fluids. They found good correlation between these only in the case of fluids viscosified with clays and not for polymeric fluids.

In other work, Maxey⁴ observed the changes in viscoelastic properties with frequency and over long times at low frequencies. A variety of aqueous and invert emulsion fluids were examined for signs of deterioration of structure over time as an indicator of sag potential. This is the approach taken in this work.

Superimposed Oscillations

In addition to traditional oscillatory testing of the fluids, which best characterize the structural behaviour of fluids under static (no-flow) conditions, tests have been performed with oscillations superimposed on a constant stress. In this way, changes in viscoelastic properties can be monitored near the yield stress and when the fluid is actively flowing. This is of interest as drilling fluids are recognized to be highly thixotropic yielding fluids which can build structure while actively flowing.^{7,8}

Despite periodic study over the past four decades, the viscoelastic properties of fluids under shear has received relatively little attention. Fluids can present some unusual behaviour in such tests, including exhibiting a phase angle of greater than 90° and negative storage modulus at low frequencies. These phenomenon have been predicted by models and were experimentally observed by several authors.^{9,10,11,12} Care should be taken when performing such tests, as no commercial instruments allow for a negative storage

modulus and thus will potentially incorrectly interpret raw data.

Test Methods

Fluids were characterized under flow and oscillation using an Anton-Paar MCR301 rheometer equipped with either a double gap couette or profiled parallel plates (flow curves only). The yield stress, σ_Y , of each fluid was determined directly by increasing the stress, after preshearing and a rest period for gel formation, until flow was induced. The dynamic yield stress, σ_{DY} , was determined by increasing the stress amplitude, again after preshearing and a rest period for gel formation, until nonlinearity was observed. Oscillatory frequency and time sweeps were performed at stress amplitudes slightly below the σ_{DY} . For superposition tests, a constant stress was applied up to the measured yield stress.

For comparison, all test fluids were statically aged at 150°F for sixteen hours while placed at a 45° angle. After aging, the free oil was removed from the top of the sample and the density of the fluid at the top of the cell and the bottom of the cell was measured. From this, a sag factor was determined by the Eq. 1.

$$\text{Sag Factor} = \frac{r_{\text{bottom}}}{r_{\text{bottom}} + r_{\text{top}}} \quad (1)$$

For a fluid to exhibit acceptable suspension characteristics, the sag factor should be between 0.50 and 0.53, which allows for some expected and unavoidable settling of solids. A fluid which has a sag factor of greater than 0.53 is considered to have inadequate suspension properties.

Additionally, a flow loop test (previously described by Dye, et al.^{4,6}) was run at angles of 45° and 60° on one fluid in order to determine its dynamic sag characteristics.

Test Fluids

Four invert emulsion fluids of similar density were examined in this study, all containing organophilic clay as the primary viscosifier. Fluid #1 is a lab mud which uses a combination of barite (barium sulphate) and manganese tetraoxide as weighting agents. Fluid #2 is a field mud which includes drilled solids (additional clay) and a polymeric rheological modifier. Fluid #3 is a lab mud representing a generic invert emulsion formulation, and Fluid #4 is the same fluid diluted to contain half the organophilic clay as Fluid #3.

RHEOMETRY AND STATIC SAG

Initially, static sag tests were performed on the four sample fluids and the sag factor of each evaluated (Table 1). For Fluids #1, #2, and #3 the sag factor is below 0.51, indicating a very stable fluid that should not give static sag problems. Fluid #4, which was built with significantly less organophilic clay, exhibits a very high sag factor and visibly demonstrated barite sag in the lab.

Table 1. Static sag performance of the four test fluids.

	Fluid #1	Fluid #2	Fluid #3	Fluid #4
r_{top} (g/mL)	1.68	1.674	1.549	1.693
r_{bottom} (g/mL)	1.741	1.723	1.604	2.196
Sag factor	0.509	0.507	0.509	0.565

Previous work by Dye, et al.^{4,6} correlated dynamic sag of a group of barite-weighted invert emulsion drilling fluids used in field applications to low shear rate viscometry, from which they suggested a sag window as a benchmark requirement (for traditional barite field muds). Fluids whose viscosity profile fell below this window were found to be statistically likely to exhibit barite sag. The viscosity profiles of the four test fluids, compared with this sag window, are presented in Fig. 1. When trying to apply this sag window to static sag, agreement is

found. Fluid #4 falls significantly below the window and exhibits static sag. However, differentiation between Fluids #1, #2 (a field mud), and #3 is more difficult, as Fluids #1 and #2 exhibit significantly greater viscosity than does Fluid #3, yet result in virtually identical static sag results.

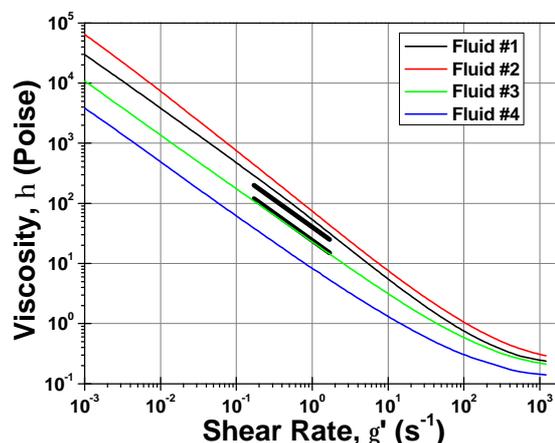


Figure 1. Flow curves for the four test fluids at 120°F, showing the sag window (heavy black lines) of Dye, et al.^{4,6}

In order to better differentiate between the fluids, oscillatory measurements of these fluids were made to determine their structural properties. The results of oscillatory frequency sweeps are presented in Fig. 2 and those of time sweeps in Fig. 3. Samples were presheared, and for frequency sweeps a ten-minute gelation period was allowed, before each test. From the frequency sweep data, variation is observed in the magnitude of G' , with Fluid #4 exhibiting the lowest G' . Fluid #2 has a significantly greater G' , likely due to higher clay content in the field fluid as compared to lab prepared fluids. However, the values of $\tan(\delta)$ are relatively similar for all four fluids indicating little difference in structural dominance over this range of frequencies.

Somewhat more differentiation can be made when examining the oscillatory time sweeps of these fluids (Fig. 3). Typically, during gel growth for drilling fluids, the $\tan(\delta)$ value will initially decrease sharply

and G' will increase over the first few minutes, indicating the growth of structural dominance in the fluid, and then continue to decrease over the first 10 – 30 minutes before levelling out. The degree to which $\tan(\delta)$ continues to decrease after the initial drop translates to what is normally referred to as the flatness or progressiveness of the gel. Once the initial gel structure is built, it is desirable to see that it is maintained over the duration of the test. Any major increases in $\tan(\delta)$ or decreases in G' are notable and indicative of changes in gel structure and/or the settling of solids.⁴ Again, Fluid #2

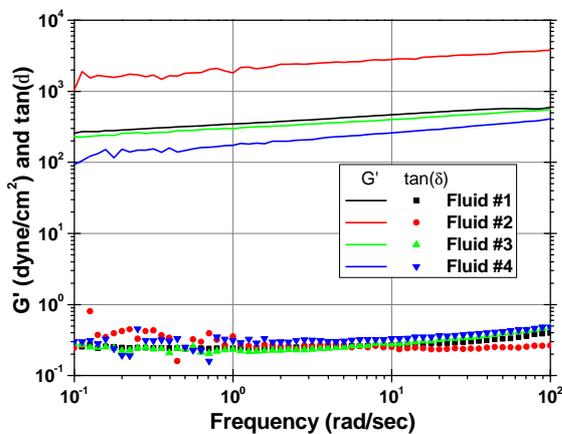


Figure 2. Storage moduli (solid lines) and $\tan(\delta)$ (symbols) from oscillatory frequency sweeps of the sample fluids at 120°F.

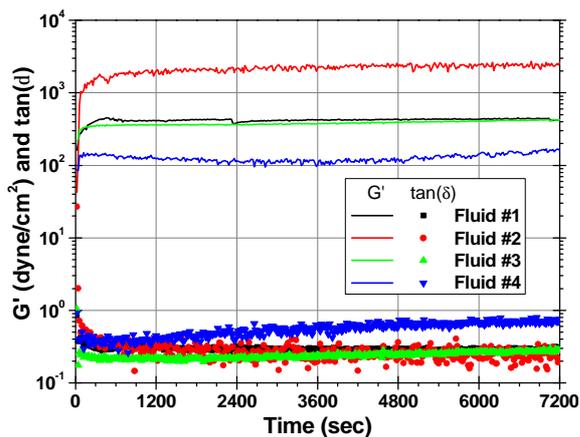


Figure 3. Storage moduli (solid lines) and $\tan(\delta)$ (symbols) from oscillatory time sweeps of the sample fluids at 120°F.

exhibits significantly greater growth of G' over time, while G' for Fluid #4 grows initially and then fluctuates over time, indicating an unstable gel structure. When comparing $\tan(\delta)$ in Fluids #1, #2, and #3, it is observed that all decrease initially and then remain flat over time while that of Fluid #4 begins to increase within the first twenty minutes of testing. With this is observe a possible structural explanation for the differences in static sag observed in Table 1: Fluid #4 builds an initial gel structure, which peaks in strength at ~10 minutes (where the oscillatory frequency sweep was conducted) and then progressively breaks down, becoming more fluid-like and less structurally dominated fluid over time.

SUPERPOSITION AND DYNAMIC SAG

Questions arise as to the validity of the above oscillatory evaluations of sag potential when considering dynamic sag. The above tests examine a fluid under stagnant conditions when gel growth is undisturbed. As previously noted, the greatest sag issues arise under dynamic flow conditions in the annulus; this is particularly true when the drill pipe is not concentric in the hole, channelling the fluid flow and producing a low shear rate section below the pipe. In this regime, the shear rate is low enough that the fluid will develop structure while flowing. If this dynamically formed structure is insufficient, solids suspension will be inadequate and sag will occur.

The dynamic sag of Fluid #1 is presented in Fig. 4. Dynamic sag was measured in a flow loop on a 20-gallon volume of fluid at 120°F, with the inner pipe 58% eccentric and the loop help at angles of 45° and 60°. Results from static sag tests, viscometry, and normal oscillatory tests indicate that this fluid exhibits strong structure and should not have issues with sag. However, under dynamic tests the fluid demonstrated significant sag, with the sag factor increasing above 0.53 below shear rates of

$\sim 5 \text{ s}^{-1}$. This indicates that both the viscometric correlation of Dye, et al.^{4,6} and inferences on gel structure stability from static oscillatory measurements are inconclusive when addressing dynamic sag potential in non-traditional fluids. Qualitative tests on Fluid #3 indicate that it, as well, exhibits dynamic sag. Fluid #2, having been sampled from the field, has not been reported to present dynamic sag problems.

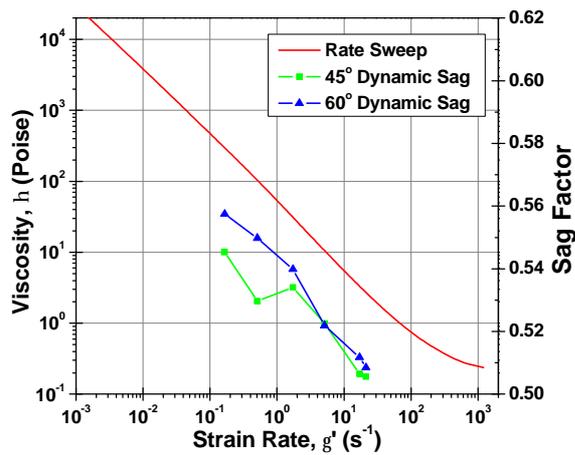


Figure 4. Dynamic sag in flow loop testing of Fluid #1 at 120°F as a function of shear rate below the pipe (solid lines with symbols), along with the viscosity profile.

In order to examine structural stability under dynamic conditions, the superposition of oscillatory tests on a constant stress applied to the sample fluids was investigated. The constant stress is gradually increased to approaching the measured yield stress (i.e. the imposed shear rate is negligible), while oscillations are superimposed at a stress amplitude, σ_a , just below the measured dynamic yield stress (see Table 2). Simply from an examination of the dynamic yield stresses, some tentative conclusions may be drawn. Fluid #2 exhibits a σ_{DY} which is around an order of magnitude greater than that found for the other three fluids. Additionally, as previously noted, Fluid #2 is the only fluid which has not presented potential or

evidence for either dynamic or static sag. From this, it is possible to postulate a connection between the dynamic yield stress and dynamic sag, warranting future investigation of this relationship.

Table 2. Yield stress, σ_Y , and dynamic yield stress, σ_{DY} , of sample fluids (all in dyne/cm²).

	Fluid #1	Fluid #2	Fluid #3	Fluid #4
σ_{DY} (10-min. gel)	1.01	7.35	0.55	0.54
σ_Y (10-sec. gel)	49.1	38.3	22.6	21.7
σ_Y (10-min. gel)	51.0	66.7	23.2	21.4
σ_Y (30-min. gel)	51.4	78.4	–	20.8

The response of the storage modulus, G' , and phase angle, δ , to superposition of constant stress and an oscillatory frequency sweep for Fluid #1 are presented in Fig. 5. As previously noted there is a potential for δ to increase above 90°, which is not accounted for by the controlling software of rheometers. In the case of the Anton-Paar MCR301, the exact behaviour of the instrument under such circumstances is not yet well understood by the author and so no correction for $\delta > 90^\circ$ or negative G' have been made.

For Fluid #1, significant low frequency increases in phase angle are induced with a constant stress of just 7-dyne/cm² and that slight changes are observed at 5-dyne/cm². When inducing a constant stress of above 9-dyne/cm² the phase angle increases to near 90° at relatively high frequencies. Corresponding to these increases in phase angle are dramatic drops in G' , which indicate that structure in the fluid is being easily destroyed at these stresses. With little observed structure in the fluid, at stresses corresponding to very low flow rates, a basis for the observed dynamic sag in this fluid is

found. Without sufficient hydraulic suspension from higher flow rates combined with a fluid not maintaining structure there remains no mechanism for prevention of sag. Additionally, it is observed that the imposed stress at which structural degradation occurs is at 10% - 15% of the measured yield stress of 49.1-dyne/cm². This gives another possible parameter for evaluating the dynamic sag potential, through observation of the ratio of superposed “break stress” (where structural degradation is observed) to the yield stress.

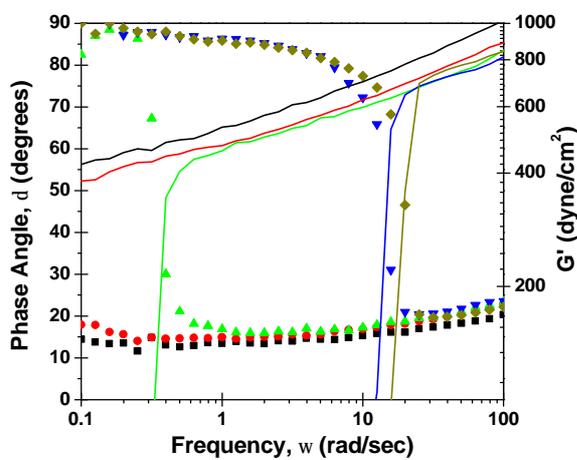


Figure 5. Superposed constant stress and oscillatory frequency sweeps at 120°F and $\sigma_a=0.8$ -dyne/cm² for Fluid #1, showing changes in δ (symbols) and G' (lines) for $\sigma=0$ (black), $\sigma=5$ (red), $\sigma=7$ (green), $\sigma=9$ (blue), and $\sigma=10$ dyne/cm² (yellow).

When examining superposed constant stress and dynamic oscillations for Fluid #2, a similar pattern of onset of structural degradation at low frequencies with increasing stress is observed. However, for Fluid #2, the apparent break stress is between 20 and 22-dyne/cm², or ~55% of the measured yield stress of 38.3-dyne/cm². This greater degree of structural stability likely explains why dynamic sag has not been observed with Fluid #2 while Fluid #1, which has a similar viscosity (see Fig. 1) but less apparent structural stability, exhibits a high degree of dynamic sag.

It should also be noted that for both Fluid #1 and Fluid #2, a uniform decrease in G' is observed below the break stress (see Fig. 5 for $\sigma=5$ -dyne/cm² and Fig. 6 for $\sigma=20$ -dyne/cm²). This decrease in G' has been previously reported.^{9,10,11,12} From this it can be concluded that, while structure is still present in the fluid, the degree of structuring is less than that observed for static oscillatory tests. At imposed stresses above the break stress, the high frequency storage moduli exhibit little differentiation until they approach the critical frequency at which phase angle begins to increase.

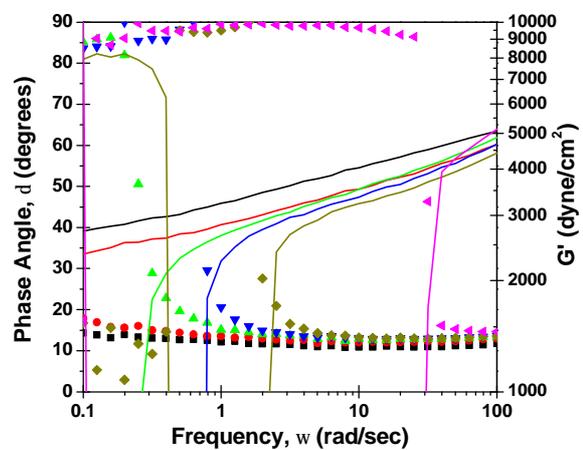


Figure 6. Superposed constant stress and oscillatory frequency sweeps at 120°F and $\sigma_a=7$ -dyne/cm² for Fluid #2, showing changes in δ (symbols) and G' (lines) for $\sigma=0$ (black), $\sigma=20$ (red), $\sigma=22$ (green), $\sigma=25$ (blue), $\sigma=30$ (yellow), and $\sigma=33$ dyne/cm² (magenta).

Further superposition tests were performed employing oscillatory time sweeps combined with a constant stress. The same values of imposed stress from the superimposed frequency sweeps were used for time sweeps. The results of such tests for Fluid #1 and Fluid #3 are presented in Fig. 7 and Fig. 8. Below the break stress the storage moduli initially increase and then remain relatively constant over time while the phase angle initially decreases and then remains constant over time. As previously

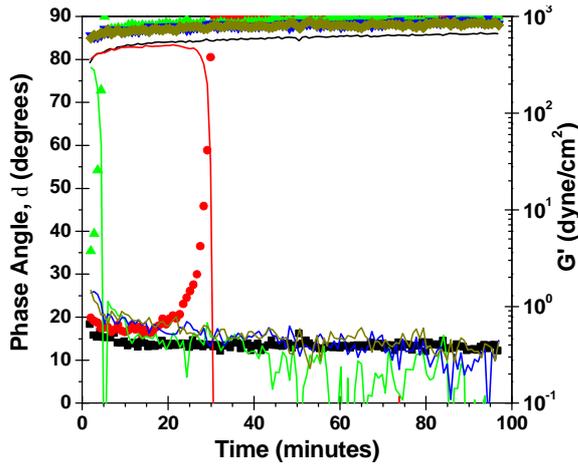


Figure 7. Superposed constant stress and oscillatory time sweeps at 120°F, 0.81-rad/sec, and $\sigma_a=0.8$ -dyne/cm² for Fluid #1, showing changes in δ (symbols) and G' (lines) for $\sigma=0$ (black), $\sigma=5$ (red), $\sigma=7$ (green), $\sigma=9$ (blue), and $\sigma=10$ dyne/cm² (yellow).

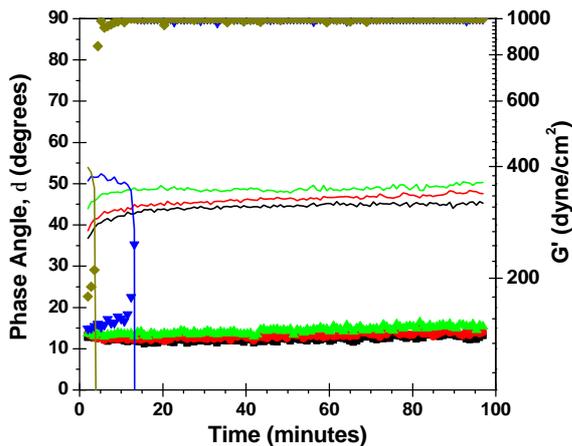


Figure 8. Superposed constant stress and oscillatory time sweep at 120°F, 0.81-rad/sec, and $\sigma_a=0.5$ -dyne/cm² for Fluid #3, showing changes in δ (symbols) and G' (lines) for $\sigma=0$ (black), $\sigma=1$ (red), $\sigma=2$ (green), $\sigma=3$ (blue), and $\sigma=4$ dyne/cm² (yellow).

noted, this is indicative of structural growth and long-term stability. However, when superposed with a constant stress above the observed break stress, an initial structural presence is observed which is less persistent at higher imposed stresses. Additionally, the

storage moduli quickly decrease while the phase angle begins to approach 90°.

It is observed in Fig. 8 that Fluid #3 exhibits a break stress of between 2 and 3-dyne/cm², or ~10% of the measured yield stress of 22.6-dyne/cm². This ratio of break stress to yield stress is similar in magnitude to that found for Fluid #1, and again is significantly lower than that of Fluid #2. Such a comparatively low break stress again explains the apparent dynamic sag observed in this fluid.

CONCLUSIONS

Indirect methods for evaluating sag produce insight into a drilling fluids potential for solids settling. By low shear rate viscometry alone, the potential of a fluid for dynamic sag can be accurately discerned; however, this is only applicable within a specific set of fluid systems for which correlations have been made. Through the observation of both low shear viscosity and oscillatory frequency and time sweeps, the potential for static sag of a fluid can be better inferred. Such a method is not restricted to specific fluid systems, but can be generalized to any fluid tested. However, this best represents the potential for static sag in the fluid and does not adequately characterize the potential for dynamic sag.

One potential avenue for improved prediction is through evaluation of the dynamic yield stress. This method holds the advantage of being a relatively simple and quick test to perform. However, definition of a critical dynamic yield stress will likely be dependant upon the fluid system, particularly on the viscosifier (polymeric verses clay) and weighting materials used, and may not be generally applicable.

The study of drilling fluids under superposed stress and oscillation yields another method for indirect evaluation of dynamic sag. By this method the critical frequency for structural degradation may be observed and the long-term stability of the fluid structure evaluated under conditions

when the fluid is stressed to near-flow and to induced low shear rates. Additionally, another metric, the ratio of break stress to yield stress, may be determined and used to characterize dynamic sag potential.

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